**Circular Economy Practices for Net Zero: Analysis of Barriers in Indian Small and Medium Enterprises Context**

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**Abstract**

Circular Economy (CE) acts as a green technologies approach that helps to achieve the target of net zero through waste reduction, emissions, and improvement of different traditional performance metrics of the organization. Business organizations in developing economies like India still face difficulty in adopting CE in actual practice due to a diverse set of barriers, obliviousness about the criticality of the barriers, and possible actions to mitigate the same. Therefore, this study identifies and evaluates the significant CE barriers for net zero in Indian Small and Medium Enterprises (SMEs). To identify barriers authors used a systematic literature review, and further used expert panel opinions to categorize the same. To investigate CE barriers, the Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP) has been used in this study.A total of 28 barriers are identified and further investigated in this study. Further, it has been found that ‘management support’ and ‘legal framework in the CE journey’ as the most critical barriers to achieving net zero. This research provides a systematic, constructive, and well-organized pathway to decision-makers and industrial practitioners to adopt CE effectively and efficiently in the manufacturing practice to achieve the target of net zero.The study is of the first kind that explores and examines different barriers to CE in Indian SMEs to boost the applicability of CE principles.

**Keywords:** Circular Economy; Net Zero; Manufacturing; Barriers; Sustainability; PF-AHP; SMEs

1. **Introduction**

To make Earth a livable planet for future generations, it is essential to reduce current greenhouse gas (GHG) emissions by 50% (Yadav et al., 2023). This goal aligns with achieving net zero emissions by the middle of this century. Net zero entails reducing global GHG emissions to as close to zero as possible (Das and Ghosh, 2023). Achieving net zero requires a comprehensive transformation in how we produce, consume, and transport. Global industrial organizations must set short-term goals that prioritize immediate emission reductions. Additionally, these organizations need to adopt innovative and sustainable practices to meet net zero targets and enhance organizational environmental sustainability (Mubarak et al., 2021). Keeping into account considerable savings of energy, waste, and effects, the circular economy (CE) approach can potentially contribute to achieving organizational sustainability.

The current trend shows that the manufacturing industry is facing challenges to reduce current emissions of pollutants due to increased intergovernmental pressure and different pacts to environmental protection (Ghosh et al., 2022; Howard et al., 2022.). The issues of waste generation, GHGs emissions, and resource scarcity are on prominent challenges to sustain in the global market (Malik et al., 2022; Mishra et al., 2022). Industries are looking to adopt a more sustainable and innovative strategic approach to tackle these issues related to sustainability and move towards net zero emission of GHGs. For this CE can work as a sustainable alternative to the earlier dominant economic model to reduce the emission of GHGs. It incorporates the 6Rs (reduce, reuse, repair, redesign, recycle, and remanufacture) and keeps resources in a closed loop that consequently results in improved organizational sustainability (Kumar et al., 2019; van Bueren et al., 2022).

European countries are pioneers in the adoption of sustainable practices like CE. They have well-established norms for CE embracing in supply chain (SC) administration (Merli et al., 2018). Business organizations in European nations have attained SDGs by adopting CE. Emerging economies, such as India, continue to struggle with integrating CE throughout the SC of Indian SMEs (Lahane et al., 2020). This can be attributed to not adoption of stringent laws, regulations, and norms for adopting CE in existing SC practices. India has been ranked fifth in the generation of e-waste globally (Goyal et al., 2018). The adoption of CE practices within India SMEs can improve the environmental sustainability in significant way. Thus. Indian SMEs have to adopt CE practices with their operations and system to cope with the challenges related to waste and emission of GHGs. There is a need to develop and formulate stringent strategies for the effective adoption of CE in the manufacturing SC management of Indian SMEs. Based on the issues mentioned above of unsustainability, implementation of CE is a challenging task for manufacturing organizations in India due to several barriers that hinder its adoption. Thus, there is a need to realize and assess the CE barriers from the perspective of Indian SMEs.

For this, present study tends to answer the following research question: "What are the key barriers to CE adoption in the context of net zero for Indian SMEs and how to mitigate the same for improved circularity? This research utilizes the Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP) technique to anayze the barriers of CE. The standard analytical hierarchy (AHP) method is inadequate for managing the hesitancy and ambiguity associated with subjective human opinion (Çalık, A.et al, 2021). Therefore, this study incorporates Pythagorean fuzzy sets (PFSs) into the traditional AHP approach. PFSs enable experts to provide their perspectives on a certain decision-making issue.

The paper is organized into seven sections including the introduction. The second section provides a brief literature assessment on CE adoption difficulties. This research's methodology is described in section 3. The fourth section demonstrates that the proposed research paradigm applies to the Indian manufacturing industry. Section 5 illustrates the result and discussion. Section 6 provides important implications and recommendations to the policymakers. Section 7 presents the conclusions, limitations and future aspects of the study.

1. **Literature review**

The global socioeconomic situation influences industries to adopt sustainable business practices to make their operations and SCs more sustainable (Mohan et al., 2024). To remain competitive in today's economic environment, industries are implementing new and strategic sustainable frameworks into their existing production processes and SC practices. This is because traditional manufacturing operations from the birth of a product to supply to customers generate an enormous amount of waste through unsustainable business practices. It creates several issues of unsustainable development, such as GHGs, scarcity of resources, climate change, and ecological unease in industries (Jaeger and Upadhyay, 2020). Thus, enterprises need to have an efficient and more sustainable manufacturing and SC model in their operational activities to tackle these issues. Therefore, CE acts as one of the sustainable solution approaches to this problem of unsustainability. CE works on the value recovery 6Rs principles and primarily focuses on value gain aspects of sustainability (Lüdeke‐Freund et al., 2019). CE practice can be categorized at three levels based on its applicability across the industry. These three levels are micro, meso, and macro.

Developed nations have already taken major leap to endorse the circularity concepts However, developing nation like India still faces the issue of the unavailability of stringent norms for CE adoption. The Indian SMEs have enormous potential to obtain sustainable growth by adopting CE as a sustainable strategy. For this it is imperative to create awareness, interest, and improving knowledge among the stakeholders of the industry. Adoption of CE in the industry is a comprehensive task as it leads to major changes in the system, infrastructure and other allied practices. So, the adoption of CE is not deprived of different challenges or obstacles that lead to the failure of CE program within an organization. Barriers are the aspects that obstruct the adoption procedure of any project in a business organization (Lahane and Kant, 2021b). The literature consists of studies related to CE barriers in different organizations context. For instance, Kirchherr et al. (2018) identified the potential obstacles to CE adoption in the context of the European Union (EU). The research finding reveals that a lack of customer attention is a significant barrier to CE adoption in EU industrial sectors. According to Rizos et al. (2015), the most significant impediment to CE adoption in SMEs is a lack of government assistance, knowledge, interest, awareness, and supply and demand network support. Kumar et al. (2019) recognized the critical CE adoption barriers in the UK and EU manufacturing sectors. This study has identified the financial, social, regulatory, and ecological CE barriers. Gedam et al. (2021) identified the potential CE adoption barriers from the perspectives of the food SC in developing economies. The dearth of technological invention, the nonexistence of estimation of food waste, the lack of financial resources, and high investment costs have been found as the significant barriers to CE execution. Agyemang et al. (2019) examined the facilitators and hurdles to CE adoption in Pakistan's vehicle industries. Unawareness, financial and cost constraints, and lack of expertise are identified as the most significant barriers to CE implementation in the Pakistan automobile industry. Upadhyay et al. (2021) explore the enablers and barriers to CE practice execution from the mining industry perception. Mangla et al: (2018) reported the barriers to CE adoption in the manufacturing industry's SC in developing economies. The lack of funds for CE adoption and investment costs related to production activities are considered important barriers to CE adoption in SC management. Masi et al. (2018) recognized the lack of quality of products, design for circularity, information lacking, and lack of knowledge about CE identifies the most vital hurdles to CE implementation. Lahane and Kant (2021b) evaluated the barriers to circular SC implementation using decision-making techniques. Their study results show that top management's poor support is an important barrier to CE adoption. Rizos et al. (2016) identified the enablers and barriers to CE business model adoption in SMEs of the EU. This study shows that lack of financial resources and lack of technical skills are significant barriers to CE adoption in the business sector of the EU. According to Nasir et al. (2017), the absence of effective planning and administration for CE concepts is the most significant obstacle to CE implementation. Garca-Quevedo et al. (2020) investigated obstacles to the CE in European SMEs. According to their investigation, the most important CE adoption barriers are the convolution of managerial actions and the cost of achieving rules standards. Hina et al. (2022) examined the internal and external barriers to the implementation of the CE business model.

This study distinguishes itself from existing research by focusing on the unique challenges and solutions for small and medium-sized enterprises (SMEs) in developing countries, particularly India, in adopting CE practices. Unlike previous studies that often emphasize developed economies or provide generic insights, this research offers a granular analysis of 28 specific barriers to CE adoption for SMEs, including financial, technological, and cultural obstacles. Additionally, the study provides a comparative analysis of CE practices in India, China, and Brazil, offering cross-contextual insights into how different regulatory and business environments affect CE adoption in developing countries. This comparative approach provides valuable lessons for policymakers seeking to implement CE-friendly regulations. Most existing research on CE emphasizes its application in developed economies with well-established infrastructures, such as the European Union or China. This study, however, explores the adoption of CE in developing countries, with particular attention to Indian SMEs. It emphasizes how CE can be adapted to resource-constrained environments, tackling specific issues like the high short-term costs of CE implementation and the shortage of technological expertise. This focus on SMEs in developing countries is relatively underexplored, and the study adds value by showing how CE can help these businesses innovate within their financial and operational constraints. This study employs the Pythagorean Fuzzy Analytic Hierarchy Process (PF-AHP), a unique methodology for analysing and ranking these barriers. Unlike traditional methods, PF-AHP handles ambiguity and uncertainty in expert opinions more effectively, offering a nuanced understanding of the challenges SMEs face. Finally, the study delivers tailored policy recommendations for SMEs, emphasizing financial incentives, infrastructure development, and collaborative platforms to ease the CE transition. By addressing the specific needs of SMEs, this research adds actionable insights that bridge the gap between theory and practice in developing economies.

A comprehensive body of research on Circular Economy (CE) exists in the literature; however, no study has specifically addressed the barriers to CE in achieving net zero within the context of Indian SMEs. Therefore, it is crucial to identify the CE barriers faced by Indian SMEs. Furthermore, a deeper understanding of each barrier and its impact on CE implementation is essential for its successful adoption. The lack of sustainable practices in Indian SMEs hinders the industry's resilience and the delivery of eco-friendly products. Thus, this study rigorously explores and investigates the barriers to CE in Indian SMEs, aiming to facilitate the achievement of net zero.

1. **Adopted Methodology**

The various phases of the adopted research methodology are as below:

***Phase1: Identify the CE barriers through literature review and experts' input***

In this phase, the barriers to CE (Table 1) implementation are identified and finalized through a literature review and input taken from industrial experts. 28 CE barriers were identified through literature survey and experts' opinions. The expert panel was carefully selected to ensure a diverse and comprehensive representation of industry knowledge. In addition to department heads from production, manufacturing, quality, waste management, and logistics, the panel also included experts from a broader range of departments, such as research and development (R&D), procurement, and sustainability. Experts were selected not solely based on years of industrial experience (minimum of 15 years), but also on their active involvement in CE-related projects, leadership in sustainability initiatives, and expertise in innovation and resource management. This multi-faceted selection criterion ensured that the panel included individuals with both practical experience and specialized knowledge relevant to CE practices. Additionally, the panel represented various organizational levels persons, from department heads to senior managers and CE coordinators, for providing a comprehensive view of barriers across organizational functions. Table 2 depicts the list of the experts.

Upon finalization of CE barriers, the expert panel categorized these barriers into five main criteria, namely financial barriers (FINBs), technological barriers (TECHBs), strategic and operational barriers (SOPEBs), social barriers (SCBs), and regulatory barriers (REGBs), Then, a hierarchy of proposed research framework is developed according to goal, criteria, and sub-criteria of CE barriers.



Fig.1. Methodology adopted

***Phase 2: Determining the weight of CE barriers using the PF-AHP***

In this phase, the PF-AHP technique has been used to determine the relative importance of selected CE barriers. The relative importance weights has been calculated based on a questionnaire form filled out by an expert panel of case organizations. These panelists are tasked with entering their replies into the PC table of primary criteria and sub-criteria of CE barriers using the PF-AHP scale. After several rounds of brainstorming sessions about the criticality of a given problem, decision-making members finally entered their responses in the PC tables of the main criteria and sub-criteria of CE barriers. The identified barriers were ranked through PFS theory to understand its impact on CE Implementation.

***PFSs theory***

For the calculation of criteria weights and standing of options, several decision-making techniques are available. The efficacy of these methods depends upon the nature of the study under contemplation. However, the subjective opinion of experts is very much needed to solve these problems. To address these concerns, Zadeh (1965) designs the fuzzy set, which is characterized by a membership grading function with a value between 0 and 1. Atanassov (1986) then presented the Intuitionistic fuzzy sets (IFSs). It helps to mitigate the uncertainty in the decision-making problem. This set is distinguished by three distinct functions, including membership function, non-membership function, and degree of hesitancy. However, in some instances, these sets do not satisfy the scenario of degrees of membership and non-membership greater than one, because IFSs do not account for this circumstance.

Table 1. CE barriers to Indian SMEs.

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| Key Barriers | Label | Sub-Barriers | Sources |
| Financial Barriers (FINBs) | FINB1 | Lack of economic resources and constraints  | Neves and Marques, 2022;  |
| FINB2 | Lack of monetary benefits in a short period | Malik et al., 2022 |
| FINB3 | Absence of up-front capital expenditures in circular SC management | Lahane and Kant, 2021b  |
| FINB4 | Risks associated to cannibalization  | Neves and Marques, 2022 |
| FINB5 | Lack of incentives, policies, grant, and subsidies from the government towards adoption of circularity practices | Malik et al., 2022 |
| (TECHBs) Technological Barriers | TECHB1 | Lack of technologies for products recovery mechanisms | Malik et al., 2022; Lahane and Kant, 2021c |
| TECHB2 | Nonexistence of ecologically superior measures | Govindan and Hasanagic, 2018  |
| TECHB3 | Lack of technical experts in CE adoption | García-Quevedo et al., 2020 |
| TECHB4 | Lack of technologies to trace the secondary products | Neves and Marques, 2022 |
| TECHB5 | Lack of technology transfer | Kazancoglu et al., 2020  |
| Strategic and Operational Barriers (SOPEBs) | SOPEB1 | Deficiency management commitment and support toward the adoption of CE practices | Urbinati et al., 2021 |
| SOPEB2 | Lack of strategic vision to plan to implement CE activities | Neves and Marques, 2022 |
| SOPEB3 | Lack of organizational infrastructure  | Malik et al., 2022 |
| SOPEB4 | Dearth of CE prototypes and framework to adopt circular practices | García-Quevedo et al., 2020; Agyemang et al., 2019 |
| SOPEB5 | Lack of reverse logistics and industrial symbiosis network | García-Quevedo et al., 2020 |
| SOPEB6 | Lack of enough collection centers for product recovery | Lahane and Kant, 2021b  |
| SOPEB7 | Lack of circular design aspects | Guldmann and Huulgaard, 2020 |
| Social Barriers (SCBs) | SCB1 | Non-availability of prescribed waste practices | Neves and Marques, 2022 |
| SCB2 | Lack of acceptability of sharing business models | Malik et al., 2022 |
| SCB3 | Emotional attachment with end of used products  | Ratner et al., 2021 |
| SCB4 | Low adequacy to use recovered products | D’Agostin et al., 2020 |
| SCB5 | Lack of training awareness campaigns to members of SCs | Urbinati et al., 2021 |
| SCB6 | Lack of awareness, knowledge, skills amongst stakeholders | Malik et al., 2022 |
| Regulatory Barriers (REGBs) | REGB1 | Lack of laws, regulations, policies towards environmental aspects of CE adoption  | Lahane and Kant, 2021c |
| REGB2 | Lack of suitable performance measurement systems | Neves and Marques, 2022; Mangla et al., 2018 |
| REGB3 | Lack of suppliers selection strategies | Neves and Marques, 2022; Lahane and Kant, 2021c |
| REGB4 | Lack of product end of life management directives  | Malik et al., 2022  |
| REGB5 | Lack of environmental management certifications and systems | Neves and Marques, 2022 |

This study suggests using PFSs to handle imprecision and ambiguity in expert-provided information. PFSs are more adept at dealing with uncertainty than IFSs Consider that \_P and v P represent the Pythagorean membership grade, while \_I and \_I represent the Intuitionistic membership grade. It is evident from Figure 1 that all IFS locations are underlined by the equation \_I + \_I = 1. In contrast, every point in PFSs lies along the line 2 P + 2 P = 1.



**Fig.2.** Comparison of spaces of PFSs and IFSs

Thus, PFSs give large liberty to experts to express their opinion on the given problem. Thus, this research employs the PFSs in the classic AHP technique to minimize the biases of human judgment.

Table 2. The list of experts

|  |  |  |  |  |
| --- | --- | --- | --- | --- |
| **Sr No** | **Department** | **Position** | **Role in Industry** | **Years of Experience** |
| 1 | Production | Head of Production | Oversees manufacturing processes, resource allocation, and productivity optimization. | 21 years |
| 2 | Production | Production Supervisor | Manages day-to-day production activities and ensures alignment with targets. | 17 years |
| 3 | Manufacturing | Director of Manufacturing | Manages manufacturing operations, process improvements, and cost control. | 20 years |
| 4 | Manufacturing | Manufacturing Engineer | Supports the development of efficient systems, processes, and machinery. | 16 years |
| 5 | Quality | Head of Quality Assurance | Ensures product quality, regulatory compliance, and process standardization. | 22 years |
| 6 | Quality | Quality Control Manager | Supervises product testing, inspection, and quality improvement processes. | 15 years |
| 7 | Waste Management | Director of Waste Management | Implements waste reduction, recycling initiatives, and resource recovery. | 22 years |
| 8 | Waste Management | Environmental Officer | Develops policies and practices for waste management and environmental compliance. | 16 years |
| 9 | Logistics | Head of Logistics | Oversees supply chain management, transportation, and distribution efficiency. | 17 years |
| 10 | Logistics | Logistics Coordinator | Coordinates logistics operations, inventory management, and transportation schedules. | 18 years |
| 11 | Research & Development | Senior R&D Manager | Leads innovation and product development, focusing on CE practices. | 24 years |
| 12 | Procurement | Procurement Manager | Manages sourcing, supplier relationships, and sustainable procurement practices. | 17 years |
| 13 | Sustainability | Chief Sustainability Officer | Develops and leads sustainability strategies, focusing on CE initiatives and compliance. | 19 years |
| 14 | Sustainability | Sustainability Analyst | Analyzes and tracks sustainability metrics and performance. | 18 years |
| 15 | Finance | Finance Director | Oversees financial strategy, budgeting, and investments in CE initiatives. | 21 years |
| 16 | Finance | Cost Accountant | Monitors costs related to CE implementation and ensures financial efficiency. | 16 years |
| 17 | Human Resources | Head of Human Resources | Manages HR policies and talent acquisition, focusing on CE-driven roles. | 18 years |
| 18 | Human Resources | HR Specialist | Focuses on recruitment and training for CE-related positions and initiatives. | 16 years |
| 20 | IT | IT Systems Analyst | Analyzes and implements IT systems for tracking and optimizing CE activities. | 15 years |
| 21 | Marketing | Marketing Director | Develops CE branding strategies and promotes sustainable products and initiatives. | 18 years |
| 22 | Marketing | Digital Marketing Specialist | Implements digital campaigns to highlight the company's CE efforts. | 17years |
| 23 | Research & Development | R&D Project Manager | Manages CE-focused projects, coordinating teams and ensuring timelines are met. | 24 years |
| 24 | Procurement | Sourcing Specialist | Identifies and negotiates with suppliers for sustainable materials and services. | 19 years |
| 25 | Procurement | Supplier Relationship Manager | Develops and maintains relationships with suppliers to ensure CE compliance. | 18 years |
| 26 | Production | Process Engineer | Works on optimizing production processes to meet CE standards and improve efficiency. | 20 years |
| 27 | Logistics | Supply Chain Planner | Plans and optimizes supply chain processes to minimize waste and improve resource efficiency. | 18 years |
| 28 | Sustainability | Sustainability Coordinator | Assists in implementing sustainability projects and ensuring alignment with CE goals. | 19years |
| 29 | Sustainability | Circular Economy Analyst | Analyzes the company’s performance in achieving Circular Economy goals. | 17 years |
| 30 | IT | Data Analyst | Works on data collection and analysis for tracking sustainability and CE-related metrics. | 16 years |
| 31 | Human Resources | Training Manager | Develops and delivers training programs related to CE initiatives and employee awareness. | 18 years |
| 32 | Finance | Sustainability Finance Analyst | Analyzes financial implications and investments in CE projects and initiatives. | 15 years |
| 33 | Marketing | Brand Manager | Develops and manages the company’s brand image focusing on sustainability and CE messaging. | 17 years |
| 34 | Research & Development | Innovation Specialist | Identifies new technologies and processes to support CE in product development. | 17 years |
| 35 | Manufacturing | Lean Manufacturing Engineer | Implements lean manufacturing processes to reduce waste and improve efficiency. | 19 years |
| 36 | Quality | Compliance Specialist | Ensures all products and processes comply with CE-related regulations and standards. | 18 years |
| 37 | Waste Management | Waste Reduction Specialist | Works on projects to reduce industrial waste and improve recycling efforts. | 17 years |
| 38 | Logistics | Warehouse Operations Manager | Oversees warehouse operations focusing on reducing waste and optimizing inventory. | 18 years |
| 39 | Sustainability | Green Energy Manager | Manages energy procurement and usage, focusing on transitioning to renewable energy sources. | 19 years |

***PF-AHP method***

This study applies the PFSs theory with the AHP method to address the inaccurate and imprecise data acquired from case industry specialists. The PF-AHP approach includes the following steps (source: Lahann and Kant, 2021a):

**Step 1:** Develop a PC matrix B=(b ik) (mn) utilizing the PF-AHP scale about expert opinion (Please See Table 1).

B=(b ik) (mn) is an example of a PC matrix created by an expert's judgement, as illustrated below:

B= $\left[b\_{ij}\right]\_{m×n}$ = $\left[\begin{matrix}b\_{11}&b\_{12}&\cdots &b\_{1n}\\b\_{21}&b\_{22}&\cdots &b\_{2n}\\\vdots &\vdots &\ddots &\vdots \\b\_{m1}&b\_{m2}&\cdots &b\_{mn}\end{matrix}\right]$ (i= 1, 2 … m and j = 1, 2… n)

**Step 2:** Using Eqs. (1) and (2), calculate the differences matrix D=(d ik)

$d\_{ikL}=μ\_{ikL}^{2}-ν\_{ikU}^{2}$ (1)

$d\_{ikU}=μ\_{ikU}^{2}-ν\_{ikL}^{2}$ (2)

**Step 3:** Find Interval multiplicative matrix $S=\left(s\_{ik}\right)\_{m×n}$ using Eqs. (3) and (4):

$S\_{ikL}= \sqrt{1000^{d\_{ikL}}}$ (3)

$S\_{ikU}= \sqrt{1000^{d\_{ikU}}}$ (4)

**Step 4:** Evaluate the determinacy value $τ=\left(τ\_{ik}\right)\_{m×n}$ of the $a\_{ik}$ using Eq. (5):

$τ\_{ik}=1-\left(μ\_{ikU}^{2}-μ\_{ikL}^{2}\right)-\left(ν\_{ikU}^{2}-ν\_{ikL}^{2}\right)$ (5)

**Step 5:** Define matrix of weights, $T=\left(t\_{ik}\right)\_{m×n}$ using Eq. (6):

$t\_{ik}=\left(\frac{S\_{ikL +}S\_{ikU}}{2}\right)τ\_{ik}$ (6)

**Step 6:** Calculate the normalized priority weights, $w\_{i}$ using Eq. (7):

$w\_{i}=\frac{\sum\_{K=1}^{m}t\_{ik}}{\sum\_{i=1}^{m}\sum\_{K=1}^{m}t\_{ik}} $ (7)

**4. Results and Discussion**

In Indian SMEs, the applicability of the proposed research approach is examined. The chosen case manufacturer produces a variety of automobile components and aggregates. This company intends to adopt a sustainable manufacturing strategy to achieve the numerous goals of sustainable development. The effectiveness and applicability of the proposed PF-AHP technique have been performed in Indian SMEs. Case industry XYZ was established in 1996, and more than 5000 employees are currently working there. It has an annual turnover of around 25.7 US dollars and is located in Aurangabad, Maharashtra. The selected case organization manufactures various automotive components like seat cowling, fenders, windshields, fairing, etc. It also manufactured diverse plastic components of home appliances. However, this company is facing issues of waste generation across the whole manufacturing system. The case company doesn’t have the facility to manage these generated wastes. Thus, to deal with and manage this developed waste, organizations need to adopt some sustainable strategies in their manufacturing practices to convert generated waste into valuable resources. As a result, case organizations can achieve several benefits by adopting circularity in existing SC operations. However, adoption of the CE concept in traditional manufacturing and SC is not an easy task for case organizations due to the presence of numerous barriers.

These barriers hamper the adoption procedure of CE in the production system. Hence, the selected case company executives are interested in identifying and realizing the impact of CE barriers on its implementation process. Therefore, this research uses the PF-AHP decision-making technique to assess and prioritize the significant CE barriers based on their relative importance weights. Thus, this research would assist industrial practitioners in knowing the prominent CE barriers and helps to formulate sustainable strategies to mitigate their negative influence on CE adoption.

Utilizing the PF-AHP approach, the relative relevance of certain CE barriers has been determined. The relative relevance weights are derived from a questionnaire filled out by a panel of case organization experts. These panellists are required to enter their replies into the PC table of the primary criterion and sub-criteria of CE barriers using the PF-AHP scale. Members of the decision-making group finally entered their responses in the PC tables of the primary criteria and sub-criteria of CE barriers, following a series of brainstorming sessions concerning the significance of a specific problem. The PC matrix for the primary criteria and sub-criteria of CE barriers is presented in Tables 3 to 8. These tables also provide the weights obtained by every CE barrier and its sub-barrier. The section 3.2 stages are used to calculate the relative relevance weights for each CE barrier. Multiplying the weight of the primary CE barrier by the local weight of each sub-barrier yields the global weight of each CE barrier (Table 9).

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| Table 3. PC matrix for main CE barriers. |
|  | FINBs | TECHBs | SOPEBs | SCBs | REGBs | Weight | Rank |
| FINBs | EE | AI | AI | HI | HI | 0.2456 | 2 |
| TECHBs | AI | EE | LI | LI | HI | 0.1429 | 4 |
| SOPEBs | AI | HI | EE | HI | AAI | 0.2659 | 1 |
| SCBs | LI | HI | LI | EE | LI | 0.1266 | 5 |
| REGBs | LI | LI | BAI | HI | EE | 0.2191 | 3 |

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| Table 4. PC matrix for FINBs sub-criteria. |
|  | FINB1 | FINB2 | FINB3 | FINB4 | FINB5 | Weight | Rank |
| FINB1 | EE | HI | HI | CHI | HI | 0.3362 | 1 |
| FINB2 | LI | EE | CHI | LI | AI | 0.2291 | 3 |
| FINB3 | LI | CLI | EE | HI | VHI | 0.1534 | 4 |
| FINB4 | CLI | HI | LI | EE | CHI | 0.2586 | 2 |
| FINB5 | LI | AI | VLI | CLI | EE | 0.0226 | 5 |

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| Table 5. PC matrix for TECHBs sub-criteria. |
|  | TECHB1 | TECHB2 | TECHB3 | TECHB4 | TECHB5 | Weight | Rank |
| TECHB1 | EE | AAI | VHI | VHI | AI | 0.3694 | 1 |
| TECHB2 | BAI | EE | BAI | HI | HI | 0.1536 | 3 |
| TECHB3 | VLI | AAI | EE | VHI | VHI | 0.3568 | 2 |
| TECHB4 | VLI | LI | VLI | EE | LI | 0.0243 | 5 |
| TECHB5 | AI | LI | VLI | HI | EE | 0.0959 | 4 |

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| Table 6. PC matrix for SOPEBs sub-criteria. |
|  | SOPEB1 | SOPEB2 | SOPEB3 | SOPEB4 | SOPEB5 | SOPEB6 | SOPEB7 | Weight | Rank |
| SOPEB1 | EE | HI | CHI | AI | VHI | VHI | LI | 0.3433 | 1 |
| SOPEB2 | LI | EE | LI | BAI | VHI | VHI | VHI | 0.1137 | 4 |
| SOPEB3 | CLI | HI | EE | VHI | HI | HI | HI | 0.1399 | 2 |
| SOPEB4 | AI | AAI | VLI | EE | VHI | VHI | VHI | 0.0723 | 7 |
| SOPEB5 | VLI | VLI | LI | VLI | EE | LI | VHI | 0.1120 | 5 |
| SOPEB6 | VLI | VLI | LI | VLI | HI | EE | VHI | 0.0844 | 6 |
| SOPEB7 | HI | VLI | LI | VLI | VLI | VLI | EE | 0.1344 | 3 |

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| Table 7. PC matrix for SCBs sub-criteria |
|  | SCB1 | SCB2 | SCB3 | SCB4 | SCB5 | SCB6 | Weight | Rank |
| SCB1 | EE | HI | CHI | CHI | VHI | VHI | 0.4976 | 1 |
| SCB2 | LI | EE | LI | BAI | VHI | VHI | 0.1650 | 3 |
| SCB3 | CLI | HI | EE | VHI | HI | HI | 0.1734 | 2 |
| SCB4 | CLI | AAI | VLI | EE | VLI | AI | 0.0296 | 6 |
| SCB5 | VLI | VLI | LI | VHI | EE | LI | 0.0873 | 4 |
| SCB6 | VLI | VLI | LI | AI | HI | EE | 0.0471 | 5 |

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| Table 8.PC matrix for REGBs sub-criteria |
|  | REGB1 | REGB2 | REGB3 | REGB4 | REGB5 | Weight | Rank |
| REGB1 | EE | VHI | VHI | AI | LI | 0.3345 | 1 |
| REGB2 | VLI | EE | LI | BAI | VLI | 0.0277 | 5 |
| REGB3 | VLI | HI | EE | VHI | LI | 0.2309 | 3 |
| REGB4 | AI | AAI | VLI | EE | HI | 0.1173 | 4 |
| REGB5 | HI | VHI | HI | LI | EE | 0.2895 | 2 |

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| --- |
| Table 9**.** Final weight of sub-CE barriers |
| Main CE barriers | Main CE barriers weight | Sub-CE Barriers | Sub-CE barriers local weight | Global weight | Global rank |
| Financial Barriers (FINBs) | 0.2456 | FINB1 | 0.3362 | 0.0826 | 2 |
| FINB2 | 0.2291 | 0.0563 | 7 |
| FINB3 | 0.1534 | 0.0377 | 11 |
| FINB4 | 0.2586 | 0.0635 | 4 |
| FINB5 | 0.0226 | 0.0055 | 26 |
| Technological Barriers (TECHBs) | 0.1429 | TECHB1 | 0.3694 | 0.0528 | 8 |
| TECHB2 | 0.1536 | 0.0219 | 19 |
| TECHB3 | 0.3568 | 0.0510 | 9 |
| TECHB4 | 0.0243 | 0.0035 | 28 |
| TECHB5 | 0.0959 | 0.0137 | 22 |
| Strategic and Operational Barriers (SOPEBs) | 0.2659 | SOPEB1 | 0.3433 | 0.0913 | 1 |
| SOPEB2 | 0.1137 | 0.0302 | 14 |
| SOPEB3 | 0.1399 | 0.0372 | 12 |
| SOPEB4 | 0.0723 | 0.0192 | 21 |
| SOPEB5 | 0.1120 | 0.0298 | 15 |
| SOPEB6 | 0.0844 | 0.0224 | 17 |
| SOPEB7 | 0.1344 | 0.0357 | 13 |
| Social Barriers (SCBs) | 0.1266 | SCB1 | 0.4976 | 0.0630 | 6 |
| SCB2 | 0.1650 | 0.0209 | 20 |
| SCB3 | 0.1734 | 0.0220 | 18 |
| SCB4 | 0.0296 | 0.0037 | 27 |
| SCB5 | 0.0873 | 0.0111 | 23 |
| SCB6 | 0.0471 | 0.0060 | 25 |
| Regulatory Barriers (REGBs) | 0.2191 | REGB1 | 0.3345 | 0.0733 | 3 |
| REGB2 | 0.0277 | 0.0061 | 24 |
| REGB3 | 0.2309 | 0.0506 | 10 |
| REGB4 | 0.1173 | 0.0257 | 16 |
| REGB5 | 0.2895 | 0.0634 | 5 |

This research adopted the PF-AHP technique for the determination of the weights of CE barriers. Table 9 presents the final global weight of CE barriers. The main CE barriers are ranked based on their importance and weight are strategic and operational barriers (SOPEBs) > financial barriers (FINBs) > regulatory barriers (REGBs) > technological barriers (TECHBs) > social barriers (SCBs). From this results analysis, it has been observed that strategic and operational along with financial barriers influence significantly (50%) CE adoption procedures in context of Indian SMEs. This means that manufacturing organizations in the Indian context need to focus more on these types of CE barriers.

It has been found that SOPEB1 (Lack of top management commitment and support towards the adoption of CE practices) obtained the highest priority among all CE barriers. It has a global weight equal to 0.0913. The support from top executives of the organization is an important factor in CE adoption success as paradigm shifts from linear to CE business model organizations needs huge change in the existing SC system and infrastructure (Lahane and Kant, 2021b). This finding is also supported by the study of Ahmed et al., (2024), they stated in their study that management commitment and support to adoption of CE is vital to achieve the laid objectives of the CE. The FINB1 (Lack of economic resources and constraints) is placed in 2nd position. It is the foremost significant barrier because the implication of all the aspects of circularity in SCs requires substantial financial investments in terms of infrastructure development, procurement of new equipment, types of machinery for product recovery mechanisms, adoption of new technologies, construction of new recycling plants, inventory management of return products, in-house recycling / remanufacturing facilities, etc. (Urbinati et al., 2021). Thus, for effective adoption of CE in manufacturing organizations need to have enough financial sources and capabilities to manage all the aspects of circularity.

 The barriers ‘Lack of laws, regulations, policies towards environmental aspects of CE adoption’ (REGB1) got the third priority in ranking of the barrier. Increased energy demand, and ecological concerns, government agencies must enact strict laws and regulations. Developing economies like India do not have strict ecological laws, policy standards, and regulations to espouse CE in their SC activities (van Keulen and Kirchherr, 2021). Therefore, government agencies and institutions must develop stringent laws and policies to adopt CE effectively in India's manufacturing sector. The fourth most significant CE barrier is FINB4 (Risks associated with cannibalization). It is a challenging task for manufacturing organizations to set the price of recovered products. It directly affects the selling price of new products. This effect is known as cannibalization (D'Agostin et al., 2020). Lack of certifications to ecological protection and systems (REGB5) is placed in the fifth position of weight priority. In industries, the environment management system plays a significant role in environmental management. The sixth vital CE barrier is the non-availability of formal waste management practices (SCB1). Developing economies like India do not have adequate waste disposal facilities and lack formal waste management practices.

The seventh most crucial CE barrier is the lack of monetary benefits in a short period (FINB2). If the organization is looking to gain environmental benefits from CE, it will suffer some losses in terms of financial perspectives for a short period. It raises the industry's short-term cost (Lieder and Rashid, 2016). Thus, a lack of monetary benefits in a short period act as a prominent barrier to CE adoption in SMEs towards net zero. But to cope up with finance gain, one possible approach is the gradual implementation of CE practices, where government agencies and institutions can adopt a phased or incentive-based regulatory framework. Instead of imposing mandatory adoption at the outset, financial incentives, tax rebates, and subsidies could be provided to support SMEs in overcoming initial cost barriers. For instance, case studies from the European Union and China demonstrate that targeted subsidies and public-private partnerships (PPPs) can reduce the financial burden of CE adoption and foster innovation in sustainable business practices (Domenech et al., 2019; Masi et al., 2018). By investing in CE infrastructure and offering low-interest loans or green bonds, governments can create an environment where SMEs can transition without facing overwhelming short-term financial strain. In addition, encouraging collaborative CE platforms or industry clusters can help SMEs share resources and reduce costs through collective waste management, shared logistics, and resource pooling. A relevant case from South Korea’s industrial parks shows that cooperative efforts between SMEs reduce costs by pooling resources for recycling and waste reduction (Park et al., 2018).

Next, the eighth-ranked CE barrier is a lack of technologies for product recovery mechanisms (TECHB1). Technologies are essential for the adoption of any new project in an organization. Thus, for product recovery mechanism in CE needs to have advanced technologies (Nasir et al., 2017). The ninth significant CE barrier is a lack of technical experts in CE adoption (TECHB3).

The shortage of technological experts and high initial costs remain key barriers to CE adoption for SMEs, a more strategic, long-term solution would involve directing government funding not just towards short-term cost alleviation but also towards building robust CE infrastructure and supporting research initiatives. Investing in such infrastructure—both physical (e.g., recycling facilities, remanufacturing technologies) and digital (e.g., data sharing platforms, CE innovation hubs)—would not only reduce initial implementation costs but also establish a supportive environment for the development of technological expertise (Ghisellini et al, 2016).By channeling funding towards education and training programs, research into CE technologies, and the creation of collaborative platforms between industries, SMEs, and research institutions, it would be possible to address the shortage of technological experts in the long run. (Leising et al., 2018) This strategic shift could create a sustainable CE ecosystem, enabling SMEs to transition smoothly while enhancing national CE capabilities. Such an approach can ensure the longevity and scalability of CE practices, fostering a culture of innovation and shared resources nationwide. The lack of supplier selection strategies (REGB3) is the tenth crucial CE barrier. Selecting a suitable supplier strategy plays a vital role in adopting CE management. Environmental aspects must be considered before selecting suppliers, which is one of the important dimensions of sustainability (Nascimento et al., 2019). The ranks of other CE barriers are: FINB3 > SOPEB3 > SOPEB7 > SOPEB2 > SOPEB5 > REGB4 > SOPEB6 > SCB3 > TECHB2 > SCB2 > SOPEB4 > TECHB5 > SCB5 > REGB2 > SCB6 > FINB5 > SCB4 > TECHB4. The CE barrier lack of technologies to trace the secondary products is obtained the lowest weight in priority. The low-rank CE barrier is also equally important for the organization to mitigate its impact on the adoption of CE. Thus, ranking facilitates the decision makers/practitioners to systematically investigate the influence of these barriers on the success of CE implementation.

The findings of the present study also supplement to the study of Ahmed et al., (2024) who identified CE barriers in the context of Bangladesh, partuclarly in the context of prioritization of the barriers that facilitates prompt actions to address critical barriers to the adoption of CE. CE barriers found in other developing countries regarding implementation are similar. The difference has been found in its ranking with regards to the manufacturing sector applicability and national policies. One of the examples is like a financial barrier has a lower ranking in European & other developing nations whereas its top in developing nations like India. This highlight that barriers ranking is dependent on the ecosystem where the manufacturing industry operates.

The comparative analysis for the adoption of CE adoption in India, China, and Brazil, highlighting both the similarities and differences. While China has benefitted from top-down governmental intervention (Bleischwitz et al., 2022), India and Brazil are experiencing more bottom-up innovation driven by SMEs. This comparison offers valuable lessons for policymakers and businesses in developing countries, showcasing both successes and challenges in CE adoption. For example, China’s government-led initiatives, such as the Circular Economy Promotion Law, have supported CE adoption across industries through incentives and the promotion of public-private partnerships (Yuan et al., 2006). In contrast, India’s policy landscape faces challenges due to insufficient infrastructure and lack of coordination among stakeholders, calling for targeted reforms. The manuscript also delves deeper into the policy implications for developing countries, emphasizing actionable strategies like capacity-building initiatives, regulatory support, and the establishment of CE innovation hubs to help businesses transition to circular practices. This highlights the critical role of government support, business innovation, and collaborative partnerships in accelerating CE adoption. Key takeaways for policymakers include the importance of incentivizing circular innovation, developing regulatory frameworks tailored to SMEs, and fostering international collaborations for knowledge exchange. For businesses, the conclusion underscores the need for investment in CE technologies and the advantages of adopting circular business models for long-term sustainability and competitiveness.

**5. Research implications**

***5.1 Implications for academics and practitioners***

The present research provides a detailed view of CE barriers that significantly hamper the adoption of CE implementation in Indian SMEs. CE concept has extended grip in developing economies, particularly among Indian SMEs. This is because Indian SMEs face several challenges related to sustainability in their SC processes. So, these SMEs are initiating to adoption of CE as a sustainable solution approach to these challenges. However, they find it challenging to implement CE in actual practice due to several hurdles. Thus, the list of CE barriers provided in this research helps the practitioners to understand the relative importance of each CE barrier and its influence on CE adoption. Most of the frameworks are available on CE implementation in previous literature. However, the frameworks that determine the relative importance of CE barriers in Indian SMEs are still missing in the existing literature. Thus, the research framework in this study will assist the practitioners in developing and formulating effective strategic measures to CE execution. Consequently, it helps to gain economic advantages and social and environmental sustainability in SC operations. It also helps the decision-makers to systematically adopt CE in a stepwise manner by understanding the importance of each barrier.

***5.2 Recommendations to Policymakers***

The implementation of CE is crucial to the development of the nation's economy in terms of triple-bottom-line sustainability. To attain net zero, it generates major employment possibilities, increases financial benefits, eliminates raw material shortage difficulties, and minimizes GHGs emission. So, it is projected that government agencies will develop and implement severe laws, regulations, and policies for the adoption of CE measures. Policymakers must provide grants, subsidies, and other incentives to enterprises that are willing to implement CE. Such creativity increases the organization's awareness of circularity and pushes them to construct a circular image that reflects the importance of CE to their enterprises. It is suggested that government agencies or policymakers/planners organize training and awareness programs on sustainability for various stakeholders interested in enhancing the sustainable performance of businesses. The PF-AHP ranking enables policymakers to have a deeper understanding of the impact of each barrier to CE adoption and assists government officials in planning and formulating effective plans to overcome the identified barriers. Therefore, this campaign helps to increase the rate of CE adoption in developing nations, particularly among Indian SMEs.

**6. Conclusions, limitations, and future scope**

Circular economy practices offer potential pathways for reorganizing the value chain to achieve net-zero emissions. Emerging economies, especially India, still face challenges in implementing CE practices in supply chain operations, despite the numerous benefits of adopting CE. For this, in this study, 28 CE barriers have been identified in the context of SMEs for net zero. The findings indicate that "Lack of commitment and support from top management towards the adoption of CE practices" is the most important barrier to CE adoption in Indian SMEs. It is followed by “Lack of economic resources and constraints”; “Lack of laws, regulations, policies towards environmental aspects of CE adoption”; “Risks associated to cannibalization”; “Lack of environmental management certifications and systems” are coming under top five prominent barriers of CE adoption and implementation.

The identification of CE barriers in the present study will help CE practitioners to tailor frameworks for addressing the challenges faced to the adoption of CE. Further, the prioritization of barriers will help practitioners to focus primarily on the critical barriers for improving circularity. As lack of funds is one of the key barriers to CE adoption, this encourages increased collaboration and partnership among different financial institutions to raise funds for CE adoption. The present study also fosters resource allocation within the exiting CE framework as government or industries can channelize their investment, tracing of the resources in the areas where they are needed the most. Furthermore, the barriers stemmed like lack of technical knowledge base will provide a guideline to industrial mangers or add existing frameworks to enhance the capacity building to improve the technical knowledge base of the industrial personnel to comprehend different aspects of CE. In nutshell, the prioritization of the CE barriers provided here strengthen the existing CE frameworks by providing deeper understanding of barriers, designing and creating effective solutions to overcome the same, and nurturing the collaboration among the different statehooders and partners of SC form improving the circularity to achieve net zero.

Besides valuable contribution to the study, there are a few limitations of the study. Human subjective opinion is the only input source for this study. Thus, extreme care should be taken during calculations. This research has been conducted in a single Indian case industry. So, the results may vary from industry to industry and nation to nation. The present study offers different avenues of research for potential researchers related to the field of sustainability. In the upcoming analysis, the study can be considered by experts from other business organizations with a more prevalent data set. In offing, potential researchers can compare the results of the study by systematic investigations of barriers in different nations. Researchers can also use more advanced methods such as SWARA, WASPAS, TOPSIS, VIKOR, ELECTREE, TODIM, and PROMETHEE with extensions to PFSs to calculate weights. In future research, the inter-relationship between CE barriers can be determined using DEMATEL and ISM-MICMAC techniques.

**Conflict of Interest**

The authors have NO affiliations with or involvement in any organization or entity regarding any financial interest (such as honoraria; educational grants; participation in speaker’s bureaus; membership, employment, consultancies, stock ownership, or expert testimony or patent-licensing arrangements), or non-financial interests (such as personal or professional relationships, affiliations, knowledge or beliefs) in the subject matter or material discussed in this manuscript.

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