Circular economy and critical barriers: Mapping the pathways and success metrics for sustainable circular success in industrialised South Asian developing nations

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ABSTRACT

The economy of a developing country is often industry centric, and is recognised globally. The circular economy (CE) model involves a manufacturing approach where products are systematically remanufactured and recycled within facilities to minimize waste. The emerging domain of CE in industrialised South Asian economies offers considerable benefits for developing countries due to its sustainable production, although its adoption is obstructed by various barriers. This research aims to develop a model for adopting CE within the industrial sector of South Asian developing nations by analysing the interrelation between overcoming circular economy adoption barriers (CEABs) and sustainable circular success (SCS). To attain this, questionnaire was completed by 310 industrial experts in Pakistan. Furthermore, a partial least square structural equation modelling (PLS-SEM) approach was employed to specify the barriers and inspect the interrelation between overcoming CEABs and SCS. The findings revealed a high correlation, with addressing the CEABs contributing 66.1 % to the SCS of the industrial sector. The results of this study indicate the outer loadings and average variance extracted values for all constructs surpassed the minimum threshold of 0.5, validating their acceptance. Moreover, the constructs in the study were measured reliably, exceeding a value of 0.8, which signify strong internal consistency. Additionally, the average path coefficient value (β) of 0.172 indicates a medium and positive correlation between CEABs and SCS. The study's findings can be used as a reference for policymakers to explore the primary barriers to CE adoption in developing nations and achieve SCS in industrial projects.

1. Introduction

Manufacturing operations need to be reshaped in alignment with sustainability due to rapidly altering climatic ambience, intense socio-environmental distress, and the draining supply of land resources. Circular economy (CE) stands out as an optimistic tool for directing these circumstances, offering a distinct approach. In its regenerative design, CE involves reintroducing discarded products or parts into a closed-loop system, emphasizing repair, reusing, remanufacturing, and recycling to reclaim value and reduce negative indirect effects [1]. The Ellen MacArthur Foundation made an important contribution, in shaping the concept of CE across America and Europe. Ellen MacArthur Foundation expresses CE as "an industrial system that is restorative or regenerative by intention and design" [2]. Following this, CE has evolved into a method for the effective treatment of resources and the value generation.

CE positions out as a significant contributor to global sustainability, playing an essential part in strengthening environmental balance worldwide [3]. From a life-cycle perspective, CE initiatives profoundly impact governance, ecosystems, and societal structures. Worldwide economy witnesses a substantial contribution from the CE sector, responsible for a noteworthy 3.9 % of the European Union's gross national return by 2030 [4]. Notwithstanding the economic benefits accompanying this growth, a substantial responsibility looms, with the industrial sector bearing the weight of a surprising 75 % of the world's energy consumption [5]. Simultaneously, it contributes to a similarly

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alarming 6.6 billion metric tons of energy-related greenhouse gas (GHG) emissions, leading to the overutilization of natural resources within the range of 40 %–60 %. In CE, resources and by-products are required to pass through batch manufacturing and consumption patterns, as well as end-of-life treatments, following the principles of reuse, reduce, and recycle (3Rs) [6–11]. This transformation aims to shift linear production systems towards closed-loop systems. Ideally, these systems should be driven by renewable energy, reflecting the increasing global awareness of finite resource availability [7]. Recycling processes consume energy, and vast majority of materials cannot undergo infinite recycling without experiencing some degree of loss in volume and standard [12–15]. Additionally, a briefing paper from the European Parliament acknowledged that addressing the existing ecological crisis requires resource-sufficient methods and the rigorous Implementation of fixed reduction goals [16].

By prioritizing reuse, recycling, and remanufacturing, the industrial sector provides substantial support for advancing CE principles, embedding sustainability at the core of the production process [17]. The study [18] states organisations that opts for solely recycled materials, even if it means higher expenses, demonstrates a commendable commitment to ‘circularity’. Hence, eco-product design and CE practices, through their explicit application, allow the industrial sector to adopt the concept of ‘end-of-life’ with restoration, removal of harmful materials, and reduction of waste. As stated by current literature, the CE exhibits substantial potential in the attainment of sustainability goals. CE’s significant waste reduction capabilities lead to an ultimate enhancement in both ecological performance and industrial efficiency. According to Refs. [19,20], the global water pollution, including water scarcity, excessive consumption, and contamination from both geological and human activities is a critical threat, especially to developing countries. The emphasises is on the health and environmental risks raised by water pollutants, including toxicity and carcinogenicity, and the critical importance of effective wastewater treatment, particularly in water-stressed regions. Additionally, the research [21], proposes an innovative solution by valorizing agro-industrial biowaste to develop green nanomaterials, such as bio-nanocatalysts, bio-nanosorbents, and bio-nanodisinfectants for wastewater treatment. This approach aligns with key concepts such as nexus thinking, circular economy, and zero-waste manufacturing with focus on minimising environmental impacts and improving resource recovery. While having minimal impact on consumption, some studies also argue that the CE can decrease natural resource utilization through eco-friendly production techniques [22–24]. However, for ensuring the operational success and sustainability of the industrial sector, it is crucial to trace the entire product lifecycle or the development of CE initiatives [25]. On a global scale, and particularly within the garment sector, the textile industry emerges as one of the most environmentally damaging industries, propelling the overconsumption of resources with a recycling rate of mere 1 % [26]. Similarly, in building sector, to manufacture a single ton of ordinary Portland cement it generates emission of approximately one ton of CO_2 into the atmosphere as this process requires 110 kWh of energy and between 60 and 130 kg of liquid fuel to achieve temperatures exceeding 1000 °C [27]. The conventional approach leads to higher fuel consumption, elevated greenhouse gas emissions, depletion of energy resources, and global warming. Consequently, in response to this pressing issue, numerous governments have prioritized CE practices and implemented a range of sustainable industrial regulations. Thy newly designed ISO 59000 standards, equip organisations with crucial tools, instructions, and frameworks to facilitate their transition towards a CE model, efficiently monitoring their impact and performance [28]. Numerous studies highlight the benefits and potential of implementing CE methods across different industrial sectors, outlined in Table 1. For instance, studies in the automotive sector show that CE techniques can lower the cost of sheet metal scrap by more than 40 %, aligning it as an effective cost-saving strategy [29].

In industrialised nations, manufacturing companies often embrace

Table 1
Studies on the prospects of circular economy.

S. No	Research Title	Prospects	Research Industry	Author
01	Facilitating Industrial Symbiosis to Achieve Circular Economy Using Value-Added by Design: A Case Study in Transforming the Automobile Industry Sheet Metal Waste-Flow into Voronoi Facade Systems	Energy Saving, Cost Effectiveness	Automobile	[29]
02	Eco-innovation and Firm Growth in the Circular Economy: Evidence from European small- and medium-sized enterprises	Minimize Pollution and Economic Benefits	SME	[30]
03	Forest sector circular economy development in Finland: A regional study on sustainability driven competitive advantage and an assessment of the potential for cascading recovered solid wood	Economic and Competitive Benefit	Timber Industry	[31]
04	Spatial modeling of a second-use strategy for electric vehicle batteries to improve disaster resilience and circular economy	Re-use Opportunities	Electric Vehicle Batteries	[32]
05	Prioritizing barriers to adopt circular economy in construction and demolition waste management	Waste Reduction and Environmental Protection	Construction	[33]
06	Barriers and challenges to plastics valorization in the context of a circular economy: Case studies from Italy	Ecological and Economic Benefits	Plastic	[34]
07	Implementing smart waste management system for a sustainable circular economy in the textile industry	Smart Waste Management Systems	Textile Industry	[35]
08	Transition to circular economy on firm level: Barrier identification and prioritization along the value chain	Reduction of Waste, Sustainable Development	Manufacturing	[36]
09	Microwave processing of oil palm wastes for bioenergy production and circular economy: Recent advancements, challenges, and future prospects	Bioeconomy and Bioenergy Production	Energy and Agriculture Sectors	[37]

(*continued on next page*)

Table 1 (*continued*)

S. No	Research Title	Prospects	Research Industry	Author
10	Industry 4.0 and prospects of circular economy: a survey of robotic assembly and disassembly	Manufacturing and Remanufacturing Frameworks	Industry 4.0	[38]
11	The Contribution of Sustainable Packaging to the Circular Food Supply Chain	Sustainable Packaging, Processing and Consumption of Food Products	Food and Packaging	[39]
12	Insights and dynamics of circular business model in developing countries' context: The empirical analysis of the returnable glass bottles process	Designing and Transitioning of Circular Business Models	Manufacturing	[40]
13	Promoting Circular Economy in the shipping industry	Shipping Industry and Sustainable Growth	Maritime Industry	[41]

the CE as it represents a progressive approach for both sustainable production and the efficient utilization of clean energy, with the aim of achieving Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 11 (Sustainable Cities and Communities). Germany, Netherlands and Denmark take the lead as industries in European Union countries witness notable growth and dedication to the CE, driven by a general strategy, European Green Deal [42,43]. In 2018, the CE in Germany demonstrated significant economic importance, generating approximately €76 billion in annual earnings, employing around 290,000 people across 11,000 companies, and contributing significantly with a net amount of about €21.5 billion [44]. Meanwhile, Denmark, with the aim of maiden climate-neutral production industry and an innovative manufacturing sector centred on automation, reports a 65 % export rate and an annual turnover of approximately €31 billion [45]. With one-third of materials assimilated into CE, the Netherlands and France demonstrates substantial progress in resource productivity and sustainable practices with a Circular Material Use (CMU) rates of 29 % and 19.5 %, respectively [46]. China is anticipated to become the leading CE by 2040, with an expected Gross National Income (GNI) of $ 25.1 trillion, while Japan closely follows with a projected GNI of $ 11.54 trillion [47].

In comparison, the implementation of CE practices in developing nations exhibits diverse scenarios, highly influenced by geographical location and the unique circumstances of each country. While significant growth in the use of CE practices has been observed in countries like India and Indonesia, the adoption of CE in the industrial sector remains in its initial stages in many Asian and African countries. To begin with a national strategy, developing countries must enact legislation that prioritizes circularity as a fundamental step. In the industrial sectors of less developed countries such as Egypt, Morocco, South Africa, Algeria, and Nigeria, the adoption of CE practices, primarily in recycling projects, remains exceptionally low [48]. Opting for conventional industrial methods, these nations prioritize resource security, adhere to conventional linear models, face financial constraints, and encounter challenges in adopting technologies and knowledge from developed nations, thus hindering the acceptance of circular methods [48]. A major limitation of the conventional linear economy, compared to the CE, lies in its emphasis on the instant disposal of reused goods. This approach places significant pressure on production and industrial facilities to increase production to satisfy high consumer demand, which in turn leads to the over-extraction of natural resources [49–54].

Applying the global–local context (GLC) method, this study highlights its international significance, focusing and amplifying the issues under examination. To highlight the implication of a study, one approach involves establishing the significance of the broader area of concern [55]. Henceforth, adopting a GLC approach, this study centres on developing states, with Pakistan serving as the native context. Conducted within the industrial sector of Pakistan, the study specifically focuses on the metropolitan states of Sindh and Punjab, which jointly hold a larger number of country's industries. As a consequence, the outcomes of this study hold the potential to revolutionize industrial projects, impacting not just Pakistan but also other developing nations of South Asia, where industrial projects are executed using similar and traditional methods [56]. Focusing on Pakistan, one of the prominent developing nations in South Asia, this study seeks to fill the knowledge gap in the existing literature. GDP serves as the basis for selecting Pakistan as a major South Asian country, alongside its geographical significance [57].

In Pakistan, industries often depend on relationships that obstruct the adoption of circularity, such as the potential risk of damaging relationships with retailers and traders by offering repair or refurbishment services, as well as limited opportunities for product manufacturers and other Non-Original Equipment Manufacturers (OEMs) to embrace circular business models given their placement in the production chain [58]. A significant challenge within the Pakistani industry arises from the dominance of informal recycling networks, which involves scavengers, intermediaries, and industrial processing, operating outside formal channels [59]. Additionally, Pakistani industries often emphasise high-resource consumption methods, leading to a deficiency in technological innovation that is typically observed in top-tier sectors. In 2017, Pakistan's industrial value-added stood at a mere 17.9 % of GDP, starkly lower than that of China (40.5 %), Malaysia (38.8 %), Bangladesh (27.8 %), Iran (34.9 %), Indonesia (39.4 %), and India (26.5 %) [60]. These statistics shows Pakistan's relatively poor performance in industrial productivity compared to its regional counterparts.

According to Ref. [61], in waste management, Pakistani industries encounter challenges, as there is inadequate on-site segregation and non-standardised processes, which compromise the quality of plastic recycling. Standardization is lacking in the processes adopted by the majority of these industries. Findings from the study [61] highlight environmental issues, including surplus water utilization (3315 L/ton), insufficient wastewater reprocessing, high power usage (172.5 kWh/ton), increased temperatures (36.5 °C) for lacking the implementation of CE. Nevertheless, companies in Pakistan, receive inadequate support from government and regulatory bodies, lacking significant compensation in the form of subsidies, financial assistance, or tax benefit. This absence of support increases the likelihood of higher costs for green products. Furthermore, the primary factor restricting the adoption of CE in Pakistan is the lack of policy, aligning the procedures for incorporating CE methods into the industrial sector. Based on the above discussion a research question arises, i.e. What elements contribute to the realisation of CE, and what impediments necessitate resolution for successful implementation?

The novelty of this study is twofold. First, this research examines the implication of various barriers on the adoption of CE in Pakistan. The adoption of CE practices will assist the transition towards more advanced and sustainable industrial production, achieving substantial economic, ecological and societal benefits. Second, this study devised a CE adoption model based on the identified barriers and strategies, that is innovative in the approach of CE and pinpoints the precise factors of CE's adoption within industrial firms. By evaluating CE adoption strategies, the findings contribute to the current body of research on achieving sustainable production goals in the industrial sector. Intending to address the existing gap, this research employs the Partial Least Square Structural Equation Modeling Approach (PLS-SEM) to mathematically analyse the correlation between overcoming circular economy adoption barriers (CEABs) and achieving sustainable circular success (SCS) in the industrial sector of Pakistan as a developing nation. The significance of the study resides from the limited knowledge regarding the importance of CE and industries in the developing countries. Achieving the study's objectives involve:

1. Determine the CEABs and SCS factors.
2. Utilising the PLS-SEM methodology, to investigate the correlation between transitioning from CEAB and achieving SCS.
3. Constructing a model for the adoption of CE.

Regarding the significance of the research, examining the challenges of CE in South Asian developing countries will offer economic advantages to decisionmakers, statutory authorities, and stakeholders by promoting sustainable circular manufacturing in production processes. Furthermore, this study is distinguished from previous research by critically analysing the impact of crucial barriers such as stakeholder perception and resistance, infrastructure and technological access, sociocultural factors, and communication. It also examines how economic resilience, environmental impact, and social equity influence CE techniques and practices in South Asian industries. The study strengthens published work in the sector by presenting a comprehensive research framework based on the key findings. The key objectives of the research are:

1. To determine the variables influencing and obstructing CE implementation in industrial manufacturing operations.
2. To evaluate the interrelationship of the identified barriers to CE adoption and the effectiveness of sustainable circular manufacturing in industrial context.
3. To develop a strategic model for implementing CE adoption in the industrial sector of developing countries.

2. Circular manufacturing and its barriers

The integration of CE into the industrial operations of developing nations challenges existing norms, demanding substantial changes. Due to the slow adoption of innovation within the industry, CE initiatives face resistance and encounter numerous obstacles. Despite the global endorsements and advantages associated with the adoption of CE, the industrial sector encounters frequent barriers blocking the pervasive implementation. Consequently, diverse perspectives have been examined by numerous scholars associated with the challenges linked to CEAB. As an instance, preceding studies such as [62–71], and other research have highlighted several barriers to CE implementation in the industrial sector. These include (1) claims that stakeholders resist and exhibit skepticism; (2) inadequate awareness and understanding; (3) past unfavorable encounters; (4) high perceived initial expenditures; (5) obstacles in securing funding and investments; (6) inadequate waste management infrastructure; (7) restricted access to CE technologies; (8) absence of tools for benchmarking CE practices; (9) shortage of proficient CE professionals; and (10) necessity for international cooperation and knowledge exchange.

Moreover [58], points out various barriers hindering the adoption of CE in Pakistan, comprising challenges in incorporating CE practices into the supply chain, a lack of collaborative technical support from non-organisational stakeholders, ineffective recycling processes, limited resource availability, and issues concerning the quality of end-products. In addition, according to the findings by Ref. [61], there are several obstacles obstructing the integration of CE practices in Pakistan, such as disregard for the health and safety of workers, rising raw material costs, deficiency of standard operating protocols and sustainable manufacturing policies, and nonexistence of guidelines in recycling processes and wastewater treatment. According to Refs. [26,72,73], these barriers are grouped into five primary sections: (1) stakeholder perception and resistance; (2) economic viability and financial support; (3) infrastructure and technological access; (4) governance and metrics framework; and (5) sociocultural factors and communication. Table 2 presents a comprehensive breakdown of the barriers. The barriers of stakeholder perception and resistance significantly impacts attitudes, that affects the acceptance of CE initiatives [74]. Economic Viability and Financial Support barriers are linked with feasibility and financial backing, cash flows and risks. Infrastructure and technological access barriers are associated to promote innovation, assure sustainability, and strengthen competitiveness [75]. Governance and metrics framework barriers are related to integration of environmental, social, and governance (ESG) aspects into decision-making procedures and measuring their influence on sustainable value generation [76]. Sociocultural factors and communication barriers are related to hindrance of transition to CE and prolong linearity across the product progression [77].

The SCS approach prioritizes economic stability, environmental accountability, and social welfare in project objectives, incorporating the core tenets of sustainable development [78]. The literature extensively emphasises the concept of CE and sustainability. However, the complexity lies in transforming the strategic CE techniques and milestones of industrial projects. Economic, environmental, and social aspects must be harmonized to establish a well-rounded foundation. In industrial activities, the contribution of CE aligns with three primary dimensions of sustainability: social, economic, and environmental [79]. Table 2 classifies 23 CEABs and 3 SCS factors compiled from the literature.

3. Research methodology

This study employs a three-step process, as shown in Fig. 1. The steps involve (1) conducting a comprehensive literature review to identify and analyse the CEABs, (2) developing a questionnaire survey to assess the significance of addressing CEABs in attaining SCS, and (3) utilising PLS-SEM to analyse the correlation between addressing CEABs and achieving SCS for industrial projects.

3.1. Step 1: Comprehensive literature review

A comprehensive review was performed to identify the CEABs, for classification of model's constructs and indicators. This detailed investigation utilised internet databases such as Scopus, Google Scholar, and Web of Science. Specific keywords and their combinations, such as 'Circular Economy', 'Barriers in Circular Economy', 'Pakistan', 'Sustainability', 'Sustainable Industrialization', and 'Developing Countries', were used during the review. The review's objective was to gather and incorporate all relevant research on the subject. To comprehensively explore, synthesise, and analyse research data, the researchers carried out an in-dept review of the existing body of literature. This process includes acquisition, refinement, and classification of data at various stages. This step was crucial in identifying the CEABs and establishing our theoretical framework. To construct the theoretical framework, a rigorous analysis of the data was conducted, necessitating to reduce the quantity of information through cautious selection, extraction, and simplification, of relevant data and information. Furthermore, the researchers sifted through the numerous researched subjects to avoid duplicating components and discard unnecessary studies. Over a span of 11 years, from 2013 to 2024, an examination of CEABs presented a comprehensive insight into the investigations. Displayed in Fig. 2 is the theoretical model that forms the basis of the coding system employed in this study.

3.2. Step 2: Questionnaire survey development

Focusing on the industrial projects within Pakistan, an emerging nation, the aim of the questionnaire survey was to explore the impact of overcoming CEABs on achieving SCS. The questionnaire comprises four main sections: (1) a synopsis of respondents' demographic statistics; (2)

Table 2
Circular manufacturing constructs and interrelated indicators.

Construct	Type	Indicator	Code	Reference
Stakeholder Perception and Resistance (SPR)	Independent Variable (IDV)	Claims that stakeholders resist and exhibit skepticism	SPR-1	[62,74]
		Inadequate awareness and understanding	SPR-2	[63]
		Past unfavorable encounters	SPR-3	[64,80]
Economic Viability and Financial Support (EFS)	IDV	High perceived initial expenditures	EFS-1	[65]
		Insufficient financial incentives	EFS-2	[66,81]
		Obstacles in securing funding and investments	EFS-3	[82]
Infrastructure and Technological Access (ITA)	IDV	Inadequate waste management infrastructure	ITA-1	[67,83]
		Restricted access to circular economy technologies	ITA-2	[68]
		Limited advancements in circular economy technologies	ITA-3	[75,84]
Governance and Metrics Framework (GMF)	IDV	Gaps in government backing and involvement	GMF-1	[85]
		Absence of tools for benchmarking circular economy practices	GMF-2	[69,86]
		Lack of standardized metrics	GMF-3	[70,87]
		Challenges in integrating circular principles into business models	GMF-4	[88]
		Issues with monitoring and enforcement	GMF-5	[89]
		Absence of conceptual framework in the context of sustainable industrial practices	GMF-6	[90]
Sociocultural Factors and Communication (SFC)	IDV	The negative impact on industry and potential employment displacement	SFC-1	[91]
		Consumer reluctance towards circular practices	SFC-2	[92,93]
		Inadequate educational and training initiatives	SFC-3	[94]
		Shortage of proficient circular economy professionals	SFC-4	[71]
		Inefficient waste management hindering circularity	SFC-5	[95]
		Cultural factors influencing acceptance	SFC-6	[72]
		Insufficient awareness campaigns	SFC-7	[77]
		Lack of incentives for consumers to embrace circular products	SFC-8	[96]
		Necessity for international cooperation and knowledge exchange	SFC-9	[97,98]
Sustainable Circular Success (SCS)	Dependent Variable (DV)	Environmental Impact (measuring the positive influence on environmental sustainability)	SCS-1	[99–101]
		Social Equity (assessing the inclusivity and societal benefits of the circular economy implementation)	SCS-2	[102,103]
		Economic Resilience (evaluating the economic stability and benefits derived from the circular economy model)	SCS-3	[7,104]

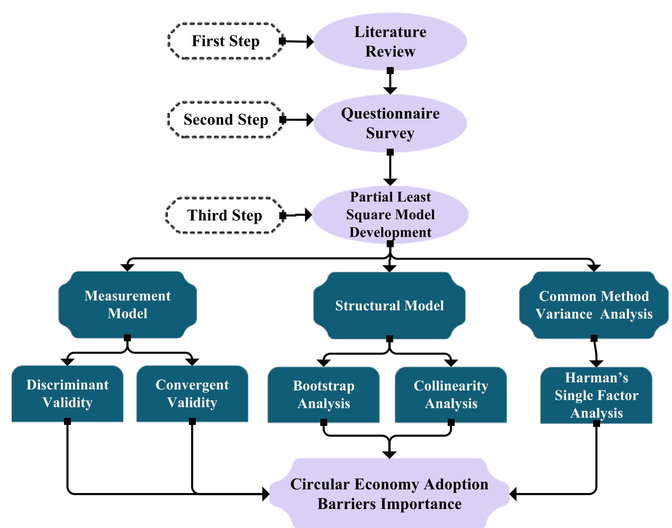

Fig. 1. Study's three-step research flowchart.

closed-ended questions to assess respondents' perspectives on how CEABs affect the achievement of SCS; (3) closed-ended questions to evaluate respondents' perception on the environmental, social, and economic attributes of SCS; and (4) permitting respondents to identify any notable barriers they consider in achieving SCS through an open-ended format. The participants utilised their experience and understanding to evaluate the CEABs and SCS, through a five-level Likert scale for assessment. This method is a common practice used by many prior studies such as [105–107].

3.2.1. Pilot testing

Following the preliminary analysis, the pilot study assessed the questionnaire for its efficacy, coherence, and thoroughness. A pilot study has a crucial role in filtering research procedures, identifying obstacles, and assuring the validity and consistency of the study's design. A least sample size of 20 participants is required for the pilot study [108]. Hence, the pilot questionnaire was created and distributed among 30 professionals, comprising 20 industrial production experts

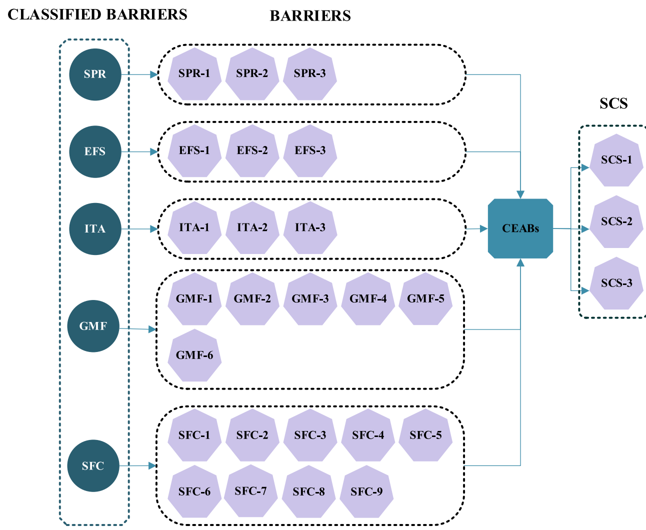

Fig. 2. Theoretical model with the Study's coding system.

Fig. 3. Industrial map of Pakistan (Source: [113]).

and 10 academics, each with a decade of experience. As part of this study, participants thoroughly inspected the phrasing of questions, determine problems in the questions, authenticated the survey's CEABs and SCS factors, and provided their feedback. Following input from the 30 experts, certain questions underwent rephrasing in accordance with the proposed recommendations.

3.2.2. Reliability and consistency of responses

Cronbach's alpha coefficient, a metric indicating consistency, was employed to assess the pilot questionnaire's reliability [109]. Calculation of the Cronbach's alpha coefficient is essential to verify the uniformity of participant responses, particularly in evaluating the impact of overcoming CEABs and SCS factors in industrial projects. This process also validates the reliability of Likert scale measurement methods. Depicting the Cronbach alpha coefficient is **Equation (1)**, in which the total number of barriers is denoted by (K), the variance in the current sample for respondents is signified by (S^2i), and the summation of variance for respondents is stated as (S^2 sum). An evaluation of the pilot sample produced an overall Cronbach's alpha coefficient of 0.92, this figure specifies a credible level of consistency, as stated by Ref. [110].

$$\text{Cronbach alpha coefficient } (\alpha) = \left(\frac{K}{K+1}\right)\left[1 - \frac{\sum S^2 i}{S^2\ Sum}\right] \tag{1}$$

3.2.3. Questionnaire target population

The targeted participants for the questionnaire were industry professionals from Pakistan, specialising in industrial engineering, environmental engineering, or waste management. Derived from Hassan et al. [111], the researchers employed two selection criteria to identify suitable respondents: (Criterion 1) possession of a degree in industrial engineering, environmental engineering, or waste management; and (Criterion 2) a least experience of 5 years in these fields.

3.2.4. Sample size selection

Due to the emerging nature of CE in Pakistan, this study applied a random probability sampling approach, giving every professional in major cities Lahore, Karachi, Faisalabad and Multan [112] an equal opportunity for selection, as main industries are situated in these cities shown in Fig. 3 [113]. The authors utilised this technique to ensure the collection of credible and precise responses. The dataset provided by the Pakistan Bureau of Statistics (PBS) indicates a population of 3435 stakeholders engaged in CE [114]. Applying the Glenn Israel method, a sample size of 310 responses is identified, considering a 5 % margin of error, a 93.5 % confidence level, and a response distribution of 50 % [115]. The method is for determining the ideal sample size for surveys or studies that involves factors like population size, margin of error, confidence level, and variability. As precision increases or confidence levels rise, the required sample size also expands. This study utilised SEM approach for analysis, necessitating the collection of a minimum sample of 100 cases. The collection exceeded this requirement with 310 cases, confirming its capability for the selected methodological approach. Data was gathered by emailing a questionnaire to selected participants in Karachi, Lahore, Faisalabad, and Multan who met the specified criteria. From the 500 questionnaires distributed, 310 valid responses were obtained, yielding a response rate of 62 %, exceeding the least acceptance threshold.

3.2.5. Profile of respondents

Presented in Table 3 is the demographic data of respondents, representing a diverse spectrum of experts engaged in Pakistan's industrial sector. The dataset reveals that a considerable number of participants acquired fewer than 5 years of experience, with 63 % of the respondents have 3–5 years of experience. Followed by those with below 10 years' experience. A significant proportion comprised engineering professionals. A bulk of respondents have conducted CE industrial projects. This observation is significant, highlighting the atypical application of CE in this setting. Consequently, individuals from waste management, CSR, and product design were incorporated into the investigation.

3.3. Step 3: PLS-SEM development

This research aims to investigate how addressing CEABs influences CE adoption in industrial projects. Furthermore, it seeks to assess the relationship between CE adoption and SCS through a scientific methodology. In addition, the research seeks to validate the proposed theoretical framework, that integrates formative and contemplative aspects sourced from current literature. Researchers utilised the widely-used statistical method PLS-SEM to analyse the correlations among latent factors in a structural equation model, aiming to validate the suggested theoretical framework and accomplish the study objectives [116]. In this research, PLS-SEM was preferred over covariance-based SEM (CB-SEM) as it offers a analytic statistical tool for assessing multifarious factors, managing experimental disparity, and forecasting more accurately [117]. Moreover, its flexibility surpasses that of CB-SEM as it can manage both formative and contemplative aspects. PLS-SEM owns the

Table 3
Respondent demographics.

Demographics	Frequency	Percentage (%)
1. Level of Education		
Bachelor's Degree	125	40.3
Master's Degree	152	49.0
PhD Degree	27	8.7
Post Doctoral	6	1.9
2. Job Position		
Executive/Managerial	60	19.4
Industrialist/Corporate	79	25.5
Technical/Engineering	97	31.3
Academia	74	23.9
3. Circular Economy Industrial Experience		
1–5 Years	120	38.7
6–10 Years	116	37.4
11–15 Years	50	16.1
Above 15 Years	24	7.7
4. Type of Organisation		
Public Organisation	76	24.5
Private Organisation	113	36.5
Non-Governmental Organisation (NGO)	71	22.9
Self Employed	50	16.1
5. Circular Economy Projects conducted in the past 3 years		
1 to 10 Projects	124	40
11 to 20 Projects	109	35.2
Above 20 Projects	38	12.3
None	39	12.6
6. Organisational Role		
Industrialist	44	14.2
Sustainability/Corporate Social Responsibility Manager	75	24.2
Product Designer/Engineer	84	27.1
Circular Economy Advisor	60	19.4
Waste Management Specialist	47	15.2

favorability of being least susceptible to distributional assumptions and sample size compared to CB-SEM [117]. For studies focused on predicting outcomes rather than testing hypotheses about the underlying data structure, the PLS-SEM method is particularly suitable. The two-phase PLS-SEM method begins with confirmatory factor analysis (CFA), which is used for validation by ensuring that the measured indicators accurately signify the related constructs in the measurement model [118]. In the succeeding phase, the testing of research hypotheses begins with the implementation of path analysis, followed by the development of the structural model.

4. Results

4.1. First Order Measurement Model construct

The assessment of the measurement model requires estimating both discriminant and convergent validities. Evaluating convergence validity requires a detailed analysis of average variance extracted (AVE), composite reliability, Cronbach's alpha, and outer loading. Conversely, discriminant validity involves (1) Cross-loading criterion and (2) Fornell and Larcker's criterion.

To begin with, outer loadings assess the extent to which each indicator contributes to its respective construct. Indicator outer loading values generally range from 0.40 to 0.70 [119], illustrating the intrinsic variation among indicators. According to Sarstedt et al., an outer loading limit of 0.50 is deemed acceptable [119]. Fig. 4 depicts the outer loadings for all variables in the measurement model, with the corresponding values from the model outlined in Table 4. From the findings, it was evident that all outer loadings met the acceptable criteria, with none of the indicators being removed from the original measurement model. These indicators demonstrated substantial impact on the designated constructs, as their outer loading values exceeded 0.5. The individual construct has high indicator loadings i.e., greater than 0.75, which shows that the variables are reliable metrics of their respective constructs. Such as SPR and GMF which represents strong internal consistency is reflected in their high loadings. Additionally, the model reveals that although all constructs impact SCS, the SFC variable exert the greatest influence. This highlights the significance of addressing SFC capabilities to reach sustainability objectives.

Next, the Cronbach alpha serves as the metric of consistency, assessing the coherence between a set of indicators and their designated variables. While inconsistencies and challenges exist in Cronbach alpha's performance, it attains parity with composite reliability, that should exceed 0.7 threshold. Table 4 demonstrates the specified criteria that are fulfilled by the variables of the SEM. Thirdly, in light of the constraints presented by Cronbach's alpha, which measures sensitivity regarding the quantity of factors implicated, the evaluation was focused on composite reliability. For acceptance in this analysis, the composite reliability threshold must surpass 0.7. Table 4 illustrates that the SEM variables meet this criterion.

In evaluating the model's constructs, the average variance extracted (AVE) serves as a standard metric for assessing convergent validity. Values for AVE should exceed 0.50 to be considered admissible [117]. Table 4 illustrates the AVE results, confirming the acceptance of all constructs following this assessment. Once the construct adequately deviates from others according to practical standards, discriminant validity is clearly established. Similarly, discriminant validity assures the uniqueness and distinctiveness of each construct within the model, highlighting aspects not captured by other constructs in the model [120]. Two diverse methods exist for establishing discriminant validity: the cross-loading criterion and Fornell and Larcker's criterion. Initially, Fornell and Larcker's criteria is used to assess the relationship between the construct and its square root of AVE. As per Fornell and Larcker's principle, the square root of the AVE of the construct should surpass its correlation with other constructs. The findings in Table 5 confirm the discriminant validity of the model. When evaluating construct validity, it is crucial to verify that, for each indicator on a given row, its loading value alongside its associated construct exceeds the loading value of any alternative construct. All constructs listed in the table, including EFS, GMF, ITA, SFC, SPR, and SCS are displaying high internal consistency. The AVE values are between 0.799 and 0.867 as this range suggests that a significant fraction of the variance in each construct is precisely gathered by its respective measures. The relationships among the constructs show relatively high correlation.

Table 6 shows the outcomes of cross-loadings, which examine the discriminant validity of indicators. The results indicate significant one-dimensionality within each construct. The indicators for each construct illustrate higher loadings on their respective constructs. For example, EFS and GMF show loadings of 0.861 for EFS-1 and 0.822 for GMF-2 that is considerably surpassing their cross-loadings with other constructs. Thus, indicating strong discriminant validity, proving that these indicators are unique and specific to their respective constructs. The table overall verifies that the indicators effectively sustain discriminant validity for all constructs and to make sure that each one assesses a specific aspect without major overlap with the others.

4.2. Second order measurement model construct

Primary constructs, which serve as the independent variables signify the second-order constructs. Utilising the bootstrap method, the assessment of each first-order construct's benefaction was conducted. The CEABs comprise a formative construct, while the SCS is characterised as a reflective construct. Highly correlated indicators are rarely predicted by formative measurement models. Furthermore, the presence of collinearity, stemming from the notable associations among the formative factors, is perceived as challenging [121]. With a designated upper limit of 5, the examination of collinearity among the formative elements of the constructs within the model, particularly when employing PLS modelling, is effectively achieved using the Variance

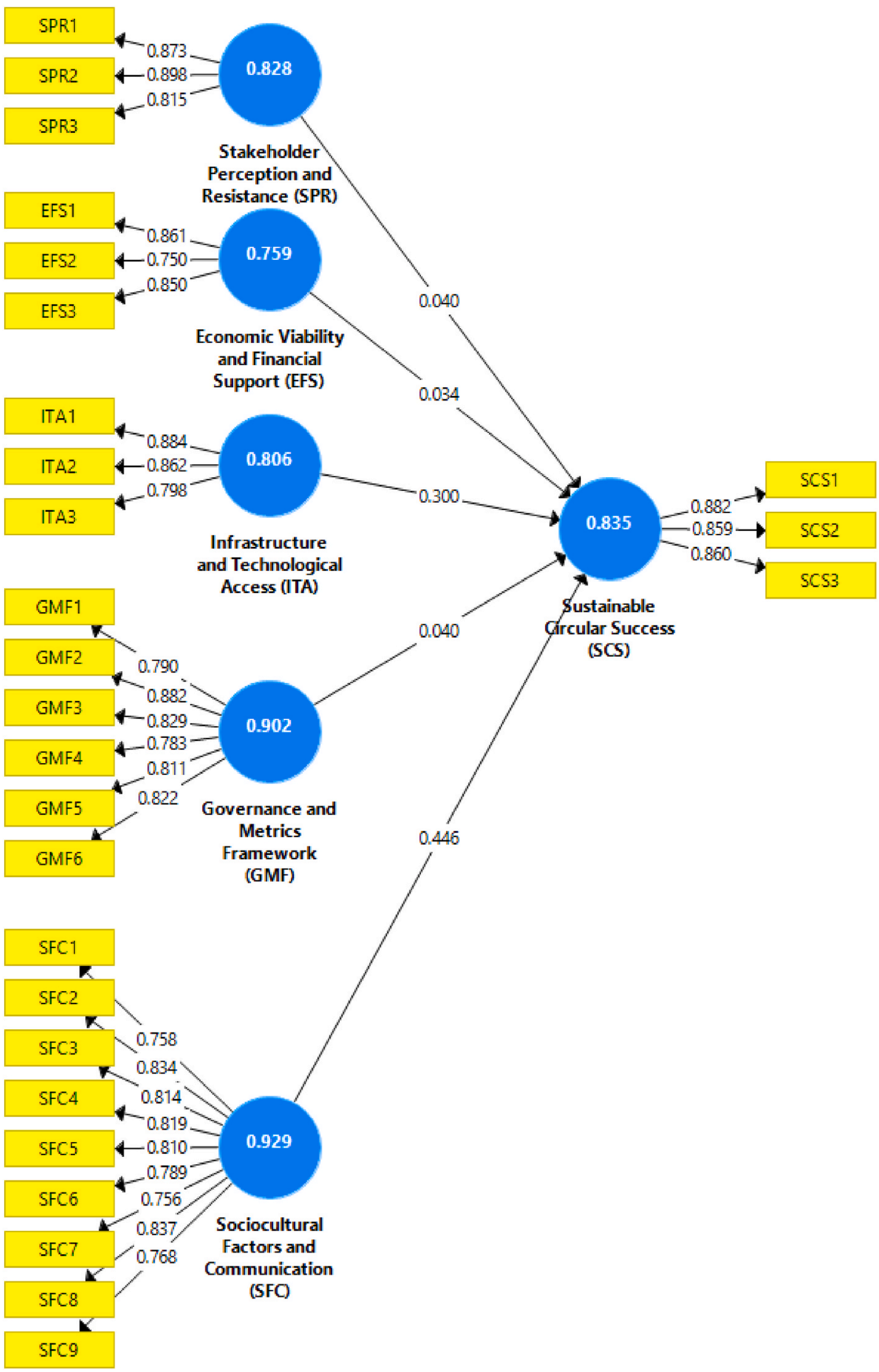

Fig. 4. First order measurement model with outer loading values for circular economy adoption barriers.

Inflation Factor (VIF) [117].

Fig. 5 presents significant path coefficient (β) and p-values across five primary subscales, each addressing barriers to the adoption of CE: stakeholder perception and resistance, economic viability and financial support, infrastructure and technological access, governance and metrics framework, and sociocultural factors and communication. Within the model, the β value serves as a statistical measure indicating the extent of correlation between constructs. The significance level of path coefficients, as indicated by the p-value, should not surpass 0.05 for acceptance [122].

Fig. 4 and Table 7 illustrate the path coefficient and VIF values for all constructs. Of utmost significance is the path coefficient relating to the SFC, marked by a β value of 0.446, indicating its substantial variance and influence on CEABs. This emphasise the critical role of social factors and communication in achieving CE. Conversely, the path coefficient deemed least significant is associated with the EFS, characterised by a β value of 0.034 as it exhibits a lower variance value and exerts the least influence on CEABs. This indicates a small but significant path coefficient as its contribution is supportive but less substantial. Moreover, it is noteworthy that all VIF values remained below 5, indicating the independent contribution of these subdomains to the higher-order construct.

Table 4
Construct reliability and validity tests.

Latent Variables	Items	Outer Loadings Model Values	Composite Reliability	Cronbach's Alpha	Average Variance Extracted (AVE)
SPR	SPR-1	0.873	0.897	0.828	0.744
	SPR-2	0.898			
	SPR-3	0.815			
EFS	EFS-1	0.861	0.862	0.759	0.676
	EFS-2	0.750			
	EFS-3	0.850			
ITA	ITA-1	0.884	0.885	0.806	0.721
	ITA-2	0.862			
	ITA-3	0.798			
GMF	GMF-1	0.790	0.925	0.902	0.672
	GMF-2	0.882			
	GMF-3	0.829			
	GMF-4	0.783			
	GMF-5	0.811			
	GMF-6	0.822			
SFC	SFC-1	0.758	0.941	0.929	0.638
	SFC-2	0.834			
	SFC-3	0.814			
	SFC-4	0.819			
	SFC-5	0.810			
	SFC-6	0.789			
	SFC-7	0.756			
	SFC-8	0.837			
	SFC-9	0.768			
SCS	SCS-1	0.882	0.901	0.835	0.752
	SCS-2	0.859			
	SCS-3	0.860			

Table 5
Fornell-Larcker's discriminant validity and construct correlation.

Constructs	EFS	GMF	ITA	SFC	SPR	SCS
EFS	0.822					
GMF	0.814	0.820				
ITA	0.824	0.872	0.849			
SFC	0.802	0.882	0.829	0.799		
SPR	0.774	0.828	0.773	0.755	0.863	
SCS	0.703	0.756	0.763	0.787	0.668	0.867

4.3. Structural equation Model's path analysis

In SEM, path analysis explores both direct and indirect relationships among variables within a given theoretical model [119]. The initial phase of SEM analysis utilizes the structural model to explain the interrelationships among theoretical components. This approach methodically arranges theoretical constructs, concluding in path analysis to ensure a thorough investigative process in academic research. Following the model fitting process, the structural model emerges as the second pivotal stage in SEM analysis. Determining the correlations among the variables is a fundamental aspect of implementing the structural model. As a result, the analyses of structural model primarily focuses on evaluating the model fit and estimated parameters, addressing their significance, direction, and magnitude [122].

Table 6
Assessing discriminant validity of indicators through cross loadings.

Construct/Indicators	EFS	GMF	ITA	SFC	SPR	SCS
EFS-1	0.861	0.680	0.704	0.671	0.633	0.619
EFS-2	0.750	0.633	0.623	0.624	0.646	0.492
EFS-3	0.850	0.695	0.702	0.684	0.640	0.611
GMF-1	0.603	0.790	0.666	0.681	0.643	0.592
GMF-2	0.706	0.882	0.750	0.777	0.714	0.665
GMF-3	0.679	0.829	0.746	0.744	0.701	0.617
GMF-4	0.638	0.783	0.692	0.681	0.612	0.563
GMF-5	0.691	0.811	0.699	0.730	0.722	0.602
GMF6	0.682	0.822	0.735	0.719	0.677	0.669
ITA-1	0.733	0.749	0.884	0.734	0.699	0.703
ITA-2	0.701	0.749	0.862	0.684	0.639	0.653
ITA-3	0.662	0.726	0.798	0.694	0.629	0.582
SCS-1	0.649	0.647	0.675	0.712	0.596	0.882
SCS-2	0.566	0.652	0.659	0.658	0.575	0.859
SCS-3	0.611	0.668	0.652	0.678	0.568	0.860
SFC-1	0.635	0.617	0.585	0.758	0.545	0.608
SFC-2	0.660	0.786	0.706	0.834	0.652	0.670
SFC-3	0.647	0.711	0.640	0.814	0.648	0.632
SFC-4	0.696	0.728	0.709	0.819	0.635	0.652
SFC-5	0.617	0.715	0.659	0.810	0.565	0.633
SFC-6	0.635	0.690	0.651	0.789	0.570	0.610
SFC-7	0.571	0.619	0.619	0.756	0.541	0.545
SFC-8	0.647	0.777	0.709	0.837	0.704	0.658
SFC-9	0.653	0.680	0.669	0.768	0.556	0.642
SPR-1	0.659	0.679	0.650	0.631	0.873	0.599
SPR-2	0.704	0.778	0.722	0.706	0.898	0.605
SPR-3	0.641	0.685	0.626	0.616	0.815	0.521

During the investigation, bootstrapping was utilised to generate samples mirroring the original dataset via random re-sampling. Focusing on the hypothesis outlined in Fig. 4, the analysis emphasised on the impact of overcoming CEABs to attain SCS for industrial projects. In assessing the hypothesis significance, the research utilised the bootstrapping method, considering statistical importance and dataset dependability [119]. In the bootstrapping method used, $\beta_{SPR \to SCS} = 0.040$, $\beta_{EFS \to SCS} = 0.034$, $\beta_{ITA \to SCS} = 0.300$, $\beta_{GMF \to SCS} = 0.040$, and $\beta_{SFC \to SCS} = 0.446$ emphasise the statistically significant and noteworthy influence of tackling CEABs on SCS, as shown by Fig. 5 and Table 7.

4.3.1. Explanatory power of SEM with R^2

The capacity of the structural model to account for the variance in the dependent variable symbolises its explanatory power. The coefficient of determination (R^2) measures the explanatory power of the structural model, quantifying the variance in the dependent variable by the independent variables, represented from 0 to 1 [122]. The effectiveness of the SEM is determined by its capacity to assess the changeability of the dependent variable it clarifies. Utilising the PLS algorithm, several squared correlations are calculated for the dependent component. A higher R^2 value specifies improved predictiveness, demonstrating the model's adeptness in capturing variability within the data. In this investigation, the SEM analysis yielded an R^2 value of 0.661 for the endogenous latent variable SCS, suggesting that approximately 66.1 % of its variance is accounted for by the predictors included. This finding is in line with Hair et al., which states a high level of explanatory power, as illustrated in Table 8 [122].

4.3.2. Predictive relevance (Q^2) of SEM

Assessing the model's predictive relevance (Q^2) is considered a crucial aspect of a structural model's evaluation. Determined via cross-validation techniques, Q^2 indicates the fraction of variance predicted beyond the sample data. Considering the data presented in Table 9, a Q^2 value of 0.241 (higher than zero) strengthens the reliability of the SEM

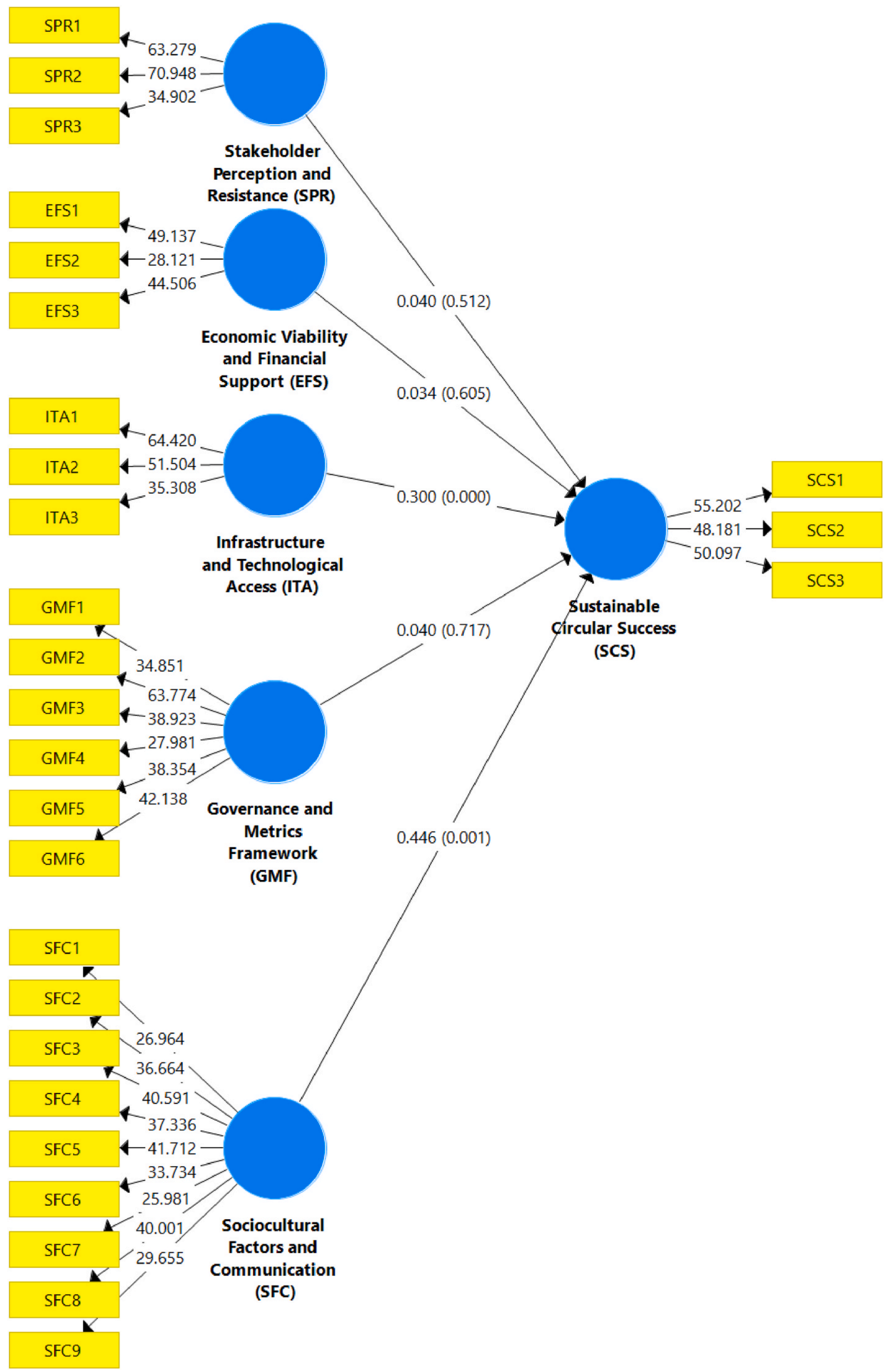

Fig. 5. SEM presentation bootstrapping path coefficients and P-values.

Table 7
Results of bootstrapping for the second order reflective construct.

Path	β	p - Values	Inner VIF
SPR → CEABs	0.040	<0.001	3.532
EFS → CEABs	0.034	<0.001	3.990
ITA → CEABs	0.300	<0.001	4.128
GMF → CEABs	0.040	<0.001	4.241
SFC → CEABs	0.446	<0.001	4.584

Table 8
The coefficient of determination (R^2) values for SEM.

Latent Variable (Endogenous)	$0 < R^2 < 1$	Adjusted R^2	Size Classification
SCS	0.661	0.656	High

in predicting the dependent variable from an independent variable beyond the sample data. Hence, according to Hair et al., the SEM indicates significant predictive validity [122].

Table 9
Predictive relevance (Q^2) values for SEM.

Latent Variable (Endogenous)	Sum of squares of observations (SSO)	Sum of squared errors (SSE)	Q^2 (=1-SSE/SSO)
SCS	135.263	102.762	0.241

5. Discussions

Our research examined the importance of CEABs alongside SCS associated industrial practices in driving the implementation of CE. The PLS-SEM analysis reveals that CEABs facilitate a crucial role in advancing CE implementation, leading to enhanced industrial performance. This study builds upon the findings of previous research [123–125], emphasised that additional research of capabilities could assist businesses in progressing towards greater sustainability within their industries. Moreover, our results on the connection between CEABs and SCS execution could support organisations in shifting negative perceptions into proactive strategies for CE adoption. Notably, our study evaluates the overall barriers to CE performance as the results suggest that barriers related to SFC and ITA have a positive and significant influence on the adoption of CE. The study [126], focuses that technological progress could be crucial in facilitating the adoption of CE techniques within industries. In contrast [72], identified a negative association between technical barriers and the adoption of CE, as well as with [127], who found no correlation between technology related obstacles and the implementation of CE. Furthermore, the findings by Ref. [128], indicate that consumer awareness and cultural factors are significant obstacles to innovation in CE practices.

Based on research [129], the production of precast concrete poles is a highly energy-intensive process which mainly contributes to greenhouse gas emissions, with a focus on a manufacturing facility in Lahore, Pakistan. By implementing sustainable techniques such as incorporating recycled concrete aggregates (RCA) and substituting cement clinker with fly ash, can reduce the manufacturing procedure's energy intensity by as much as 44 %. This approach not only decreases energy use but also cuts CO_2 emissions upon 30 %. By utilising repurposed materials and cutting down on waste helps the industry to reduce the need for extracting new resources, aligning with the central concept of CE [130]. By mitigating waste and energy usage industries can cut operational expenses and support ecological sustainability which ultimately leads to long term economic benefits. A case study conducted in Islamabad illustrates the practical implementation of the proposed business model in local conditions. Applied to the city's municipal waste management system, the model addressed a daily waste generation of approximately 1534 tons, with 47.3 % consisting of biodegradable waste. The paper [59] proposes a locally designed, cost-effective machine, the New Sorting Machine for Low-Income Countries (NSMFL). The NSMFL is engineered to sort municipal solid waste into various categories and includes a feature to compact sorted materials into bales, such as plastic nylon, bags, and combustibles. The case study [59] emphasises the incorporation of technological advancements, like waste segregation equipment, and the formalisation of the recycling process. This approach addresses informal scavenging issues and enhances the efficiency of the waste management sector.

5.1. Stakeholder Perception and Resistance Barriers

SPR barriers are linked with the attitudes, behaviors, and beliefs of stakeholders including consumers, businesses, and government entities. The SPR barriers ranked fourth with a β value of 0.040. Resistance to CE practices arises from stakeholders, familiar with linear economic model view the shift as complex and disruptive to established workflow. Also, the misalignment of interests and priorities among various stakeholders create obstacle to the widespread adoption of CE [131]. The complexity of CE demands significant collaboration and coordination across trades, resources, and workflow, both before and throughout the industrial process. Effective coordination is crucial for ensuring that projects achieve their goals and are completed on schedule and within budget constraints. Successful implementation of CE relies significantly on the collective efforts of the project team, where a unified objective forms the core of the process. Successful planning and execution of a CE process demand extensive coordination, and communication among all involved stakeholders. Adopting this approach is essential for achieving the planned project results and should be central part of any CE implementation strategy.

5.2. Economic Viability and Financial Support Barriers

EFS barriers are related to the substantial financial investments, risks, and the monetary decisions required throughout project's lifecycle. The EFS barriers ranked fifth with a β value of 0.034. The CE method within the industrial sector is considered high investment and resource reliant [132]. indicate that adopting the CE method requires significant upfront capital, covering new technologies, sustainable procurement, infrastructure upgrades and specialised equipment and expertise. Moreover, redesigning processes, recycling facilities, and reworking existing systems to align with CE principles needs significant investment. The scarcity of financial resources and support from public and private sectors is a key challenge. The limited availability of CE facilities and fabricators lead to elevated costs, making the justification hard of CE investments' economic viability for businesses [133]. Nevertheless, such barriers are commonly faced in the early phases of CE adoption, given that only a few industries have integrated CE into their processes. As the circular transformation of industries expands, governmental and institutional support and development of industry consortiums would enhance financial feasibility and reduce implementation costs in the long run. According to Ref. [134], the study identifies economic growth as a main factor for applying a considerable impact on shaping environmental policies in underdeveloped nations. Such policies are essential for addressing the financial needs of underprivileged communities.

5.3. Infrastructure and Technological Access Barriers

ITA barriers show a limitation in existing infrastructure, lack of access to advanced technologies, and insufficient technological capabilities among stakeholders. From the findings, The ITA barriers ranked second with a path coefficient β of 0.300. The existing practices within developing countries demand a thorough evaluation when applying innovations like CE. Implementing CE requires specialised technological competencies and skills that are different from those utilised in conventional industrial systems, such as traditional waste management, manufacturing facilities, and logistics operations. Therefore, to tackle these challenges it is important to effectively introduce CE. Due to the specific nature of CE and its innovative technological demands, many stakeholders have shown varying levels of resistance [135]. support this classification, arguing that the adoption of CE is significantly influenced by the technical expertise of the professionals involved in the execution process. In addition, numerous obstacles prevent the adoption of CE. These challenges include technological difficulties, costs that outweigh the benefits, and deficiencies within the supply chain system.

5.4. Governance and Metrics Framework Barriers

GMF barriers are linked with policies, regulations, standards, and measurement systems that oversee and assess the initiatives. The GMF barriers ranked third with a β value of 0.040. In numerous industrialised developing nations, existing regulations often fail to meet the unique demands for CE, resulting in uncertainty and a lack of consistency. Similarly, the lack of standardized metrics and certification schemes generate ambiguity and limit market acceptance for CE. The absence of adequate monitoring result in non-compliance which reduces the effectiveness of CE initiatives. Another essential factor in CE industrial projects is the concept of value for money. The stakeholders expect transparency and accountability. Without proper implementation, the industries will result in greenwashing. A study by Ref. [136], assess CE metrics using Multiple Correspondence Analysis (MCA) method, with the important one being 'monitoring the development of the CE'. Such metric fall under GMF obstacles. Moreover [137], discusses the key barriers in industry for implementing CE using fuzzy DEMATEL method. The study states that lack of legislation and awareness towards CE in government institutions results in hindrances towards successful CE transition.

5.5. Sociocultural Factors and Communication Barriers

SFC barriers represents obstacles related to social conventions, cultural attitudes, and effectiveness of communication among stakeholders. According to the findings, the SFC barrier ranked first with a path coefficient (β value) of 0.446. Societal values prioritize new products over reused or recycled ones, that obstruct the adoption of CE practices and viewing the latter of lower quality [138]. The lack of understanding about the concept of CE among stakeholders result in misconceptions and unwillingness towards embracing circular strategies. Similarly, the sociocultural challenges arise from decision-making processes that lack inclusivity which result in unequal access to resources and opportunities [97]. highlight that CE remains at an early stage in few developing countries, which makes it susceptible to unskilled professionals. Additionally, a study conducted by Ref. [139] examined the skill set for CE. The most important barrier identified was 'the skills to integrate stakeholders in the business ecosystem', which is considered as communication barrier. The study [140] discusses that a circular dynamic environment (CDE) also positively influences the level of CE implementation. This indicates that external factors, such as regulatory frameworks, market trends, and societal expectations, play a crucial role in motivating companies to pursue circular practices.

5.6. Sustainable circular success

Results specify that tackling CEABs contributes to 66.1 % of achieving SCS in industrial projects. This highlights the necessity of overcoming this barrier is essential for achieving substantial sustainability in these projects. Additionally, the average β value of 0.172 from the study specifies a connection between overcoming CEABs and achieving SCS. This signifies that for every unit improvement in an industry's capacity to attain CEABs, the SCS of industrial projects rises by 0.172. Likewise, the results of the study display a consistency with SCS. This section's aim has been fulfilled, and results are aligned with previous studies as it indicates the important role of environmental, social, and economic objectives for sustainable industries.

5.7. Proposed strategies for overcoming CE barriers

Prior studies neglected to focus on CEABs and the strategies required to overcome these barriers for achieving SCS in industrial projects. In

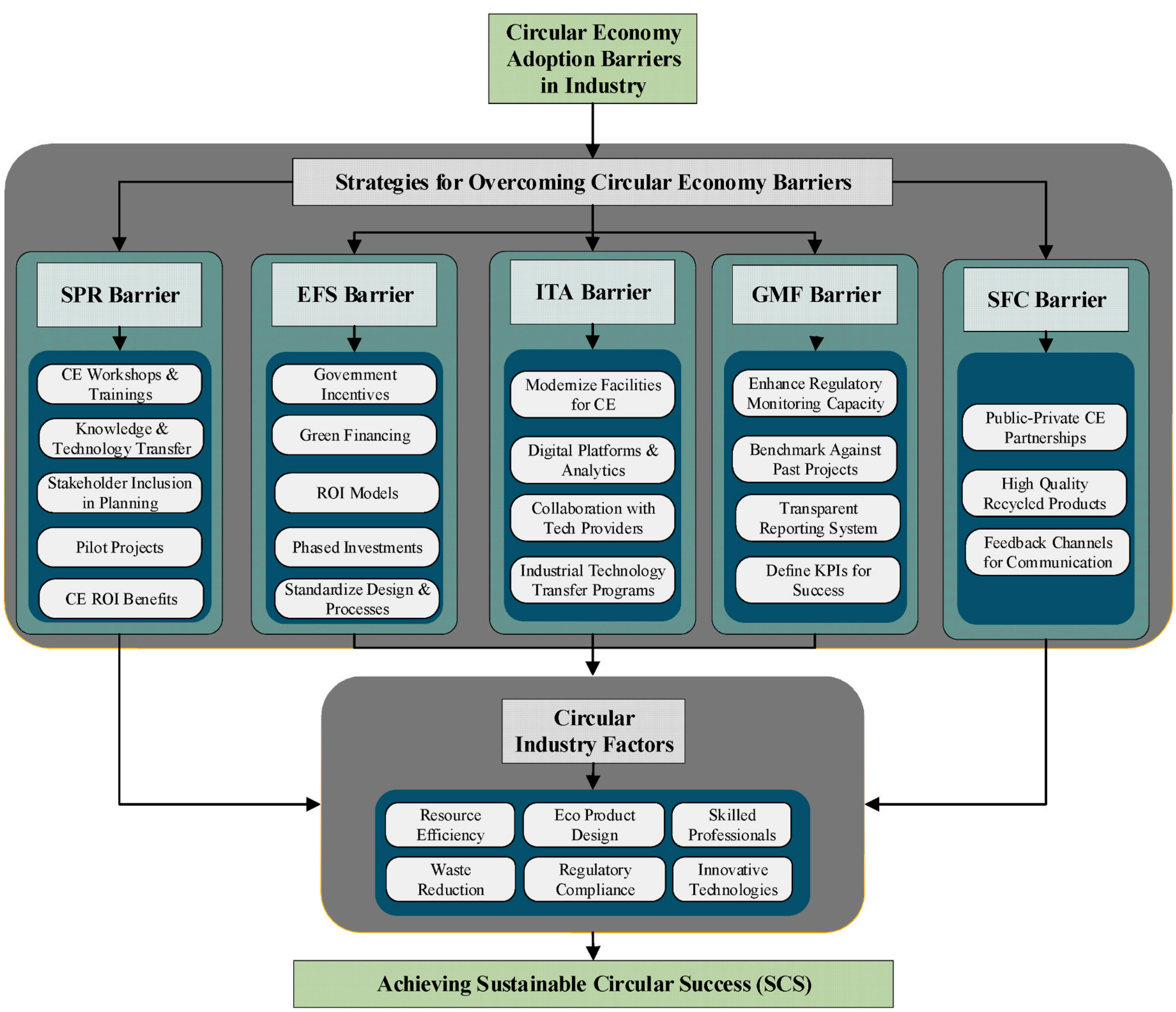

Fig. 6. Strategies for achieving sustainable circular success.

response, this study proposes for a unified approach, combining various methods and strategies to effectively address the complex network of challenges as shown in Fig. 6.

1. *For SPR Barrier:* (1) Organising workshops and training to enhance CE skills and insight among engineers, industrialists, and practitioners; (2) communicating the long-term benefits and return on investment (ROI) of CE using data and metrics; (3) involving stakeholders in planning and decision-making processes, increasing their buy-in; (4) launching pilot projects and sharing success stories to exemplify the feasibility and advantages of CE practices, making the concept less intimidating; (5) facilitating knowledge and technology transference to allocate expertise in circular industries to local stakeholders.
2. *For EFS Barrier:* (1) Utilising government incentives and exploring green financing options i.e., green bonds to support CE initiatives; (2) developing ROI models to forecast the economic benefits of CE initiatives and utilising phased investments to mitigate risks; (3) standardising design and processes in the CE to reduce cost and boost efficiency through mass remanufacturing and recycling, and automation.
3. *For ITA Barrier:* (1) Modernising facilities to support CE adoption such as waste-to-energy systems, remanufacturing and recycling industrial units; (2) using digital platforms and analytics to track resources and optimising waste management throughout supply chain; (3) collaborating with technology providers and research institutions; (4) joining industrial technology transfer programs to obtain innovative CE technologies from developed nations.
4. *For GMF Barrier:* (1) Developing capacity for regulatory agencies to monitor CE compliance; (2) using previous CE projects to acquire benchmarking data against for continuous improvement; (3) implementing transparent reporting systems to track progress; (4) defining key performance indicators (KPIs) for measuring the success of CE initiatives.
5. *For SFC Barrier:* (1) Promoting public-private partnerships to direct community focused CE projects; (2) ensuring high quality in recycled products to build consumer trust; (3) forming feedback channels to address stakeholder concerns for effective two-way communication.

6. Validation

Following the development of the statistical model, the study's findings and outcomes were thoroughly validated. In this framework, validation involves assessing the method's effectiveness in achieving its intended objective. Therefore, expert authentication was conducted to assess study's validity and confirm the proposed framework. This approach was undertaken to verify detailed, effective, and impartial research outcomes. For verification of the research results, an organized questionnaire survey was selected as the chosen method. Shared among 30 experts who joined in the pilot test and demonstrated keen interest in the subject matter. Utilising a Likert scale, participants were requested to specify their agreement levels with each survey question, facilitating the validation process. Designed to evaluate understanding, resilience, and receptiveness, the questionnaire survey sought to identify areas in need of improvement as well. Based on prior research, four questions were utilised in the current study to assess result validity.

The survey was divided into two parts: open-ended questions and closed-ended questions. In the closed-ended questions, participants were asked to rate their agreement level with each verification criterion. In contrast, the open-ended questions provided an opportunity to suggest areas needing improvement. The validation process included the following five closed-ended questions:

Q1. Does the study provide a logical and adequate viewpoint regarding the constraints related to CE adoption?

Q2. Are the proposed strategies for overcoming barriers to CE adoption regarded practical, acceptable, and relevant?

Q3. Does this research effectively demonstrate the causal relationship between overcoming CEABs and achieving CE for attaining SCS??

Q4. Do the findings reported in this research generate reasonable and practical results?

Q5. Is the CE adoption model proposed in this study applicable in a broader context?

7. Conclusion

The focus on circular sustainability in the manufacturing sector is gaining recognition as many countries seek to achieve the Sustainable Development Goals (SDGs), particularly SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), SDG 12 (Responsible Consumption and Production), and SDG 11 (Sustainable Cities and Communities). Nowadays, in many developing nations CE is extensively adopted for its prominent advantages and sustainability. Nonetheless, the adoption of CE practices in these countries remains relatively low. The study's primary aim is to identify the essential barriers to the adoption of the CE method as overcoming these challenges is essential for effective implementation in South Asian nations. The study inspects the influence of economic resilience, environmental impact, and social equity on CE techniques and practices within South Asian industries. In the Pakistan's industrial sector, the implementation of CE practices remains limited primarily due to the scarcity of research in this area.

Following an extensive literature review, 24 barriers restricting CE adoption were identified. Subsequently, data was gathered using a questionnaire involving 310 professionals within the Pakistan's industrial sector. To assess the interrelation between addressing CEABs and achieving SCS in industrial sector, the PLS-SEM methodology was utilised. The Fornell-Larcker criterion results demonstrates that all constructs exhibit strong discriminant validity. The path coefficient (β) value of 0.172 demonstrates a significant correlation between CEABs and SCS, confirming the hypothesis that overcoming CEABs is essential for attaining SCS in the industrial sector of developing nations. Moreover, the study's constructs illustrate high reliability, with value surpassing 0.8, confirming strong internal consistency. The findings highlighted a strong correlation, with tackling the CEABs accounting for 66.1 % of the SCS within the industrial sector. Furthermore, the predictive relevance (Q^2) value of 0.241 shows that the model effectively predicts the dependent variable SCS beyond the sample data, demonstrating strong predictive accuracy. Founded on the results from the path analysis, the prime construct barriers are ranked in the descending order, from most to the least effective in industrial adoption of CE:

1. Sociocultural Factors and Communication Barriers
2. Infrastructure and Technological Access Barriers
3. Governance and Metrics Framework Barriers
4. Stakeholder Perception and Resistance Barriers
5. Economic Viability and Financial Support Barriers

8. Implications

This study presents progressive and distinctive addition to the domain of CE in South Asian developing country of Pakistan by emphasizing on the recognition of CEABs within manufacturing industries. The utilization of PLS-SEM to construct a mathematical model represents an unconventional approach, which has rarely investigated in the context of CE barriers. This method has the capability to present significant perceptions into the intricate connections between addressing CEABs and attaining SCSs. This research seeks to address this discrepancy by investigating the impact of overcoming CEABs on CE adoption, employing PLS-SEM in industrial projects across Pakistan to attain maximum sustainability results. The findings of this study have significant implications for academia and the industrial sector of Pakistan and other South Asian nations.

8.1. Theoretical implications

This study contributes significantly to the theoretical framework by.

1. Delivering a detailed list of CEABs.
2. Providing valuable strategies for overcoming these barriers to support the adoption of CE techniques.
3. Emphasizing the importance of each classified CEAB and offering an in-depth analysis into their complexities.
4. Identifying cause-and-effect correlations between variables, such as addressing CEABs and CE implementation, that can aid in developing theories that clarify these connections.
5. Deepening the understanding of how overcoming CEABs relates to achieving SCS in industrial projects.

8.2. Practical implications

Beyond its theoretical contributions, this research offers practical insights that can aid stakeholders and legislators in developing nations, in particular.

1. Providing industry practitioners with a thorough knowledge of the obstacles and mitigation strategies related to the CE approach, thus enabling more successful implementation in the future.
2. By utilising the insights from this study, decision-makers and public officials can develop fact-based policies that progress the sustainable execution of CE practices in developing nations throughout South Asia.
3. The study offers methodical findings that can assist Pakistan and other less developed countries, particularly in South Asia to address existing barriers and adopt CE effectively.
4. Providing a detailed framework for capitalising on CE to develop sustainable industrial manufacturing.

9. Research limitations

Although this study makes substantial addition to both theory and practice, the limitations present multiple prospects for further research. Even with these challenges, the research not only met its objectives but also surpassed expectations. Initially, the research's regional domain is constrained, as the survey was exclusively distributed to industrial experts in Lahore, Karachi, Faisalabad, and Multan, Pakistan. Future research should include a wider and more varied sample of Pakistani industrial professionals, incorporating end-users and client officials from different regions across Pakistan, rather than limiting the study to Lahore, Karachi, Faisalabad, and Multan. Following that, the study's findings reveal that the Pakistani industry do not place a high priority on research and development. Participation in survey forms is rare in this industry, with many experts perceiving involvement in data surveys and researches as time-intensive and unproductive.

CRediT authorship contribution statement

Kumeel Rasheed: Writing – original draft, Visualization, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Syed Saad:** Writing – review & editing, Validation, Resources, Formal analysis. **Ahmad Zaland:** Supervision, Software. **Muhammad Waqas Khan:** Resources, Project administration. **Zawar Ali:** Visualization, Validation. **Muhammad Haris:** Project administration. **Syed Ammad:** Resources, Project administration. **Touseef Sadiq:** Resources, Funding acquisition.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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