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Full-length article

# How Industry 4.0 capabilities shape the Circular Economy–Sustainable Performance nexus at the micro-level: A mixed-methods approach

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## HIGHLIGHTS

- Examines how Industry 4.0 capabilities shape the circular economy–sustainable performance nexus at the firm level.
- Distinguishes between operational and managerial Industry 4.0 capabilities using a mixed-methods design.
- Shows that circular economy practices are the primary drivers of economic, social, and environmental performance.
- Demonstrates that managerial Industry 4.0 capabilities mediate sustainability outcomes, while operational capabilities do not.
- Provides actionable insights for entrepreneurs, managers, and policymakers on CE-led digital transformation.

## ARTICLE INFO

*Keywords:*
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## ABSTRACT

This study examines how Circular Economy (CE) practices and Industry 4.0 (I4.0) capabilities influence Sustainable Performance (SP) at the firm-level amid increasing environmental, social, and regulatory pressures. Although prior research suggests that digital technologies can support circular strategies, limited empirical evidence explains how I4.0 capabilities shape the CE–SP relationship at the firm-level across industries. To address this gap, the study investigates the direct, mediating, and moderating roles of operational and managerial I4.0 capabilities within the CE–SP nexus. A sequential mixed-methods design was employed, combining survey data from 138 firms analyzed using partial least squares structural equation modeling (PLS-SEM) with 10 semi-structured expert interviews for contextual validation. The findings show that CE practices positively influence economic, social, and environmental performance. Managerial I4.0 capabilities partially mediate the relationship between CE practices and social and environmental performance, whereas operational capabilities show no significant mediating effects. Although CE practices support the development of both operational and managerial digital capabilities, the moderating effects of I4.0 capabilities were limited and only marginally significant across selected sustainability dimensions. The study advances understanding of the CE–I4.0–SP relationship by showing that sustainability outcomes depend primarily on CE practices and managerial rather than purely operational digital capabilities. It also provides practical insights for managers and policymakers seeking to align digital transformation initiatives with CE objectives.

## 1. Introduction

In recent years, escalating environmental degradation, resource scarcity, and intensifying regulatory and societal pressures have fundamentally reshaped how organizations pursue economic growth [1]. Firms across sectors are increasingly required to reduce waste, improve resource efficiency, and address social responsibilities while maintaining competitiveness [2,3]. In response, two strategic paradigms have gained prominence: the Circular Economy (CE) and Industry 4.0 (I4.0). CE promotes regenerative production and consumption systems that aim to decouple economic value creation from resource depletion and environmental degradation [4]. I4.0 technologies, such as artificial intelligence (AI), the Internet of Things (IoT), and data analytics, enable real-time monitoring, automation, and digitally supported decision-making that can enhance organizational efficiency and transparency [5]. Recent research further highlights the growing role of AI-enabled system design and intelligent decision-support mechanisms in supporting CE transformation processes across organizational settings [6].

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Together, CE and I4.0 are increasingly viewed as complementary approaches for enhancing economic, social, and environmental performance. From a sustainable technology perspective, I4.0 extends beyond efficiency-enhancing digital tools by supporting the implementation and coordination of CE practices at the firm-level. In this context, digital transformation enhances resource efficiency, transparency, and circular value creation. However, despite increasing investment in circular and digital transformation initiatives, many firms still struggle to achieve consistent and measurable sustainability outcomes at the firm-level [7,8].

Existing research highlights the potential synergies between CE practices and I4.0 technologies in advancing organizational sustainability [7,9,10]. CE practices such as eco-design, resource recovery, and closed-loop systems have been associated with reductions in waste and improvements in environmental performance. In parallel, digital technologies can enhance transparency, traceability, and operational efficiency, supporting more effective implementation of sustainability initiatives.

Despite growing scholarly attention to the CE–I4.0 nexus, empirical research remains fragmented and theoretically underdeveloped [9,10]. First, prior studies frequently conceptualize I4.0 primarily in terms of technology adoption rather than capability development [11]. Consequently, limited attention has been given to how firms develop and deploy digital capabilities to support sustainability transformation. Second, although many studies report positive associations between digitalization and SP, empirical evidence remains inconclusive regarding the mechanisms through which I4.0 contributes to economic, social, and environmental outcomes [3,10]. Existing research also does not clearly explain whether sustainability benefits result directly from digital technologies or from complementary organizational and managerial capabilities. Third, although growing research examines CE and I4.0 integration at the firm-level, existing evidence remains fragmented across micro-, meso-, and macro-level perspectives [12,13]. As a result, limited understanding exists regarding how firm-level digital capabilities shape the translation of CE practices into sustainability outcomes.

Consequently, micro-level analyses are essential for understanding how CE practices and I4.0 capabilities translate into Sustainable Performance (SP) outcomes [3,14]. In this study, the term “micro-level” refers to the firm as the primary unit of analysis, focusing on organizational-level implementation of CE practices and I4.0 capabilities rather than individual- or employee-level processes [15]. Despite growing interest in CE and I4.0 integration, empirical research rarely differentiates between operational and managerial digital capabilities or examines how these capabilities shape CE-driven sustainability outcomes across organizational contexts [7,9].

Operational I4.0 capabilities primarily support activities such as automation, monitoring, and process optimization. In contrast, managerial I4.0 capabilities involve higher-order functions related to strategic alignment, data-driven decision-making, organizational coordination, and capability reconfiguration [11,16]. From a Dynamic Capabilities perspective, sustainability transformation depends not only on digital technology adoption, but also on firms’ ability to integrate these technologies within circular business practices [16].

To address this gap, the present study empirically investigates the direct, mediating, and moderating roles of I4.0 capabilities in the CE–SP nexus at the micro-level. By focusing on the firm-level, the study advances CE–I4.0 research in three ways. First, it explains how operational and managerial digital capabilities influence the relationship between CE practices and economic, social, and environmental performance outcomes. Second, it clarifies whether I4.0 capabilities function primarily as mediating or moderating mechanisms within the CE–SP relationship. Third, it advances micro-level understanding of how digital capability development influences sustainability outcomes across organizational contexts.

The study further advances CE–I4.0 research beyond technology adoption perspectives by proposing a capability differentiation framework that explains how operational and managerial digital capabilities contribute differently to sustainability transformation. Accordingly, the study is guided by the following research questions:

**RQ1:** To what extent do Circular Economy practices contribute to enhancing Sustainable Performance across economic, social, and environmental dimensions at the micro-level?

**RQ2:** How do operational and managerial capabilities enabled by Industry 4.0 technologies mediate the relationship between Circular Economy practices and Sustainable Performance at the micro-level?

**RQ3:** In what ways do operational and managerial Industry 4.0 capabilities moderate the strength or direction of the relationship between Circular Economy practices and Sustainable Performance at the micro-level?

The following section develops a capability-based conceptual framework grounded in Dynamic Capabilities Theory (DCT) and the Resource-Based View (RBV) to examine the direct, mediating, and moderating relationships within the CE–SP nexus.

The remainder of the paper is structured as follows. Section 2 presents the theoretical background and the development of hypotheses. Section 3 outlines the research methodology. Section 4 presents the empirical results. Section 5 discusses the findings and outlines the theoretical and practical implications. Section 6 concludes the study and suggests directions for future research.

## 2. Conceptual framework and hypothesis development

### *2.1. Theoretical foundations: An integrated dynamic capabilities and resource-based perspective*

This study is primarily grounded in DCT [16,17], which explains how firms adapt, integrate, and reconfigure internal and external competencies to address rapidly changing environments. DCT is particularly suitable for examining the integration of CE practices and I4.0 capabilities because sustainability-oriented transformation requires firms to continuously sense environmental and technological opportunities. Such transformation also depends on managerial capabilities to seize opportunities and reconfigure organizational resources to support long-term SP [18]. In this study, I4.0 technologies are conceptualized as digital resources that enable the development of organizational capabilities.

CE implementation requires firms to redesign products, restructure production systems, and coordinate closed-loop resource flows, which demand capabilities beyond routine operational efficiency. I4.0 technologies enable real-time data collection, automation, and digital connectivity; however, prior research emphasizes that digital technologies generate performance benefits only when they are strategically orchestrated and aligned with organizational objectives [11]. Accordingly, DCT helps explain why firms differ in their ability to translate similar digital investments into SP outcomes.

To complement this dynamic perspective, the RBV [19,20] is used as a foundational framework to conceptualize CE practices and I4.0 capabilities as firm-specific strategic resources. From an RBV perspective, practices such as eco-design, environmental management systems, and green investment recovery represent firm-specific resources that are valuable and difficult to imitate, thereby supporting competitive advantage and SP [2,21]. However, RBV alone cannot explain how these resources are translated into sustained outcomes in dynamic environments, highlighting the importance of DCT.

RBV and DCT, therefore, play complementary roles in the study. From an RBV perspective, CE practices and I4.0-related resources may constitute valuable firm-specific assets that support competitive advantage and sustainability performance [19,20]. In contrast, DCT explains how firms strategically integrate, reconfigure, and deploy these resources to respond to dynamic environmental and technological conditions [16,17]. RBV provides the resource foundation of the conceptual model, whereas DCT explains how these resources are translated into SP outcomes.

Consistent with this perspective, the study distinguishes between operational and managerial I4.0 capabilities. Operational capabilities refer to execution-oriented uses of digital technologies that primarily enhance process efficiency and responsiveness [11]. In contrast, managerial capabilities represent dynamic orchestration capabilities, including data-driven decision-making, strategic alignment, workforce development, and continuous performance evaluation [16]. These managerial capabilities enable firms to sense opportunities, coordinate digital and CE resources, and support SP outcomes. Together, the integrated RBV–DCT perspective explains how CE-related resources support SP outcomes through I4.0 capabilities. In particular, managerial capabilities play a critical role in aligning digital resources with sustainability-oriented objectives and organizational adaptation processes.

The study differentiates between operational digital capabilities and managerial orchestration capabilities associated with sustainability-oriented adaptation and resource reconfiguration. Operational I4.0 capabilities primarily support execution-oriented activities such as automation, monitoring, and process efficiency, whereas managerial I4.0 capabilities enable firms to sense opportunities, align digital transformation with sustainability objectives, and reconfigure organizational resources accordingly. This distinction is theoretically important because prior CE–I4.0 studies often treat digital capability as a homogeneous construct, overlooking the role of managerial orchestration in sustainability transformation.

While operational I4.0 capabilities primarily enhance process efficiency and responsiveness, they do not independently enable firms to strategically adapt circular business models or sustainability objectives. In contrast, managerial I4.0 capabilities support higher-order organizational processes related to strategic coordination, resource orchestration, and continuous adaptation, which are essential for sustainability-oriented transformation in dynamic environments [11, 16]. In CE implementation, long-term sustainability outcomes depend not only on operational efficiency, but also on firms' ability to align digital transformation initiatives with broader organizational and environmental objectives.

Accordingly, the conceptual framework positions I4.0 technologies as digital resources that support the development of operational and managerial capabilities, rather than as direct drivers of sustainability performance.

### 2.2. Industry 4.0 capabilities at the micro-level: Operational and managerial capabilities

I4.0 is widely recognized as a complex and multi-dimensional paradigm encompassing advanced digital technologies such as IoT, big data analytics, cloud computing, and automation [22]. However, conceptualizing I4.0 solely through technology adoption provides limited explanatory power because performance outcomes depend on how digital resources are deployed, integrated, and governed. Accordingly, this study conceptualizes I4.0 as a set of organizational capabilities rather than a bundle of discrete technologies. Drawing on DCT, the study distinguishes between operational and managerial I4.0 capabilities. Operational capabilities primarily enhance efficiency, whereas managerial capabilities enable firms to sense opportunities, make strategic decisions, and reconfigure resources in response to environmental change [16,18].

At the micro-level, operational I4.0 capabilities refer to the execution-oriented deployment of digital technologies to enhance process efficiency, responsiveness, and operational coordination [11]. While these capabilities support the exploitation of existing routines, they do not independently enable strategic adaptation or sustainability-oriented transformation. In contrast, managerial I4.0 capabilities represent dynamic orchestration capabilities related to data-driven decision-making, strategic alignment, workforce development, and continuous performance evaluation. Unlike generic managerial competencies, managerial I4.0 capabilities are specifically associated with the strategic orchestration, integration, and governance of digitally enabled processes and data-driven organizational transformation. Rather than representing generic managerial competence or DCT more broadly, managerial I4.0 capabilities are conceptualized here as context-specific digital orchestration capabilities through which firms apply data-driven decision-making, digital governance, and technology-enabled coordination to support CE implementation and sustainability-oriented reconfiguration. These managerial capabilities enable firms to interpret digital insights, orchestrate the integration of I4.0 technologies with CE practices, and engage in sensing, seizing, and reconfiguring activities that are essential for achieving SP outcomes. By aligning digital transformation initiatives with sustainability objectives, managerial capabilities help firms coordinate circular processes, adapt organizational routines, and integrate sustainability into strategic decision-making. In contrast, operational capabilities primarily support the efficient execution and monitoring of circular activities.

### 2.3. Hypotheses development

#### 2.3.1. CE and SP

The CE is an emerging concept [2,23,24] aimed at extending the lifecycle of resources across the design, manufacture, and delivery of goods and services. CE restores the functionality of production and consumption outputs through circular resource strategies, enabling the development of innovative business models. CE practices are widely recognized as an effective approach to advancing corporate sustainability. Economically, CE practices enhance organizational resilience by reducing supply chain vulnerabilities through closed-loop resource flows. CE practices also foster cost efficiencies by reducing waste management costs, energy consumption, and dependence on virgin materials [25]. Socially, CE practices generate employment opportunities and promote new business models through sharing-based systems, contributing to more equitable resource access [26,27]. Finally, the environmental benefits of adopting CE practices include reduced virgin resource extraction through regenerative models, enhanced efficiency in water, energy, and raw material use, and lower pollution and waste generation [28,29].

Despite these advantages, CE implementation alone may be insufficient to achieve sustainability outcomes without complementary systemic changes [2]. Nevertheless, CE remains a critical strategy for achieving ecological balance by reducing resource use and waste generation while simultaneously enhancing business performance [30].

Specifically, eco-design and environmental management systems can enhance environmental performance by reducing material consumption, emissions, and waste generation throughout product life cycles [31,32]. Environmental-related customer cooperation and green investment recovery practices may further improve economic performance through cost reductions, resource recovery, and enhanced operational resilience [2,33,34]. In addition, CE practices can strengthen social performance by promoting stakeholder collaboration, supporting sustainable employment opportunities, and improving community and employee well-being [26,27].

Existing literature suggests that CE practices positively contribute to SP at the micro-level. Based on the above discussion, we propose the following hypotheses:

**H1.** Micro-level CE practices have a direct and positive impact on SP.

**H1a.** Micro-level CE practices have a direct and positive impact on the economic performance of firms.

**H1b.** Micro-level CE practices have a direct and positive impact on the social performance of firms.

**H1c.** Micro-level CE practices have a direct and positive impact on the environmental performance of firms.

*2.3.2. The mediating role of Industry 4.0–enabled capabilities in the CE–SP relationship*

By shifting from linear to closed-loop production systems, CE practices increase firms' need for digital capabilities that support process transparency, coordination, and real-time decision-making [35].

The integration of CE and I4.0 technologies to advance sustainability remains an emerging research domain, with limited empirical evidence validating their synergistic potential [36,37]. Few empirical studies have examined this relationship specifically at the micro-level, supporting a positive association between CE and I4.0 technologies [38,39]. In contrast, numerous studies have demonstrated that CE approaches significantly enhance SP through hazardous material minimization, resource efficiency, energy conservation, and waste reduction [40,41]. While some studies have begun exploring CE–I4.0 synergies [9], comprehensive empirical evidence at the firm-level that links their integration to specific SP outcomes remains limited [3].

Drawing on DCT, the study conceptualizes I4.0 capabilities as mechanisms through which CE practices influence SP outcomes. From this perspective, the implementation of CE practices increases firms' need to sense inefficiencies and sustainability opportunities, seize digital solutions to address them, and reconfigure operational and managerial processes accordingly [16]. I4.0 capabilities, therefore, function as enabling mechanisms that support the alignment of circular practices with micro-level performance objectives. In this study, mediation reflects the internal organizational processes through which CE practices are translated into sustainability outcomes via the development and deployment of I4.0 capabilities.

Importantly, the mediating role of I4.0 capabilities is expected to differ by capability type. As defined earlier, operational I4.0 capabilities support the execution and monitoring of circular processes by enhancing efficiency, traceability, and process control. In contrast, managerial I4.0 capabilities govern the strategic alignment, coordination, and continuous adaptation of digital initiatives, enabling firms to integrate CE practices into decision-making and performance management systems. Consequently, managerial capabilities are expected to play a more decisive mediating role than purely operational capabilities in translating CE practices into SP outcomes.

Based on this reasoning, the following hypotheses are proposed:

**H2.** I4.0 capabilities mediate the relationship between micro-level CE practices and SP.

**H2a.** Micro-level CE practices have a direct and positive impact on firms' operational I4.0 capabilities.

**H2b.** Micro-level CE practices have a direct and positive impact on firms' managerial I4.0 capabilities.

**H2c**. Firms' operational I4.0 capabilities directly and positively impact their economic performance.

**H2d**. Firms' operational I4.0 capabilities directly and positively impact their social performance.

**H2e.** Firms' operational I4.0 capabilities directly and positively impact their environmental performance.

**H2f.** Firms' managerial I4.0 capabilities directly and positively impact their economic performance.

**H2g.** Firms' managerial I4.0 capabilities directly and positively impact their social performance.

**H2h.** Firms' managerial I4.0 capabilities directly and positively impact their environmental performance.

*2.3.3. The moderating role of Industry 4.0–enabled capabilities in the CE–SP relationship*

While the mediating role of I4.0 capabilities explains the internal mechanisms through which CE practices may be translated into SP outcomes, moderation captures how differences in firms' I4.0 capabilities influence the strength of these relationships across organizational contexts. Organizations across industries are increasingly pursuing sustainability through integrated frameworks; however, the effectiveness of CE practices in generating SP outcomes varies considerably across firms [42,43]. While CE practices define the strategic intent to reduce resource use, waste, and environmental impact, their performance implications depend on firms' ability to effectively implement, coordinate, and adapt these practices within existing operational and managerial structures [44]. This variability highlights the importance of I4.0-enabled digital capabilities as potential boundary conditions shaping the strength of the CE–SP relationship at the micro-organizational level.

However, the moderating influence of I4.0 capabilities may not be uniform or consistently observable across firms and sustainability dimensions. The effectiveness of digital capabilities likely depends on contextual conditions such as organizational readiness, implementation quality, strategic alignment, and digital maturity [11,16]. Empirical evidence from sector-specific studies further suggests that digital–circular integration pathways are shaped by organizational and contextual conditions, including implementation maturity, governance structures, and industry-specific transformation dynamics [45]. In addition, CE implementation and digital transformation are often highly integrated organizational processes. As a result, I4.0 capabilities may function more strongly as internal enabling mechanisms that support the execution and coordination of CE practices rather than as external boundary conditions that systematically strengthen CE–SP relationships across firms [3,16]. Accordingly, the moderating effects of I4.0 capabilities are expected to be context-dependent and relatively modest across sustainability dimensions. Furthermore, moderation effects in organizational research are often empirically difficult to detect because interaction effects tend to exhibit relatively small effect sizes and may be sensitive to contextual heterogeneity across firms and industries [46].

The effectiveness of I4.0 capabilities may also vary across industries and regional contexts due to differences in digital maturity, regulatory pressures, infrastructure readiness, and sustainability priorities. Comparative evidence across meso- and macro-level contexts similarly suggests that the sustainability implications of I4.0 technologies are highly sensitive to contextual and institutional conditions [47]. Firms operating in technologically advanced or resource-intensive industries may therefore exhibit stronger CE–SP relationships than firms operating in less digitally mature environments [13].

From a DCT perspective, I4.0 capabilities may under certain organizational conditions function as moderating mechanisms that influence how effectively CE practices are translated into economic, social, and environmental performance outcomes. While CE practices establish circular objectives, I4.0 capabilities enhance firms' capacity to coordinate activities, respond to operational disruptions, and adapt processes in real time. By strengthening firms' ability to coordinate and adapt circular initiatives within organizational processes, I4.0 capabilities may reinforce the impact of CE practices on SP outcomes when supported by effective strategic alignment and organizational integration [16].

Importantly, the potential moderating influence of I4.0 capabilities is expected to differ by capability type. Operational I4.0 capabilities are likely to moderate the CE–SP relationship by improving process efficiency, traceability, and operational control, thereby enhancing the execution of circular practices. Managerial I4.0 capabilities may moderate this relationship by aligning CE initiatives with strategic priorities, integrating sustainability objectives into decision-making processes, and facilitating organizational learning and adaptation. However, the moderating effects of both operational and managerial I4.0 capabilities are expected to be limited and contingent on specific dimensions of SP, rather than uniform across economic, social, and environmental outcomes.

Accordingly, the proposed moderation relationships are theoretically plausible but context dependent. Despite growing interest in the CE–I4.0 nexus, empirical research examining the moderating role of I4.0 capabilities at the micro-level remains limited, particularly across the economic, social, and environmental dimensions of SP. Given the emerging and context-dependent nature of moderation research within the CE–I4.0 literature, the present study examines the following hypotheses regarding the potential moderating role of I4.0 capabilities:

**H3**. I4.0 capabilities moderate the relationship between micro-level CE and SP.

**H3a.** The operational I4.0 capabilities positively moderate the relationship between micro-level CE and the economic performance of firms.

**H3b.** The operational I4.0 capabilities positively moderate the relationship between micro-level CE and the social performance of firms.

**H3c.** The operational I4.0 capabilities positively moderate the relationship between micro-level CE and the environmental performance of firms.

**H3d.** The managerial I4.0 capabilities positively moderate the relationship between micro-level CE and the economic performance of firms.

**H3e.** The managerial I4.0 capabilities positively moderate the relationship between micro-level CE and the social performance of firms.

**H3f.** The managerial I4.0 capabilities positively moderate the relationship between micro-level CE and the environmental performance of firms.

Fig. 1 summarizes the capability-based conceptual framework, illustrating the mediating and moderating roles of Industry 4.0–enabled operational and managerial capabilities in the relationship between CE practices and SP at the micro-level, while depicting the constructs and hypotheses developed in this section.

## 3. Methods and research design

This study adopts a sequential explanatory mixed-methods design, integrating quantitative and qualitative approaches to examine the relationships among CE practices, I4.0 capabilities, and SP (Fig. 2). In Phase 1, quantitative data were collected through a cross-sectional survey and analyzed using partial least squares structural equation modeling (PLS-SEM) to identify statistically significant patterns and relationships among the core constructs. In Phase 2, semi-structured interviews were conducted to validate and contextualize the quantitative findings while explaining the organizational mechanisms and implementation challenges underlying the observed relationships.

The sequential explanatory mixed-methods design was considered appropriate for this study because the research seeks not only to examine statistically significant relationships among CE practices, I4.0 capabilities, and SP, but also to understand the organizational mechanisms underlying these relationships. Consistent with mixed-methods research guidance [48], the quantitative phase was prioritized to test the hypothesized direct, mediating, and moderating relationships using PLS-SEM across a heterogeneous sample of firms. The qualitative phase was subsequently employed to explain and contextualize the quantitative findings, particularly the partially significant and asymmetric effects observed across operational and managerial I4.0 capabilities. This structure enabled methodological complementarity by integrating statistical patterns with contextual insights into firm-level implementation.

### 3.1. Sampling

This study targeted organizations operating across diverse industrial sectors and geographic regions, with a specific focus on the micro-level, defined as individual firms, SMEs, and production units. Firms from regions commonly associated with both emerging and developed economic contexts were included to capture variation in digitalization maturity and sustainability practices, consistent with prior micro-level sustainability research [3,14]. In this study, the firm was used as the unit of analysis and, accordingly, a one-time, single-respondent survey instrument was adopted, which is common in firm-level research on digital transformation and sustainability where senior informants possess comprehensive organizational knowledge [11,49]. The target population comprised senior organizational informants, such as CEOs, business owners, directors, and senior or middle managers involved in planning, implementing, or overseeing I4.0 technologies and CE practices. Purposive sampling was considered appropriate because the study required respondents with direct organizational knowledge of CE implementation, I4.0 technologies, and sustainability-related decision-making processes [50]. In addition, a snowball sampling technique was employed, whereby initial participants referred other potential respondents who met the study's inclusion criteria [51]. An initial pool of approximately 521 professionals was contacted, resulting in 316 formally submitted questionnaires. Following post-collection screening, 138 valid firm-level responses were retained for analysis to ensure consistency with the study's unit of analysis and inclusion criteria. The final analytical sample included organizations from diverse industries and geographic regions, thereby enhancing contextual variation within the study. This heterogeneity was appropriate given the study's exploratory aim of examining CE–I4.0–SP relationships across organizational contexts. The sample size was sufficient for estimating the proposed structural relationships, given the study's exploratory and prediction-oriented design and the complexity of the mediation and moderation model. PLS-SEM is particularly suitable for research involving complex models and moderate sample sizes [52]. Although purposive and snowball sampling limit statistical generalizability, these approaches were considered appropriate for identifying respondents with direct experience in CE practices and I4.0 implementation within their organizations.

### 3.2. Instrument development

The questionnaire was developed in English and designed to capture firm-level practices related to CE implementation, I4.0 capabilities, and SP. To evaluate the clarity, relevance, and completeness of the measurement items, the initial version of the questionnaire was reviewed by academic and industry experts with expertise in sustainability, digital transformation, and operations management, following established survey development practices [53,54]. Based on their feedback, minor modifications were introduced to improve item clarity, contextual relevance, and conceptual consistency with the study constructs. The revised instrument was subsequently pre-tested with participants from diverse industrial sectors and professional roles to evaluate the overall suitability of the survey for the target population, as recommended for firm-level survey research [49]. Feedback from the pre-test confirmed that the questionnaire was appropriate for the target population and capable of capturing the intended information. The survey was administered using the SurveyMonkey platform, and the structure of the questionnaire required responses to all items before submission. This design ensured that only complete questionnaires were formally submitted and retained for analysis, thereby reducing the risk of truncated responses and improving data usability.

Scale adaptation followed a structured process to ensure content validity and contextual alignment. Measurement items were adapted from previously validated studies and refined to reflect the firm-level context of CE implementation, I4.0 capabilities, and SP. An expert review was conducted to evaluate item clarity, relevance, and conceptual consistency with the study constructs. The revised instrument was subsequently pre-tested to assess wording, interpretability, and practical suitability for the target respondents. These procedures enhanced the methodological rigor and overall quality of the survey instrument prior to full-scale data collection [53,54].

### 3.3. Data collection

Prior to the beginning of data collection, ethical approval was obtained from the Institutional Review Board (Protocol # H24-016). The survey was administered through LinkedIn invitations accompanied by a Participant Information Sheet outlining the study objectives, confidentiality assurances, and voluntary participation. Potential participants were identified through a systematic review of professional

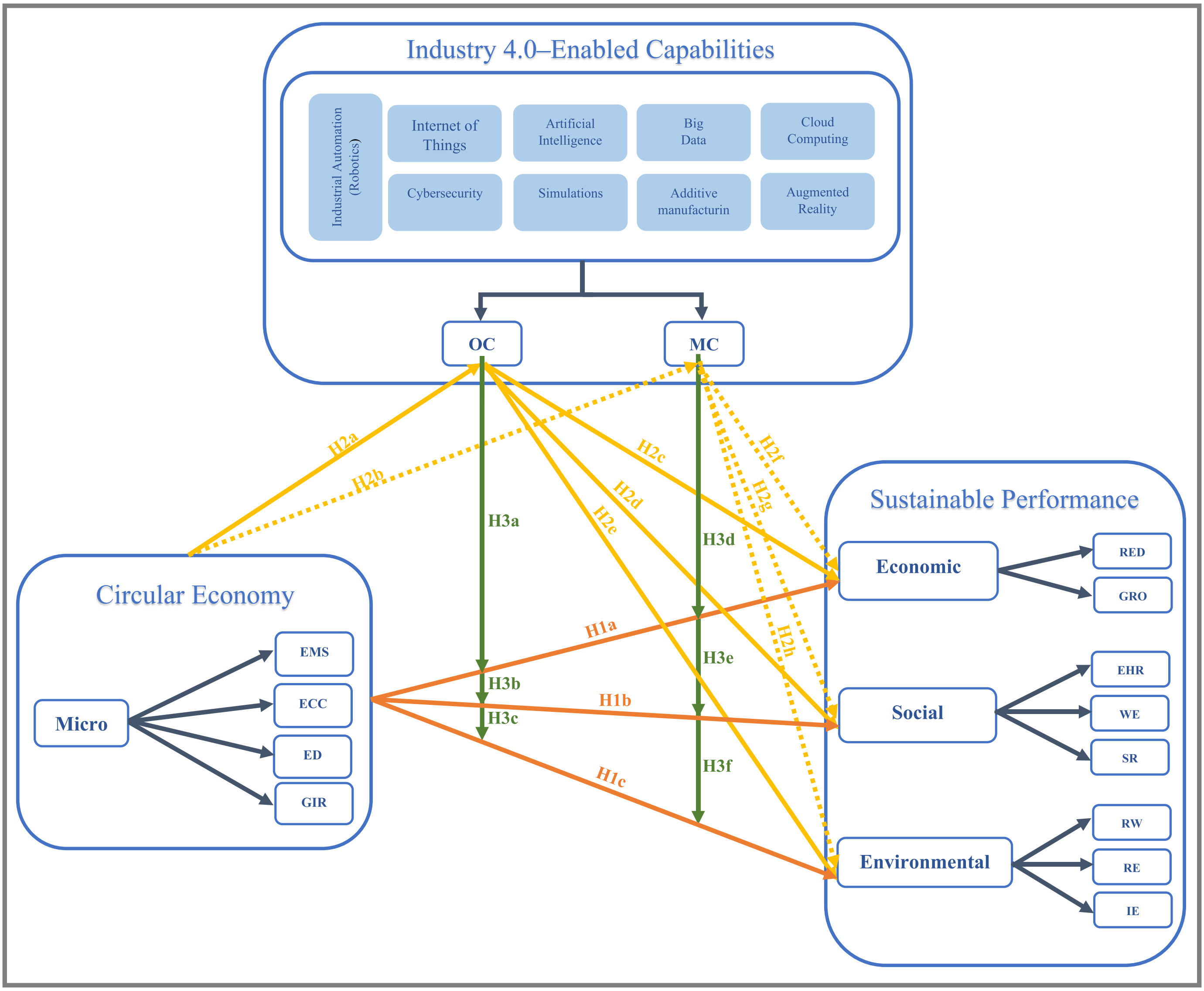


**Fig. 1.** The conceptual framework of the research.
**Abbreviations:** EMS, Environmental Management Systems; ECC, Environmental-related Customer Cooperation; ED, Eco-design; GIR, Green Investment Recovery; OC, Operational Capability; MC, Managerial Capability; RED, Reduction; GRO, Growth; EHR, Employees and Human Rights/Employees; WE, Work Environment; SR, Stakeholders and Relationships/Stakeholders; RW, Reduction Waste; RE, Reduction Emissions; IE, Improvement Efficiency.

profiles and invited to participate on a voluntary basis. The questionnaires were collected over eight months, with multiple follow-up reminders issued to enhance participation. Following data screening and eligibility assessment procedures, 138 valid firm-level responses were retained for analysis. Fig. 3 illustrates the distribution of participants across job positions, highlighting the diversity of roles represented in the sample. The characteristics of the final sample are presented in Table 1.

Potential non-response bias was assessed using the early–late respondent comparison approach proposed by Armstrong and Overton [55]. Early and late responses were compared across key respondent characteristics and main construct scores to examine whether systematic differences existed between the two groups. Several procedural remedies were implemented to reduce the potential influence of common method variance (CMV). Respondents were assured of anonymity and confidentiality, and measurement items were adapted from previously validated scales. Questionnaire wording was refined through expert review and pre-testing to improve clarity and reduce response ambiguity, consistent with recommendations by Podsakoff et al. [49].

### 3.4. Measurement items

A comprehensive review of the literature was conducted to identify valid and widely used measures for CE practices, I4.0 technologies, and SP. The measurement items included in the questionnaire were adapted from established scales reported in prior empirical studies, ensuring content validity and consistency with existing research. Previously validated measures reported in the literature were used to operationalize the study constructs (Appendix). All constructs were assessed using five-point Likert-type scales. CE practices and I4.0 technologies were measured on scales ranging from 1 ("Not considering it") to 5 ("Successful implementation achieved"), reflecting the degree of adoption and implementation maturity. SP was measured using a scale ranging from 1 ("Worsened significantly") to 5 ("Improved significantly"), capturing respondents' perceived changes in economic, social, and environmental performance over time.

The use of perceptual measures for SP was considered appropriate because objective sustainability indicators are often difficult to obtain and compare across firms, industries, and geographic contexts. This

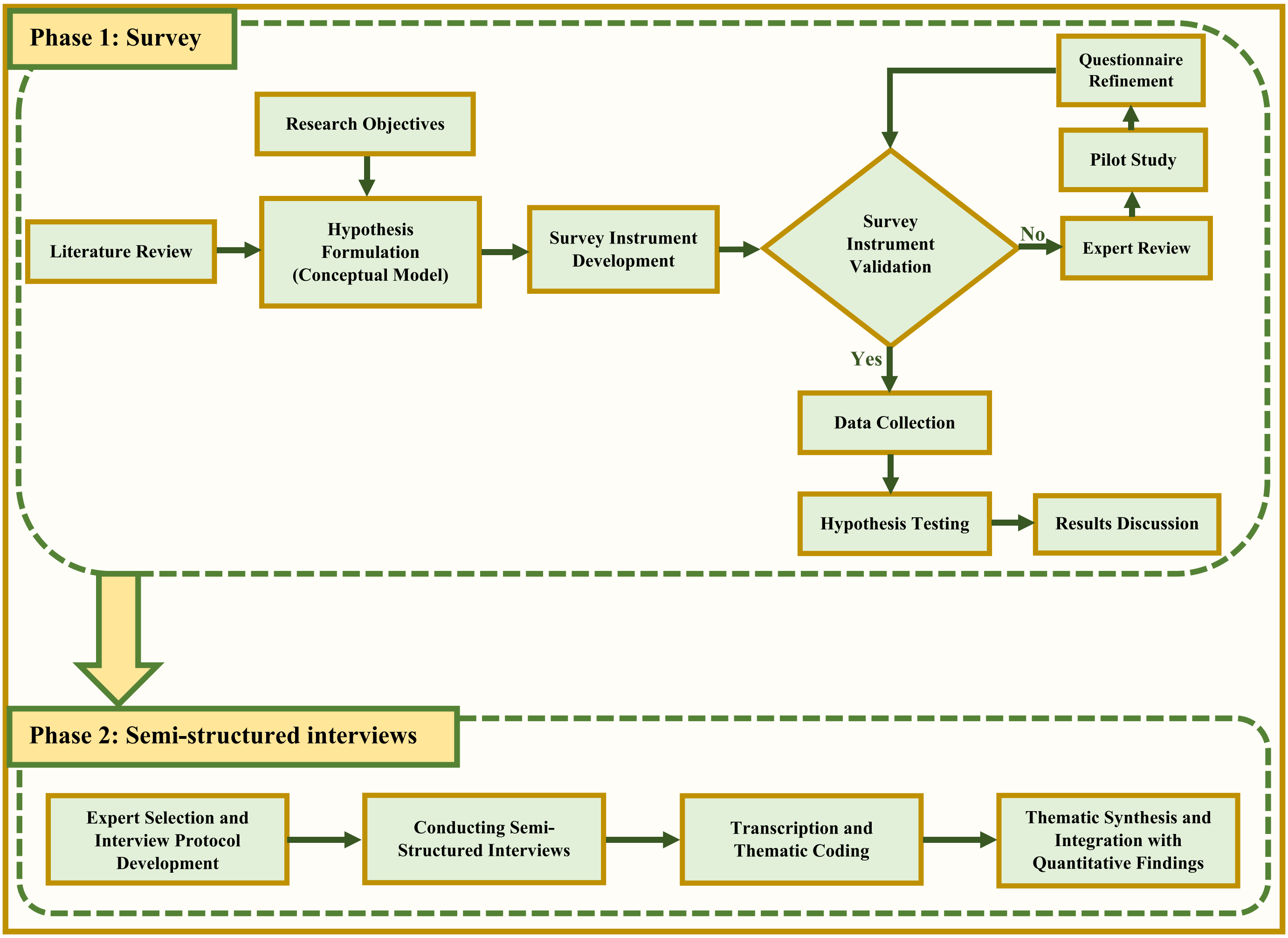


**Fig. 2.** Research design.


**Fig. 3.** Job positions and distribution of participants (created by the author on worditout.com).

**Table 1**
Sample characteristics.

| Respondent classifications | | Total | % |
|---|---|---|---|
| Industry sector | Manufacturing | 16 | 11.59% |
| | Technology | 14 | 10.14% |
| | Electric/Electronic | 3 | 2.17% |
| | Healthcare | 1 | 0.72% |
| | Energy and Utilities | 13 | 9.42% |
| | Transportation and Logistics | 3 | 2.17% |
| | Construction, Buildings, and Infrastructure | 14 | 10.14% |
| | Food and Agriculture | 6 | 4.35% |
| | Retail and E-commerce | 5 | 3.62% |
| | Other (please specify) | 63 | 45.65% |
| Education | College Level (Diploma/Certificate) | 15 | 10.87% |
| | Undergraduate | 37 | 26.81% |
| | Postgraduate and Doctorate | 86 | 62.32% |
| Respondent position | Middle Manager | 31 | 22.46% |
| | Senior Manager | 18 | 13.04% |
| | CEO | 18 | 13.04% |
| | Business Owner | 19 | 13.77% |
| | Executive | 15 | 10.87% |
| | General Manager | 6 | 4.35% |
| | Department Head | 16 | 11.59% |
| | Other (please specify) | 15 | 10.87% |
| Experience (years) | <10 | 54 | 39.13% |
| | 10–15 | 25 | 18.12% |
| | 15–25 | 34 | 24.64% |
| | 25+ | 25 | 18.12% |
| Geographic area | Africa | 16 | 11.59% |
| | Europe | 38 | 27.54% |
| | Asia | 28 | 20.29% |
| | Middle East | 16 | 11.59% |
| | North America | 16 | 11.59% |
| | Other (please specify) | 24 | 17.39% |

challenge is particularly relevant in multi-sector studies, where economic, social, and environmental outcomes are frequently evaluated using different organizational systems and reporting standards. Prior research suggests that perceptual performance measures are appropriate when respondents possess direct organizational knowledge and are capable of assessing relative organizational performance changes [56,57].

The survey instrument included respondent background information and 59 measurement items assessing the six primary constructs of the conceptual model (Fig. 1), as detailed in Appendix. CE practices were operationalized using 16 measurement items distributed across four sub-constructs representing key dimensions of circular implementation at the firm-level: Environmental Management Systems, reflecting the adoption of environmental standards, pollution prevention practices, and performance monitoring; Environmental-related Customer Cooperation, capturing collaboration with customers on eco-design, cleaner production, and energy-efficient logistics; Eco-design, assessing the extent to which products are designed to minimize material and energy consumption, facilitate reuse and recycling, and reduce hazardous substances; and Green Investment Recovery, measuring practices related to recycling, reuse, and recovery of end-of-life products and materials.

To capture firms' engagement with I4.0 capabilities, respondents were first asked to indicate the digital technologies adopted within their organizations, such as IoT, AI, and cloud computing. Subsequently, eleven measurement items were used to assess I4.0 technologies as organizational capabilities, conceptualized into two sub-constructs. Operational I4.0 capability reflects the use of digital technologies to support real-time monitoring, data visualization, process control, and decentralized decision-making. Managerial I4.0 capability captures the strategic and governance-oriented use of digital technologies, including data-driven decision-making, analytics infrastructure development, employee training, implementation oversight, performance monitoring, and adaptive capability development.

SP was assessed using 32 items, grouped into three sub-constructs reflecting the triple bottom line perspective. Economic performance was measured through two dimensions capturing cost efficiency and growth-related outcomes. Social performance was operationalized using three dimensions related to employee well-being, work environment, and stakeholder relationships. Environmental performance was measured using three dimensions capturing waste reduction, emission reduction, and improvements in resource and energy efficiency. The presentation of the measurement items is available in Appendix.

All constructs were specified as reflective because their indicators were conceptualized as observable manifestations of the underlying latent variables. In this specification, variations in CE practices, I4.0 capabilities, and SP were expected to be reflected through corresponding variations in their respective indicators. The appropriateness of the reflective measurement specification was subsequently examined through reliability and validity assessments conducted within the measurement model evaluation.

### 3.5. Qualitative phase: Semi-structured interviews

To complement the quantitative analysis and deepen understanding of the organizational processes and implementation dynamics associated with the observed relationships, semi-structured interviews were conducted as part of the second phase of the sequential mixed-methods design. Qualitative inquiry is particularly suited to exploring how and why complex organizational phenomena unfold in practice, especially in emerging research domains such as the integration of CE practices and I4.0 capabilities [58,59]. Accordingly, the qualitative phase provided explanatory and contextual insights into the quantitative findings.

A purposive sampling strategy was employed to select interviewees with substantial and relevant experience in CE implementation and the application or governance of I4.0 technologies, consistent with established qualitative research practices [60]. Inclusion criteria required participants to have direct professional involvement in sustainability-oriented decision-making, digital transformation initiatives, or the operational implementation of CE and I4.0 practices. Ten experts were selected to provide interpretive insights into firm-level implementation processes.

Although participants came from diverse professional backgrounds, all had sustained engagement with firm-level decision-making, implementation, or advisory activities related to CE and digital transformation. The unit of analysis remained the firm. Accordingly, interviewees were treated as knowledgeable informants who provided contextual insights into firm-level mechanisms identified in the quantitative analysis. An overview of participants' industry backgrounds, roles, and years of experience is provided in Table 2. To ensure confidentiality, all participants were anonymized using expert codes.

Interviews followed a semi-structured protocol aligned with the study's research questions and conceptual framework. Semi-structured interviews enable flexibility while ensuring coverage of core themes, making them particularly suitable for examining complex, process-oriented organizational phenomena [61]. Interview questions focused on three broad thematic areas. These included: (1) perceived mechanisms underlying the direct and mediating relationships between CE practices, I4.0 capabilities, and SP; (2) barriers and constraints limiting the mediating role of I4.0 capabilities; and (3) contextual factors shaping challenges and opportunities associated with the moderating influence of I4.0 capabilities in the CE–SP relationship. All interviews were conducted virtually via Microsoft Teams, audio-recorded with participants' informed consent, and transcribed in full for analysis. Interview duration ranged from approximately 30 to 45 min. All interview procedures were conducted in accordance with the approved ethical protocol, and informed consent was obtained from all participants.

**Table 2**
Background information of interviewed experts.

| Expert code | Industry sector | Respondent role | Experience in years |
|---|---|---|---|
| E1 | Manufacturing within academia | Reader in sustainable systems engineering | 15 |
| E2 | Manufacturing and supply chain | Supply chain excellence consultant | 18 |
| E3 | Prefabricated construction, construction and academia | Senior lecturer | 19 |
| E4 | Ministry of Environment and consultations | Environmental and sustainability consultant | 44 |
| E5 | Government | Demand side management expert | 20 |
| E6 | Defense (technology and manufacturing) and academia | Consultant and former academic | 45 |
| E7 | Heavy equipment and machinery distribution | CEO | 44 |
| E8 | Government | Head of department of partnerships | 22 |
| E9 | Academia | Director of circular economy practice and Director of business development | 17 |
| E10 | Consultancy (sustainability, management and finance) | Director/senior advisor | 17 |

Data analysis was conducted using an inductive thematic analysis approach, which is well-suited for identifying patterns and meanings grounded in participants' perspectives [62]. Initial open coding was applied to the interview transcripts to identify meaning units using participants' own language. Through iterative comparison across interviews, related codes were grouped into higher-order categories and subsequently refined into broader themes capturing recurrent patterns as well as contrasting perspectives across interviews. To support systematic data management and analytical transparency, the coding process was facilitated using Dedoose qualitative analysis software [63].

Analytical rigor and credibility were enhanced through multiple strategies. A subset of transcripts was independently coded by two researchers, and discrepancies were discussed until consensus was reached, supporting inter-coder reliability [64]. Reflexive discussions were conducted throughout the analysis to challenge emerging interpretations and reduce confirmation bias. Both convergent and contradictory perspectives were considered to ensure that the qualitative findings illuminated organizational tensions, implementation dynamics, and contextual contingencies.

Data collection and analysis proceeded iteratively until thematic saturation was reached, defined as the point at which additional interviews no longer generated substantively new themes, implementation challenges, or interpretive insights relevant to the CE–I4.0–SP relationships under investigation [65]. Saturation was largely observed after the seventh interview, where recurrent patterns and organizational mechanisms began to converge across participants. The remaining interviews were conducted to confirm thematic consistency and assess whether additional sector-specific insights emerged; however, no substantively new themes were identified. Accordingly, data collection was concluded after the tenth interview.

Overall, the qualitative findings provide contextual depth and explanatory insight into the CE–I4.0–SP nexus, complementing the quantitative results by clarifying how firm-level capabilities, organizational constraints, and strategic choices shape sustainability outcomes in practice.

Integration between the quantitative and qualitative phases occurred at the design, analysis, and interpretation stages of the study. The interview protocol was informed by the quantitative findings, particularly the partially significant mediation effects, the weak moderation results, and the differing roles of operational and managerial I4.0 capabilities. Qualitative themes were subsequently compared with the statistical findings to identify areas of convergence and interpretive explanation. This integration clarified the organizational conditions, implementation barriers, and capability-related dynamics shaping the CE–I4.0–SP relationships.

**Table 3**
Descriptive distribution of respondents' reported engagement with Industry 4.0 technologies.

| I4.0 Technology | Response count |
|---|---|
| Artificial intelligence | 87 |
| Cloud computing | 74 |
| Internet of Things | 74 |
| Cybersecurity | 66 |
| Big data | 53 |
| Simulation/s | 34 |
| Robotics | 20 |
| Additive manufacturing | 10 |
| Augmented reality | 8 |

**Note:** Response frequencies indicate the number of respondents identifying each technology as relevant, implemented, or utilized within their organizations. I4.0 = Industry 4.0.

## 4. Data analysis and results

PLS-SEM was employed to test the proposed research model and hypotheses because it is suitable for moderate sample sizes, exploratory and predictive research, complex mediation–moderation models, and data that do not require strict normality assumptions [52]. Fig. 4 presents the hypothesis-testing model. In addition, semi-structured interviews with experts from academia and industry were conducted to validate and contextualize the quantitative findings, providing deeper insight into the organizational mechanisms and practical dynamics underlying the CE–I4.0–SP nexus. The structural model was estimated using survey data from 138 micro-level organizations.

### *4.1. Descriptive overview of Industry 4.0 technology responses*

Prior to assessing the measurement model, a descriptive analysis was conducted to examine respondents' engagement with different I4.0 technologies. Table 3 presents the frequency of responses for each technology as reported by the participants. Artificial Intelligence received the highest number of responses (87), followed by Cloud Computing and the Internet of Things, each with 74 responses. This suggests that data-driven and connectivity-oriented technologies represent the most prevalent I4.0 technologies among the sampled firms. Conversely, technologies such as Augmented Reality (8) and Additive Manufacturing (10) received fewer responses, indicating comparatively lower levels of organizational adoption or implementation maturity among the participating firms. This distribution contextualizes the technological profile of the sampled firms and informs the subsequent model analysis.

### *4.2. Assessment of the measurement model*

The measurement model was assessed for content validity, construct validity, and reliability, as suggested by Hair et al. [53]. Content validity was supported through validated measurement items adapted from prior research. Reliability was assessed using Cronbach's alpha and Composite Reliability (CR), with values above the recommended threshold of 0.70 indicating satisfactory internal consistency reliability [53]. As shown in Table 4, Cronbach's alpha values for all constructs (CE, I4.0 technologies, and SP) exceeded 0.7, confirming internal consistency. Similarly, CR values for all constructs were above 0.8, indicating strong composite reliability.

Construct validity was assessed through convergent validity and discriminant validity analyses [66]. Convergent validity was evaluated

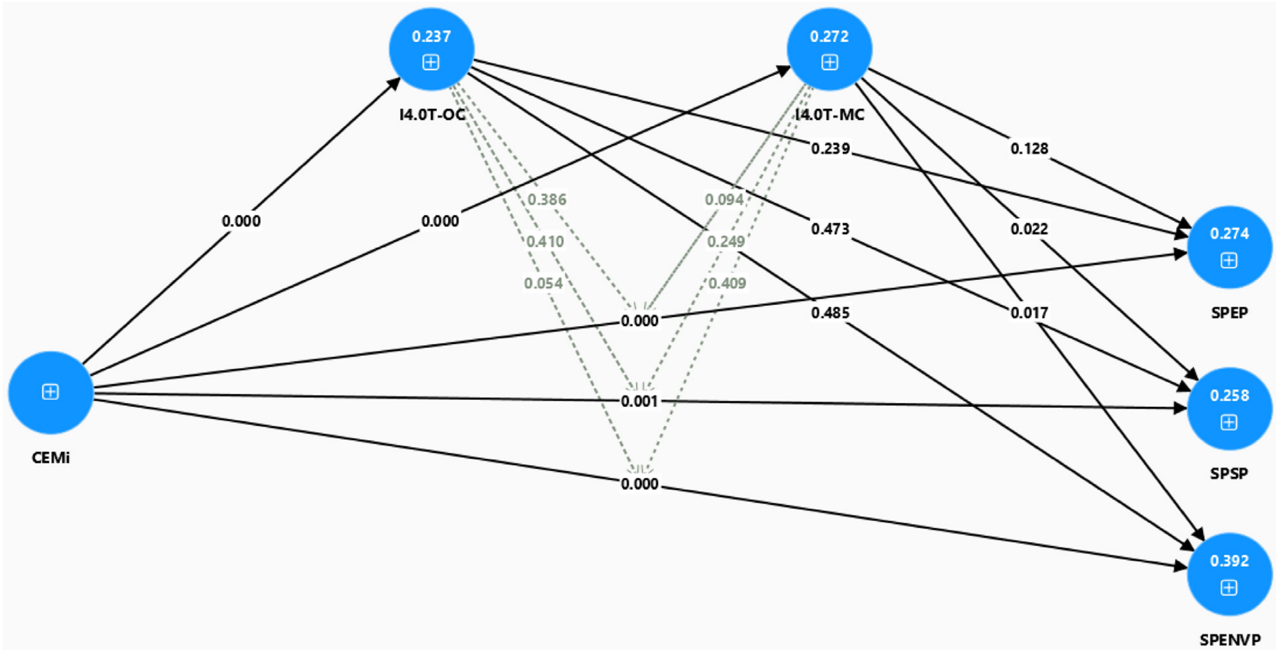


**Fig. 4.** Empirically tested and validated structural framework using SmartPLS 4 and partial least squares structural equation modeling (PLS-SEM).
**Note:** The figure presents the empirically tested direct, mediating, and moderating relationships among Circular Economy practices at the micro-level (CEMi), Industry 4.0 operational capabilities (I4.0T-OC), Industry 4.0 managerial capabilities (I4.0T-MC), and Sustainable Performance dimensions, including economic performance (SPEP), social performance (SPSP), and environmental performance (SPENVP). Values displayed on the paths represent bootstrapped significance levels, while values within endogenous constructs indicate $R^2$ values.

using factor loadings and Average Variance Extracted (AVE). Factor loadings ranged from 0.587 to 0.903, with most values exceeding the ideal threshold of 0.70. While standardized factor loadings of 0.50 or higher are generally acceptable and 0.70 or above is considered ideal, these results support the robustness of the measurement model [67].

The AVE values were 0.528 for Circular Economy practices at the micro-level (CEMi), 0.666 for I4.0 operational capability (I4.0T-OC), and 0.705 for I4.0 managerial capability (I4.0T-MC). For the SP dimensions, the AVE values were 0.444 for economic performance (SPEP), 0.511 for social performance (SPSP), and 0.593 for environmental performance (SPENVP). Most constructs exceeded the recommended AVE threshold of 0.50, thereby supporting convergent validity.

Although the AVE value for economic performance (AVE = 0.444) fell slightly below the recommended threshold, the construct was retained because its composite reliability (CR = 0.888) and Cronbach's alpha ($\alpha = 0.861$) exceeded recommended thresholds, indicating satisfactory internal consistency reliability. Prior PLS-SEM research suggests that AVE values marginally below 0.50 may remain acceptable when composite reliability is sufficiently high and the construct demonstrates conceptual validity [53,67,68].

In addition, several indicators exhibited loadings below the ideal threshold of 0.70 but exceeded the minimum acceptable threshold of 0.50 commonly accepted in exploratory and theory-building research. These indicators were retained because they contributed to content validity and captured conceptually important dimensions of CE practices and SP constructs. Removing these indicators did not meaningfully improve reliability or alter construct meaning.

Discriminant validity was evaluated using the cross-loadings criterion and the Fornell–Larcker criterion [69]. Cross-loading analysis demonstrated that each measurement item loaded highest on its intended construct, confirming appropriate item–construct associations and measurement accuracy [70]. In addition, discriminant validity is established when a latent construct explains more variance in its own indicators than in those of other constructs [71]. As shown in Table 5, and consistent with the Fornell–Larcker criterion, the square root of the AVE for each sub-construct (CEMi, I4.0T-OC, I4.0T-MC, SPEP, SPSP and SPENVP) exceeds its correlations with all corresponding latent variables, thereby affirming the discriminant validity of all sub-constructs within the model. In addition, common method bias was assessed through collinearity diagnostics using variance inflation factors (VIFs), following recommendations for PLS-SEM research [53,72]. The VIF results did not indicate critical collinearity concerns, suggesting that common method bias and multicollinearity were unlikely to pose serious concerns within the model.

### *4.3. Structural model assessment and hypothesis testing*

#### *4.3.1. Structural model assessment*

The structural model was assessed using SmartPLS 4.0 to analyze the direct and indirect relationships among CE practices, I4.0 technologies, and SP. Key evaluation metrics included path coefficients ($\beta$), coefficients of determination ($R^2$) and predictive relevance ($Q^2$), as recommended by Hair et al. [53] (see Table 8).

Path coefficients ($\beta$) and $R^2$ values were used to assess the strength and explanatory power of the hypothesized relationships. A bootstrapping approach was conducted to obtain *p-values* and *t-values* for each path. Path coefficients were considered statistically significant when $\beta > 0$ and $p < 0.05$. Based on this criterion, hypotheses H1a, H1b, H1c, H2a, H2b, H2g, and H2h were supported, indicating significant relationships ($\beta > 0$, $p < 0.05$). In contrast, hypotheses H2c, H2d, H2e, H2f, H3a, H3b, H3e and H3f were not supported due to either low $\beta$ values and/or p-values exceeding the 0.05 threshold. H3c and H3d show directionally consistent but statistically weak interaction estimates (H3c: $\beta = 0.173$, $p = 0.054$; H3d: $\beta = 0.177$, $p = 0.094$). Given the exploratory nature of the moderation analysis, the moderate sample size, and the number of interaction tests conducted, these marginal effects are interpreted cautiously and should not be considered confirmatory evidence of stable moderating relationships. The results indicate that CE practices at the micro-level (CEMi) have strong positive effects on both I4.0 technologies and SP, suggesting that firms prioritizing CE practices can simultaneously advance technological adoption and achieve triple-bottom-line outcomes. However,

**Table 4**
Reliability and convergent validity assessment of the measurement model constructs.

| Construct | Subconstructs | Item | Loading | Cronbach's alpha | rho_A | rho_c | AVE |
|---|---|---|---|---|---|---|---|
| Circular economy practices | Micro (CEMi) | CEMi-EMS-1 | 0.750 | 0.939 | 0.946 | 0.947 | 0.528 |
| | | CEMi-EMS-2 | 0.652 | | | | |
| | | CEMi-EMS-3 | 0.737 | | | | |
| | | CEMi-EMS-4 | 0.728 | | | | |
| | | CEMi-EMS-5 | 0.761 | | | | |
| | | CEMi-ECC-1 | 0.669 | | | | |
| | | CEMi-ECC-2 | 0.700 | | | | |
| | | CEMi-ECC-3 | 0.660 | | | | |
| | | CEMi-ECC-4 | 0.617 | | | | |
| | | CEMi-ED-1 | 0.806 | | | | |
| | | CEMi-ED-2 | 0.830 | | | | |
| | | CEMi-ED-3 | 0.794 | | | | |
| | | CEMi-ED-4 | 0.751 | | | | |
| | | CEMi-GIR-1 | 0.773 | | | | |
| | | CEMi-GIR-2 | 0.752 | | | | |
| | | CEMi-GIR-3 | 0.592 | | | | |
| Industry 4.0 Technologies | Operational Capability (I4.0T-OC) | I4.0T-OC-1 | 0.846 | 0.874 | 0.883 | 0.908 | 0.666 |
| | | I4.0T-OC-2 | 0.848 | | | | |
| | | I4.0T-OC-3 | 0.717 | | | | |
| | | I4.0T-OC-4 | 0.858 | | | | |
| | | I4.0T-OC-5 | 0.803 | | | | |
| | Managerial Capability (I4.0T-MC) | I4.0T-MC-1 | 0.768 | 0.915 | 0.919 | 0.935 | 0.705 |
| | | I4.0T-MC-2 | 0.778 | | | | |
| | | I4.0T-MC-3 | 0.832 | | | | |
| | | I4.0T-MC-4 | 0.903 | | | | |
| | | I4.0T-MC-5 | 0.858 | | | | |
| | | I4.0T-MC-6 | 0.890 | | | | |
| Sustainable performance | Economic Performance (SPEP) | SPEP-RED-1 | 0.671 | 0.861 | 0.863 | 0.888 | 0.444 |
| | | SPEP-RED-2 | 0.677 | | | | |
| | | SPEP-RED-3 | 0.678 | | | | |
| | | SPEP-RED-4 | 0.645 | | | | |
| | | SPEP-RED-5 | 0.598 | | | | |
| | | SPEP-RED-6 | 0.693 | | | | |
| | | SPEP-GRO-1 | 0.735 | | | | |
| | | SPEP-GRO-2 | 0.661 | | | | |
| | | SPEP-GRO-3 | 0.688 | | | | |
| | | SPEP-GRO-4 | 0.605 | | | | |
| | Social Performance (SPSP) | SPSP-EHR-1 | 0.748 | 0.912 | 0.918 | 0.926 | 0.511 |
| | | SPSP-EHR-2 | 0.716 | | | | |
| | | SPSP-EHR-3 | 0.784 | | | | |
| | | SPSP-EHR-4 | 0.719 | | | | |
| | | SPSP-WE-1 | 0.712 | | | | |
| | | SPSP-WE-2 | 0.587 | | | | |
| | | SPSP-WE-3 | 0.688 | | | | |
| | | SPSP-SR-1 | 0.697 | | | | |
| | | SPSP-SR-2 | 0.745 | | | | |
| | | SPSP-SR-3 | 0.801 | | | | |
| | | SPSP-SR-4 | 0.711 | | | | |
| | | SPSP-SR-5 | 0.642 | | | | |
| | Environmental Performance (SPENVP) | SPENVP-RW-1 | 0.701 | 0.923 | 0.931 | 0.936 | 0.593 |
| | | SPENVP-RW-2 | 0.746 | | | | |
| | | SPENVP-RE-1 | 0.788 | | | | |
| | | SPENVP-RE-2 | 0.782 | | | | |
| | | SPENVP-RE-3 | 0.846 | | | | |
| | | SPENVP-IE-1 | 0.788 | | | | |
| | | SPENVP-IE-2 | 0.839 | | | | |
| | | SPENVP-IE-3 | 0.750 | | | | |
| | | SPENVP-IE-4 | 0.760 | | | | |
| | | SPENVP-IE-5 | 0.686 | | | | |

**Abbreviations:** rho_A, reliability coefficient; rho_c, composite reliability; AVE, average variance extracted.

**Table 5**
Discriminant validity assessment using the Fornell–Larcker criterion.

| | CEMi | I4.0T-MC | I4.0T-OC | SPENVP | SPEP | SPSP |
|---|---|---|---|---|---|---|
| CEMi | 0.726 | | | | | |
| I4.0T-MC | 0.522 | 0.840 | | | | |
| I4.0T-OC | 0.487 | 0.805 | 0.816 | | | |
| SPENVP | 0.573 | 0.460 | 0.394 | 0.770 | | |
| SPEP | 0.433 | 0.399 | 0.362 | 0.682 | 0.666 | |
| SPSP | 0.433 | 0.442 | 0.364 | 0.573 | 0.557 | 0.715 |

**Note:** Diagonal values represent the square root of the average variance extracted (AVE) for each construct. Discriminant validity is established when the square root of the AVE exceeds the inter-construct correlations.

the lack of mediation by (I4.0T-OC) highlights the importance of managerial readiness (I4.0T-MC) in translating I4.0 implementation into sustainability gains.

As shown in Table 6, the practices of CEMi have significant positive direct effects on both dimensions of I4.0 technologies, including (I4.0T-OC: $\beta = 0.487$, $p < 0.05$) and (I4.0T-MC: $\beta = 0.522$, $p < 0.05$), as well as on the SP dimensions of economic (SPEP: $\beta = 0.339$, $p < 0.05$), social (SPSP: $\beta = 0.294$, $p < 0.05$), and environmental performance (SPENVP: $\beta = 0.483$, $p < 0.05$). The consistent rejection of hypotheses H2c, H2d, H2e, H2f, H3a, H3b, H3e, and H3f indicates that operational I4.0 capabilities alone have limited predictive capacity for SP outcomes. This suggests that process-level digitalization may support efficiency and monitoring, but it may be insufficient to generate broader sustainability outcomes without complementary managerial integration and strategic alignment with CE objectives. These findings support the theoretical proposition that operational capabilities require complementary integration with both (CEMi) and managerial I4.0 competencies to achieve meaningful sustainability transformation.

While operational capabilities (I4.0T-OC) do not exhibit statistically significant mediating effects on SP outcomes, managerial capabilities (I4.0T-MC) demonstrate partial mediation regarding social and environmental performance, as indicated in Table 7. These results suggest that managerial readiness is important for translating digital investments into sustainability outcomes. Furthermore, the rejection of hypotheses H2c, H2d, H2e, H2f, H3a, H3b, H3e, and H3f highlights the limited predictive capacity of operational I4.0 technologies when considered in isolation from strategic managerial orientation and CE integration. This finding aligns with the theoretical premise that digital transformation must be embedded within broader organizational and sustainability frameworks to generate meaningful outcomes.

As shown in Table 8, the $R^2$ values are 0.237 (I4.0T-OC), 0.272 (I4.0T-MC), 0.274 (SPEP), 0.258 (SPSP), and 0.392 (SPENVP), all of which exceed the minimum acceptable threshold of 0.10, indicating moderate explanatory power [73]. The Stone-Geisser test ($Q^2$) values: 0.215, 0.250, 0.126, 0.158, and 0.301 for I4.0T-OC, I4.0T-MC, SPEP, SPSP, and SPENVP, respectively, are all greater than zero, confirming the model's predictive relevance [73].

#### *4.3.2. Hypothesis testing*

*4.3.2.1. The direct effect.* The analysis of eleven direct hypotheses revealed three central findings. First, CEMi significantly influenced all dimensions of SP: economic (H1a: $\beta = 0.339$, $p = 0.000$), social (H1b: $\beta = 0.294$, $p = 0.001$), and environmental (H1c: $\beta = 0.483$, $p = 0.000$). Second, CEMi significantly influenced both operational (H2a: $\beta = 0.487$, $p = 0.000$) and managerial capabilities (H2b: $\beta = 0.522$, $p = 0.000$), highlighting its role as a critical enabler of I4.0 technologies implementation and sustainable outcomes. Specifically, only managerial competencies consistently contributed to sustainability gains. Third, the impact of I4.0 technologies varied by capability type: managerial competencies positively influenced social (H2g: $\beta = 0.299$, $p = 0.022$) and environmental performance (H2h: $\beta = 0.231$, $p = 0.017$), while operational capabilities showed no significant effect on economic (H2c: $\beta = 0.097$, $p = 0.239$), social (H2d: $\beta = -0.011$, $p = 0.473$), or environmental performance (H2e: $\beta = -0.005$, $p = 0.485$). Although the path from managerial capabilities to economic performance was directionally positive (H2f: $\beta = 0.158$, $p = 0.128$), it was not statistically significant.

*4.3.2.2. Mediating effects (In-direct relationships).* In assessing the indirect effects, the findings indicate that I4.0 managerial capability (I4.0T-MC) partially mediates the relationship between CE practices at the micro-level (CEMi) and both social (SPSP) and environmental performance (SPENVP) dimensions, as the mediating effects were statistically significant (*P = 0.033 and 0.024,* respectively), as shown in Table 7. However, the mediating effects of I4.0 operational capability (I4.0T-OC) in the relationship between CE practices at the micro-level (CEMi) and SP outcomes were found to be non-significant. This suggests that CE practices generate stronger sustainability outcomes when aligned with managerial rather than operational I4.0 capabilities.

*4.3.2.3. Moderating effects.* The moderation analysis revealed limited empirical support for the proposed moderating effects of both operational and managerial I4.0 capabilities on the relationship between CEMi and SP outcomes. I4.0T-OC exhibits a directionally consistent but statistically weak moderating effect on the CEMi–environmental performance (SPENVP) relationship ($\beta = 0.173$, $p = 0.054$), indicating a modest potential under certain organizational conditions to support environmental outcomes through process-oriented technological enhancements. Conversely, I4.0T-MC demonstrates a directionally consistent but statistically weak moderating impact on the CEMi–economic performance (SPEP) relationship ($\beta = 0.177$, $p = 0.094$), suggesting that strategic oversight and decision-making integration of I4.0 tools may condition the economic value derived from circular practices. Given the exploratory nature of moderation analysis and the number of interaction tests conducted, marginal effects ($p < 0.10$) are interpreted cautiously and should not be considered confirmatory evidence [46, 53]. However, neither capability type exerted statistically significant moderation across the remaining dimensions of SP, underscoring the limited and domain-specific effectiveness of isolated capabilities in reinforcing CE–SP synergies.

These findings suggest that I4.0 capabilities may contribute more strongly as organizational enabling and integrative mechanisms than as direct boundary conditions strengthening CE–SP relationships across firms. From a DCT perspective, the limited moderation effects may reflect the integrated and context-specific nature of sustainability transformation processes. While digital capabilities can support coordination, monitoring, and strategic adaptation, their effectiveness likely depends on implementation quality, organizational readiness, and alignment with broader CE principles. Consequently, the sustainability benefits associated with I4.0 capabilities may emerge more consistently through managerial orchestration and capability integration rather than through direct interaction effects alone. These findings indicate that sustainability outcomes may depend less on isolated digital capabilities and more on the effective integration of operational and managerial capabilities within broader CE implementation processes.

### *4.4. Qualitative validation and contextualization of the quantitative findings*

To complement, validate, and contextualize the quantitative findings, semi-structured interviews were conducted with ten domain experts from academia, industry, and government sectors. Interview transcripts were coded iteratively in Dedoose using thematic analysis, while coding reliability was strengthened through independent coding and consensus discussions between researchers. The qualitative findings were subsequently used to interpret the organizational mechanisms and contextual conditions underlying the quantitative relationships identified in the structural model analysis.

**Table 6**
Hypothesis result.

| Hypo | Path | Path coefficient ($\beta$) | Sample mean (M) | Standard deviation (STDEV) | T values | P values | Decision "accept/reject" |
|---|---|---|---|---|---|---|---|
| H1a | CEMi → SPEP | 0.339 | 0.349 | 0.084 | 4.045 | 0.000 | Accepted |
| H1b | CEMi → SPSP | 0.294 | 0.297 | 0.092 | 3.204 | 0.001 | Accepted |
| H1c | CEMi → SPENVP | 0.483 | 0.494 | 0.081 | 5.957 | 0.000 | Accepted |
| H2a | CEMi → I4.0T-OC | 0.487 | 0.494 | 0.071 | 6.890 | 0.000 | Accepted |
| H2b | CEMi → I4.0T-MC | 0.522 | 0.528 | 0.067 | 7.847 | 0.000 | Accepted |
| H2c | I4.0T-OC → SPEP | 0.097 | 0.098 | 0.136 | 0.710 | 0.239 | Rejected |
| H2d | I4.0T-OC → SPSP | −0.011 | −0.011 | 0.166 | 0.068 | 0.473 | Rejected |
| H2e | I4.0T-OC → SPENVP | −0.005 | −0.003 | 0.126 | 0.037 | 0.485 | Rejected |
| H2f | I4.0T-MC → SPEP | 0.158 | 0.157 | 0.139 | 1.138 | 0.128 | Rejected |
| H2g | I4.0T-MC → SPSP | 0.299 | 0.306 | 0.148 | 2.020 | 0.022 | Accepted |
| H2h | I4.0T-MC → SPENVP | 0.231 | 0.225 | 0.108 | 2.131 | 0.017 | Accepted |
| H3a | I4.0T-OC × CEMi → SPEP | 0.035 | 0.046 | 0.121 | 0.289 | 0.386 | Rejected |
| H3b | I4.0T-OC × CEMi → SPSP | −0.038 | −0.026 | 0.167 | 0.227 | 0.410 | Rejected |
| H3c | I4.0T-OC × CEMi → SPENVP | 0.173 | 0.187 | 0.108 | 1.611 | 0.054 | Marginal (exploratory) |
| H3d | I4.0T-MC × CEMi → SPEP | 0.177 | 0.164 | 0.134 | 1.319 | 0.094 | Marginal (exploratory) |
| H3e | I4.0T-MC × CEMi → SPSP | 0.111 | 0.101 | 0.165 | 0.676 | 0.249 | Rejected |
| H3f | I4.0T-MC × CEMi → SPENVP | −0.026 | −0.038 | 0.110 | 0.231 | 0.409 | Rejected |

**Abbreviations:** CEMi, circular economy practices-micro level; I4.0T-OC, industry 4.0 technologies-operational capability; I4.0T-MC, industry 4.0 technologies-managerial capability; SPEP, sustainable performance-economic performance; SPSP, sustainable performance-social performance; SPENVP, sustainable performance-environmental performance.
**Note:** Effects with p-values between 0.05 and 0.10 are reported as 'Marginal (exploratory)' and interpreted cautiously in the text.

**Table 7**
Mediation analysis.

| Path | Path coefficient ($\beta$) | Sample mean (M) | Standard deviation (STDEV) | T values | P values | Decision "accept/reject" |
|---|---|---|---|---|---|---|
| CEMi → I4.0T-OC → SPEP | 0.047 | 0.048 | 0.069 | 0.687 | 0.246 | Rejected |
| CEMi → I4.0T-OC → SPSP | −0.005 | −0.007 | 0.084 | 0.066 | 0.474 | Rejected |
| CEMi → I4.0T-OC → SPENVP | −0.002 | −0.002 | 0.063 | 0.035 | 0.486 | Rejected |
| CEMi → I4.0T-MC → SPEP | 0.082 | 0.083 | 0.075 | 1.100 | 0.136 | Rejected |
| CEMi → I4.0T-MC → SPSP | 0.156 | 0.163 | 0.085 | 1.844 | 0.033 | Accepted-Partial Mediation |
| CEMi → I4.0T-MC → SPENVP | 0.121 | 0.119 | 0.061 | 1.983 | 0.024 | Accepted-Partial Mediation |

**Abbreviations:** CEMi, circular economy practices-micro level; I4.0T-OC, industry 4.0 technologies-operational capability; I4.0T-MC, industry 4.0 technologies-managerial capability; SPEP, sustainable performance-economic performance; SPSP, sustainable performance-social performance; SPENVP, sustainable performance-environmental performance.

**Table 8**
Coefficients of determination ($R^2$) and predictive relevance ($Q^2$) of endogenous constructs.

| Variables | R-square ($R^2$) | Predictive relevance ($Q^2$) |
|---|---|---|
| CEMi | – | – |
| I4.0T-OC | 0.237 | 0.215 |
| I4.0T-MC | 0.272 | 0.250 |
| SPEP | 0.274 | 0.126 |
| SPSP | 0.258 | 0.158 |
| SPENVP | 0.392 | 0.301 |

**Note:** $R^2$ values indicate the explanatory power of the structural model, while $Q^2$ values greater than zero indicate predictive relevance.
$R^2$ must be $\geq 0.19$.
$Q^2$ must be $> 0$.

#### 4.4.1. *Direct effect of CE on SP*

Interview evidence shows how CE practices reshape organizational processes and support sustainability outcomes. Interviewees described how practices such as resource recovery, eco-design, and reverse logistics reorganize production and recovery processes by restructuring material flows and operational routines. In particular, remanufacturing and resource recovery were emphasized as mechanisms that reduce reliance on virgin materials while preserving asset value through reuse and rebuilding. As one expert explained, "It enhances economic, social, and environmental performance because we are talking about new ways of generation, reduction, resource recovery, and remanufacturing." (E5).

Beyond process reconfiguration, CE implementation was also described as altering employment structures within organizations. Several interviewees highlighted that CE practices shift labor demand away from waste disposal activities toward recycling, remanufacturing, and material recovery functions. This transition was associated with the creation of new roles and skills related to circular operations. As one participant noted, "Different types of jobs are being created, for instance, facilitating material exchange. There is also a shift from jobs dealing with waste to those focused on managing recyclable materials". (E4)

Environmental benefits were further described as emerging from improved material efficiency and reduced extraction requirements, particularly in resource-intensive sectors. Interviewees emphasized that CE practices contribute to waste reduction, pollution prevention, and improved community well-being. Two experts underscored these environmental and social contributions, noting that "The circular economy creates green jobs and new mobile jobs, such as recycling activities, particularly benefiting minority groups. It also improves community health by reducing pollution from waste incineration" (E8). Another expert highlighted the material savings associated with remanufacturing, stating that "From an environmental perspective, we can save up to 85% of global metal resources; only about 15% of the machine's weight needs to be added when it is rebuilt". (E7)

In addition to these direct effects, interviewees explained that CE practices often increase the need for data visibility and process coordination, thereby stimulating the development of digital capabilities. CE initiatives such as closed-loop production, remanufacturing, and real-time waste monitoring were described as necessitating or accelerating the deployment of digital solutions. These solutions enhance operational efficiency and data transparency while encouraging organizations to invest in more strategic digital capabilities that support the management and coordination of circular activities. These insights reinforce the quantitative findings by showing that CE practices support SP through resource efficiency, organizational restructuring, workforce transformation, and digital capability development.

#### 4.4.2. Mediating role of I4.0 technologies in the CE–SP relationship

Qualitative findings explain why I4.0 technologies do not consistently mediate the CE–SP relationship. Interviewees emphasized that the effectiveness of I4.0 technologies depends less on their mere presence and more on the extent to which they are meaningfully integrated with CE initiatives. In particular, operational I4.0 capabilities such as sensors, automation systems, and decentralized process controls were often described as insufficiently aligned with circular practices, which limits their ability to translate CE initiatives into measurable sustainability outcomes.

Thematic analysis revealed several interrelated structural and organizational barriers that constrain the mediating potential of I4.0 technologies. These include fragmented and siloed technology implementation, limited digital readiness and workforce capability gaps, and weak alignment between operational data outputs and sustainability performance indicators. As one expert noted, "High investment costs and uncertainty around return on investment remain key challenges" (E1), while another explained that "In most cases, we don't know how to measure performance, for example, how to assess improvements before and after the adoption of a new technology". (E3)

Further insights revealed that even when digital technologies are adopted, they are often underutilized due to misalignment with CE goals and insufficient skills. Interviewees described situations in which data are collected but not used for optimization, and where the complexity of technologies used for operational and predictive maintenance requires advanced capabilities that organizations frequently lack. As one participant explained, "When there is misalignment or misuse, technologies may not be integrated with CE goals; for instance, data might be collected but not used for optimization. The complexity of technologies used for operational and predictive maintenance also requires advanced skills, and the lack of training leads to underutilization". (E8)

Others emphasized that knowledge gaps, training costs, and the time required for organizational culture to adapt represent persistent barriers to effective integration. One expert highlighted that "Another major barrier is the lack of knowledge. Employees often lack the necessary expertise, and training is expensive and time-consuming. It takes time for organizational culture to evolve and fully integrate these technologies and practices" (E9), while another noted that "Most of the time, achieving a positive impact requires investing in determining new ways of doing things that can generate benefits over time". (E10)

In contrast to operational capabilities, interviewees indicated that managerial I4.0 capabilities exhibit greater potential to mediate the CE–SP relationship, particularly with respect to social and environmental performance. Capabilities such as strategic oversight, cross-functional coordination, and workforce development were viewed as essential for aligning digital initiatives with sustainability objectives. However, the mediating role of managerial capabilities in economic performance was described as more limited. Key inhibiting factors included a dominant focus on short-term financial metrics, weak interdepartmental collaboration, and insufficient strategic and technical training among mid- and senior-level managers.

These observations indicate that I4.0 adoption alone is insufficient to enhance SP. Realizing their mediating potential requires coherent digital strategies, sustained managerial commitment, and organizational cultures that support long-term sustainability objectives. As one expert noted, "management buy-in and cross-departmental support" are essential for implementation, and many firms "hesitate to change if systems already work", which slows adoption and limits performance gains (E6). As one participant observed, "Firm size may also matter; SMEs often lack the resources to scale I4.0 technologies. In some industries, particularly low-margin sectors, cost-cutting is prioritized over innovation. Technical limitations can also pose barriers to integration with existing systems". (E8)

Thus, these qualitative findings reinforce the quantitative results by indicating that operational digitalization alone is insufficient to generate meaningful sustainability outcomes unless supported by managerial coordination, organizational readiness, and strategic alignment with CE practices. In this sense, managerial I4.0 capabilities appear to play a more decisive role than operational capabilities in translating CE initiatives into SP outcomes.

#### 4.4.3. Moderating influence of I4.0 technologies on the CE–SP relationship

Qualitative findings explain why I4.0 technologies do not consistently moderate the CE–SP relationship. Interview evidence suggests that the limited moderation effects reflect organizational, structural, and strategic constraints rather than limited technological potential. Interviewees emphasized that digital technologies are often implemented in fragmented and compartmentalized ways, which constrains their ability to reinforce the impact of CE practices on sustainability outcomes.

Several experts highlighted institutional rigidity and siloed technological environments as key barriers, particularly within bureaucratic or functionally segmented organizations. In such contexts, digital systems frequently fail to support cross-departmental data sharing and coordinated decision-making. As one expert explained, "Data structures often fail to facilitate information sharing across departments. When factories focus on short-term gains and quick wins instead of systematic integration, they avoid scaling sustainable practices" (E8). In addition, dependence on outdated legacy IT infrastructures was identified as a major obstacle, limiting the seamless integration of real-time data into sustainability-oriented decision-making processes.

Strategic misalignment between digital transformation initiatives and CE objectives was also repeatedly emphasized. Interviewees noted that digitalization and circularity are often pursued as separate agendas, rather than through integrated and synergistic frameworks. This disconnect was frequently attributed to limited awareness of the long-term benefits of CE-oriented digital integration. As one participant observed, "There is often a lack of knowledge among people who do not understand the long-term benefits of embedding circular economy principles into their operations". (E10)

Despite these constraints, interviewees cautioned that the absence of strong moderating effects should not be interpreted as evidence of technological ineffectiveness. Instead, they highlighted critical readiness gaps in both technical and organizational dimensions that must be addressed to unlock the moderating potential of I4.0 technologies. One expert remarked that "If you apply the principles of circular economy and sustainability effectively, your enterprise will add value now and generate greater profits in the future" (E5), emphasizing the importance of strategic alignment and long-term orientation.

To overcome the identified barriers, experts proposed several actionable strategies aimed at strengthening the moderating role of I4.0 technologies. These included the implementation of pilot CE–I4.0 initiatives linked to contextually relevant sustainability key performance indicators, which allow organizations to experiment, learn, and scale successful practices incrementally. As one interviewee suggested, "You can start with pilot programs and phased integration" (E1), while another added that such approaches "It gives you a chance to identify opportunities and gaps; how your system, market, and customers are performing". (E9)

Interviewees also emphasized the need for customized, context-specific training programs that focus on the strategic application of I4.0 technologies in circular operations. According to one expert, "By embedding I4.0 technologies into CE workflows and upskilling workers in both CE principles and digital tools, firms can bridge capability gaps" (E8). In addition, participants highlighted the importance of top-down and cross-functional collaboration frameworks to align digital transformation with sustainability and circularity goals. As one interviewee noted, "It requires both bottom-up and top-down approaches to fully understand and maximize the overall positive impact". (E10)

Finally, experts underscored the necessity of developing clear integration roadmaps and change-management initiatives that communicate the long-term benefits of CE–I4.0 adoption and ensure interoperability between new digital solutions and legacy systems. As two participants explained, "One key issue is that people often don't fully understand what these technologies are or how they can benefit them" (E2), and "The most important thing is ensuring that new technologies can 'talk' to the old ones. Companies already have existing systems, and they need to know how to integrate or transform these to work with new technologies". (E3)

Thus, these qualitative insights suggest that the moderating influence of I4.0 technologies on the CE–SP relationship depends not only on digital investment but also on broader organizational, infrastructural, and cultural transformations. Firms must embed CE principles into their digital strategies and prioritize cross-departmental data integration, strategic alignment, and workforce capability development. Accordingly, the limited and context-dependent nature of the moderating effects observed in the quantitative analysis should be interpreted with caution.

Overall, the qualitative findings reinforce and contextualize the quantitative results by demonstrating that the relationship between CE practices, I4.0 capabilities, and SP depends not only on technological adoption, but also on managerial readiness, organizational integration, workforce capabilities, and long-term strategic alignment. The findings further indicate that managerial I4.0 capabilities play a more critical role than operational capabilities in translating CE initiatives into measurable sustainability outcomes. These findings suggest that the CE–I4.0–SP relationship is shaped primarily by strategic and organizational alignment rather than by technological implementation alone. This highlights the importance of integrating technological, managerial, and organizational dimensions when implementing CE and I4.0 initiatives to achieve long-term sustainability outcomes.

## 5. Discussion

### 5.1. Discussion of findings

This study examined how micro-level CE practices and I4.0-enabled capabilities interact to shape SP across economic, social, and environmental dimensions. The findings indicate that CE practices constitute the primary driver of SP at the firm-level, while the contribution of I4.0 technologies depends on the type of capability developed and the extent of strategic integration within the organization. These findings challenge technologically deterministic assumptions that sustainability improvements emerge automatically through digital technology adoption. Instead, sustainability outcomes depend on firms' ability to strategically integrate digital capabilities within broader circular transformation processes [3,7,11]. From a DCT perspective, this indicates that the value of I4.0 technologies lies not in technological possession itself, but in firms' capacity to align, reconfigure, and deploy digital resources in support of sustainability-oriented objectives [16]. From a sustainable technology perspective, I4.0 contributes to sustainability by enabling firms to coordinate and scale CE practices more effectively. Thus, the findings support a capability differentiation perspective in which operational and managerial capabilities contribute differently to sustainability outcomes.

CE practices, particularly eco-design, recycling, remanufacturing, and environmental management systems, were found to substantially strengthen economic, social, and environmental dimensions of SP. This finding aligns with prior empirical studies demonstrating that circular strategies enhance resource efficiency, reduce waste generation, and improve organizational sustainability outcomes [10,38,74]. However, the findings extend CE literature by showing that circular practices remain the primary drivers of sustainability performance even in digitally intensive environments. While recent studies increasingly emphasize the transformative role of I4.0 technologies in sustainability transitions [9,75], the current findings suggest that digitalization alone is insufficient to generate substantial sustainability gains in the absence of strategically embedded CE practices. This finding positions CE practices as the foundation of sustainability transformation at the micro-level. By embedding circular principles early within product and process design, firms are able to create value while simultaneously addressing environmental protection and social responsibility objectives. Qualitative insights further indicate that resource recovery and closed-loop systems preserve asset value and reduce reliance on virgin materials, reinforcing the core principles of CE implementation.

Beyond their direct effects on SP, CE practices also enable the development of I4.0 capabilities. Firms implementing circular initiatives were more likely to develop both operational and managerial digital capabilities, indicating that circular practices generate demand for digital solutions that enhance data visibility, coordination, and performance monitoring. This finding is consistent with research showing that circular production systems rely on digital infrastructure to support transparency and traceability [35,76]. Accordingly, CE practices act as catalysts for digital transformation rather than passive beneficiaries of technology adoption. From a DCT perspective, CE implementation stimulates organizational coordination and capability development in support of sustainability transformation.

Although digital technologies such as AI, cloud computing, and the IoT were widely adopted, their direct contribution to SP was limited. Managerial I4.0 capabilities, including strategic oversight, data-driven decision-making, and workforce development, positively influenced social and environmental performance, whereas operational capabilities focused on automation and process control did not yield significant sustainability gains. This pattern supports prior research showing that digital technologies deliver performance benefits only when strategically aligned and orchestrated through higher-order managerial capabilities [11,16].

However, the findings also partially diverge from prior studies reporting consistently positive effects of I4.0 adoption on sustainability performance. One possible explanation is that firms often adopt digital technologies primarily for efficiency-driven operational optimization rather than for the strategic reconfiguration of organizational processes required to support sustainability-oriented transformation. Consequently, operational digital capabilities may improve process execution without substantially reshaping organizational decision-making or circular business model integration.

The differentiated roles of operational and managerial capabilities further clarify the organizational mechanisms through which CE practices are translated into sustainability outcomes. Managerial I4.0 capabilities partially mediate the relationship between CE practices and social and environmental performance, whereas operational capabilities do not exhibit a significant mediating role. This suggests that circular practices and managerial digital capabilities operate as complementary mechanisms supporting sustainability transformation. By contrast, operational technologies implemented in isolation lack the governance and coordination capacity required to translate CE initiatives into meaningful sustainability improvements [7,77].

More importantly, the non-significant mediating role of operational I4.0 capabilities should not be interpreted merely as an unsupported hypothesis, but as a theoretically meaningful finding. Operational I4.0 capabilities, such as automation, monitoring, process control, and real-time data capture, primarily enhance the execution and optimization of existing routines. However, these capabilities do not necessarily enable firms to reinterpret sustainability priorities, redesign organizational processes, or strategically reconfigure resources around CE principles. From a DCT perspective, operational I4.0 capabilities are more closely associated with routine and execution-oriented functions because they primarily support efficiency, monitoring, and process optimization rather than higher-order strategic transformation. Their limited mediating role, therefore, suggests that operational digitalization alone may be insufficient to translate CE practices into measurable sustainability outcomes at the firm-level. Instead, sustainability transformation appears to depend more strongly on managerial capabilities that support strategic alignment, cross-functional coordination, organizational learning, and resource orchestration. This finding represents an important theoretical contribution by challenging the assumption that operational digitalization automatically generates sustainability benefits. Rather, the findings indicate that the CE–I4.0–SP relationship depends less on the presence of operational technologies and more on firms' ability to strategically align and orchestrate digital resources in support of circular practices.

The generally weak and context-dependent moderating effects of I4.0 capabilities challenge technologically deterministic views of digital transformation. Although I4.0 technologies are increasingly prevalent, their deployment is often driven by short-term efficiency or cost-reduction objectives rather than long-term sustainability strategies [78]. As a result, digital tools are frequently implemented in fragmented ways, limiting their ability to amplify the effects of CE practices on SP. Rather than indicating technological ineffectiveness, these findings highlight the importance of organizational context and strategic alignment in shaping sustainability outcomes [3,79].

These findings suggest that I4.0 capabilities function more strongly as organizational enabling mechanisms than as direct boundary conditions strengthening CE–SP relationships across firms. From a DCT perspective, the limited moderation effects may reflect the integrated and context-specific nature of sustainability transformation processes. Digital capabilities can support coordination, monitoring, and strategic adaptation. However, their effectiveness likely depends on implementation quality, organizational readiness, and alignment with broader CE principles. Consequently, the sustainability benefits of I4.0 capabilities may emerge more consistently through managerial integration than through direct interaction effects.

Qualitative insights help explain why, despite strong direct effects, the mediating and moderating effects observed in the quantitative analysis were limited. Specifically, they reveal persistent organizational and structural barriers, including high implementation costs, skills shortages, limited digital readiness, and weak cross-functional coordination. In many cases, firms prioritized operational efficiency over systemic sustainability transformation, resulting in underutilized or poorly integrated digital systems. Without clear sustainability objectives, adequate training, and coherent governance structures, digital technologies were unable to deliver substantial sustainability benefits, particularly in resource-constrained organizational contexts [3,14,79].

Thus, achieving SP requires an integrated capability-based approach in which CE practices provide the strategic foundation and I4.0 technologies offer complementary value. In the absence of strategic alignment, managerial readiness, and organizational integration, digital transformation alone is unlikely to generate significant sustainability improvements. By clarifying the contingent role of digital technologies and highlighting the central importance of CE practices, this study strengthens the understanding of sustainable digital transformation at the micro-level and provides a solid basis for the implications discussed in the following subsection.

### 5.2. Implications

#### 5.2.1. Theoretical implications

This study advances the growing body of research on the CE–I4.0 nexus by providing a more nuanced and capability-based explanation of how sustainability performance emerges at the micro-level.

First, the study contributes to the literature by empirically validating the interrelationships between CE practices, I4.0-enabled capabilities, and sustainability performance within a unified framework. While prior studies often examine CE practices and I4.0 technologies separately, the present study shows that sustainability outcomes depend on the interaction between circular practices and organizational digital capabilities.

Second, the findings refine existing research on the CE and I4.0 relationship by challenging technologically deterministic assumptions in sustainable digital transformation literature. In relation to **RQ1**, the findings confirm that CE practices remain the primary drivers of economic, social, and environmental performance at the micro-level. Although prior studies report positive sustainability effects from I4.0 adoption, the findings suggest that digital technologies alone do not automatically improve sustainability performance. In relation to **RQ2**, the contribution of I4.0 technologies depends on the capability type and strategic integration within the organization. Specifically, managerial I4.0 capabilities contribute directly to social and environmental performance, whereas operational capabilities exhibit limited influence. Furthermore, regarding **RQ3**, the limited moderating effects indicate that digital capabilities do not uniformly strengthen the CE–SP relationship across organizational contexts. These findings help explain inconsistencies in prior empirical research by highlighting the importance of managerial readiness, strategic orchestration, and organizational alignment in sustainable digital transformation.

Third, the study advances CE–I4.0 research by developing a capability differentiation perspective that distinguishes between operational digital capabilities and managerial orchestration capabilities. This distinction is important because prior CE–I4.0 studies have often treated digital capability as a homogeneous construct or have focused primarily on technology adoption. The present findings show that these capability types are not theoretically or empirically equivalent: operational I4.0 capabilities mainly support execution, monitoring, and process efficiency, whereas managerial I4.0 capabilities enable strategic alignment, coordination, and resource reconfiguration. This explains why firms with similar digital technologies may achieve different sustainability outcomes.

Lastly, the study contributes to DCT and RBV by clarifying that sustainability performance depends not merely on the possession of digital resources, but on the managerial capability to orchestrate those resources in support of CE practices. In this sense, managerial I4.0 capabilities operate as dynamic orchestration capabilities that translate circular practices into social and environmental performance improvements. This extends DCT within the CE–I4.0 domain by showing that not all digital capabilities function as dynamic capabilities; rather, dynamic value emerges when managerial capabilities strategically integrate, align, and reconfigure operational digital resources toward sustainability transformation.

#### 5.2.2. Practical implications

The findings of this study provide several important implications for managers and policymakers seeking to enhance sustainability performance through CE and digital transformation initiatives.

First, since CE practices demonstrated the strongest and most consistent effects on economic, social, and environmental performance, managers should prioritize circular strategies such as eco-design, resource recovery, remanufacturing, and environmental management systems as the foundation of sustainability transformation rather than viewing digitalization as a standalone solution.

Second, the findings indicate that I4.0 technologies generate sustainability value primarily when supported by managerial digital readiness and strategic orchestration capabilities. Managers should therefore move beyond technology acquisition-oriented approaches and invest in higher-order managerial capabilities, including data-driven decision-making, cross-functional coordination, digital governance, workforce training, and sustainability-oriented leadership. Without these capabilities, digital technologies are likely to generate a limited sustainability impact.

Third, the limited moderating effects observed in the study suggest that many firms continue to implement I4.0 technologies primarily for operational efficiency and cost reduction rather than for long-term sustainability transformation. Managers should therefore align digital investments with broader CE objectives, organizational sustainability strategies, and performance management systems to ensure that digital transformation initiatives contribute to meaningful sustainability outcomes.

Finally, the findings provide important implications for policymakers and industrial support agencies. Since sustainability gains depend heavily on organizational readiness and managerial capability development, policy interventions should extend beyond technology diffusion and financial incentives alone. Policymakers should support integrated capability-building initiatives focused on digital skills development, sustainability-oriented leadership, organizational readiness, and cross-sector collaboration, particularly for SMEs and firms operating in resource-constrained environments.

Overall, the study highlights that effective sustainable digital transformation depends not only on technological adoption, but also on firms' ability to strategically integrate and orchestrate digital capabilities within broader CE transformation processes.

## 6. Conclusion, limitations, and future research directions

This study examines how CE practices shape SP and how I4.0 capabilities influence this relationship at the micro-organizational level. Using a sequential mixed-methods design combining survey data from 138 firms with 10 semi-structured expert interviews, the study provides empirical evidence on the CE–I4.0–SP nexus. The findings confirm that CE practices constitute the primary drivers of economic, social, and environmental performance at the firm-level. The results further demonstrate that managerial I4.0 capabilities partially mediate the relationship between CE practices and SP, especially for social and environmental dimensions, highlighting the importance of strategic alignment and data-driven decision-making in supporting circular initiatives. In contrast, operational I4.0 capabilities do not generate significant sustainability gains when implemented in isolation. Moreover, the moderating effects of both operational and managerial I4.0 capabilities on the CE–SP relationship are weak, marginal, and context-dependent. Thus, these results challenge technology-deterministic assumptions and underscore that SP at the micro-organizational level depends primarily on CE practices and the effective strategic integration of digital capabilities within circular transformation processes.

The study advances CE–I4.0 literature by distinguishing between operational and managerial I4.0 capabilities within the CE–SP nexus at the micro-level. While prior research has frequently treated digital capability as a homogeneous construct or focused primarily on technology adoption, the present study demonstrates that managerial I4.0 capabilities appear to play a more significant role in translating CE practices into sustainability outcomes. Specifically, managerial capabilities associated with strategic alignment, organizational coordination, and data-driven orchestration appear to contribute more strongly to sustainability transformation than operational capabilities focused primarily on process execution and monitoring. In doing so, the study extends DCT by explaining how different digital capabilities contribute unevenly to sustainability transformation. These findings are further reinforced by qualitative evidence showing that misalignment, capability gaps, and fragmented implementation constrain the effectiveness of operational digitalization. The findings further suggest that digital capabilities contribute more effectively to CE outcomes when supported by organizational readiness, managerial integration, strategic alignment, implementation quality, and sufficient levels of digital maturity.

Despite these contributions, several limitations suggest directions for future research. The cross-sectional design limits insights into how CE–I4.0–SP relationships evolve, indicating the need for longitudinal or case-based studies. In addition, the study relied on self-reported and single-respondent survey data, which may introduce perceptual or common method bias despite the procedural and statistical remedies employed. Future research could incorporate multiple informants or objective performance indicators to strengthen causal inference and reduce method-related bias. Furthermore, the use of purposive and snowball sampling may limit the statistical generalizability of the findings across industries and institutional contexts. In addition, although the study examined complex mediating and moderating relationships, the possibility of endogeneity and reciprocal relationships between CE practices, I4.0 capabilities, and SP outcomes cannot be fully excluded.

Moreover, the weak moderation effects may reflect the contextual complexity of detecting interaction effects across organizations with varying levels of digital maturity and sustainability readiness. Future research should examine the individual and combined effects of specific CE practices and I4.0 technologies, as well as the organizational conditions under which I4.0 capabilities strengthen CE–SP relationships. Extending the analysis to meso- and macro-level contexts would provide a broader understanding of CE-led digital transformation and its sustainability implications. Future studies could adopt longitudinal, multi-respondent, and cross-country designs to examine the evolution of digitally enabled CE capabilities across institutional contexts.

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## CRediT authorship contribution statement

**Than'a Alsaoudi:** Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Data curation, Conceptualization. **Adolf Acquaye:** Writing – original draft, Validation, Supervision, Software, Resources, Project administration, Investigation, Funding acquisition, Formal analysis, Conceptualization. **Malik Khalfan:** Writing – review & editing, Validation, Supervision, Project administration, Investigation, Funding acquisition, Conceptualization. **S.C. Lenny Koh:** Writing – review & editing, Supervision, Project administration, Investigation, Conceptualization.

## 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.

## Appendix. Description of constructs and measurement items

See Table A.1.

## Data availability

The data that support the findings of this study (survey dataset and interview coding framework) are available from the corresponding author upon reasonable request.

**Table A.1**
Description of constructs and measurement items.

| Constructs | Subconstructs | Items | Code | References |
|---|---|---|---|---|
| Circular Economy (CE) practices- *Micro* | Environmental Management Systems (EMS) | - Total quality environmental management*(Is the process of implementing quality management standards and principles in those manufacturing procedures and processes that directly impact the quality of the environment) | CEMi-EMS-1 | Kamble and Gunasekaran [31]; Zhu et al. [32] |
| | | - Environmental compliance and auditing programs | CEMi-EMS-2 | |
| | | - Pollution prevention programs | CEMi-EMS-3 | |
| | | - Generation of environment reports for internal evaluation purposes | CEMi-EMS-4 | |
| | | - Incorporation of environmental factors in internal performance evaluation systems | CEMi-EMS-5 | |
| | Environmental-related Customer Cooperation (ECC) | - Cooperation with customers for eco-design*(Is an approach to designing products and services that considers the effect on the environment at every stage of development and throughout the product's life) | CEMi-ECC-1 | |
| | | - Cooperation with customers for cleaner production*(Is the continuous application of an integrated preventive environmental approach to products, services, and processes to increase overall efficiency and reduce risks to humans and the environment) | CEMi-ECC-2 | |
| | | - Cooperation with customers for green packaging | CEMi-ECC-3 | |
| | | - Cooperation with customers for using less energy during product transportation | CEMi-ECC-4 | |
| | Eco-design (ED) | - Design of products to reduce materials and energy consumption | CEMi-ED-1 | |
| | | - Design of products for reuse, recycling, and recovery of materials | CEMi-ED-2 | |
| | | - Design of products to avoid or reduce the use of hazardous products | CEMi-ED-3 | |
| | | - Design of processes for minimization of waste | CEMi-ED-4 | |
| | Green Investment Recovery (GIR) | - Recycling system for used and defective products | CEMi-GIR-1 | |
| | | - Collection and recycling end-of-life products and materials | CEMi-GIR-2 | |
| | | - Sale of scrap and used materials at regular intervals | CEMi-GIR-3 | |
| Industry 4.0 (I4.0) technologies | Operational Capability (OC) | - Using the technology/technologies in your organization for information systems management to handle semi-structured and unstructured data | I4.0T-OC-1 | Riggs et al. [33]; Sangpetch and Ueasangkomsate [34]; Sahoo et al. [80]; Belhadi et al. [81] |
| | | - Using the technology/technologies in your organization to extract insights from available data to aid in root cause analysis and continuous improvement for the workflow | I4.0T-OC-2 | |
| | | - Using the technology/technologies in your organization for visualization techniques (such as graphing, diagramming, or video) used to assist users or decision-makers in understanding complex information | I4.0T-OC-3 | |
| | | - Using the technology/technologies in your organization to utilize full real-time capability | I4.0T-OC-4 | |
| | | - Using the technology/technologies in your organization for virtualization and decentralization of decision-making | I4.0T-OC-5 | |
| | Managerial Capability (MC) | - Using the technology/technologies in your organization to assess real-time data and information for better decision-making in your organization | I4.0T-MC-1 | |
| | | - Using the technology/technologies in your organization to have a good infrastructure and facilities to support analytics | I4.0T-MC-2 | |
| | | - Using the technology/technologies in your organization for training programs regularly to ensure that analysts employed by different functional departments are always up to date on analysis techniques that contribute to effective decision-making for your organization | I4.0T-MC-3 | |
| | | - Enforcing adequate plans for the utilization of Industry 4.0 (I4.0) technologies in your organization | I4.0T-MC-4 | |
| | | - Constantly monitoring the performance of the Industry 4.0 (I4.0) function in your organization | I4.0T-MC-5 | |
| | | - Frequently adjusting Industry 4.0 (I4.0) plans to better adapt to changing conditions in your organization | I4.0T-MC-6 | |

(*continued on next page*)

**Table A.1** (*continued*).

| Constructs | Subconstructs | Items | Code | References |
|---|---|---|---|---|
| Sustainable Performance (SP) - Economic Performance | Reduction (RED) | - Decreased cost of material purchased | SPEP-RED-1 | (Riggs et al. [33]; Ghaithan et al. [82]; Sangpetch and Ueasangkomsate [34]; Kamble and Gunasekaran [31]; Belhadi et al. [81]; de Sousa Jabbour et al. [2] |
| | | - Decreased cost of production | SPEP-RED-2 | |
| | | - Decreased cost of energy consumption | SPEP-RED-3 | |
| | | - Decreased spending on water and sewage treatment | SPEP-RED-4 | |
| | | - Decreased rejection and rework costs | SPEP-RED-5 | |
| | | - Decreased lead time*(Is the time it takes to complete a process/task/project, from the internal workflows to scheduling deliverables) | SPEP-RED-6 | |
| | Growth (GRO) | - Improved quality of products | SPEP-GRO-1 | |
| | | - Improved return on investment | SPEP-GRO-2 | |
| | | - Increased profits | SPEP-GRO-3 | |
| | | - Increased Sales | SPEP-GRO-4 | |
| Sustainable Performance (SP) - Social Performance | Employees and Human Rights (EHR)/ Employees | - Improved employee training and education | SPSP-EHR-1 | |
| | | - Improved employee health and safety | SPSP-EHR-2 | Riggs et al. [33]; Sangpetch and Ueasangkomsate [34]; Kamble and Gunasekaran [31]; Belhadi et al. [81]; de Sousa Jabbour et al. [2]; Cheng et al. [74] |
| | | - Improved labor relations | SPSP-EHR-3 | |
| | | - Improved awareness and production of the claims and rights of people in the community served | SPSP-EHR-4 | |
| | Work Environment (WE) | - Improved working conditions | SPSP-WE-1 | |
| | | - Improved investments in social projects (education, culture, sports) | SPSP-WE-2 | |
| | | - Decreased the number of accidents | SPSP-WE-3 | |
| | Stakeholders and Relationships (SR)/Stakeholders | - Improved the relations with the community | SPSP-SR-1 | |
| | | - Improved the overall stakeholder welfare | SPSP-SR-2 | |
| | | - Improved engagement with stakeholders | SPSP-SR-3 | |
| | | - Improved customer satisfaction | SPSP-SR-4 | |
| | | - Decreased the number of customer complaints | SPSP-SR-5 | |
| Sustainable Performance (SP) -Environmental Performance | Reduction Waste (RW) | - Reduced solid waste generation | SPENVP-RW-1 | (Riggs et al. [33]; Sangpetch and Ueasangkomsate [34]; Aldrighetti et al. [83]; Kamble and Gunasekaran [31]; Belhadi et al. [81]; de Sousa Jabbour et al. [2] |
| | | - Reduced liquid waste generation | SPENVP-RW-2 | |
| | Reduction of Emissions (RE) | - Reduced air emission/releasing pollutants | SPENVP-RE-1 | |
| | | - Reduced greenhouse gas emissions | SPENVP-RE-2 | |
| | | - Reduced emissions of polluting gases | SPENVP-RE-3 | |
| | Improvement Efficiency (IE) | - Improved the environmental situation of your organization | SPENVP-IE-1 | |
| | | - More efficient use of natural resources | SPENVP-IE-2 | |
| | | - Reduced energy consumption | SPENVP-IE-3 | |
| | | -Reduced consumption of hazardous/harmful/toxic materials | SPENVP-IE-4 | |
| | | - Reduced frequency of environmental accidents | SPENVP-IE-5 | |

## References


[1] Wojciech. Czekała, Jędrzej Drozdowski, Piotr Łabiak, Modern technologies for waste management: a review, Appl. Sci. 13 (8847) (2023).

[2] Ana Beatriz Lopes de Sousa Jabbour, Charbel Jose Chiappetta. Jabbour, Tsan-Ming Choi, Hengky Latan, 'Better together': evidence on the joint adoption of circular economy and Industry 4.0 technologies, Int. J. Prod. Econ. 252 (2022) 108581.

[3] Valerio Elia, Maria Grazia Gnoni, Fabiana Tornese, Integrating circular economy and sustainability assessment on the micro-level: An umbrella review, Sustain. Prod. Consum. (2024).

[4] Adriana Neligan, Rupert J. Baumgartner, Martin Geissdoerfer, Josef-Peter Schöggl, Circular disruption: Digitalisation as a driver of circular economy business models, Bus. Strat. Environ. 32 (2023) 1175–1188.

[5] Dr. Attia Hussien Gomaa, SCM 4.0 excellence: A strategic framework for smart and competitive supply chains, Int. J. Manag. Humanit. (IJMH) (2025).

[6] Than'a Alsaoudi, Eman Ouda, Adolf Acquaye, Malik Khalfan, Artificial intelligence for circular economy transformation: System design insights from emerging applications, in: 2025 International Conference on INnovations in Intelligent SysTems and Applications, INISTA, IEEE, 2025, pp. 1–6.

[7] Dounia Skalli, Abdelkabir Charkaoui, Anass Cherrafi, Jose Arturo Garza-Reyes, Jiju Antony, Alireza Shokri, Analyzing the integrated effect of circular economy, lean six sigma, and Industry 4.0 on sustainable manufacturing performance from a practice-based view perspective, Bus. Strat. Environ. 33 (2024) 1208–1226.

[8] Than'a ALSaoudi, Adolf Acquaye, Malik Khalfan, A review of the impact of circular economy on sustainable performance with moderating role of industry4. 0: A conceptual framework, 2025.

[9] Sandra Matarneh, Arsalan Zahid Piprani, Riwan Matloob Ellahi, Diep Ngoc Nguyen, Trang Mai Le, Sajid Nazir, Industry 4.0 technologies and circular economy synergies: Enhancing corporate sustainability through sustainable supply chain integration and flexibility, Environ. Technol. Innov. 35 (2024) 103723.

[10] Than'a Alsaoudi, Adolf Acquaye, Vikas Swarnakar, Malik Khalfan, Exploring the intersection of Industry 4.0 technologies, circular economy, and sustainable performance: A systematic literature review and future research directions, Heliyon 11 (2025).

[11] Karl S.R. Warner, Maximilian Wäger, Building dynamic capabilities for digital transformation: An ongoing process of strategic renewal, Long Range Plan. 52 (2019) 326–349.

[12] Jan Drofenik, Tine Seljak, Zorka Novak Pintarič, A multi-level approach to circular economy progress: Linking national targets with corporate implementation, J. Clean. Prod. 493 (2025) 144902.

[13] Than'a Alsaoudi, Adolf Acquaye, Empirical analysis of circular economy–Industry 4.0 integration for enhancing sustainable performance: A multi-level framework across micro, meso, macro, Green Technol. Sustain. 4 (2026) 100356.

[14] Heidi Simone Kristensen, Mette Alberg Mosgaard, A review of micro level indicators for a circular economy–moving away from the three dimensions of sustainability? J. Clean. Prod. 243 (2020) 118531.

[15] Jakomijn Van Wijk, Charlene. Zietsma, Silvia Dorado, Frank G.A. De Bakker, Ignasi Martí, Social innovation: Integrating micro, meso, and macro level insights from institutional theory, Bus. Soc. 58 (2019) 887–918.

[16] David J. Teece, Explicating dynamic capabilities: the nature and microfoundations of (sustainable) enterprise performance, Strat. Manag. J. 28 (2007) 1319–1350.

[17] David J. Teece, Gary Pisano, Amy Shuen, Dynamic capabilities and strategic management, Strat. Manag. J. 18 (1997) 509–533.
[18] David J. Teece, Dynamic capabilities and entrepreneurial management in large organizations: Toward a theory of the (entrepreneurial) firm, Eur. Econ. Rev. 86 (2016) 202–216.
[19] Jay Barney, Firm resources and sustained competitive advantage, J. Manag. 17 (1991) 99–120.
[20] Birger Wernerfelt, A resource-based view of the firm, Strat. Manag. J. 5 (1984) 171–180.
[21] Stuart L. Hart, A natural-resource-based view of the firm, Acad. Manag. Rev. 20 (1995) 986–1014.
[22] Yongxin Liao, Fernando Deschamps, Eduardo de Freitas Rocha Loures, Luiz Felipe Pierin Ramos, Past, present and future of Industry 4.0-a systematic literature review and research agenda proposal, Int. J. Prod. Res. 55 (2017) 3609–3629.
[23] Andrea Genovese, Adolf A. Acquaye, Alejandro Figueroa, S.C. Lenny Koh, Sustainable supply chain management and the transition towards a circular economy: Evidence and some applications, Omega 66 (2017) 344–357.
[24] Than'a ALSaoudi, Adolf Acquaye, Malik Khalfan, Vikas Swarnakar, Enhancing sustainable performance through circular economy and Industry 4.0: A conceptual framework for leveraging drivers and mitigating barriers, in: 2024 IEEE International Conference on Industrial Engineering and Engineering Management, IEEM, IEEE, 2024, pp. 755–759.
[25] Hasith Chathuranga Victar, Anuradha Samarajeewa Waidyasekara, Optimising construction waste management in Sri Lanka through circular economy strategies: a focus on construction and renovation and use and operate stages, Eng. Constr. Archit. Manag. (2024).
[26] Jenny Palm, Daniela Lazoroska, Melanie Valencia, Nancy Bocken, Karolina Södergren, A gender perspective on the circular economy: A literature review and research agenda, J. Ind. Ecol. 28 (2024) 1670–1683.
[27] Kanchana Dissanayake, Rudrajeet Pal, Toward a just circular economy: Exploring societal implications of used clothing supply chains, Soc. Impacts 5 (2025) 100101.
[28] Cervantes Puma, Genesis Camila, Adriana Salles, Janez Turk, Viorel Ungureanu, Luís Bragança, Utilisation of reused steel and slag: analysing the circular economy benefits through three case studies, Buildings 14 (979) (2024).
[29] Nwankwo Constance Obiuto, Nwakamma Ninduwezuor-Ehiobu, Emmanuel Chigozie Ani, Kehinde Andrew, Implementing circular economy principles to enhance safety and environmental sustainability in manufacturing, Int. J. Adv. Multidiscip. Res. Stud. 4 (2024) 22–29.
[30] Ozlem Ayaz, Ekrem Tatoglu, Unveiling the power of social value: catalyzing circular economy in emerging market SMEs, J. Clean. Prod. 453 (2024) 142245.
[31] Sachin S. Kamble, Angappa Gunasekaran, Analysing the role of Industry 4.0 technologies and circular economy practices in improving sustainable performance in Indian manufacturing organisations, Prod. Plan. Control 34 (2023) 887–901.
[32] Qinghua Zhu, Joseph Sarkis, Kee-hung Lai, Green supply chain management implications for closing the loop, Transp. Res. Part E: Logist. Transp. Rev. 44 (2008) 1–18.
[33] Randy Riggs, José L. Roldán, Juan C. Real, Carmen M. Felipe, Opening the black box of big data sustainable value creation: the mediating role of supply chain management capabilities and circular economy practices, Int. J. Phys. Distrib. Logist. Manage. 53 (2023) 762–788.
[34] Petchlada Sangpetch, Pittawat Ueasangkomsate, The influence of the big data analytics and circular economy on the sustainable performance of SMEs, Thammasat Rev. 26 (2023) 114–139.
[35] Usman Uzuagbe Mamudu, Chijioke Declan Obasi, Shallan Kwabla Awuye, Hayford Danso, Praise Ayodele, Paul Akinyemi, Circular economy in the manufacturing sector: Digital transformation and sustainable practices, Int. J. Sci. Res. Arch. 12 (2024) 129–141.
[36] Alessandra Neri, Enrico Cagno, Ebru Susur, Alberto Urueña, Cali Nuur, Vikas Kumar, Samuele Franchi, Ciro Sorrentino, The relationship between digital technologies and the circular economy: A systematic literature review and a research agenda, R & D Manage. (2024).
[37] Selçuk Perçin, Yasar Bayraktar, Vikas Kumar, Evaluating the adoption of Industry 4.0, sustainability and circular economy drivers to achieve sustainable development goals–oriented agri-food supply chains, Bus. Strat. Environ. (2025).
[38] Zhang Yu, Syed Abdul Rehman Khan, Muhammad Umar, Circular economy practices and Industry 4.0 technologies: A strategic move of automobile industry, Bus. Strat. Environ. 31 (2022) 796–809.
[39] Eleonora Di Maria, Valentina De Marchi, Ambra Galeazzo, Industry 4.0 technologies and circular economy: The mediating role of supply chain integration, Bus. Strat. Environ. 31 (2022) 619–632.
[40] D.O. Oyejobi, A.A. Firoozi, David Blanco Fernandez, Siva Avudaiappan, Integrating circular economy principles into concrete technology: Enhancing sustainability through industrial waste utilization, Results Eng. (2024) 102846.
[41] Lucas Moreno-Bermedo, Jonathan Correa-Puerta, Claudio González-Fuentes, Néstor Escalona, Christian Onfray, Abdoulaye Thiam, Tea waste as a sustainable catalyst support for enhanced removal of contaminants of emerging concern via the electro-fenton process: A circular economy approach, Appl. Sci. 15 (1418) (2025).
[42] Mohammadreza Akbari, John L. Hopkins, Digital technologies as enablers of supply chain sustainability in an emerging economy, Oper. Manag. Res. 15 (2022) 689–710.
[43] Marco Antonio Paula Pinheiro, Daniel Jugend, Ana Beatriz Lopes de Sousa Jabbour, Charbel Jose Chiappetta Jabbour, Hengky Latan, Circular economy-based new products and company performance: The role of stakeholders and Industry 4.0 technologies, Bus. Strat. Environ. 31 (2022) 483–499.
[44] Christian Hagelüken, Daniel Goldmann, Recycling and circular economy—towards a closed loop for metals in emerging clean technologies, Miner. Econ. 35 (2022) 539–562.
[45] Than'a Alsaoudi, Adolf Acquaye, Pathways of digital–circular integration in the construction industry: Empirical insights from the UAE, Green Technol. Sustain. (2026) 100406.
[46] Herman Aguinis, Jeffrey R. Edwards, Kyle J. Bradley, Improving our understanding of moderation and mediation in strategic management research, Organ. Res. Methods 20 (2017) 665–685.
[47] Than'a ALSaoudi, Adolf Acquaye, Malik Khalfan, Abdelrahman E.E. Eltoukhy, Comparative analysis of Industry 4.0 technologies in enhancing the circular economy–sustainable performance nexus: A survey-based study at meso and macro levels, in: 2025 IEEE International Conference on Technology Management, Operations and Decisions, ICTMOD, IEEE, 2025, pp. 1–6.
[48] John W. Creswell, Vicki L. Plano Clark, Designing and Conducting Mixed Methods Research, Sage publications, 2017.
[49] Philip M. Podsakoff, Scott B. MacKenzie, Jeong-Yeon Lee, Nathan P. Podsakoff, Common method biases in behavioral research: a critical review of the literature and recommended remedies, J. Appl. Psychol. 88 (879) (2003).
[50] Steve Campbell, Melanie Greenwood, Sarah Prior, Toniele Shearer, Kerrie Walkem, Sarah Young, Danielle Bywaters, Kim Walker, Purposive sampling: complex or simple? Research case examples, J. Res. Nurs. 25 (2020) 652–661.
[51] Nickolas Ollington, Jenny Gibb, Mark Harcourt, Online social networks: an emergent recruiter tool for attracting and screening, Pers. Rev. 42 (2013) 248–265.
[52] Joseph Hair, Abdullah Alamer, Partial least squares structural equation modeling (PLS-SEM) in second language and education research: Guidelines using an applied example, Res. Methods Appl. Linguist. 1 (2022) 100027.
[53] Joseph F. Hair, Jeffrey J. Risher, Marko Sarstedt, Christian M. Ringle, When to use and how to report the results of PLS-SEM, Eur. Bus. Rev. 31 (2019) 2–24.
[54] Robert F. DeVellis, Carolyn T. Thorpe, Scale Development: Theory and Applications, Sage publications, 2021.
[55] J. Scott Armstrong, Terry S. Overton, Estimating nonresponse bias in mail surveys, J. Mark. Res. 14 (1977) 396–402.
[56] Gregory G. Dess, Richard B. Robinson Jr., Measuring organizational performance in the absence of objective measures: the case of the privately-held firm and conglomerate business unit, Strat. Manag. J. 5 (1984) 265–273.
[57] Natarjan Venkatraman, Vasudevan Ramanujam, Measurement of business performance in strategy research: A comparison of approaches, Acad. Manag. Rev. 11 (1986) 801–814.
[58] Irene Korstjens, Albine Moser, Series: Practical guidance to qualitative research, Part 2: Context, research questions and designs, Eur. J. Gen. Pr. 23 (2017) 274–279.
[59] Sharan B. Merriam, Robin S. Grenier, Qualitative Research in Practice: Examples for Discussion and Analysis, John Wiley & Sons, 2019.
[60] Neetij Rai, Bikash Thapa, A study on purposive sampling method in research, Kathmandu: Kathmandu Sch. Law 5 (2015) 8–15.
[61] Hanna Kallio, Anna-Maija Pietilä, Martin Johnson, Mari Kangasniemi, Systematic methodological review: developing a framework for a qualitative semi-structured interview guide, J. Adv. Nurs. 72 (2016) 2954–2965.
[62] Virginia Braun, Victoria Clarke, Using thematic analysis in psychology, Qual. Res. Psychol. 3 (2006) 77–101.
[63] Michelle Salmona, Eli Lieber, Dan Kaczynski, Qualitative and Mixed Methods Data Analysis using Dedoose: A Practical Approach for Research Across the Social Sciences, Sage Publications, 2019.
[64] Greg Guest, Kathleen M. MacQueen, Emily E. Namey, Applied Thematic Analysis, sage publications, 2011.
[65] Monique Hennink, Bonnie N. Kaiser, Sample sizes for saturation in qualitative research: A systematic review of empirical tests, Soc. Sci. Med. 292 (2022) 114523.
[66] Weng Marc Lim, A typology of validity: content, face, convergent, discriminant, nomological and predictive validity, J. Trade Sci. 12 (2024) 155–179.
[67] Muhammad Saeed. Shahbaz, Raja Zuraidah R.M. Rasi, M.D. Fauzi Bin Ahmad, A novel classification of supply chain risks: Scale development and validation, J. Ind. Eng. Manag. (JIEM) 12 (2019) 201–218.
[68] Claes Fornell, David F. Larcker, Evaluating structural equation models with unobservable variables and measurement error, J. Mark. Res. 18 (1981) 39–50.
[69] Jörg Henseler, Christian M. Ringle, Marko Sarstedt, A new criterion for assessing discriminant validity in variance-based structural equation modeling, J. Acad. Mark. Sci. 43 (2015) 115–135.
[70] Marko Sarstedt, Christian M. Ringle, Joseph F. Hair, Partial least squares structural equation modeling, in: Handbook of Market Research, Springer, 2021, pp. 587–632.

[71] Arash Shahin, Angappa Gunasekaran, Sima Ebrahimi, Analysing the influence of supply chain risk on supply chain sustainability using structural equation modelling-with a case study in the home appliance industry, World Rev. Sci. Technol. Sustain. Dev. 15 (2019) 230–251.
[72] Ned Kock, Common method bias in PLS-SEM: A full collinearity assessment approach, Int. J. E-Collaboration (Ijec) 11 (2015) 1–10.
[73] Muhammad Ashraf Fauzi, Partial least square structural equation modelling (PLS-SEM) in knowledge management studies: Knowledge sharing in virtual communities, Knowl. Manag. & E-Learning 14 (2022) 103–124.
[74] T.C. Edwin Cheng, Sachin S. Kamble, Amine Belhadi, Nelson Oly Ndubisi, Kee-hung Lai, Manoj Govind Kharat, Linkages between big data analytics, circular economy, sustainable supply chain flexibility, and sustainable performance in manufacturing firms, Int. J. Prod. Res. 60 (2022) 6908–6922.
[75] Than'a Anwer Alsaoudi, Adolf Acquaye, Vikas Swarnakar, Integration of Industry 4.0 with circular economy to enhance sustainable performance-a strategic framework, Clean. Eng. Technol. 31 (2026) 101151.
[76] Lucero.Jazmín Cuevas-Pichardo, Gonzalo. Maldonado-Guzmán, Antonio Duréndez. Gómez-Guillamón, Jose Arturo Garza-Reyes, The mediating role of circular economy in the relationship between Industry 4.0 and sustainable performance in the manufacturing industry, Bus. Strat. Environ. 34 (2025) 1735–1750.
[77] João J. Ferreira, João M. Lopes, Sofia Gomes, Hussain G. Rammal, Industry 4.0 implementation: Environmental and social sustainability in manufacturing multinational enterprises, J. Clean. Prod. 404 (2023) 136841.
[78] Than'a ALSaoudi, Adolf Acquaye, Malik Khalfan, Applying AHP to identify and prioritize barriers impacting Industry 4.0 technologies on the nexus of circular economy and sustainable performance, in: 2024 IEEE International Conference on Technology Management, Operations and Decisions, ICTMOD, IEEE, 2024, pp. 1–6.
[79] Morteza Ghobakhloo, Industry 4.0, digitization, and opportunities for sustainability, J. Clean. Prod. 252 (2020) 119869.
[80] Saumyaranjan Sahoo, Arvind Upadhyay, Anil Kumar, Circular economy practices and environmental performance: Analysing the role of big data analytics capability and responsible research and innovation, Bus. Strat. Environ. 32 (2023) 6029–6046.
[81] Amine Belhadi, Sachin Kamble, Angappa Gunasekaran, Venkatesh Mani, Analyzing the mediating role of organizational ambidexterity and digital business transformation on Industry 4.0 capabilities and sustainable supply chain performance, Supply Chain Manag.: An Int. J. 27 (2022) 696–711.
[82] Ahmed M. Ghaithan, Yasser Alshammakhi, Awsan Mohammed, Khwaja Mateen Mazher, Integrated impact of circular economy, Industry 4.0, and lean manufacturing on sustainability performance of manufacturing firms, Int. J. Environ. Res. Public Health 20 (5119) (2023).
[83] Riccardo Aldrighetti, Daria Battini, Ajay Das, Marco Simonetto, The performance impact of Industry 4.0 technologies on closed-loop supply chains: insights from an Italy based survey, Int. J. Prod. Res. 61 (2023) 3004–3029.