

**A Study on the Interrelationships among Industry 4.0
Technologies, Circular Economy Practices and Corporate Social
Responsibility**

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Abstract

This thesis investigates how the adoption of Industry 4.0 technologies promotes corporate social responsibility (CSR) through circular economy practices (CEP) in the oil and gas sector. Despite growing attention to Industry 4.0 and circular economy (CE), the mechanisms among Industry 4.0 technologies, CEP and CSR remain underexplored, especially in high-emission industry facing complex supply chains, such as oil and gas sector. This thesis aims to fill this theoretical gap while offering practical insight for the industry. Drawing on a systematic literature review (SLR) of 60 included studies from Scopus and Web of Science and structural equation modelling (SEM) analysis method using survey data collected from the respondents across 155 Chinese oil and gas firms, this research applies the resource-based view (RBV) theory, moral responsibility theory of corporate sustainability (MRCSS), and institutional theory to examine their relationships among the adoption of Industry 4.0 technologies, CEP and CSR. The findings identify the increasing research interests and trends, the core Industry 4.0 technologies used in the industry to support CE, key factors and challenges influencing the adoption of Industry 4.0 technologies and point out future research directions. Meanwhile, it shows that the adoption of Industry 4.0 technologies positively affects CSR, and CEP plays both mediating and suppressing roles in this relationship. Further analysis introduces sustainable strategies (SS) and institutional pressure (IP) as moderators, showing that in all aspects of CSR except for employees, SS can enhance CEP's contribution to

CSR, while IP indirectly strengthen this effect. This research provides theoretical contributions by integrating Industry 4.0, CE and CSR within a novel combined framework, and highlights the moderating roles of SS and IP. In practice, it provides managerial implications for firms to utilise advanced technologies and CEP to improve CSR, develop effective SS and promote responsibility to their employees.

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Declaration

Chapter 3 of this thesis is based on my paper 'How Industry 4.0 Technologies Reshape Corporate Social Responsibility: A Dual Role of Circular Economy Practices', and part of which was presented at the Essex Business School Research Conference 2025. I declare that this thesis is the research result of my original work. Also, all sources of information, ideas and results in this thesis have been acknowledged and properly referenced. This thesis is merely submitted for the degree of Doctor of Philosophy in the University of Essex.

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List of Abbreviations

3R	Reduce, Reuse, Recycle
AI	Artificial Intelligence
AMOS	Analysis of Moment Structures
AVE	Average Variance Extracted
QBWM	Quantiles and Best Worst Method
CE	Circular Economy
CEP	Circular Economy Practices
CFA	Confirmatory Factor Analysis
CFI	Comparative Fit Index
CI	Confidence Interval
CMB	Common Method Bias
CP	Coercive Pressure
CR	Composite Reliability
CSR	Corporate Social Responsibility
CSRC	Corporate Social Responsibility to Customers
CSRE	Corporate Social Responsibility to Employees
CSRG	Corporate Social Responsibility to Government
CSRS	Corporate Social Responsibility to Social and Non- Social Stakeholders
DEMATEL	Decision-Making Trial and Evaluation Laboratory
ECS	Economic Strategy
ED	Eco-design
EFA	Exploratory Factor Analysis

EMF	Ellen MacArthur Foundation
ENS	Environmental Strategy
FRM	Finance and Risk Management
GFI	Goodness Fit Index
GHG	Greenhouse Gas
HRM	Human Resources Management
IEM	Internal Environment Management
IFI	Incremental Fit Index
IoT	Internet of Things
IP	Institutional Pressure
IR	Investment Recovery
ISO	International Organization for Standardization
KMO	Kaiser–Meyer–Olkin
MP	Normative Pressure
MRCs	Moral Responsibility Theory of Corporate Sustainability
MSV	Maximum Shared Variance
NP	Normative Pressure
p	p-value
PRISMA	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
QM	Quantities Method
QR	Quick Response
RBV	Resource-Based View
RM	Regression Model

RMSEA	Root Mean Square Error of Approximation
RQ	Research Question
SEM	Structural Equation Modelling
Sig.	Significance
SLR	Systematic Literature Review
SOS	Society Strategy
SPSS	Statistical Package for the Social Sciences
SS	Sustainability Strategies
TISM	Total Interpretive Structural Modelling
TLI	Tucker–Lewis Index
TM	Technology Management
TQM	Total Quality Management
VIF	Variance Inflation Factor
WEF	World Economic Forum
β	Standardized regression coefficient
χ^2	Chi-square

Chapter 1

Introduction

1.1 Background

The oil and gas industry faces increasing pressure to tackle environmental pollution and degradation, social concerns, stakeholder needs, and the improvement of firms' financial performance. As a response, firms are increasingly managing to explore approaches that balance investment, operations and long-term plans (Magrini and dos Santos Lins, 2007). Therefore, sustainable development emphasising the significance of aligning short-term requirements with long-term goals attracts increasing attention by firms (Wu et al., 2017). Based on the perspective of the resource-based view (RBV) theory, to obtain long-term competitive advantage, firms can pursue sustainability by accumulating unique rare resources and capabilities hard to imitate (Wernerfelt, 1984; Barney, 1991; Huang et al., 2015; Liu, 2025). Under this context, the integration of technology and innovative strategies plays a critical role in achieving sustainability (Guan et al., 2023). With the support provided by technology and strategic practices, firms can enhance their capability and reputation to meet both stakeholders' expectations and market demands (Magrini and dos Santos Lins, 2007; Yusuf et al., 2013).

The adoption of Industry 4.0 technologies has clear potential to enhance corporate sustainability, while also providing a unique competitive advantage as the improvement of production of operational efficiency (Bocken et al., 2016; Gopal et al., 2025). Various technologies, including artificial intelligence (AI), Internet of Things (IoT), additive manufacturing, virtual and augmented reality including digital twins, and big data are adopted in the industry and lead to evolutionary changes (Dua, 2025). They offer significant capacity to evolve the process of production, distribution and sales, becoming a critical enabler of sustainable development in the oil and gas industry (Ghobakhloo and Fathi 2021).

Moreover, with the encouragement of waste reduction, energy and material recycling, and resource reuse, circular economy (CE) has been considered one of the core principles for industrial and environmental policies (Donaghy, 2022). Through the circular economy practices (CEP) applied in firms, companies can minimise the impact of chemicals and increase the efficiency of materials, facilitating the transitions from a linear to a circular economy (Heyes et al. 2018). It can also help address social issues such as public health, lack job opportunities, unfair working conditions, and poor education (Sarkar and Pingle, 2018; Fairbrother and Banks, 2023; Luthin et al., 2023). This is reflected in the use of Industry 4.0 technologies that improve workplace safety through IoT and big data, create job opportunities through smart production systems, and enhance employee's education with digital training platforms. Moreover, the exploration

and adaptive capabilities deriving from the implementation of CEP provide firms with improved market resilience and enhanced reputation, contributing to their economic, environmental and social performance (Chaudhuri et al., 2022; Kennedy and Linnenluecke, 2022).

Additionally, by the fulfilment of corporate social responsibility (CSR) to different stakeholders, the trust between firms, suppliers and customers and the positive reputation can be assisted in their establishment. Baah et al. (2023) argue that integrating the principles of CE in CSR methods not only drives sustainability towards environment but also contribute to social aspects such as social equity and rights protection, enabling firms to be more attractive and influential to customers and investors. Based on CE orientation, adopting Industry 4.0 technologies to promote their CSR performance creates a virtuous cycle. For instance, growing market demand reflecting customers' needs for waste management for restoration and regeneration of materials encourages greater investment in research and development in Industry 4.0 technologies to improve the efficiency and affordability, while improvements in price-performance ratios further stimulate the adoption of technological solutions, reinforcing the overall CE framework (Zhang et al., 2023). Specifically, the efficiency gains by technological innovation along with positive environmental and social impacts, and enhanced reputation reinforce each other, ultimately result in long-term sustainability and competitiveness for firms (Chuang and Huang; 2018).

1.2 Research Gaps and Questions

Although scholars have connected Industry 4.0 and sustainability and CE and point out that it can contribute to economic, environmental and social aspects, how the challenges during this implementation such as investment allocation, employee skill gaps, cybersecurity risks can be addressed through strategic planning and proactive initiatives remain unanswered (Dua, 2025). Meanwhile, despite extensive literature on Industry 4.0 technologies, CEP, and CSR, there is scant empirical research exploring the interrelationships among these factors (Gupta et al., 2021; Govindan, 2022; Matarneh et al., 2024). Thus, this thesis aims to investigate and extend the knowledge of the consequences and mechanisms of the application of Industry 4.0 technologies and CEP on CSR. The main research question of the thesis is: ***How does the application of Industry 4.0 technologies and circular economy practices influence corporate social responsibility?***

Three interrelated chapters consisting of one systematic review chapter and two empirical chapters collectively examine the current application of Industry 4.0 technologies in promoting CE in the oil and gas industry and the relationships among Industry 4.0, CEP, and CSR. The main research question of the thesis will be answered through several more specific research questions of three

chapters.

1.2.1 The Current Situation of Industry 4.0 Implementation in The Oil and Gas Industry

Although the emerging implementation of Industry 4.0 technologies provides technological transmission and more significant approaches for sustainability in the oil and gas sector, barriers and challenges remain in the process of application (Ghobakhloo and Fathi 2021). Generally, many firms in the oil and gas sector are state-owned and described as critical to the national economy, which restricts significantly the availability of public data (Malone et al., 2015; Valenza, 2018). This lack of transparent data leads to the inadequate research in this area. Although some previous studies have investigated the Industry 4.0 technologies applied in the oil and gas industry, they mainly concentrated on the application of individual technology on their efficiency improvement, methodological approaches and limitations, with a parallel focus on CE principles and policies (Jain et al., 2020; Salem et al., 2022; Al-Rbeawi, 2023; Dua and Jain, 2024). Few have integrated the Industry 4.0, CE, and the oil and gas industry. Most contributions are conceptual or exploratory, offering insights but failing overall review and empirical evidence. This gap is especially serious in the oil and gas industry, which has high level emission and pollution. For instance, over the last 20 years, the world's 20 largest oil and gas firms have been responsible for

approximately 53.9% to 57.0% of the total global greenhouse gas (GHG) emissions (Ma et al., 2023). Given its high environmental impact, this industry requires circular economy solutions that can reduce environmental impact while maintain economic benefits and contribute to society (Su and Urban, 2021; Lau et al., 2022). Consequently, there is a pressing need for more comprehensive and systematic investigations that provide overview on the current situation and capture the challenges, opportunities, and benefits associated with the implementation of Industry 4.0 in the sector. Therefore, a systematic literature review is conducted in Chapter 2, examining 60 included papers from Scopus and Web of Science ranging 2013 to 2024. This study proposes and addresses the following research questions:

RQ1): What is the current trend and scope of Industry 4.0 in the oil and gas industry for circular economy?

RQ2): Which Industry 4.0 technologies find application to develop circular economy in this sector?

RQ3): What are the key factors affecting the adoption of Industry 4.0 technologies to enable circular economy in this sector

RQ4): How does the Industry 4.0 technology implementation benefit the oil and gas industry for circular economy purposes?

1.2.2 Industry 4.0, Circular Economy Practices and Corporate Social

Responsibility

Some research argues that Industry 4.0 technologies are not the only measures that organisations adopt to purchase sustainability on economic, environmental, and social aspects. Although Industry 4.0 has brought transformative changes across multiple streams of the oil and gas industry, its potential to gain sustainability cannot be entirely realised by itself. To achieve more effective sustainable outcomes, it is evitable that the technology innovations need to be complemented by other methods such as CE (Hamdouna and Khmelyarchuk, 2025). While the adoption of CE contributes to addressing environmental pollution, resource waste, and social issues, its connection with Industry 4.0 to jointly improve social performance are still not fully identified in the oil and gas industry (Baca-Neglia et al., 2025; Cuevas-Pichardo et al., 2025).

Furthermore, the fulfilment of CSR is the practical step for achieving sustainable development in firms, which also assists in the process of obtaining competitiveness through Industry 4.0 technologies and CEP (Lii and Lee, 2012; Tetrault Sirsly and Lvina, 2019; Sardana et al., 2020). Although the joint effect of the adoption of Industry 4.0 technologies with CEP on CSR has been treated as unique capabilities that bring organizations competitive advantage, which is difficult to imitate, the role of CEP in benefiting social aspects is still questioned. This is because its social contributions are unclear due to structural barriers in practical implementation (Corvellec et al., 2022; Monciardini et al., 2024). This

exposes another critical knowledge gap about how Industry 4.0 technologies, CEP, and CSR interact and promote firms' competitive advantage. Thus, Chapter 3 aims to contribute to the above research gaps by answering the research questions as follows:

RQ1): How do Industry 4.0 technologies influence corporate social responsibility in the oil and gas industry?

RQ2): How do Industry 4.0 technologies and circular economy practices synergistically affect corporate social responsibility?

1.2.3 Deeper Mechanisms between Circular Economy Practices and Corporate Social Responsibility

Although attention on the adoption of CEP for sustainability has increased, most studies mainly focused on economic or environmental benefits led by this initiative (Korhonen et al., 2018; Nikolaou et al., 2021). Scholars argue that all dimensions of economic, environmental, and social should be balanced and not overlook its social impact (Pies et al., 2021; Fleurbaey and Ponthière, 2023). The adoption of CEP contributes to the improvement of CSR and then promote firms' sustainable competitive advantage in the aspect of social performance (Baah et al., 2023). To maintain long-term development of CSR, internal comprehensive sustainable strategies (SS) is required to ensure strategic management

framework and a balanced resource allocation plan (Reeves et al., 2015). During the process, institutional pressure (IP) from government, regulations, market, and customers drives its design and development (Baah et al., 2023; Hong et al., 2024)

Although SS and IP have been pointed out as external factors influencing CSR, few studies have examined their interactions between CEP and CSR. This study aims to address this knowledge gap by investigating how SS and IP impact the relationships between CEP and CSR. Thus, Chapter 4 raises and answers the following questions:

RQ1: How does CEP affect CSR?

RQ2: How does SS affect the associations between CEP and CSR?

RQ3: How does IP affect the relationships between SS, CEP and CSR?

These research gaps and unsolved issues identified in the above literature motivate this study. This thesis seeks to address these gaps by offering a comprehensive perspective on the basis of empirical investigation. In the next section, the specific research objectives of each chapter are outlined.

1.3 Aims and Objectives

Drawing on the motivations, Chapter 2 in the form of systematic literature review

(SLR) is conducted to investigate the current situation of the implementation of Industry 4.0 in the oil and gas sector for CE purpose. This chapter aims to review prior literature, examine the trends and the challenges of applying Industry 4.0 technologies in the oil and gas industry when pursuing circular economy, identify their economic, environmental and social benefits, and summarise directions for future research.

Furthermore, based on the findings of Chapter 2, it is evident that the application of Industry 4.0 technologies and CE has drawn increasing attention and achieved effectiveness in many use cases. However, the social contributions of CE in the oil and gas sector have gained less and inadequate attention compared to their economic and environmental contributions in the context of Industry 4.0 (Sharma et al. 2023). Thus, this study focuses on the broader social impacts and aims to explore that how the implementation of Industry 4.0 technologies and CEP contribute to CSR, addressing the literature gap of lacking study on their social values.

Finally, as Chapter 3 has investigated the relationships among Industry 4.0 technologies application, CEP and CSR, Chapter 4 aims to explore the deeper mechanism influencing their relationships with external factors, revealing practical managerial implications. Thus, the objective of Chapter 4 is to explore the deeper mechanism between CEP, SS, IP and CSR. The findings will assist in understanding the importance of detailed and comprehensive SS and appropriate

IP in the relationship between CEP and CSR and providing managerial implications for decision makers to promote CSR more effectively in practice.

1.4 The Thesis Structure

This thesis is constructed in five chapters, including one literature review chapter and two empirical chapter. Following the Introduction chapter, chapter 2 focuses on the current situation of Industry 4.0 technologies in the oil and gas sector aimed at CE. This chapter applies to a SLR on Industry 4.0 in the oil and gas sector towards CE and identifies 60 included papers from 2013 to 2024 based on Scopus and the Web of Science databases.

The key contributions of Chapter 2 are to examine the trends and the challenges of applying Industry 4.0 technologies in the oil and gas industry when pursuing circular economy and summarise directions for future research. The findings of review show that there is an increasing interest and study trend in the field of Industry 4.0 in the energy sector. It has also been found that although the adoption of Industry 4.0 technologies for achieving CE is on the rise, influencing factors and challenges remain present. Of all influencing factors, institutional pressures represent the most critical concern. Similar to influencing factors, the challenges encountered are categorized into institutional barriers, operational and managerial barriers and technological and financial barriers, with

institutional barriers are the most impactful. Despite the presence of challenges, applying Industry 4.0 technologies into the business mode of CE brings considerable benefits in turn (Awan et al., 2021). Economic, environmental, and social benefits are confirmed that they can be attainable in this process. Meanwhile, unsolved issues in this field discussed in extant literature have also been reviewed. Building on these findings, future potential research directions are concluded and pointed out, which include total quality management, evaluation for technological integration, and social contributions of Industry 4.0 in the oil and gas industry. These findings provide valuable insights and comprehensive understanding of the status of the implementation of Industry 4.0 in the oil and gas industry and suggest promising future avenues in this field.

Chapter 3 focuses on the improvement of the application of Industry 4.0 technologies on CSR and the mediating effect of CEP. Based on the discussion in Chapter 2, a research model linking Industry 4.0, CEP, and CSR, connecting technology, CE and social contributions. By using the survey data from 155 companies covering all sectors of the oil and gas industry and results in 430 valid responses, the findings show that the application of Industry 4.0 technologies has direct positive affect on CSR. Meanwhile, CEP plays both mediating and suppressing roles on the relationships between the application of Industry 4.0 technologies and CSR. The suppressing effect of CEP is an unexpected analysis results that was unforeseen in the theoretical development. Accordingly, a focused discussions is carried out to investigate and understand the potential

origin.

The theories support for this study is the resource-based view (RBV) theory. Barney (1991) illustrates that the unique resources hard to be imitated and duplicated are the core of an organization to achieve sustained competitive advantage. Technological innovations enabled by Industry 4.0, cost reduction and resource efficiency gained through CEP, and emerging reputation achieved from the improved CSR create valuable intangible resources to firms, contributing to their core competitiveness in the market (Hall, 1993; de Sousa Jabbour et al., 2022; Chaudhuri et al., 2022).

The primary contribution of Chapter 3 lies in the reveal of the influencing mechanism among the application of Industry 4.0 technologies, CEP, and CSR, which extends the literature by explaining how Industry 4.0 technologies affect CSR through the mediating and suppressing effects of CEP. CEP is emphasised as supplementary support and should be embedded into firms' future strategies for pursuing sustainable development instead of merely taking account of technological innovation. The findings of this study can be applied by practitioners to improve firms' social performance. Given the expected results of the suppressing effect of CEP, this study also contributes to the literature on suppressing effect analysis. As the mediation test in this story does not follow the traditional Baron and Kenny's guidelines (1986), it has the opportunity to reveal a deeper mechanism of CEP with the hidden suppressing effect.

Chapter 4 primarily focuses on the relationships between CEP and CSR. In addition to these two core factors, sustainable strategies (SS) and institutional pressure (IP) are also introduced as moderating variables to further examine the mechanism between CEP and CSR based on previous literature (Kauppi and Hannibal, 2017; Aragón-Correa et al., 2022). The findings reveal that the implementation of CEP within firms significantly contributes to the improved fulfilment of their social responsibilities. This is broadly in line with prior research (Apostol and Näsi, 2014; Junaid et al., 2024). Further analysis shows that SS positively moderates the relationships between CEP and CSR. Notably, strict and detailed SS demonstrate a stronger moderating effect compared to the loose and simple ones. Moreover, IP reinforces the positive impact of CEP on CSR with its indirect moderating effects by imposing firms to adopt stricter and more detailed SS. However, these moderating effects vary across different dimensions of CSR, which is evident in the aspects of social and non-social stakeholders, customers and government, but not extend to the employees. As internal stakeholders, employees tend to gain less emphasis compared to external stakeholders such as society, customers and government. Especially in the context of limited funds that can be used for CE transition, firms always deprioritise employees when designing the SS.

The main contributions of Chapter 4 are identifying the positive impact of CEP on CSR and the moderating roles of SS and IP, aiding the current literature.

Besides, this research extends the application of moral responsibility theory of corporate sustainability in the fields of CE and CSR. By identifying the failure of SS in the relationship between CEP and CSRE (corporate social responsibility to employees), this study reveals that firms tend to prioritize external stakeholders other than internal stakeholders due to limited resources on CE transition. Bias in the allocation of budget is always inevitable, yet it results in the cost of failing to meet the needs of some stakeholders (Fleurbaey and Ponthière, 2023; Ho et al., 2023; Jensen, 2003). Accordingly, managerial implications are proposed that budget should be balanced when making SS and more attention should be paid to the enhancement of employees' welfare.

In all, this thesis reviews the current situation, key characters and challenges and barriers of applying Industry 4.0 technologies targeted at CE in the oil and gas industry and uses quantitative approaches to explore the relationships between Industry 4.0 technologies, CEP and CSR. To provide deeper insights, SS and IP are introduced as moderators in the relationships between CEP and CSR. While the findings highlight the significance of SS and IP, their potential effects on the direct relationships between the adoption of Industry 4.0 technologies and CSR have not been investigated. Thus, future research is encouraged to explore their direct relationships, offering a more comprehensive understanding of the mechanisms between Industry 4.0 technologies, CEP and CSR. The conceptual model of the thesis is shown in Figure 1.1 as below.

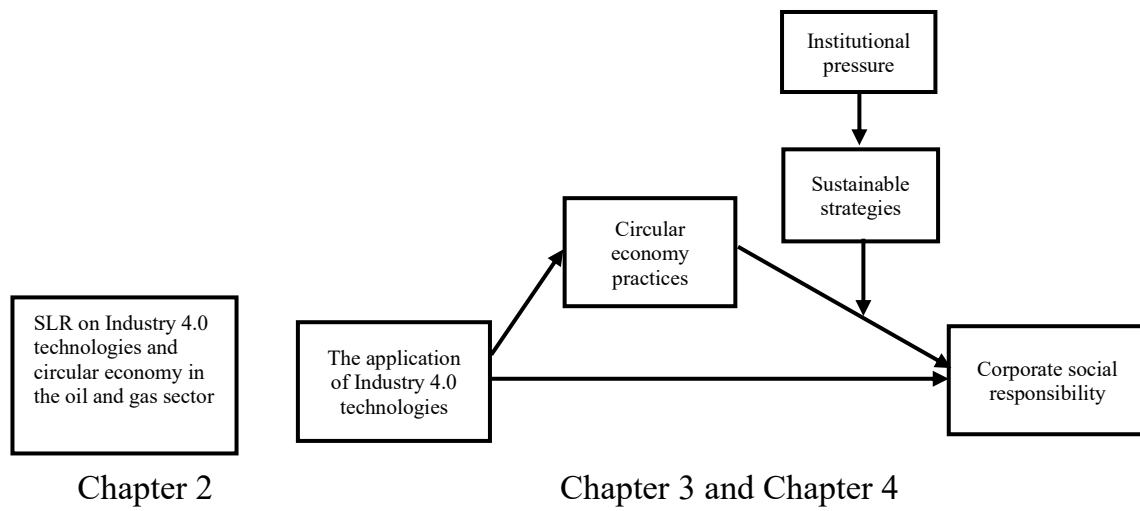


Figure 1.1: Conceptual model of the thesis.

Chapter 2

Industry 4.0 implementation in the oil and gas industry for circular economy: A systematic literature review

2.1 Introduction

The oil and gas industry which is recognised as the backbone of the global economy is at the forefront of experiencing technological transformation (Prestidge, 2022). This industry has traditionally relied on large-scale physical infrastructure and manual intervention but is progressively being changed by the advent of Industry 4.0 which has opened a new era in industrial development. Industry 4.0 has demonstrated a convergence of digital, physical, and biological realms, revolutionizing how industries operate and evolve. This integration has redefined exploration, production, distribution, sales and management processes within the oil and gas industry. Furthermore, Industry 4.0 has become an indispensable factor in achieving sustainable development in the energy sector by enabling accelerated material reuse and recycling while lowering emissions, material costs, and energy usage (Ghobakhloo, 2020; Zhao et al., 2021).

The oil and gas sector is integrating Industry 4.0 technologies in a variety of

ways, with a focus on resource management to lessen environmental impact and promote the circular economy (CE) through increased productivity and efficiency, reduction in environmental impact through improved resource management, reduction in waste generation and operational costs, and improvements in safety standards. The 3R's (reduce, reuse, and recycle) are addressed in Industry 4.0 by shifting supply chains from linear to circular processes (Rajput and Singh, 2019). CE enables the industrial system to minimise the impact of chemicals and materials which enhances resource efficiency and environmental performance in supply chains (Heyes et al., 2018). Since its introduction, CE has become one of the core principles for industrial and environmental policies in many countries (Donaghy, 2022). The application of Industry 4.0 technologies has promoted the sustainable use of resources, reduced unplanned outages, and extended the lifespan of critical infrastructure (Bonilla et al., 2018). Moreover, digitalisation has contributed to increasing energy efficiency and reduction in carbon emissions and enhanced environmental monitoring and compliance, ensuring more sustainable and responsible operations (Puskarskij et al., 2022).

The digitalisation of manufacturing is embodied in the next phase of Industry 4.0. With a technological base as a physical network system and the Internet of Things, it is expected to realise rapid and efficient product supply by making manufacturing and information data digitised and intelligent with the aid of a Cyber-Physical System (Langmann and Rojas-Peña, 2016). The technologies

converge to create a highly connected and smart system that is capable of autonomous operation and data-driven decision-making. Industry 4.0 and the novel digital business mode are considered to offer significant opportunities for sustainability in the oil and gas sector (Ghobakhloo and Fathi, 2021).

However, challenges exist in Industry 4.0 integration in the oil and gas industry for CE. The primary concerns emerge from the oil and gas market itself. Investors are worried about the energy sector because of price fluctuations and the need to demonstrate results in an uncertain environment (World Economic Forum, 2017). The high initial cost of deploying the advanced technologies is also a significant barrier (Khan and Turowski, 2016). Additionally, due to the increased reliance on digital systems, cybersecurity risks are significant in this sector (Wu et al., 2018). The oil and gas industry also faces a skills gap as the workforce needs to adapt to evolving technological demands, which requires extensive training and development programs (Georgiou et al., 2021). Furthermore, competitive intensity has reduced the attention and resource allocation towards sustainable and environmental issues (Dong et al., 2022; Hendijani and Saeidi Saei, 2020). Nevertheless, Industry 4.0 technologies demonstrate significant potential, which is not only for enhancing production and operational efficiency but also act as a key method to address environmental challenges and promote sustainability (Rajput and Singh, 2019). Thus, it is essential to explore approaches through the adoption of Industry 4.0 technologies to achieve sustainability.

This paper aims to provide two main contributions. First, the oil and gas industry is undergoing rapid economic, environmental and social changes all of which require greater attention than what has been offered in extant literature. This has become increasingly important with the advent of Industry 4.0 technologies. Although some previous studies have discussed Industry 4.0 technologies in general, they do not answer the key research question, ‘What approaches can be taken to improve the results of the application of Industry 4.0 for CE in the oil and gas industry?’. This is owing to insufficient data and a dearth of adequate research in the oil and gas industry. Industry 4.0 applications in the oil and gas sector for CE are still emerging and only a few scholarly studies have drawn attention to it. Bai et al. (2020) and Ghobakhloo (2020) discuss that the Industry 4.0 and sustainability research has drawn relatively more attention towards economic objectives while little emphasis has been given to the environmental and social contributions of Industry 4.0 technologies.

This study, therefore, aims to review extant literature, examine the trends and the challenges of applying Industry 4.0 technologies in the oil and gas industry when pursuing circular economy and summarise directions for future research. A systematic literature review (SLR) of Industry 4.0 technologies applied in the oil and gas industry is conducted to provide a comprehensive overview of the concept. We raise the following research questions: *Question 1: What is the current trend and scope of Industry 4.0 in the oil and gas industry for circular*

economy? Question 2: Which Industry 4.0 technologies find application to develop circular economy in this sector? Question 3: What are the key factors affecting the adoption of Industry 4.0 technologies to enable circular economy in this sector? Question 4: How does the Industry 4.0 technology implementation benefit the oil and gas industry for circular economy purposes?

Summary of findings. The main findings of this research are that (i) the implementation of Industry 4.0 in the oil and gas industry for CE is a novel interdisciplinary research field and has attracted increasing interest in recent years. (ii) Various Industry 4.0 technologies such as the Internet of Things (IoT), artificial intelligence (AI) and big data have been widely applied in the oil and gas value chain. Due to the influence of these technologies, the industry is experiencing technological change such as intelligentisation and digitalisation. (iii) There remain challenges impeding the application of Industry 4.0 technologies in the oil and gas industry for CE. These are identified as institutional barriers, operations and management barriers and technological and financial barriers. Among these, institutional barriers have the greatest impact. (iv) The oil and gas industry can benefit from the implementation of CE principles covering economic, environmental and social aspects. However, social benefits require more attention in this field. (v) Suggestions for future research include total quality management, evaluation for technological integration and social contributions of Industry 4.0 in the oil and gas industry.

The rest of the paper is structured as follows. An overview of the concepts of ‘circular economy’ and ‘Industry 4.0’ is provided in the next section, and the review protocol and methods are outlined in section 3. The review findings are presented in section 4. In section 5, future research directions are detailed while in section 6, the conclusions and limitations of this review are proposed.

2.2 Background and conceptual definitions

2.2.1 Circular economy

The circular economy is defined as an industrial economy which is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value (Ellen MacArthur Foundation, 2015). It represents the integration of economic activity and environmental well-being in a sustainable way (Murray et al., 2017). Over time, the definitions of CE have differed among scholars (Korhonen et al., 2018). While few have related CE to the reduction, reuse, and recycling of materials, others have defined CE as a broader concept that seeks to maintain the value of any resource used. A review of the literature on different definitions of CE is summarised and shown in Table 2.1.

Table 2.1: Different interpretations of CE

Sources	Interpretations
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- European Parliament News, 2023 The circular economy is a model of production and consumption, which involves sharing, leasing, reusing, repairing, refurbishing and recycling existing materials and products as long as possible.
- Berbel et al., 2023 CE is a method which seeks to maintain the value of resources during the whole product lifecycle and reduce waste.
- Ellen MacArthur Foundation, 2022 CE tackles climate change and other global challenges like biodiversity loss, waste and pollution, by decoupling economic activity from the consumption of finite resources.
- Castro et al., 2022 Circular economy is an umbrella concept for closing material loops towards enhanced environmental performance.
- Alhawari et al., 2021 CE is a dual-loop regenerative system that focuses on the effective and efficient utilization of resources in the ecosystem, which is beneficial to environmental and economic performance optimization.
- Korhonen et al., 2018 CE is an economy constructed from societal production-consumption systems that maximise the service produced from the linear nature-society-nature material and energy throughput flow.
- Kirchherr, Reike, and Hekkert, 2017 CE is an economic system which is based on the business model, which uses reducing, reusing, recycling and recovering material to replace the 'end-of-life' in production, distribution and consumption processes.
- Haupt, Vadenbo, and Hellweg, 2017 The concept of circular economy consists of a production and consumption system with minimal losses of materials and energy through extensive reuse, recycling, and recovery.
- Geissdoerfer et al., 2017 The circular economy is a regenerative system in which resource input and waste, emission, and energy leakage are minimised by slowing, closing, and narrowing material and energy loops.
- Singh and Ordoñez, 2016 CE is an economic strategy that suggests innovative ways to transform the current predominantly linear system of consumption into a circular one while achieving economic sustainability with much needed material savings.
- Ellen MacArthur Foundation, 2016 CE is an industrial economy that is restorative and regenerative by design and makes effective use of materials and energy in a digitally-enabled model of

	development.
Bocken, Rana, and Short, 2015	CE is a design and business model strategy which is slowing, closing, and narrowing resource loops.
European Commission, 2015	In a circular economy, the value of products and materials is maintained for as long as possible; waste and resource use are minimised, and resources are kept within the economy when a product has reached the end of its life, to be used again and again to create further value.
Stahel et al., 2013	The circular economy is defined as an economic model inspired by natural systems, intentionally restorative of natural and social capital.
Ellen MacArthur Foundation, 2013	The circular economy is an industrial economy that is restorative or regenerative by intention and design.
Geng and Doberstein, 2008	The circular economy is a realization of closed-loop material flow in the whole economic system.

Although scholars have defined CE in different ways, these are primarily postulated on the concept proposed by the Ellen MacArthur Foundation (Bai et al., 2024). Thus, in this paper, the definition of CE by Ellen MacArthur Foundation (2016) is adopted. CE is proposed to achieve the goal of sustainable development with resource reuse.

While tracing the initial concept and development of CE, Murray et al. (2017) suggest that CE can contribute to sustainable business models. However, CE stresses the benefits of the ecological environment through the redesign of the manufacturing and service systems rather than human social aspects. This impedes the inclusion of social dimensions such as social equality and intra-generation equity. Thus, the authors define CE as ‘an economic model wherein

planning, resourcing, procurement, production and reprocessing are designed and managed, as both process and output, to maximise ecosystem and human well-being’.

2.2.2 Industry 4.0

Industry 4.0 refers to the fourth industrial revolution where the first three industrial revolutions are related to mechanical power (Industry 1.0), mass production (Industry 2.0) and the digital revolution (Industry 3.0) (Culot et al., 2020; Wagire et al., 2020). Industry 4.0 has been defined as the integration of information and communication technologies with industrial technology (Ben-Daya et al., 2019). The economic and productive change triggered by the fourth industrial revolution identifies various applications based on technologies such as the IoT, AI, big data analytics, cybersecurity and 3D printing among others (Bagnoli et al., 2018; Massaro et al., 2021). According to Jena et al. (2020) and Machado et al. (2020), the digitalisation of the manufacturing industry may offer a wide variety of benefits which include production efficiency, manufacturing productivity, business process innovation, collaborative working and knowledge sharing, and better customer experience. Industry 4.0 is further posited as a paradigm shift within the industrial value chains (Sony and Naik, 2020) ranging from the digitization of manufacturing and value creation processes to the intelligence process of plants, suppliers, customers, and

distribution channels (Ghobakhloo, 2020).

Industry 4.0 technologies can be integrated into business practices which have the potential to significantly influence sustainability as well (Bai et al., 2020; Bai et al., 2024). Sustainability is not merely a firm's strategy but critical to a firm's future survival (Cillo et al., 2019). Adoption of Industry 4.0 technologies supports CE (de Sousa Jabbour et al., 2018; Di Maria et al., 2022), which can offer profitable models for digital businesses, high quality and efficiency, effective support for risk assessment, and low-cost solutions for enterprises (Hofmann and Rüsçh, 2017; Zheng et al., 2021; Yadav et al., 2022). Considering Industry 4.0's benefits, the adoption of Industry 4.0 technologies can create a digital breakthrough for organizations aiming to develop a CE (Ramakrishna et al., 2020; Yu et al., 2022).

2.3 Review methodology

2.3.1 Review principles and methods

This study reviewed the literature systematically to provide an overview of Industry 4.0 technologies applied to the circular economy in the oil and gas industry. The PRISMA protocol was employed to ensure the validity and reliability of the SLR process. PRISMA, as an abbreviation of 'Preferred

reporting items for systematic reviews and meta-analyses’, is a set of standards established for the research quality of systematic reviews and applies to a review of published literature, which aims to improve the specificity and comparability of systematic reviews. PRISMA is an effective review method for reporting systematic literature reviews (Pai et al., 2004). Based on PRISMA protocols, the inclusion and exclusion criteria for this study were established as displayed in Table 2.2. Figure 2.1 shows the applied PRISMA procedure for the SLR for this study.

Table 2.2: Inclusion and exclusion criteria developed for this study.

Criteria	Criteria Explanation
Exclusion	
EX-1	The paper is not written in English.
EX-2	No access to the full text but to the title, abstract and keywords of the paper.
EX-3	The paper is not a journal paper.
EX-4	The paper only uses search keywords in the title, keywords and references, or as a cited concept and provides no insights into the review, discussion or analysis.
EX-5	The paper mentions search keywords in the main text but does not focus on the scope of this study.
Inclusion	
INC-1	The paper is related to but without the concept of the keywords.
INC-2	The keywords are part of the themes of the paper.
INC-3	The keywords are the central theme of the paper and have been thoroughly examined and analysed.

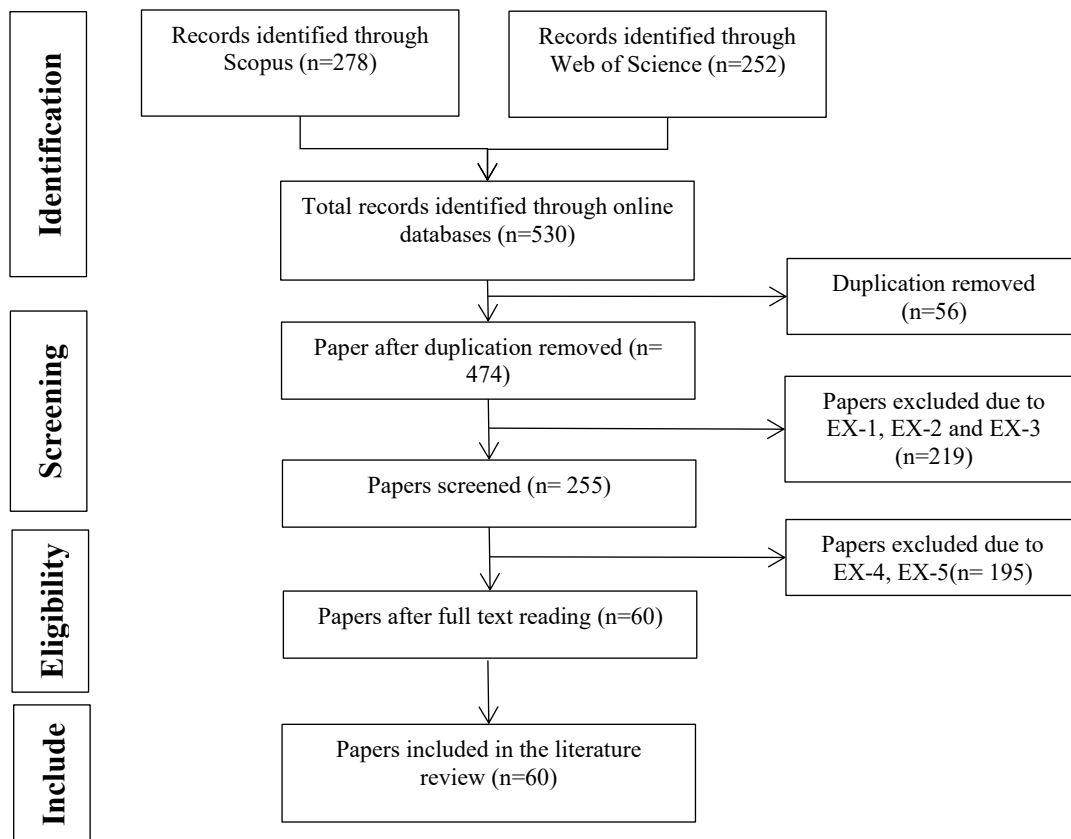


Figure 2.1: PRISMA procedure for the SLR

2.3.2 Paper collection

Taking into consideration the study's emergent nature, the scope of the review was expanded to wide-ranging journals in addition to the top-ranked ones to review as much extant research as possible. The databases Scopus and Web of Science were used for the analysis to ensure a variety of scholarly articles. However, to avoid the problem of low-quality papers resulting from a large search scope, only journal publications were selected for the study. Literature such as conference proceedings, magazine articles, books, book chapters and

industrial reports were excluded.

The search string used in this study includes three different categories. The first category contains keywords related to Industry 4.0. The second category contains keywords related to supply chain and circular economy. The third category contains keywords related to the oil and gas industry. Time restriction was adopted for the search. The study's reviewed paper publication year began in 2013, which is when Industry 4.0 came into focus after the German government introduced it (Sanders et al. 2016), The search was conducted by taking one keyword of each category at a time. Categories and search strings are shown in Table 2.3. To supplement the search results, the same search approach was also used in the Web of Science database (Martín-Martín et al. 2018).

The initial search yielded many papers, and not all were related to the study. Therefore, inclusion and exclusion criteria were applied to screen the articles.

Table 2.3: Categories and search strings

Category	Search string
Industry 4.0 - related keywords	“Industry 4.0” or “The fourth industrial revolution” or “The 4th Industrial Revolution” or “Gas 4.0” or “Oil 4.0” or “Cybersecurity” or “Big data” or “3D printing” or “Augmented reality” or “Internet of things” or “Cloud computing” or “System integration” or “Robotics”
Supply chain and Circular Economy - related keywords	“Supply chain management” or “Green supply chain” or “Green supply chain management” or “CE” or “Circular Economy” or “Sustainability” or “Sustainable development”

Oil and gas industry “Oil and gas” or “Oil and gas industry” or “Petroleum and gas industry” or
- related keywords “Oil and natural gas industry” or “Oil and gas energy industry”

The initial keywords-based search resulted in 530 papers (252 papers from Web of Science and 278 papers from Scopus). After a quick scan of the titles by merging the results from these two databases, 56 duplicates were identified and removed. For the remaining 474 papers, screening was conducted in three stages to exclude ineligible ones.

The first screening was used to exclude the papers that were not written in English (EX-1) and papers with no access to the full text (EX-2). The second screening was carried out to exclude the papers that were not academic (EX-3). To ensure scholarly journal articles, books, white papers, doctoral theses, conference papers, etc. were excluded from the search. In total 219 papers were removed after the first and the second screening.

The third screening excluded papers that only contained keywords in the titles, keywords and references, or as a cited concept (EX-4) as well as papers that mentioned search keywords in the main text but did not focus on the scope of this study (EX-5). In this stage, the abstract was assessed to identify if the relevant concepts such as Industry 4.0, oil and gas industry and circular economy were mentioned as well as the full text was read through. This was to ensure that the paper was indeed written on the topic relevant to this search and had not been included based on the search phrase alone. The screened papers were reviewed

comprehensively to answer the research questions in this study.

2.3.3 Data collection and analysis

Both qualitative and quantitative analyses were conducted to record and collect data from all the included papers. The first category of data contained descriptive information about the papers such as (1) titles, (2) keywords, (3) publication year and author names, and (4) databases and sources, which were collected and categorised via Endnote and Microsoft Excel. The second category of data aimed to address the questions in the Introduction section: (1) For Question 1: data on research types and methods were collected and analysed. (2) For Question 2: data on different types of Industry 4.0 technologies applied in different stages of the oil and gas value chain were collected and analysed. (3) For Question 3: data on the challenges and barriers during the implementation of Industry 4.0 in the oil and gas industry were examined. (4) For Question 4: data on the benefits that the oil and gas industry can obtain from Industry 4.0 technology were collected and analysed.

2.4 Analysis and results

Based on the exclusion and inclusion criteria shown in Table 2.2, 60 papers out

of the 530 papers from the initial search were analysed. This section presents the analysis. The answers to the research questions raised previously form the overarching framework of the analysis.

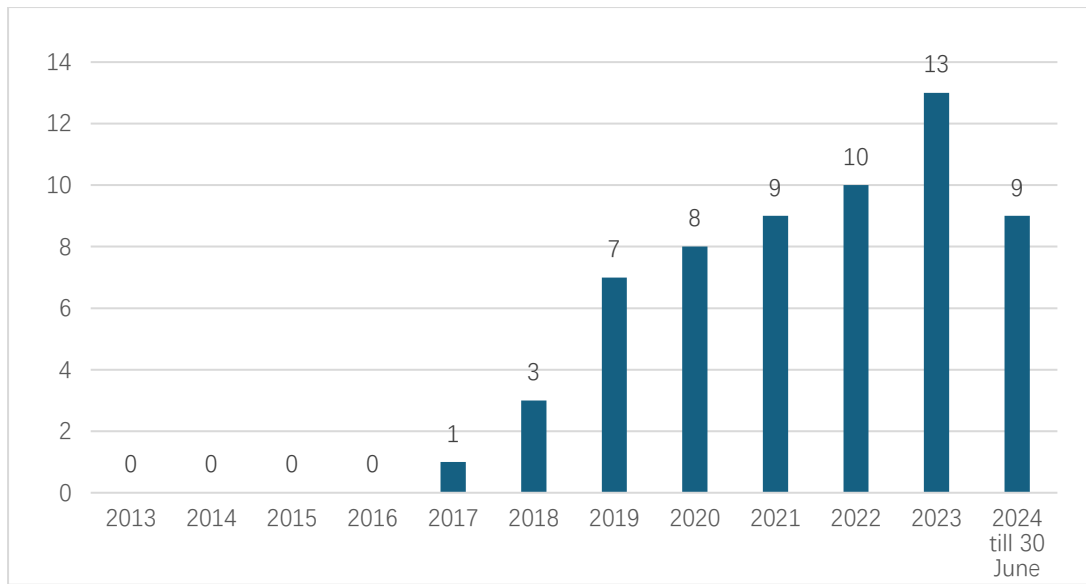
2.4.1 Current trend and scope of Industry 4.0 applied for circular economy in the oil and gas industry

The trend in the number of papers published by year on Industry 4.0 technologies applied for CE in the oil and gas industry from 2013 to 2024 is displayed in Figure 2.2(a). We find that although the concept of CE was first introduced in China in 1990s, and Industry 4.0 began to gain focus in 2013, the earliest studies on their application in the oil and gas field dated back to 2017, reaching a peak of 13 published papers in 2023. By the end of June 2024, the number of published papers was 9, which can be predicted to have increased beyond this timeframe. We infer therefore that the interest in this field has gradually increased over time as indicated by the increase in the number of papers in recent years.

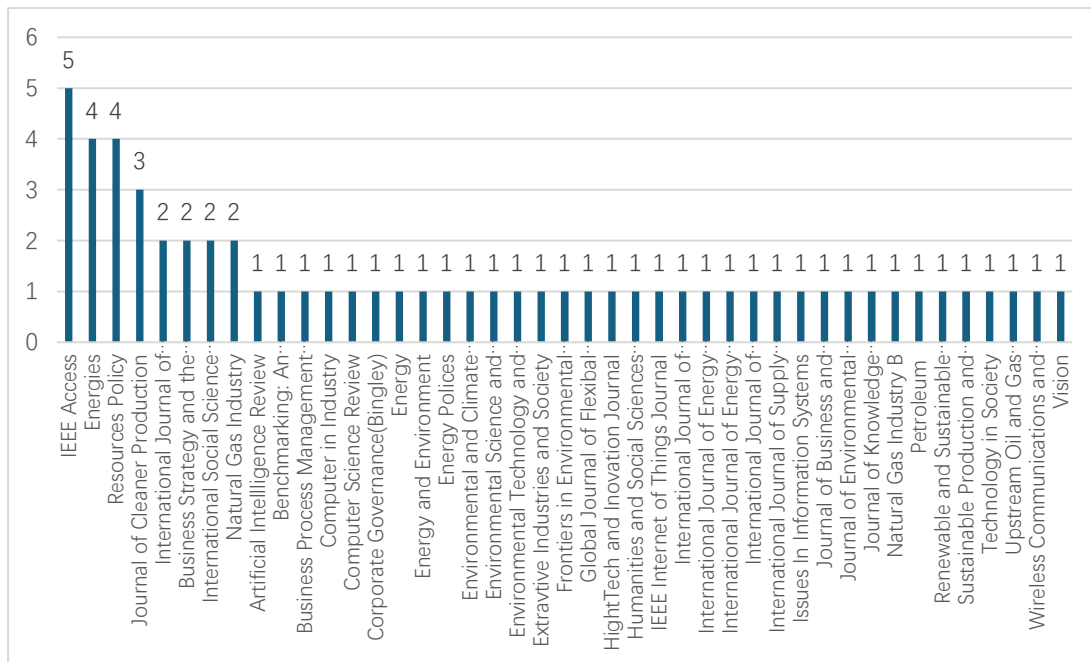
Figure 2.2(b) ranks the journals based on their publication. We find that research related to this field has appeared in 43 diverse journals that range from sustainability, energy, business management and technology management studies (IEEE Access (8.3%), Energies (6.7%) and Resource Policy (6.7%)). More than 70% have been published in interdisciplinary journals such as

Resources Policy and the Journal of Cleaner Production. This demonstrated that the research's preferred publication target lay in the intersection of sustainability, technology, and management.

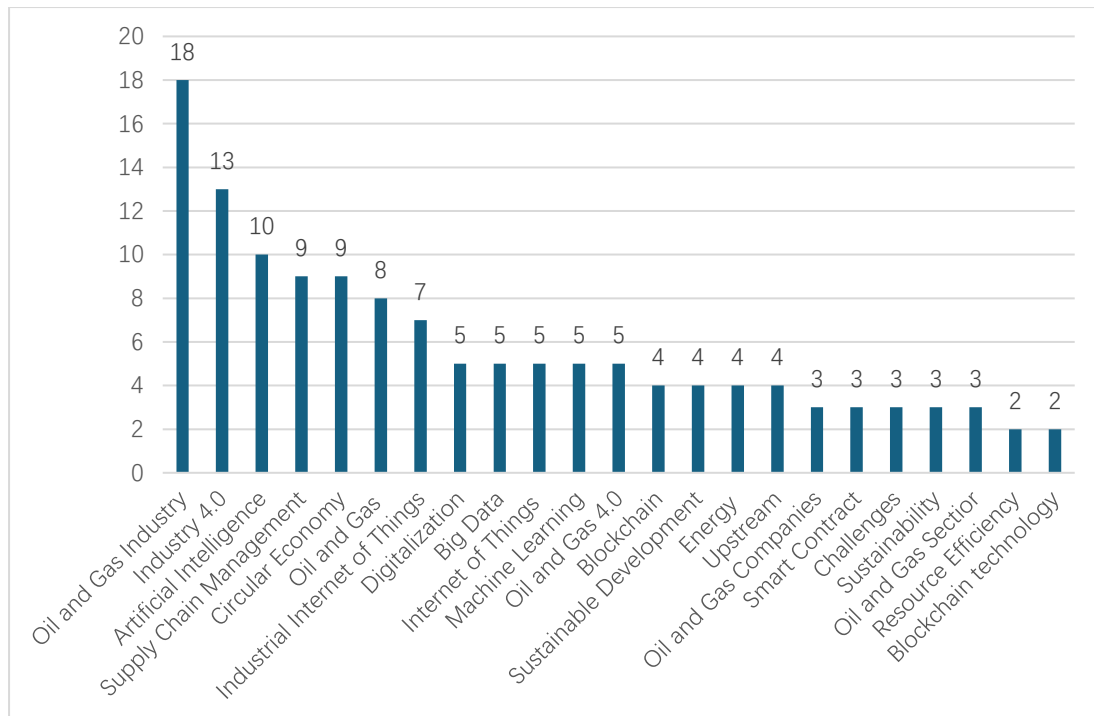
Keywords represented the most related and significant concepts discussed and analysed in the main context of a paper. In the Scopus database, the keywords of each paper consisted of author keywords (set by authors in the papers) and index keywords (automatically generated by Scopus). Only the author keywords from the Scopus database were taken into consideration in this literature review. In the Web of Science database, the author keywords were extracted for further analysis as well. The analysis showed that the 60 papers have 191 typographically different keywords. For brevity, keywords with the occurrence of at least two were considered. Figure 2.2(c) provides a distribution of keywords that have an occurrence of 2 times or more within all included papers. The top 5 keywords are 'oil and gas industry', 'Industry 4.0', 'artificial intelligence', 'supply chain management' and 'circular economy', mentioned separately. The oil and gas industry and Industry 4.0 are the top ranked, followed by technologies comprising Industry 4.0 such as artificial intelligence. The prominence of technology-related keywords such as artificial intelligence, big data and internet of things indicates the present and future value of Industry 4.0 applications in the oil and gas industry.



(a) Numbers of included papers published by year



(b) Distribution of journals for included papers



(c) Distribution of keywords for included papers

Figure 2.2: Analysis of included papers.

Figure 2.3 shows the distributions of research types of the included papers. Qualitative research makes up 76.7% of the total papers (46 out of 60) and quantitative 23.3% (14 out of 60). Among the quantitative research papers, 71.4% (10 out of 14) were conducted through primary data via questionnaires, surveys and interviews, and 28.6% (4 out of 14) were investigated via secondary data analysis. The 14 quantitative research method papers adopted a variety of mathematical models or analysis methods, such as Total Interpretive Structural Modelling (TISM), Regression model, Structural equation modelling (SEM), Decision-Making Trial and Evaluation Laboratory (DEMATEL), Quantiles and Best Worst Method (QBWM). Figure 2.4 illustrates the distribution of the models and methods applied in the included papers. We find that 35.7% (5 out

of 14) applied the Regression Model (RM) for analysis, 28.6% (4 out of 142) used Structural Equation Modelling (SEM) and 14.3% (2 out of 14) used Decision-Making Trial and Evaluation Laboratory (DEMATEL).

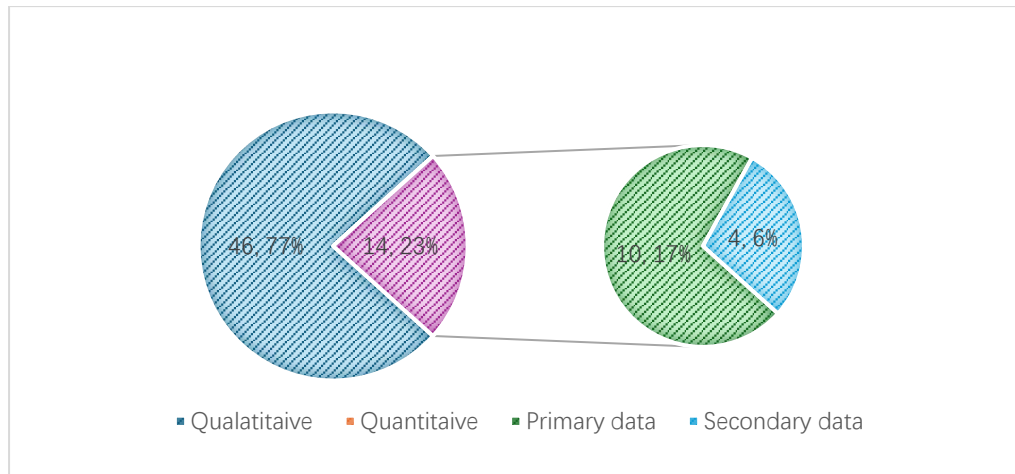


Figure 2.3: Distribution of research types in included papers

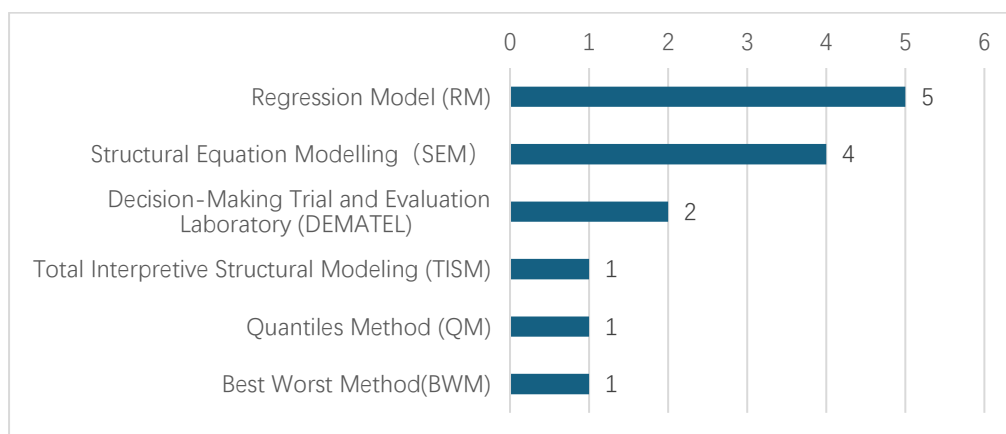


Figure 2.4: Distribution of models and methods applied in included papers

Through the review of the included papers, the literature that applied theories can be classified into three main perspectives: resources, organisations and management. The first category is about how to achieve and utilise rare and

inimitable resources to gain competitive advantages, which is represented by Aslam et al (2023). The second category concerns internal and external factors for organisations, such as aligning the interests of stakeholders (Aslam et al., 2023), and decision-making concerning energy efficient investment (Kluczek et al. 2021). The third category is related to management methods such as maintaining a positive relationship between leaders and employees (AlNuaimi et al, 2020), fitting in order between organisation structure and strategy choices (Ebrahimi et al, 2018). Table 2.4 summarises the theories applied from included papers regarding the topic on the Industry 4.0 technology deployed for CE in the oil and gas industry.

Table 2.4: Theories applied in included papers.

Theory	Theory focus	Research discipline description	Sources
The RBV Theory	Resource	Internal managerial resources can be both drivers and restrictions of an organisation's growth. These are the resources that are difficult to replicate by other competitors, providing unique value and advantages for organisations. Organisational resources must fulfil four different attributes that are valuable, rare, imperfectly imitable and non-substitute to achieve sustainable competitive advantages.	Penrose, 1959; Wernerfelt, 1984; Barney, 1991
Dynamic Capabilities Theory	Resource	Firms have abilities to identify and use opportunities, detect threats, and reconfigure resources to maintain competitive advantages in rapidly changing environments. Organisations can use processes of innovation, integration of new technologies, learning, and relocation of assets to adjust to changing environments.	Teece, Pisano and Shuen, 1997
The Theory of Contingency	Organisation	Leadership styles consist of task-motivated, and relationship-motivated, which are concerned primarily with reaching a goal and developing lasting relationships with individuals or	Fiedler, 1982

Diffusion of Innovation	of Organisation	organisations respectively. Leaders are highly likely to influence their employees if they possess a good relationship with their employees.	Rogers, 1962
The Institutional Theory	Organisation	The implementation of innovation is a social process, which is influenced by the innovations' characteristics, communication channels, and social systems. An idea, product, technology or service spreads within social system in a period.	Rogers, 1962
The Institutional Theory	Organisation	A rationalized cultural element exists in the process of modernisation of society. Under the interaction of complicated social activities, an inherent structure and environmental principles formed in organisations. There are three mechanisms of institutional isomorphic change, coercive isomorphism, mimetic processes and normative pressures that institutions can exert on organisations.	Meyer and Rowan, 1977; DiMaggio and Powell, 1983
Transaction-cost theory	Organisation	Whether activities would be internalised within a firm depended on their transaction costs. Decision-makers determine the strategies of companies by measuring transaction costs and production costs.	Williamson, 1991
The Prospect Theory	Management	An individual's attitude toward risk depends on whether they face losses or gains and how risk-taking decisions differ from the predictions of normative models. This is called risk aversion, which means that people prefer outcomes with low uncertainty to those outcomes with high uncertainty, even if the average outcome of the latter is equal to or higher in monetary value than the more certain outcome.	Kahneman and Tversky, 1979
Triple Bottom Line	Management	Corporate performance includes not only economic profits but also environmental and social aspects. Corporate performances are assessed on how well they create economic value, minimise environmental impact, and improve social well-being.	Elkington, 1997
Principal-agent theory	Management	The principal-agent problem typically arises where the two parties have different interests and <u>asymmetric information</u> . The agency problem can be intensified when an agent acts on behalf of multiple principals	Jensen and Meckling, 1976

The increasing number of published papers over the years represents the emerging interest in this field. Most papers in this area are at the intersection of sustainability, technology and management. In terms of research methods, among the studies on Industry 4.0 and circular economy in the oil and gas industry, the qualitative research method occupies the mainstream status. This also leaves additional scope for quantitative research in this field. Following the descriptive analysis of the papers, we discuss the applications and impact of Industry 4.0 technologies in the oil and gas industry and the challenges and barriers in subsequent sections.

2.4.2 Industry 4.0 technologies applied for circular economy in the oil and gas sector

Based on the literature, we first present the oil and gas value chain schematic comprising of upstream, midstream and downstream stages (Figure 2.5) (Lu et al., 2019; Koroteev and Tekic, 2021). Upstream comprises mining, production and development processes. Midstream refers to the storage and transportation of oil and gas, while downstream refers to the refining and terminal sales of oil and gas products.

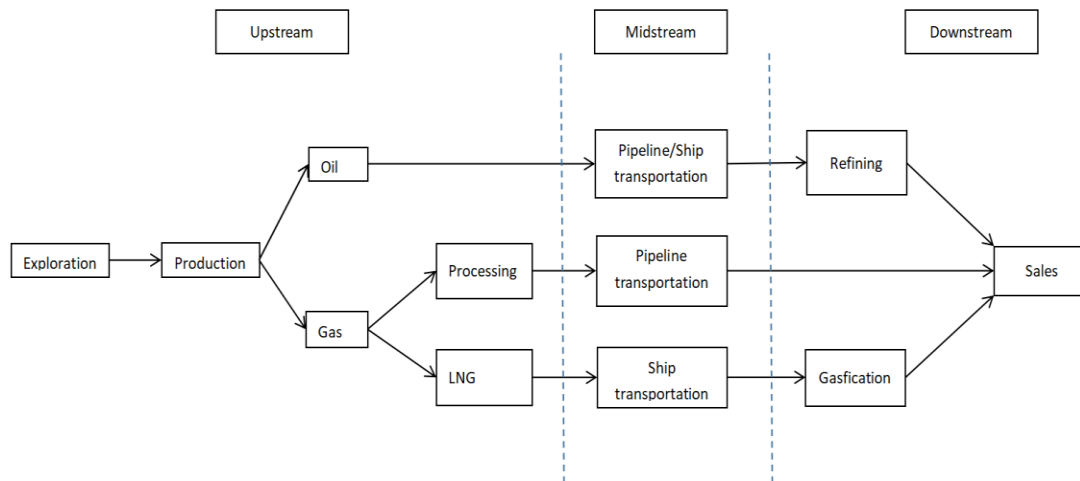


Figure 2.5: Oil and gas value chain (Lu et al., 2019; Koroteev and Tekic, 2021)

The analysis showed that the majority of studies have examined individual Industry 4.0 technologies such as AI, Big Data and blockchains rather than multiple technologies with combined contribution to oil and gas industry. Figure 2.6 shows the category of core technologies that are related to Industry 4.0 applied in the oil and gas industry, such as the Internet of Things (27 papers), artificial intelligence (25 papers), big data (22 papers), blockchain (15 papers) and system integration (10 papers). These technologies are deployed into different sectors in the oil and gas chain, such as robotics in upstream and downstream (Sircar et al., 2021), digital twin in upstream and midstream (Zborowski, 2018; Mustard and Stray, 2023), blockchain in upstream, midstream and downstream (Ahmad et al., 2022). Meanwhile, AI, IoT and big data are deployed in all sectors of the oil and gas chain (Koroteev and Tekic, 2021).

Based on Figure 2.6, the IoT, AI and big data emerge as the top 3 applied Industry 4.0 technologies in the oil and gas industry. Since Khan et al. (2017)

first proposed an IoT-based oil and industry framework, several companies have updated and developed IoT platforms in the oil and gas industry such as Siemens and Bien Dong POC (Lu et al. 2019; Tung et al., 2020). Although the earliest AI was applied in the oil and gas industry in the 1970s, it began to gain attention only in recent years (Li et al., 2021). AI can aid economic growth by enhancing efficiency as well as improve environmental conditions by reducing resource waste (Waqar et al., 2023), which has been confirmed in industrial studies such as Chinese manufacturing sector (Li et al., 2023). Similarly, the application of big data in the oil and gas industry emerged in recent years due to the essential requirements of data analysis to improve the production chain (Nguyen et al., 2020). Table 2.5 presents the definitions of Industry 4.0 technologies that are currently deployed in the oil and gas industry.

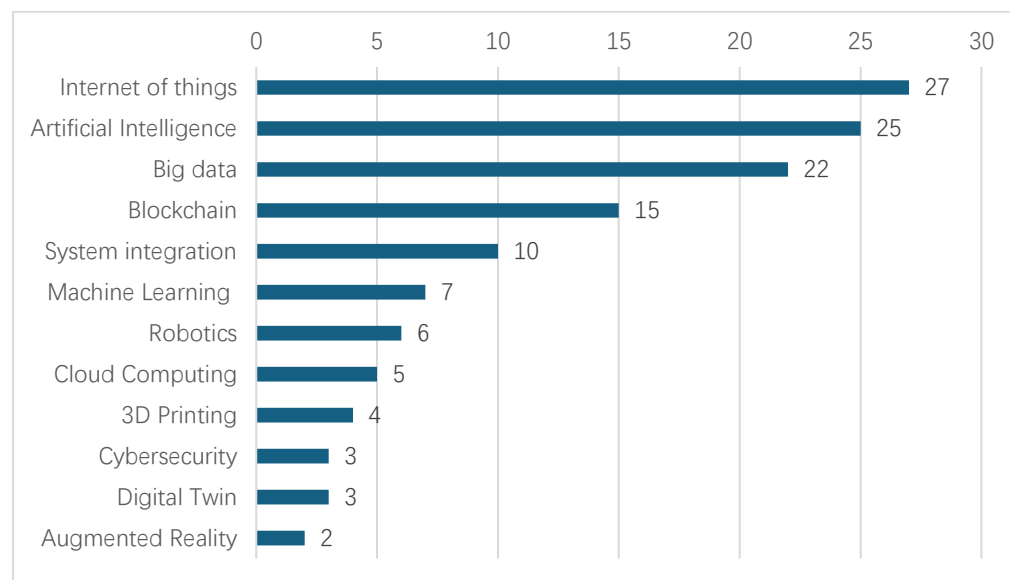


Figure 2.6: Core Industry 4.0 technologies deployed in the oil and gas industry

Table 2.5. The definitions of Industry 4.0 technologies in the oil and gas industry

Industry 4.0 Technology	Definition	Source
Internet of Things (IoT)	The physical devices can be connected to the internet and exchange information with other devices, dispensing with any human interaction.	Kumar and Barua, 2022
Artificial Intelligence (AI)	A set of advanced analytic technologies that make machines study, think, and operate like real humans.	Liao et al., 2022
Big Data	A strategy of studying and analysing large sets of data from diverse sources to explore any hidden signs, patterns, rules and trends.	Al-Rbeawi, 2023
Blockchain	A technology that can store and secure the safety of data by processing it in a permissioned network	Bai and Sarkis, 2020
System Integration	Consists of vertical integration (link system components), horizontal integration (link plural system) and end-to-end integration (link physical and virtual objects)	Sanchez et al., 2020
Machine Learning	Refers to the system that is programmed to have an iteration function and can create the relationship between the data, analyse and interpret the data on their own.	Rai et al., 2021
Robotics	Refers to machine technology based on AI and automation. It helps reduce human activities in production and significantly increases productivity.	Vaisi, 2022
Cloud Computing	A technology that provides computing services including network, storage, analysis and servers through the internet.	Hashem et al., 2015
3D Printing (Additive manufacturing)	Refers to a process for creating prototypes and functional components achieved by consolidation of material layer by layer.	Omiyale and Farayibi, 2020

Cybersecurity	Internet security technology that prevents data loss, leakage or stolen	Nguyen et al., 2020
Digital Twin	A technology that links the physical world with the digital world provides a digital model of the physical assets or processes.	Zborowski, 2018
Augmented Reality	A technology that calculates the position in three-dimensional space with images, videos and models, which connects the real world with the virtual world.	Furmanski et al., 2002

The review of the included papers yielded five different characteristics of Industry 4.0 in the oil and gas industry, that is intelligentisation, digitalisation, automation, integration and modularisation (see Figure 2.7). Intelligentisation was found in 37 papers, while digitalisation in 28 articles. Automation was studied in 20 papers, followed by integration and modularisation which were mentioned in 16 papers and 5 papers, respectively. A detailed definition of the five characteristics of Industry 4.0 in the oil and gas industry is provided in Table 2.6. This area of research shows the direction of technology innovation that the oil and gas industry has undertaken with the implementation of Industry 4.0.

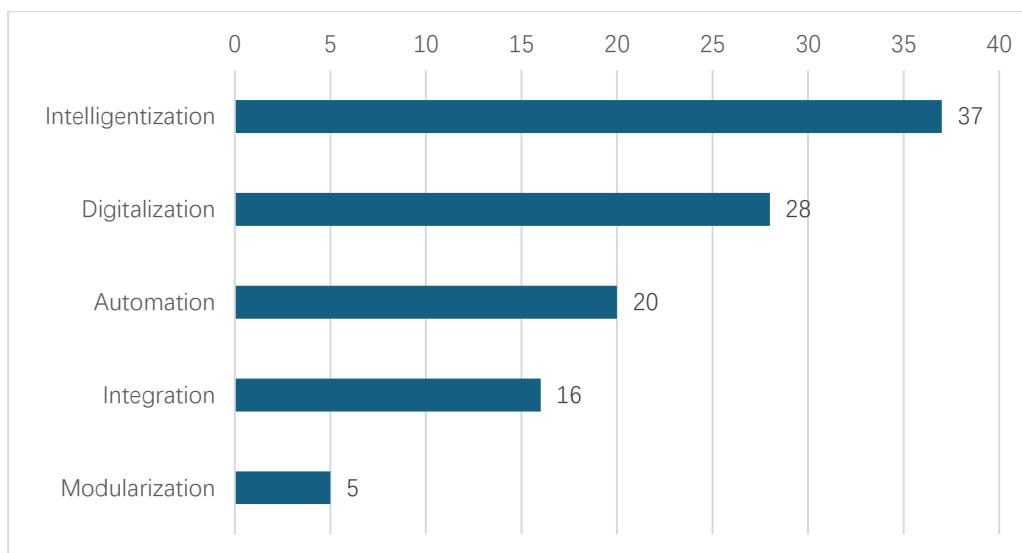


Figure 2.7: Characteristics of Industry 4.0 in the oil and gas industry

Table 2.6: Definition of the characteristics of Industry 4.0 in the oil and gas industry

Characteristics	Definition	Source
Intelligentisation	The general trend of science and technology, which guides and transfers complicated work to data, reduces the resource requirements and emerges efficiency with creativity and adaptability.	Lu et al., 2019
Digitalisation	The usage of physical and digital technology to manage different sectors of the oil and gas industry (upstream, midstream and downstream) by boosting productivity, maximizing efficiency, reducing cost and loss and enhancing the management process.	Al-Rbeaw, 2023
Automation	As the foundation of digitalisation, automation systems and digitally connected infrastructure are deployed to address the issues of labor force shortage, streamline the production and distribution processes, reduce costs and gain higher benefits. The whole supply chain could be simplified via automation.	Lu et al., 2019
Integration	Refers to vertical integration and horizontal integration which covers	Elijah et

the cooperation across sectors of the industry and different departments within companies respectively. Integration contributes to the transparency and efficiency of operation in the oil and gas chain. al., 2021

Modularisation Refers to the pre-production of equipment and systems in factories and assembled on site. Modular scheme secures professional skills, reduces costs, reduces construction period and enhances construction quality and safety. Lu et al., 2019

In summary, the analysis indicated that IoT had a high contribution to the CE process, followed by AI and big data. They were primarily applied upstream, midstream and downstream of the oil and gas value chain, respectively. The analysis also showed that the oil and gas industry is undergoing strategic, structural and technological transformation. In the included papers, intelligentisation is ranked as the most frequent attribute of Industry 4.0. This indicates that while modularisation is still some way off, it is becoming easier for the oil and gas industry to facilitate intelligentisation as a result of Industry 4.0 implementation.

2.4.3 Factors that influence Industry 4.0 technology implementation in the oil and gas industry for circular economy

The SLR revealed that challenges and barriers exist in the process of implementation of Industry 4.0 technologies in the oil and gas industry. As seen in Figure 2.8, the foremost challenge stemmed from the institution. 43.3% of the

included papers (26 papers) have identified at least one aspect of it. The subcategories under institutional challenges are governance and regulation, expected goals, competitors and social responsibility initiatives. The results demonstrated that the impact of institutions is a major concern in the existing body of literature. Other factors besides institutional challenges are - operations and management (16 papers), technology (13 papers) and finance (9 papers). The challenge of operations and management occurred frequently compared to other factors. These all point to the obstacles that the oil and gas sector has while implementing Industry 4.0 technologies for CE.

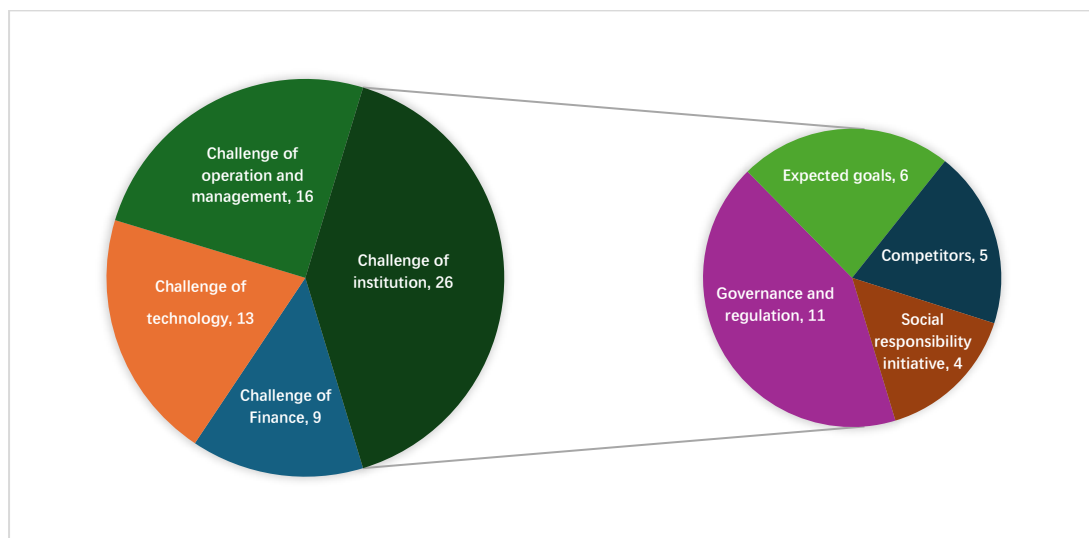


Figure 2.8: Distributions of challenges and barriers in applying Industry 4.0 in the oil and gas industry

Delving into institutional challenges, AlNuaimi et al. (2020) emphasised that an important impediment to applying Industry 4.0 technologies in the oil and gas

industry is the lack of government guidance. A poorly prepared agenda and guidance results in incomprehension, query and resistance to implementing Industry 4.0. Furthermore, there is a lack of regulatory control during the process of applying Industry 4.0 technologies (Chen et al., 2020). Organizations have been under heightened pressure to make their operations and practices environmentally responsible (Jain et al., 2023). Through various means including the introduction of new technologies, organizations have attempted to balance the need to comply with institutional pressures and the need to respond to environmental demands (D'Andreamatteo et al., 2019)

Evidence was found in the review that Industry 4.0 technology applications face challenges due to management dilemmas and obstacles. While some businesses have embraced and put these new technologies into practice, the replacement of outdated technologies with new technologies is sluggish because of inadequate supporting infrastructure and platforms (Wanasinghe et al., 2021). Another obstacle hindering the adoption of new technologies in organizations is the lack of communication between employers and employees. Since these technologies are new to them, employees might not understand them well at first. This issue may lead to conflicts between employers and employees which could damage the company's brand and consumer trust (Ejsmont, 2015).

In addition, the risks associated with data security are equally serious. Data theft is one instance of this. Data on manufacturing flows that enter refineries attracts

hackers. Protecting pipeline networks against remote cyber-attacks is one of the biggest concerns for midstream. Any manipulation of these flow values can create reporting discrepancies between production and refinery units which can gravely affect the company's performance and stock prices (Mahmood et al., 2023). Cyber incidents also arise from data leaks. Due to the large volume of drilling operations, the intricate ecology, and the involvement of various engineering firms, drilling operations are rated as having the highest severity of cyber-attacks. The diverse and expansive nature of the oil and gas value chain makes it challenging to build a single cybersecurity protocol (Massaro et al., 2021).

The review of past work also showed that the complexities of Industry 4.0 technologies itself bring challenges of deployment. Schuh et al. (2017) stressed that the application of Industry 4.0 technologies tends to require time to assess and adjust the strategy according to the new environment. Furthermore, there is an increase in operational complexity with technology interaction indicating that the interplay of different technologies in a complex system may pose challenges (Benbya et al., 2020). The key point, therefore, is to solve the interconnectedness of related technologies. Attention should be paid to the standardization of technologies and building interfaces (Vermesa and Fries, 2013). In addition, the education and training of employees are an integral part of such transitions (Kumar et al., 2020).

The review also showed that the introduction of Industry 4.0 technologies is significantly impacted by financial challenges. New technologies require a reinvention of the operating model. Changes in operating models require the replacement of many equipment and systems which require significant capital investments. In certain cases, the implementation of Industry 4.0 technologies can cause a subsequent financial shortage resulting in the suspension or discontinuation of the remainder of the programme (Sehnem et al., 2022).

To summarise, there are clear challenges of institution, technology, finance, operations and management that influence Industry 4.0 implementation in the oil and gas industry for CE. By analysing literature that discuss challenges and barriers to Industry 4.0, we find that institution is the most influential factor further divided into governance and regulation, expected goals, competitors and social responsibility initiatives. Although some governments, such as those of China, Saudi Arabia and the United Arab Emirates have issued policies to accelerate the implementation of Industry 4.0, the lack of guidance, regulation and strategic planning, pressure from competitors and requirements from society still impede the process (Zhou et al., 2020; Dua, 2025). The requirements for the deployment of Industry 4.0 in the oil and gas industry must be taken into consideration and addressed to embrace CE as the future growth strategy. Stated differently, future efforts to address the challenges must consider the above factors.

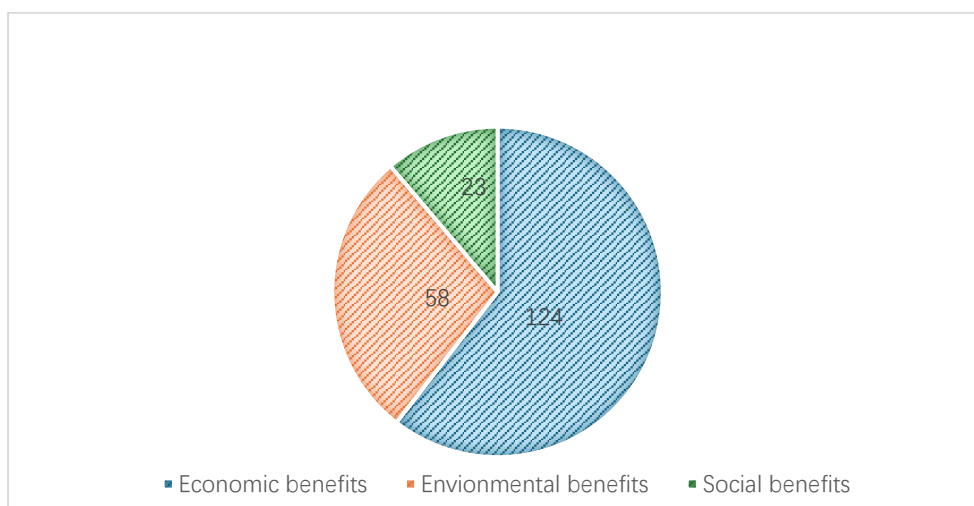
2.4.4 Benefits to the oil and gas industry from Industry 4.0 technology implementation for circular economy

As discussed above, between 2017 to 2024, the number of publications on Industry 4.0 technologies applied to achieve CE in the oil and gas industry grew consistently. This reflects an increasing interest in the subject. Figure 2.9(a) presents the distribution of the benefits of Industry 4.0 in relation to CE in this sector. The economic benefits of Industry 4.0 technologies were the most frequently discussed followed by environmental and social benefits. Figures 2.9(b), (c) and (d) list the six economic benefits that Industry 4.0 can provide for the oil and gas industry, along with six environmental benefits and five social benefits among the papers reviewed.

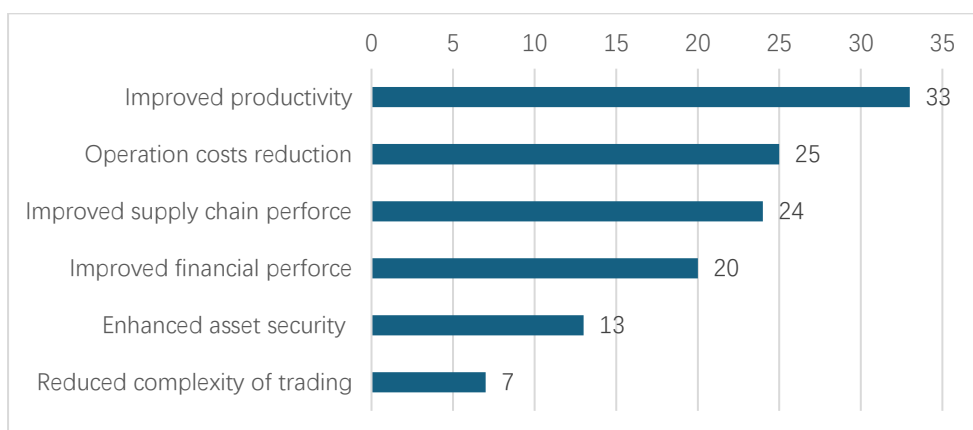
55% of the included papers (33 papers) emphasise the improvement of productivity. Also, much attention has been paid to operational cost reduction (25 papers), and improved supply chain performance (24 papers). This is followed by studies on financial performance (20 papers) and enhanced asset security (13 papers). Therefore, improved productivity, operational cost reduction and improved supply chain performance are the most prevailing advantages that Industry 4.0 technologies offer for the oil and gas industry.

Industry 4.0 technologies also contribute to the environmental and social dimensions of CE. As shown in Figure 2.9(c), it is expected that environmental

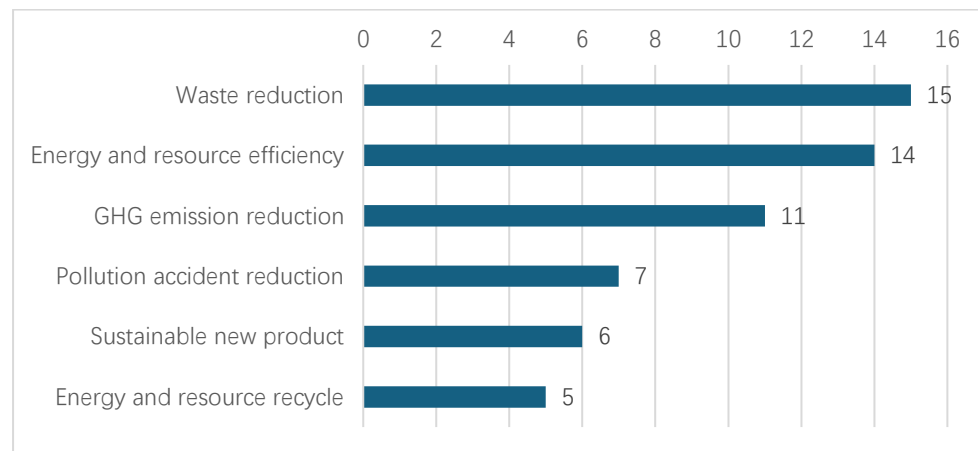
aspects such as waste reduction (15 papers), energy and resource efficiency (14 papers) and GHG (Greenhouse gas) emission reduction (11 papers) result from Industry 4.0 technologies. As seen in Figure 2.9(d), one-sixth of the included papers (9 papers) highlighted that employment opportunities are an important benefit among other social contributions of Industry 4.0 technologies. Besides, 10% (6 papers), 6.7% (4 papers), 5% (3 papers) and 4% (1 paper) mentioned benefits such as enhanced social responsibility, enhanced working conditions of labour, enhanced welfare and reduced cost for customers respectively.



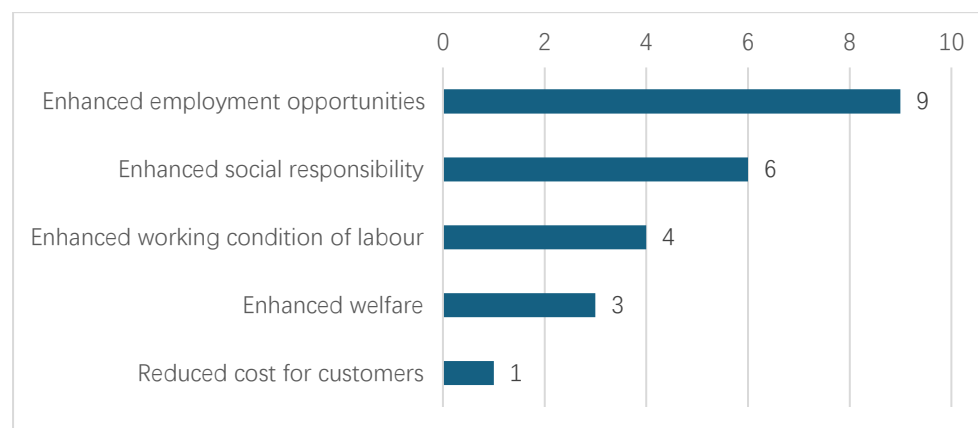
(a) Distribution of studies examining the benefits of Industry 4.0 in relation to CE in the oil and gas industry



(b) Economic benefits of applying Industry 4.0 for CE in the oil and gas industry



(c) Environmental benefits of applying Industry 4.0 for CE in the oil and gas industry



(d) Social benefits of applying Industry 4.0 for CE in the oil and gas industry

Figure 2.9: Benefits of Industry 4.0 in relation to CE in the oil and gas industry from included literature

To establish a better insight into the benefits of Industry 4.0 in the oil and gas industry, these benefits categorised according to three dimensions, namely economic, environmental and social benefits. Drawing on the results presented

in this section, we conclude that even though the application of Industry 4.0 for CE goals in the oil and gas sector is still emerging, these technological advancements contributed to sustainable development by increasing employment opportunities, reducing waste, and improving productivity. Besides, among all three different perspectives, economic benefits have drawn the most attention of researchers, while fewer studies have focused on the social perspective. As an effective implementation of CE needs to cover all three aspects, it is necessary to expand and enrich scholarly work by addressing all three dimensions in CE oriented

2.5 Directions for future research

The SLR conducted in this study on Industry 4.0 applications in the oil and gas industry provides an unambiguous map of the current literature. The existing literature gaps are identified and recorded. Building on the structured analysis above, four main research priorities are presented for further research. These are – i) Management and operations, ii) Technology upgrade and integration, iii) Failure factors of the CE (or factors that offset CE objectives) and iv) Social contributions. A summary of the future directions is proposed in Table 2.7.

First, studies have examined the potential effects of Industry 4.0 technology management on promoting CE in oil and gas sector. Kumar and Barua (2022)

have investigated disruptive technologies' role in sustainable supply chain management; and the various sustainability dimensions where disruptive technologies can play a vital role, such as GHGs, safety, technical standards etc. However, their study considers only 15 sustainable factors, whereas several other factors such as socio-political instability and natural disaster can also be considered. Likewise, Montanus (2016) stressed the meaning of new business models based on Industry 4.0 technologies. He pointed out that new business models that bring people, systems and partners across the extended value chains adapt fast to changes in technology and propel growth and investment decision-making while minimizing cost and risk. These are required for the successful implementation of Industry 4.0 in the oil and gas industry.

Second, there are certain technical difficulties with the deployment of Industry 4.0 technologies that need to be examined. Nguyen et al. (2020), for example, highlighted that governments have been aware of data privacy concerns while implementing big data analytics. There are still regulatory gaps across countries that make it challenging to manage cross-border data, despite significant attempts to create and update legal systems for improved privacy protection for Industry 4.0. Moreover, Georgiou et al. (2021) noted that while there are few pertinent research studies, the deployment of machine learning approaches focused on the automated classification of job opportunities and skillsets to identify job requirements for different sector in the oil and gas industries and improve human resource management efficiency is still lacking. Further research

on technical issues to solve practical problems in production and operations in the oil and gas field is required.

Third, prior research has focused mostly on the environmental and economic benefits of Industry 4.0 technologies in the oil and gas sector. The oil and gas industry's social aspects may undergo changes as a result of Industry 4.0 technologies. Sharma et al. (2023) emphasised the significance of paying attention to social factors. Although some decision makers or managers have an interest in the social impacts of CE, however, due to the complicated roots of social issues, this aspect has lacked attention and further exploration. As a proper understanding of CE is essential to lead organizations in implementing circularity, greater emphasis must be devoted to the research of social benefits.

Fourth, the deployment of technologies to promote CE does not guarantee success. Potential causes of failure include unalignment between digital solutions and user needs, process interruption lead by insufficient funds and inadequate stakeholder engagement. Industry 4.0 requires that the failure causes for the circular economy be given the necessary attention. Massaro et al. (2021) reviewed practitioner documents and pointed out that the improvement of product value and the successful implementation of CE require the active engagement of customers and other stakeholders. The participation of multiple stakeholders ranging from firms, government, customers and society demonstrates a critical strategic element. Consequently, it is important for

scholars to investigate the reasons behind the CE's failure such as lack of stakeholder's engagement in Industry 4.0 application in the oil and gas industry.

Table 2.7: Directions for future research

Research priorities	Future directions	Potential research gaps	Sources
Management and operations	The impact of total quality management and supplier relationship management in the oil and gas industry.	A gap exists on the impact of total quality management and supplier relationship management in the oil and gas industry.	Afghah et al., 2023
	The effects of Industry 4.0 on sustainability in different oil and gas sectors	Insufficient and limited dimensions of the oil and gas industry are investigated	Kumar and Barua, 2022
	Evaluate the significance of performance indicators in terms of importance and applicability within the oil and gas industry.	There is no evaluation about how performance indicators align with the concept of Industry 4.0.	Olugu et al., 2022
Technology upgrade and integration	Evaluate the possibility of integrating Big data with other advanced technologies within a unified environment.	Issues on how to tackle the data privacy that occurs when deploying Big data in the oil and gas industry.	Nguyen et al., 2020
	Deployment of machine learning approaches in the oil and gas industry.	Few studies on the automated categorization of job openings and extraction of skills under the special needs of the oil and gas industry.	Georgiou et al., 2021

	Identify specific threats to the designated institution to understand the impacts of different physical security threats better.	The company's particular threats fail to be clarified due to limited data.	AI Zaabi and Zamri, 2022
Social contributions	Further research on social benefits from the implementation of CE	Society also benefits from CE practice. More attention is required on social benefits.	Sharma et al., 2023
Failure factors of the CE	The offset effect on positive outcomes and the expected energy efficiency promised by Industry 4.0 from the perspective of consumer behaviour.	The return on investment on the use of novel technologies is the subject of very few studies. The resources required to implement new energy-saving technologies may equal or even exceed those that should be conserved as a result of shifting consumer and market trends.	Ghobakhloo and Fathi, 2021

We present an integrated framework drawing a linkage between the research questions, gaps and findings in Figure 2.10. Analysis of the development of publications in this area over the previous seven years shows that interest in this field has increased. Additionally, the analysis showed that multiple technologies have been applied to the oil and gas industry. Specifically, IoT, AI and big data emerged as the most widely used technologies having the largest contributions to the industry. However, challenges of institution, operation and management, technology and finance exist and influence the implementation of Industry 4.0 for CE. Despite the challenges, CE remains an effective approach to deal with critical sustainable development issues in the oil and gas industry. Furthermore,

the analysis of the impact and benefits shows that the economy, environment and society benefit through the CE process in oil and gas industry. While the industry has benefitted from the implementation of Industry 4.0 in different dimensions, the focus has been on economic aspects while the social aspects lack attention. Lastly, based on the findings, key themes for future research are quality management, technological integration and social contributions.

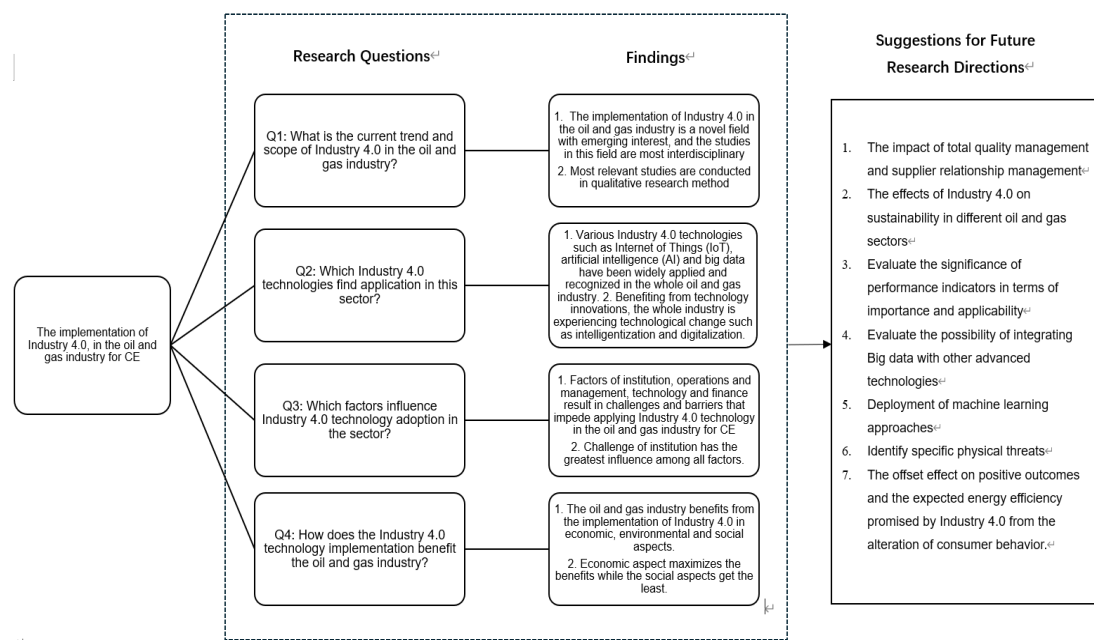


Figure 2.10: Framework summarising the findings.

2.6 Conclusion

Industry 4.0 technologies applied in the oil and gas industry have been increasingly discussed in the literature in the past few years. The present SLR identifies a pool of 60 eligible papers and proceeds with a descriptive and in-

depth assessment of the topic related to Industry 4.0 technologies applied in the oil and gas industry. The study conducts a descriptive analysis of extant scholarly research and presents the findings to the four research questions. The articles are selected following a structured approach that includes keywords, publication year, titles, abstract and detailed content analysis. Two key concepts of circular economy and Industry 4.0 are explained followed by an illustration of the oil and gas supply chain. The study explains how Industry 4.0 technologies like artificial intelligence and the Internet of Things are applied in this sector; and categorises the features and definitions of Industry 4.0 technologies. Additionally, the challenges that affect Industry 4.0 technologies' impact in the oil and gas sector are described, contending that the primary obstacle is associated with institutions, operations, and management. The study also offers an overview of how Industry 4.0 technology adoption has benefited the oil and gas sector recently. Finally, several research directions are presented and highlighted based on the research gap analysis. Researchers and practitioners interested in incorporating CE in the oil and gas industry should consider looking into these open-ended concerns when Industry 4.0 is put into practice. All things considered, it is expected that this study will have insights for scholars and oil and gas industry decision-makers, helping them realise the benefits of Industry 4.0 technologies for the economy, environment, and society.

2.6.1 Limitations

This research work has certain limitations. While two global databases Scopus and Web of Science are used to collect and analyse papers, some additional articles may have been missed if they were included in any other database not limited to the two considered in this study. Similarly, the exclusion of grey literature and technical papers may lead to the relevant research. Other limitations are concerning the exclusion of conference papers and books from the initial source pool as these could also be good sources of contemporary research work in this field. Also, the search strings do not include terms such as ‘closed loop economy’ or ‘reverse supply chain’, which could cover additional relevant studies. However, the generalizability and findings of the study would likely not change. There remains a scope, therefore, of strengthening the present work from additional analysis.

Chapter 3

How Industry 4.0 Technologies Drive Corporate Social Responsibility: The Dual Role of Circular Economy Practices

3.1 Introduction

The Fourth Industrial Revolution (Industry 4.0) that is characterised by advanced technologies such as artificial intelligence (AI), robotics, cyber systems, additive manufacturing, the Internet of Things (IoT) and Big Data, has rebuilt business operations by enhancing efficiency and enabling sustainable development (Xu et al., 2018; Klingenberg et al., 2022). These technological changes have influenced business operations, promising higher efficiency and productivity, and providing new approaches for sustainable development (de Sousa Jabbour et al., 2018; Koh et al., 2019). Accordingly, the role of Industry 4.0 technologies in driving sustainable development has gained the sustained attention of scholars and practitioners (Liao et al., 2017). In particular, Industry 4.0 technologies can optimise resource utilisation and improve efficiency while reducing negative environmental impacts, which makes them a critical enabler of corporate sustainable development, especially in industrial sectors associated with high

waste and resource consumption (Stock et al., 2018; Bag et al., 2021). Some studies in this context argue that technological innovation is not optional for lasting sustainable rewards (Boons et al., 2013; Kalkanci et al., 2019; Xiao and Su, 2022).

While Industry 4.0 technologies hold promise, they must be complemented by broader approaches such as the circular economy (CE) to effectively tackle multifaceted sustainability changes as research indicates that Industry 4.0 technologies are not the only measures that organisations adopt to promote sustainable economic, environmental, and social contributions. The key to tackling these issues lies in CE principles that address air and water pollution, forest and biodiversity loss (Esposito et al., 2017; Paleari, 2024), or social issues such as customer protection rights, high unemployment, and poor education (Sarkar and Pingle, 2018; Luthin et al., 2023), in addition to economic concerns such as high costs and resource waste (Lieder and Rashid, 2016; Perey et al., 2018). While the CE has gained substantial traction in addressing environmental pollution, resource waste, and social issues, its potential connection with Industry 4.0 still remains unidentified in the energy sector where technological and social requirements are most closely tied.

From the perspective of the resource-based view (RBV) theory, corporates' can maintain competitive advantage in the market by accumulating unique rare resources and capabilities that are valuable and difficult to imitate (Wernerfelt,

1984; Barney, 1991). By adopting circular economy practices (CEP), firms can transit from a traditional linear economic to a circular economic mode, thereby gaining strong sustainable competitive advantage (Farooque et al., 2022). As a supplement to CEP, CSR is the practical step for achieving sustainable development in firms, which results in a favourable reputation when achieving positive social performance (Lii and Lee, 2012; Tetrault Sirsly and Lvina, 2019; Sardana et al., 2020). Realising that firms have a clear responsibility towards the environment and society, governments increasingly urge firms to undertake relevant measures to reduce pollution and promote social welfare (Voegtlin and Scherer, 2017; Lyon and Maxwell, 2019). Thus, applying CEP to daily operations is not only a method that helps firms to recycle resources and reduce costs, but also a core solution in response to external pressures from government and society (Van Buren et al., 2016; Jain et al., 2020).

As discussed above, the adoption of Industry 4.0 technologies has clear potential to enhance corporate CSR including its social and environmental sustainability facets (Bocken et al., 2016). From the RBV theory perspective, the adoption of Industry 4.0 technologies, CEP, and CSR can be jointly utilised as a bundle of competitiveness that is hard to imitate. However, the oil and gas industry that accounts for roughly 42% of total global industrial carbon emissions invests only 15% of its budget to directly target CSR goals (IPCC, 2023). Furthermore, controversies around CSR in this industry suggest that technological investment may crowd out their essential social investments (Inglesi-Lotz, 2017). The role

of CEP in promoting social sustainability has also been questioned, with some scholars arguing that its social contributions remain ambiguous due to structural barriers in practical implementation (Corvellec et al., 2022; Monciardini et al., 2024). These contradictions expose a critical knowledge gap about how technological advances, CE methods, and CSR fulfilment interact to create competitive advantage.

In summary, to address these knowledge gaps, this study poses two research questions that aim to reveal the interactions among these constructs in a critical sector. *RQ1): How do Industry 4.0 technologies influence corporate social responsibility in the oil and gas industry? RQ2): How do Industry 4.0 technologies and circular economy practices synergistically affect corporate social responsibility?*

To answer these questions, the extant literature was reviewed and a novel model comprising Industry 4.0 technology applications, CEP and CSR was constructed. A questionnaire was delivered to 155 Chinese firms in the oil and gas sector spanning the whole supply chain in the industry. It should be noted that all participating firms are Chinese state-owned, which imposes a specific regulatory environment that may limit the generalisability of the findings to western or privately-owned firms. Following data collection, an empirical analysis was conducted to investigate the relationships among the variables with structural equation modelling (SEM) using SPSS 29.0 and AMOS 29.0. Prior to main study,

preliminary analysis was employed to assess the validity and reliability of the data. Next, the interrelations among the applications of Industry 4.0 technologies, CEP, and CSR were examined.

Within this framework, the direct impacts of the application of Industry 4.0 technologies on CSR and the mediating role of CEP among their relationships were examined. This study yields several key findings contributing to the theoretical field and managerial implications. First, based on the RBV, the novel model extends the relevant literature by revealing the influencing mechanism among the application of Industry 4.0 technologies, CEP, and CSR. It was observed that the application of Industry 4.0 technologies affects CSR positively on most paths. Second, findings revealed that the CEP does not merely function as a mediator in the relationship between Industry 4.0 technology applications and CSR. Resource competition can trigger the suppression effect. Notably, both mediation and suppression can strengthen the positive association between Industry 4.0 technology applications and CSR. Consequently, this study argues that the investment costs for Industry 4.0 applications can hinder CSR enhancement when they compete for limited firm resources with social responsibility budgets. To maximise the positive impact of technological innovation on CSR outcomes, decision makers should strategically balance the direct allocations between technology investments and CSR.

While previous studies have emphasised the economic outcomes of Industry 4.0

technologies, few have empirically connected Industry 4.0 technologies, CEP, and CSR. It is still not fully known how Industry 4.0 applications influence and contribute to firms' CSR and what role the CEP serving as a distinctive resource for enterprises plays in their relationship (Gupta et al., 2021; Govindan, 2022; Matarneh et al., 2024). This study aims to address this research gap. It contributes to the literature by providing a novel perspective that CEP exerts a dual influence instead of merely mediating the relationships among Industry 4.0 applications and CSR. Moreover, the findings of this study also indicate that Industry 4.0 cannot have positive impacts on all aspects of CSR, as the effect of Industry 4.0 is suppressed by CEP occasionally. By explaining the failure of Industry 4.0 applications to promote CSR as well as the factors why CEP may suppress CSR effects, the study provides valuable practical implications on balancing economic, environmental and social performance for decision makers.

The rest of this paper is organised as follows: Section 2 and Section 3 present the theoretical framework and hypotheses respectively. Section 4 describes the research methodology. Section 5 contains the research analysis and results. Section 6 discussed the findings and implications while Section 7 outlines the conclusions of this study.

3.2 Literature and theoretical background

This paper examines how Industry 4.0 technologies influence on CSR and the synergistic effect of CEP in the relationships between Industry 4.0 and CSR. Four streams of literature relevant to the paper are reviewed: namely, the RBV theory, applications of Industry 4.0 technologies in the oil and gas industry, CEP, and CSR. Through the literature review, gaps are identified in the existing research and specific testable research hypotheses are presented in Section 3.

3.2.1 The resource-based view theory

In this study, the RBV theory was adopted as the main theoretical foundation to explain firms' motivations to apply Industry 4.0 technologies and CEP and to pursue the improvement of CSR. It provided a unifying lens to analyse how Industry 4.0 technologies, CEP, and CSR collectively contribute to sustainable competitive advantage. Both advanced technological capabilities and enhanced CSR reputation are considered valuable to bring inimitable competitive advantage. Previous research has applied the RBV theory widely to effectively analyse the strategic influences that internal resources have on performance at the firm level (Chaudhuri et al., 2022; Münch et al., 2022; Osei et al., 2024). The RBV posits that resources which are difficult for competitors to replicate provide unique value and advantage for organisations (Wernerfelt, 1984), and the acquisition of them represents the core of an organisation's sustained competitive advantage (Barney, 1991). These resources can be tangible and

intangible (Hall, 1993); they include the relationship between organisations and customers, brand reputation, methods of manufacturing, management ability, financial assets, information technology, business strategies, human resources, and organisational process such as production, sales, and logistics (Barney, 1991; Teece et al., 1997; Wade and Hulland, 2004; Liang et al., 2010; Taher, 2012; Levallet and Chan, 2016; Mweru and Maina, 2016).

The application of Industry 4.0 technologies is regarded as an important resource in several studies (Liang et al., 2010; Wu and Chiu, 2015; Khanra et al., 2022). Technological innovation and upgradation can provide reliable competitive advantage, thereby improving firms' strategic capabilities (Liu et al., 2009; Herrera and de las Heras-Rosas, 2020). The CE can create value for firms by reducing the consumption of materials and energy. Transforming corporations from traditional business modes to CE modes can deliver competitive advantage owing to the circular flows of resources (de Sousa Jabbour et al., 2018; Chaudhuri et al., 2022).

Apart from Industry 4.0 technologies, previous research argues that CSR also serves as a significant driver for firms to achieve sustainable competitive advantage (Govindan, 2022). According to Branco and Rodrigues (2006), the reason why firms engage in CSR activities and disclosure is that firms believe this can create competitive advantage for them. For instance, CSR can motivate employees effectively by providing fair wages, training opportunities, and

flexible work hours. This maintains the loyalty of employees, reduces turnover and recruitment costs, and fosters employees' positive attitudes. In other words, CSR has the ability to develop human resources. It also builds a reputation-based intangible resource. In short, under Industry 4.0, both adopting CEP and CSR can provide competitive advantage, and firms are driven to pursue these unique resources. The RBV theory therefore offers a suitable theoretical foundation for this study.

From the above literature review, it can be observed that the application of Industry 4.0 technologies, CE, and CSR contributes to the firms' sustainable competitive advantage. Some studies investigated the bilateral relationships between two of these three constructs, while few studies examined the integrative effects of them collectively—particularly how Industry 4.0 and CEP synergistically impact on CSR. Thus, this study aims to address such a literature gap. While the RBV theory establishes the theoretical foundation, the following sections explore how Industry 4.0 technologies (Section 2.2) operationalise these resources, enabling CEP (Section 2.3) and CSR (Section 2.4).

3.2.2 Industry 4.0 applications in the oil and gas industry

Industry 4.0 refers to the fourth industrial revolution related to technologies such as the IoT, Big Data analytics, AI, and robotics to build communications between

people and machine, and resources through smart factories (Lasi et al., 2014; Hermann et al., 2016). These technologies have diverse applications across the entire oil and gas chain (Lu et al., 2019). As a core tangible resource under the RBV framework, Industry 4.0 technologies are specifically applied to production, storage, transportation, and operational management throughout the entire supply chain in the oil and gas industry. For instance, although still early in implementation, digital twins have shown promise in asset monitoring and lifecycle management, which is crucial for optimising operations in the oil and gas industry (Wanasinghe et al., 2020). Machine learning and AI are emerging as vital tools for data processing and decision making, further driving efficiency (Sircar et al., 2021). Big Data analytics have been effective in transforming decision-making processes, reducing downtime, and enhancing profitability (Eissa, 2020). IoT implementation helps reduce carbon emissions and improve safety and efficiency in the production processes (Khan et al., 2017). Additionally, the integration of human factors and ergonomics with Industry 4.0 technologies has proven crucial for improving safety and productivity in high-risk environments (Longo et al., 2021).

Despite these advancements, the industry still faces challenges in applying Industry 4.0 technologies due to a lack of established technology architecture, insufficient funds, talent shortages, and gaps in tailored maturity models, standardisation, cybersecurity work, and workforce readiness (Lu et al., 2019; Elijah et al., 2021; Onyeme and Liyanage, 2023). Thus, although the potential of

Industry 4.0 technologies is high, significant integration work is still needed to fully harness its benefits across all aspects of the industry to gain sustainable competitive advantage. To address this gap, this study proposes a novel perspective on the joint effects of the application of Industry 4.0 technologies, CE, and CSR, and seeks to explore supplementary methods by positioning CEP as a mediating mechanism.

3.2.3 Circular economy practices

The circular economy is defined as an industrial economy that is restorative and regenerative by design and aims to keep products, components, and materials at their highest utility and value, distinguishing between technical and biological cycles (Ellen MacArthur Foundation, 2015). Positioned within the perspective of the RBV, CEP function as dynamic capabilities that transform Industry 4.0 technological resources to sustainable outcomes. It represents an attempt to integrate economic activity and environmental well-being in a sustainable way (Murray et al., 2017). Although the principles and practices are still developing, CE has gained significant attention in recent years as an alternative to the traditional linear economic model (Farooque et al., 2022). The focus on preserving resources through recycling, reuse, and reducing waste has led to the development of various indicators and frameworks aimed at measuring and promoting circularity (García-Barragán et al., 2019; Moraga et al., 2019).

Industry 4.0 provides a platform with technological support for economic transformation, while the CE, as a new business model and firm strategy, drives firms to pursue sustainability and gain greater competitive advantage (Khan et al., 2025). Nevertheless, the practical implementation of CE remains uneven due to some management barriers and market fluctuations. Previous studies highlighted the gradual shift from linear to circular model, especially in small and medium-sized enterprises in Europe, where administrative and regulatory barriers often impede progress (Garcés-Ayerbe et al., 2019). In addition, barriers remain in defining and standardising these indicators, particularly at the micro-level, where a lack of integration and holistic frameworks impede effective measurement (Saidani et al., 2019; Kristensen and Mosgaard, 2020). In some cases, the adoption of the CE can be counterproductive. Production and consumption efficiency gains from achievements in manufacturing technologies can offset environmental benefits, necessitating further action in managing circular initiatives (Zink and Geyer, 2017).

In the energy sector, previous studies have explored the connections between CE and the industry practices (Candelise and Ruggieri, 2020; Janik et al., 2020; Sharma et al., 2023; Simpa et al., 2024). Despite some large firms having applied CEP to their businesses for sustainable competitive advantage, the implementation of CEP remains challenging in the oil and gas sector (Jain et al., 2020). These constraints include energy-saving technologies, clear strategies, and

supportive laws (Al Hosni et al., 2020; Dua and Jain, 2024). While the CE framework has been embraced globally, to achieve true environmental and social benefits, CE requires improved integration with sustainability principles. (Murray et al., 2017; Rossi et al., 2020). The ongoing development of relevant indicators continues to play a vital role in advancing the CE. However, there is a pressing need for more coherent and widely accepted practices to ensure that these efforts translate into tangible sustainability outcomes (Saidani et al., 2019).

In practice, CEP primarily support corporates to fulfil their social responsibilities through a dual pathway: production cost reduction via closed-loop material circulation, and sustainable social value creation via regenerative resource utilisation. Specific practices such as getting commitment and support from management level, providing essential training for workers for CE, establishing environmental programs, recycle or sale of excess capital and equipment, and produce eco-friendly products have been widely implemented across a broad range of organisations (Zhu et al., 2010). In the oil and gas industry, these practices have been integrated in multiple domains including upstream for exploration and production, midstream for storage and transportation, downstream for refining, chemical and sales, and other sectors such as security, accounting, research and human resource management (Ghorbanpur and Hosseinpoor, 2021; Ekunke et al., 2024).

3.2.4 Corporate social responsibility

CSR has gained extensive attention since its first introduction (Govindan, 2022). It refers to the voluntary behaviours taken by organisations to improve their environmental and social performance with broader objectives that extend beyond only profit (Carroll, 1999). Jones (1980) pointed out that, in addition to the responsibility to shareholders, organisations should also assume responsibilities to external stakeholders such as their employees, consumers, suppliers, communities, and wider society. In other words, CSR includes both social ethics and the needs of groups inside and outside the industries. This is also represented in the pyramid model of CSR consisting of four levels of responsibilities: economic, legal, ethical, and philanthropic (Carroll, 1991).

Based on the RBV theory, CSR is recognised as an intangible asset that contributes to corporate sustainable competitive advantage. It can enhance firms' reputation, improve employee engagement, and increase stakeholder trust, which are path-dependent and socially complex factors, making them difficult for competitors to replicate (Branco and Rodrigues, 2006; Quintana-García et al., 2022). Scholars posit that organisations should also focus on environmental protection, fair labour, charity, and community development (Masum et al., 2020). The implementation of Industry 4.0 technologies provides modern firms with the tools to enhance their CSR efforts by improving operational transparency, supply chain efficiency, and sustainable production practices (Fatorachian and Kazemi, 2021; Matarneh et al., 2024). This can be observed

from a number of practical uses, such as sourcing of materials based on blockchain (Liu et al., 2020), increasing resource efficiency with the support of AI (Jan et al., 2023), and improvement of workplace safety using robotics (Júnior et al., 2021). An increasing number of businesses are also relying on the acknowledgement of CSR to manage their relationships with stakeholders to pursue their long-term goals (Wang and Bansal, 2012; Ortiz-de-Mandojana and Bansal, 2016). By conducting a study on 149 manufacturing firms in Canada, Wang and Bansal (2012) identified that firms who engaged in CSR are more attractive to stakeholders with sense of social responsibility. Thus, these firms are able to reduce or avoid negative impacts of unforeseen events by utilising moral capitals they have accumulated and secure their long-term development. Aligning Industry 4.0 technological resources and CEP towards social and environmental goals can therefore strengthen CSR performance. In addition to the direct social contributions led by technology innovations, sustainable social results can also be indirectly achieved through the implementation of CEP. As mentioned above, CEP can work as a transformation mechanism that allows firms to circulate resources and reduce waste. Thus, CSR when regarded as a reputation resource, relies not only on Industry 4.0 technologies but also on the resource transformation functions performed by CEP.

From the preceding review, Industry 4.0 technology applications, CEP, and CSR are acknowledged as important interlinked driving forces for firms' sustainable competitive advantage. Extant studies have highlighted the significance of them

working in pairs. However, few have examined the interrelationships among the application of Industry 4.0 technologies, CE, and CSR as an integrated framework. Meanwhile, firms are still facing barriers in the effective implementation of Industry 4.0 technologies and the improvement of their CSR. This study aims to fill these gaps by analysing the impacts of the three constructs on each other.

3.3 Hypothesis Development

3.3.1 The application of Industry 4.0 technologies and corporate social responsibility

To achieve CSR using CE approaches, technological innovation, organisational change, and effective innovation management are required (Zwetsloot, 2003; Khan et al., 2020; Rodríguez-Espíndola et al., 2022). The deployment of technology cannot be separated from the financial and human resources support (Collins and Smith, 2006; Erzurumlu and Erzurumlu, 2013; Sony and Naik, 2020). In other words, when investigating the application of technologies, staff abilities, financial capital and technological capability should be treated as an integrated system. The three aspects complement each other and contribute to achieving the successful application of Industry 4.0 technologies.

Accordingly, the application of Industry 4.0 can be categorised into three aspects.

The first is technology management (TM), which focuses on technologies selection, deployment, governance, and upgrade. The second is finance and risk management (FRM), which relates to the funding of Industry 4.0 technologies and risk control. The third aspect is human resource management (HRM), which covers the recruitment, training, and welfare of human resources during Industry 4.0 technological implementation (Karmaker et al., 2023). Likewise, regarding the diversity of stakeholders affected by CSR, CSR can be conceptualised into four dimensions (Turker, 2009). The first is CSR to social and non-social stakeholders (CSRS), including society, natural environment, future generations and non-governmental organisations. The second is CSR to employees (CSRE), such as good working conditions, reasonable compensation standards, and education opportunities. The third is CSR to customers (CSRC), aiming to build and maintain good relationships and meet their needs. The fourth is CSR to government (CSRG), which refers to paying taxes regularly and complying with the legal regulations completely. Subsequently, the connections between Industry 4.0 technology applications and CSR are explored based on the extant literature, thereby informing the hypotheses of this research.

3.3.1.1 Technology management and corporate social responsibility

Industry 4.0 includes a broad set of emerging technologies such as AI, blockchain, robotics, IoT, augmented reality, and Big Data analytics (Bai et al.,

2020). Integrating these Industry 4.0 technologies into business strategies can create increasing commercial profits whilst contributing to society for firms (Sanchez, 2019). It allows firms to improve their resource utilisation rate, reduce waste, enhance employees' welfare and workplace safety, and support education, which are important manifestations of CSR (Ghobakhloo, 2020; Javaid et al., 2022).

More specifically, IoT is vital in providing real-time data and monitoring for resource usage, with the contribution to the optimisation of resource and waste reduction improving the CSR performance of social and non-social stakeholders (Maksimovic, 2017). Machine learning and blockchain enable supply chain prediction and resilience, improving social performance and transparency (Qader et al., 2022; de Oliveira et al., 2023). Moreover, through AI applied in the production processes, firms can make more informed decisions that shoulder the social responsibilities targeted to pollution reduction while maintaining profitability (Al-Surmi et al., 2022; Akhtar et al., 2024). Further, the generation and use of the CSR reports inevitably requires the support of data systems (Bai et al., 2015).

Beyond the contributions to societal and environmental dimensions, the implementation of novel technologies can also significantly enhance employees' welfare, including more efficient communication (Day et al., 2010) and increased workplace safety (Horton et al., 2018). Moreover, as firms' success

depends to a significant extent on customers, they manage to establish and maintain positive relations with customers (Turker, 2009). Enhanced technological readiness and updated products improve customer experience, while efficiency obtained by technological innovations reduce customer costs (Chuang and Huang, 2018; Kazemi et al., 2023). Innovative technologies can influence customers' feelings and thoughts with firms, thereby influencing their purchasing behaviours, which finally results in increased economic benefits and improved reputation. In addition, by embracing these technologies, firms can not only improve their economic performance but also align their business strategies with broader social and environmental purposes to meet the requirements of government and legal regulations (Crittenden et al., 2011; Epstein, 2018). However, some studies highlight potential challenges, such as the deployment of new technologies may initially disrupt current working process and increase operational costs (Choi et al., 2022). Moreover, technological failures could harm the expectations from such implementations, which may result in employee stress and frustration, and public disappointment (Kadir and Broberg, 2020; Ito et al., 2021). In other words, successful implementation of Industry 4.0 technologies for CSR goals may have some challenges or conditions. Overall, Industry 4.0 technologies are considered the primary drivers to realise transformation and CSR and obtain sustainability (Jabbour et al., 2020; Awan et al., 2021; Govindan, 2022). From the preceding discussion, it can be hypothesised that:

H1: Technology management positively relates to the corporate social responsibility to social and non-social stakeholders (a); corporate social responsibility to employees (b); corporate social responsibility to customers (c); and corporate social responsibility to government (d).

3.3.1.2 Finance and risk management and corporate social responsibility

Corporates take economic costs to realise CSR especially in the context of the application of Industry 4.0 technologies, making the management of funds and potential risks crucial. Scholars have observed that sufficient financial support and effective risk management contribute to implementing the social goals (Scholtens, 2006; Kim et al., 2021; Benito-Hernández et al., 2023).

For instance, firms use green bonds to raise capital for their sustainable projects, which is more common in energy, transportation, and utilities industries (Flammer, 2021; Bhutta et al., 2022). Effective financial and risk management enable firms to reconcile the diverse expectations of multiple stakeholders. First, firms can allocate resources towards social and environmental contributions such as funding support for non-government organisations that engage in environmental protection programmes through financial planning (Dahan et al., 2018; Li et al., 2018). Moreover, as part of internal controls, cost and budget

management drives firms to invest more resources into employees' welfare systems including health and compensation, which can be reflected in financial reports in the form of improved performance (Guo et al., 2016). Some empirical studies also suggest that firms characterised by strong financial management are able to increase the level of employee satisfaction, physical and mental conditions, and employees' trust in leadership (Rosid et al., 2024). Proper financial leverage ensures the firm's cash flexibility and reduces marketing costs, thereby improving customers' experience and satisfaction (Malshe and Agarwal, 2015). Furthermore, financial and risk management such as support by accounting and legal professionals and appropriate firm donations can help them to maintain their legitimacy and reinforce their public image (Martínez et al., 2018; Jeong and Kim, 2019).

Nevertheless, some studies caution that during the process of financial support, the misallocation of investments such as the improper resource distribution due to the competition of various stakeholders' demands may hinder CSR performance (Liu and Tian, 2021; D'Souza et al., 2022). Similar challenges may arise in risk management. Conservative risk control can constrain innovation in CSR initiatives, while excessive risk aversion may reduce resource distribution to CSR (Mithani, 2017). To maintain sufficient and effective financial and risk management for organizations represents a challenge. Thus, by evaluating internal corporate conditions, the external environment, and the impact from government and society, decision makers can manage funds in a way that is

consistent with their goals and company's values (Scholtens, 2006). With sufficient financial support and CSR integrated into the overall business strategy, firms can effectively reduce environmental impact and contribute positively to society. Accordingly, the following hypothesis is formulated and examined in this study:

H2: Finance and risk management positively relates to the corporate social responsibility to social and non-social stakeholders (a); corporate social responsibility to employees (b); corporate social responsibility to customers (c); and corporate social responsibility to government (d).

3.3.1.3 Human resource management and corporate social responsibility

Industry 4.0 enables rapid technological development across all sectors in the oil and gas industry. Firms that want to adapt to this trend must place considerable value on talent recruitment and training (Whysall et al., 2019). Human resources can contribute to the implementation of CSR and improve organisational sustainability, allowing firms to acquire sustainable competitive advantage (Scavarda et al., 2019). In the era of Industry 4.0, organisations respond to sustainable social requirements of their stakeholders through CSR, and human

resource management is the key to facilitating this process (Herrera and de las Heras-Rosas, 2020).

Specifically, strategic HRM initiatives such as hiring employees who have high awareness of environmental sustainability development can significantly improve firms' environmental performance, since such employees tend to show stronger interest and willingness to engage in the training and practices towards environmental protection provided by firms (Guerci et al., 2016). Furthermore, it makes the collaboration between the firms and non-government organisations easier with the support of such a group of employees committed to environmental sustainability (Kusi et al., 2021; Lin et al., 2024). Advanced technologies result in significant redefinition in employee recruitment, education, and skills development by increasing the innovation capacity of human resource systems, enhancing competence and opportunities for their future careers (Rana and Sharma, 2019; Sharma et al., 2022). Firms can also enhance employees' CSR performance through the implementation of green skills to cultivate a culture of sustainability and safety. However, not all the studies entirely support the outcomings of training projects. Intensive training related to sustainability or recruitment for highly skilled employees may lead to high costs or alter current work procedures, and only a few employees would not emphasise the contribution of Industry 4.0 technologies to their firm performance (Brozzi et al., 2020). Emotions of stress, fear and frustration of employees may occur due to new skills learning, and this can limit the effectiveness of CSR from HRM

initiatives (Kadir and Broberg, 2020; Para-González et al., 2026).

Apart from the benefits for society and employees, human resource management in the implementation of Industry 4.0 technologies contributes to customers and governments as well. Research has shown that improving human resource management during the implementation of technologies can enhance work efficiency and strengthen communications capabilities with customers, thus improving service quality and satisfaction (Wikhamn, 2019). Furthermore, the design of new products relies on the recruitment and development of talents, and these products can also increase customer satisfaction by meeting various customers' needs (Hafeez and Aburawi, 2013; Zhang and Chen, 2024). With the integration of digital technologies applied in human resource management, it enables firms to align with the digital governance overseen by government and rigorous environmental regulations (He et al., 2021; Zhang and Chen, 2024). In conclusion, it is essential to gain sufficient support through human resource management to realise CSR in organisations. Therefore, the following hypothesis posits:

H3: Human resource management positively relates to the corporate social responsibility to social and non-social stakeholders(a); corporate social responsibility to employees (b); corporate social responsibility to customers (c); and corporate social responsibility to government (d).

3.3.2 The mediating effect of circular economy practices on the relationship between Industry 4.0 technological application and corporate social responsibility

The relationship between Industry 4.0 and CE is increasingly recognised as synergistic, with studies highlighting their mutual benefits. As discussed above, as a dynamic capability, CEP facilitates the conversion of Industry 4.0 technologies into circular process which significantly strengthen CSR performance that materialises as competitive advantage in enhanced corporate reputation and greater stakeholders' trust. The purpose of CE is to achieve sustainability by using cyclical material flows and renewable resources (Korhonen et al., 2018). Through the application of Industry 4.0 technologies, firms can maximise their benefits from CEP and achieve sustainability (Rajput and Singh, 2020).

Extant studies have illustrated the relationship between Industry 4.0 technologies and CE. For instance, Industry 4.0 technologies such as the IoT and AI are crucial in enhancing the traceability of resources, enabling more efficient recycling and waste reduction processes (Pham et al., 2019; Rosa et al., 2019). Nascimento et al. (2019) and Pasco et al. (2022) suggested additive manufacturing as a key technology in reducing resource waste and enhancing business sustainability. Similarly, the application of Big Data analytics helps firms to enhance their circular economy capabilities (Bag and Pretorius, 2020). The application of

robotics can reduce the hazards of exploration and inspection (Yu et al., 2019). Digital integration allows firms to monitor their sustainability performance and undertake decisions that align with CE principles (Bag et al., 2022). Researchers organised the connections between Industry 4.0 technologies and CE approaches, underscoring the importance of coupling them with broader sustainability objectives. Hence, sustainability can be achieved through the integration of Industry 4.0 technologies and CE (Rajput and Singh, 2019).

The implementation of technology also requires sufficient funds (Owen and Demb, 2004). Although some capital must be invested in the research and development, upgradation, and deployment of Industry 4.0 technologies, the adoption of these technologies can lead to significant improvements in sustainability performance. This suggests that, while the initial investment may be high, the long-term benefits of adopting these technologies can outweigh the costs (Gupta et al., 2021). With the support of adequate financial resources, adopting Industry 4.0 technologies can enhance operational and financial performance, thus supporting the CE goals (García-Quevedo et al., 2020). Insufficient funds hinder the implementation of Industry 4.0 technologies, while adequate funds provide opportunities to enhance CE (Kumar et al., 2021; De La Cuesta-Gonzalez and Morales-García, 2022). As digital transition can be risky, a reliable risk management system can be highly beneficial for implementing Industry 4.0 technologies (Tupa et al., 2017). An effective risk management system can assist firms in identifying financial risks and undertaking decisions

to deal with potential crises. Thus, financial support and risk management are critical for applying Industry 4.0 technologies for the CE.

Transition from a linear to a circular economy is a gradual process, and this process cannot proceed without the commitment and support from top management (Bag and Pretorius, 2022) as well as skilled employees (Kumar et al., 2021). Although the benefits of integrating Industry 4.0 with CE practices are widely recognised, studies have highlighted the challenges from human resource management aspects associated with this integration. These challenges are particularly pronounced in some companies which may lack the resources and expertise required to implement Industry 4.0 technologies (Müller et al., 2018). Due to the lack of a skilled workforce in Industry 4.0, firms fail to achieve sustainability with new technologies and transit to CE (Kumar et al., 2021). Rajput and Singh (2019) highlighted that skilled labour is crucial for the application of Industry 4.0.

Based on Zhu et al. (2010), CEP can be categorised as subgroups including internal environment management, eco-design, and investment recovery. Internal environment management refers to a series of management methods within organisations, such as commitment from senior managers, support from mid-level managers, cross-functional cooperation for environmental improvements, training for employees related to environmental issues, ISO 14000 certification, pollution prevention programs, and internal environmental

reports. Eco-design includes the design of products for reduced costs of materials or energy, reuse, recycle, recovery of material, reducing or avoiding use of hazardous of products, and processes for minimization of waste. Investment recovery describes the recycle approaches including recycle or sale of scrap and used materials, sale of excess capital equipment, and build a recycling system.

As a dynamic capability, CEP can enable firms to transform their technology resources into sustainable practices, resulting in positive impacts across multiple dimensions of CSR. Specifically, through effective technology management, CEP facilitates resource circulation and process optimisation to promote community and environmental well-being, enhance employee working conditions and welfare, improve the sustainability of products to meet customer needs, and strengthen regulatory compliance and collaboration with government. These results can be supported by the practices such as cross-functional cooperation for environmental improvements, the design of products for reduced costs of materials or energy, reducing or avoiding use of hazardous of products, and recycle or sale of scrap and used materials. In terms of financial and risk management, CEP allows firms to transform capital investment and risks into sustainable approaches via practices such as pollution prevention programs and reuse, recycle, recovery of material. Regarding human resource management, the practices of internal environment management such as training for employees contribute to employee skills, the improvement of training and safety management, and sustainable working environment, which enhances employee

satisfaction, customer trust and firm reputation. However, the outcomes of CEP depend on certain conditions. In the absence of employees with awareness and interest on sustainability, sufficient commitment and support from management level or goals to meet stakeholders' requirements, CEP may present ineffective or even harm the benefits of Industry 4.0 technologies on CSR performance (Baah et al., 2023; Hong et al., 2024). In all, CEP acts not merely as supplement to technology but as a mediating mechanism through which internal firm technology resources convert into CSR performance. From the preceding discussion, thus, the following hypotheses are proposed:

H4: Circular economy practices have a mediating effect on the relationship between technology management and corporate social responsibility to social and non-social stakeholders (a); corporate social responsibility to employees (b); corporate social responsibility to customers (c); and corporate social responsibility to government (d).

H5: Circular economy practices have mediating effect on the relationship between finance and risk management and corporate social responsibility to social and non-social stakeholders (a); corporate social responsibility to employees (b); corporate social responsibility to customers (c); and corporate social responsibility to government (d).

H6: Circular economy practices have a mediating effect on the relationship between human resource management and corporate social responsibility to social and non-social stakeholders (a); corporate social responsibility to

employees (b); corporate social responsibility to customers (c); and corporate social responsibility to government (d).

The extant literature reveals a significant research gap regarding the interconnectedness of Industry 4.0 technology applications, CEP, and CSR. This study systematically examines the relationships among these three dimensions through the theoretical lens of the RBV theory. The conceptual framework in this study specifically examines not only the impact of Industry 4.0 technology applications on CSR, but also the mechanisms of how CEP affect the relationships between Industry 4.0 and CSR, establishing a novel resource conversion paradigm that progresses transformed from Industry 4.0 technological resources into CSR expressed as reputational capital via dynamic CEP abilities. The conceptual model of this research is shown in Figure 3.1.

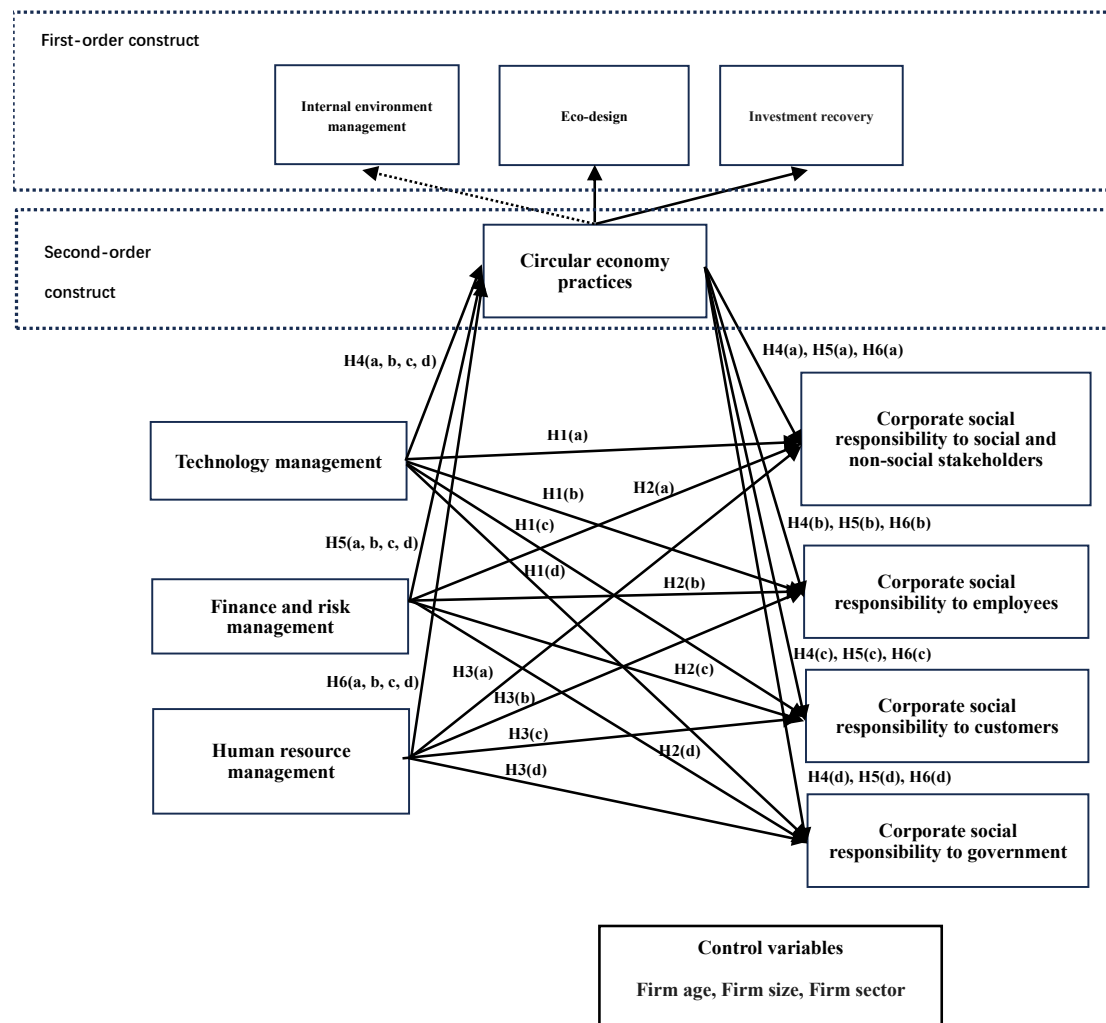


Figure 3.1: Conceptual model.

3.4 Research Methodology

3.4.1 Sampling and data collection

To achieve the research goals, the questionnaire survey method is used to collect data from companies in the oil and gas industry in China. The questionnaire is a proven survey method for examining multiple factors for universality

(Pinsonneault and Kraemer, 1993). China has boosted the implementation of Industry 4.0 technologies to support transition to CE and promote sustainable development (Zhou et al., 2020; Sun and Wang, 2022), and there is also a positive reflection in the Chinese oil and gas industry (Zhao et al., 2021). Thus, companies were randomly selected from the oil and gas chain in China. To increase the feasibility of data collection, phone calls were made to the selected firms to explain the research purpose. As a result, 155 companies agreed to participate and helped deliver questionnaires to their employees. Twelve employees including five managers working in the Chinese oil and gas industry were asked to help verify and improve the wording of the questions. The final questionnaire was distributed to the employees of the 155 companies covering all sectors in the oil and gas industry via email and QR code.

Initially, 468 replies were received from the 155 participating companies. Based on 11,412 employees contacted by the firms, the overall response rate was 4.1% (468 out of 11412). After eliminating the incomplete, non-consent, and missing data cases, 430 valid questionnaires remained (a response rate of 91.9%). The detailed demographic analysis based on the 430 valid questionnaires is presented in Table 3.1.

Table 3.1: Demographic analysis

Category	Frequency(<i>f</i>)	Percentage (%)
Firm size		
Fewer than 10 employees	0	0

10–50 employees	9	2.1
50–250 employees	25	5.8
Over 250 employees	396	92.1
Total	430	100
Firm age		
Less than 10 years	2	0.5
10–20 years	3	0.7
20–30 years	45	10.5
30–50 years	144	33.5
Over 50 years	236	54.9
Total	430	100
Sector of the industry		
Upstream sector (explore, locate, and produce)	240	55.8
Midstream sector (transportation and storage)	60	14.0
Downstream sector (refining and chemical, petroleum products distribution, and product sales)	106	24.7
Others (accounting firm , audit centre, security firm, administration, human resource training centre, research institutions, etc.)	24	5.6
Total	430	100

3.4.2 Measurement items

All constructs were developed based on the commonly and widely used 5-point Likert scale (1= strongly disagree, 2=disagree, 3= neutral, 4=agree, 5=strongly agree). All the measurement items in this study were adapted from prior research. Specifically, to measure the application of Industry 4.0 technologies, the

researcher primarily developed the items based on the studies of Kamble and Gunasekaran (2023) and Karmaker et al. (2023). The respondents were asked to provide the status of various types of Industry 4.0 technologies' implementation and the conditions of finance management, risk management, and human resource management under the context of novel technologies in their firms. For the CSR items, the scales adopted from Turker (2009) were used to reflect four dimensions (CSRS, CSRE, CSRC, CSRG). The respondents were asked to evaluate how their companies consider their responsibilities towards environmental contributions, social welfares, and economic benefits. CEP was established as a second-order variable construct with three first-order variables including internal environment management, eco-design, and investment recovery, which was adapted from Zhu et al. (2010). The respondents rated the degree to which they agreed with the listed questions on CE-oriented decisions and practices apply in their firms.

For control variables, descriptive information on firm level including firm size, firm age, and their firms' sector in the oil and gas industry was included to help increase the model accuracy, which conformed to previous studies (Verwaal et al., 2010; Dremptetic et al., 2020). As can be seen from Table 3.1, considerable differences exist between the subgroup of the control variables. To ensure that these differences do not affect the validity of the findings, this study applied SEM which accounts for both latent variables and measurement errors. Table 3.2 lists the measurement items for the model constructs as well as their sources.

Table 3.2: Model constructs and measurement items

Second-order constructs	First-order constructs	Code	Measurement items	References
Technology management (TM)		TM1	My company has implemented the application of cloud computing.	Kamble and Gunasekaran (2023); Karmaker et al. (2023)
		TM2	My company has implemented the application of Big Data analytics.	
		TM3	My company has implemented the application of the industrial Internet of Things.	
		TM4	My company has implemented the application of AI.	
		TM5	My company has implemented the application of additive manufacturing.	
		TM6	My company has implemented the application of robotics.	
		TM7	My company has implemented the application of augmented reality.	
		TM8	My company has implemented the application of a cyber security system.	
		TM9	My company has implemented the application of the digitalisation of production processes.	
		TM10	My company has implemented the application of the automation of the production chain.	
	Finance and	FRM1	My company has the management of	

risk management (FRM)	FRM2	My company has deployed an effective risk management system using AI.	
	FRM3	My company has developed effective financial control system using block chain technology.	
Human resource management (HRM)	HRM1	My company has recruited capable employees.	
	HRM2	My company has developed the competence of human resources through training.	
	HRM3	My company has set proper key performance indicators and established a reward system.	
	HRM4	My company has implemented predictive analytics for optimal use of resources.	
Corporate social responsibility to social and non-social stakeholders (CSRS)	CSRS1	My company participates to the activities which aim to protect and improve the quality of the natural environment	Turker (2009)
	CSRS2	My company makes investments to create a better life for the future generations.	
	CSRS3	My company implements special programmes to minimise its negative impact on the natural environment.	
	CSRS4	My company targets sustainable growth which considers the future generations.	
	CSRS5	My company supports the non-governmental organisations to deal with	

		problems.
	CSRS6	My company contributes to the campaigns and projects that promote the well-being of the society.
Corporate social responsibility to employees (CSRE)	CSRE1	My company encourages its employees to participate in the charity and voluntary activities.
	CSRE2	My company policies encourage the employees to develop their skills and careers.
	CSRE3	The management of my company primarily concerns with employees' needs and wants.
	CSRE4	My company implements flexible policies to provide a work-life balance for its employees.
	CSRE5	The managerial decisions related to the employees are usually fair in my company.
	CSRE6	My company supports employees who want to acquire additional education.
Corporate social responsibility to customers (CSRC)	CSRC1	My company checks the quality of products provided to customers.
	CSRC2	My company is helpful to customers and advised them about its products.
	CSRC3	My company respects its commitment to customers.
	CSRC4	My company invests in innovations which are to the advantage of customers.
	CSRC5	My company ensures that its products are

			accessible for all its customers.
	Corporate social responsibility to government (CSRG)	CSRG1 CSRG2 CSRG3	My company always pays its taxes on a regular and continuing basis My company always complies with the legal regulations. My company tries to help the government in solving social problems.
Circular economy practices (CEP)	Internal environment management (IEM)	IEM1 IEM2 IEM3 IEM4 IEM5 IEM6 IEM7 IEM8 IEM9	Senior managers commit to the environmental management in my company. Mid-level managers support the environmental management in my company. There is cross-functional cooperation for environmental improvements in my company My company provides special training for workers on environmental issues. My company has total quality environmental management. There are environmental auditing programmes such as ISO 14000 certification in my company. My company has eco-labelling of products. There are pollution prevention programmes such as cleaner production existing in my company. The internal performance evaluation system of my company incorporates

		environmental factors.
	IEM10	My company generates environmental reports for internal evaluation.
Eco-design (ED)	ED1	My company designs the products for reduced consumption of material/energy.
	ED2	My company designs the products for reuse, recycle, and recovery of material and component parts.
	ED3	My company designs to avoid or reduce use of hazardous products.
	ED4	My company designs the processes for waste reduction.
Investment recovery (IR)	IR1	My company sells excess inventories/materials
	IR2	My company sells scrap and used materials.
	IR3	My company sells excess capital equipment.
	IR4	My company collects and recycles end-of-life products and materials.
	IR5	My company has established a recycling system for used and defective products.

3.4.3 Data analysis approach

The hypotheses in this study were tested by SEM in AMOS 29.0 program. First, two pilot studies were conducted to test the validity of the questions by establishing and testing the measurement model consisting of 10 latent variables. Pilot 1 and 2 lasted for 14 days and 10 days, respectively, with 56 participants

from the upstream sector and 47 participants from the midstream and downstream sectors of the Chinese oil and gas industry in each study. These two studies were conducted via questionnaire sent to firm managers containing QR code to ensure participants could complete the survey using their mobile phones or laptops. Managers were also requested to collect participants' feedback regarding the understanding of the questionnaires. Both rounds of pilot studies successfully yielded constructive feedback that informed in the revisions to wording, the questionnaire layout, and additional brief explanations for some terms and questions, improving the overall validity of the questionnaire, which contributes to the final version. Ultimately, five managers working in the Chinese oil and gas industry were requested to review again the questionnaire to verify that all items were clear and understandable.

As seen in Table 3.3, the overall valid response rate is 90.3% (93 out of 103, and the completion rate was 98.9% (93 out of 94). Among all replies, no extremely too high or low scores were observed, indicating that they were distributed relatively evenly across different questions. This suggests that the survey was of proper length and reasonable completion time.

Table 3.3: Responses in the pilot studies

Pilot study	Invited participants	Valid response	Valid response rate
Pilot 1	53	56	94.6%
Pilot 2	40	47	85.1%
Total	93	103	90.3%

Eight main issues were identified through the feedback from 13 participant. Most feedback emphasized the complexity and misunderstanding of some questions (as shown in Table 3.4). Accordingly, brief explanations were provided above the relevant questions. Meanwhile, to reduce the influence of contextual framing of variables, the questions were designed to avoid indicating which items measured independent or dependent variables and reorganised the order of some sections.

Table 3.4: Participants' feedback and solutions taken

Pilot study	Key issues raised by participants	Solutions
Pilot 1	Terms 'internal environmental management', 'eco-design', and 'investment recovery' are difficult to understand	Added short explanations to all sections.
	The term 'institutional pressure' is difficult to understand.	Added short definitions.
	The term 'corporate social responsibility' is confusing.	Added short explanations to all sections.
	It is uncomfortable to answer personal information at the beginning.	Moved basic demographic questions to the last section.
	The sections 'circular economy practices' and 'corporate social responsibility' include too many questions and are too complex to complete.	Split long sections into smaller parts.
	Questions 'My company complies	Removed the latter question.

	with the legal regulations completely and promptly' and 'My company acts legally on all matters' are confusing. They seem to be the same.	
Pilot 2	The phrase 'promote corporate citizenship' is misunderstanding.	Added short explanations to this question.
	All parts of the section 'corporate social responsibility' are confusing.	Added short explanations to all parts of the section 'corporate social responsibility'.

Then, a second-order model in which IEM, ED and IR load on CEP was constructed. The good model fit illustrated that the second-order construct is acceptable in the structural equation model. The structural equation model included seven first-order variables and one second-order variable. Finally, the second-order variable was added into the structural equation model to investigate the hypotheses by analysing total effects, direct effects, and indirect effects.

Reliability and validity of the model were estimated via Cronbach's alpha, composite reliability (CR), average variance extracted (AVE), maximum shared variance (MSV), and comparison between the square root of AVE and the inter-construct correlations (Fornell and Larcker, 1981; Gefen et al., 2000; Hair et al., 2011; Tavakol and Dennick, 2011). The χ^2 and χ^2/df , the goodness fit index (GFI), the comparative fit index (CFI), the incremental fit index (IFI), the Tucker–Lewis index (TLI), and the root mean square error of approximation (RMSEA) were used to measure the model fit (Bentler and Bonett, 1980; Doll et al., 1994;

Byrne, 2001).

3.5 Data analysis and results

3.5.1 Results of the measurement model

Exploratory factor analysis (EFA) was conducted on the data from the 430 valid replies to test the underlying relationships among the model factors before confirmatory testing. It was employed with maximum likelihood extraction and varimax rotation, which resulted in a 10-factor solution. Meanwhile, the cumulative variance reached 62.5% covering most of the information, which showed that the constructs can meet the standards of model analysis (Mikulincer et al., 1990; Fabrigar, 1999).

First, the Kaiser–Meyer–Olkin (KMO) score was checked; which was strong at 0.957 and much higher than the minimum score of 0.5, indicating that the data were suitable for factor analysis (Dziuban and Shirkey, 1974; Kaiser, 1974). Then, the significant result of Bartlett’s Test of Sphericity (Sig. <0.05) indicated that relationships exist among variables to confirm a meaningful EFA (Hadi et al., 2016; Shrestha, 2021). The factor loadings for each item should be above 0.5 and ideally above 0.7 (Hulland, 1999; Truong and McColl, 2011; Hair et al., 2012). These indicators lower than 0.7 are also acceptable when the AVE for each construct is above 0.5 (Hair et al., 2012). As can be seen from Table 3.5,

the AVE for different constructs ranges from 0.593 to 0.746. Therefore, the factor loadings indicate a strong association among constructs. The study found that the Cronbach's alphas for all constructs range from 0.820 to 0.947, while the values of CR are ideally higher than 0.7. The values of Cronbach's alpha and CR for all constructs are higher than the threshold and close to 1, confirming model reliability (Cronbach, 1951; Gefen et al., 2000). Thus, it was concluded that the present results satisfied the criteria of convergent validity and the internal consistency of the indicators.

The confirmatory factor analysis (CFA) for convergent validity and the discriminant validity test of the model was then conducted. Table 3.5 shows that the CFI, IFI, and TLI are all above 0.90, while the RMSEA is lower than 0.08 (Byrne, 2001). Considering the strong results of other indicators and that the GFI is related to the survey sample size, although the GFI is less than 0.9, it is still considered a reasonable fit (Mulaik et al., 1989; Doll et al., 1994). Thus, the measurement model showed an acceptable fit with the sample data. To ensure the convergent validity of the analysis, the AVE was investigated, and the values of the AVE of all constructs exceeded 0.5 (Hair et al., 2011). To ensure the discriminant validity, the MSV was compared with the AVE, and the square root of the AVE was compared with and the inter-construct correlations. As illustrated in Table 3.6, the MSV is lower than the AVE, while the square roots of the AVE are all greater than the inter-construct correlations for each construct. Consequently, the discriminant validity was accepted (Fornell and Larcker,

1981).

Table 3.5: Model constructs, items, loadings and reliability of the first-order measurement model

Model construct	Items	Loading	Alpha	CR	AVE
Technology management VIF=1.865	TM1	0.705	0.934	0.934	0.586
	TM2	0.706			
	TM3	0.719			
	TM4	0.731			
	TM5	0.699			
	TM6	0.692			
	TM7	0.683			
	TM8	0.718			
	TM9	0.698			
	TM10	0.737			
Finance and risk management VIF=2.199	FRM1	0.628	0.820	0.820	0.603
	FRM2	0.660			
	FRM3	0.630			
Human resource management VIF=1.872	HRM1	0.611	0.858	0.859	0.604
	HRM2	0.678			
	HRM3	0.674			
	HRM4	0.716			
Corporate social responsibility to social and non-social stakeholders	CSRS1	0.696	0.905	0.905	0.613
	CSRS2	0.688			
	CSRS3	0.679			
	CSRS4	0.667			
	CSRS5	0.708			
	CSRS6	0.692			

Corporate social responsibility to employees	CSRE1	0.678	0.897	0.898	0.594
	CSRE2	0.653			
	CSRE3	0.639			
	CSRE4	0.704			
	CSRE5	0.645			
	CSRE6	0.633			
Corporate social responsibility to customers	CSRC1	0.681	0.878	0.878	0.591
	CSRC2	0.659			
	CSRC3	0.668			
	CSRC4	0.692			
	CSRC5	0.708			
Corporate social responsibility to government	CSRG1	0.722	0.839	0.840	0.637
	CSRG2	0.682			
	CSRG3	0.608			
Internal environment management VIF=2.272	IEM1	0.669	0.947	0.947	0.643
	IEM2	0.711			
	IEM3	0.710			
	IEM4	0.726			
	IEM5	0.717			
	IEM6	0.690			
	IEM7	0.746			
	IEM8	0.724			
	IEM9	0.723			
	IEM10	0.667			
Eco-design VIF=2.354	ED1	0.643	0.857	0.857	0.600
	ED2	0.610			
	ED3	0.593			
	ED4	0.660			
Investment recovery VIF=1.766	IR1	0.731	0.870	0.870	0.573
	IR2	0.687			

IR3	0.716
IR4	0.674
IR5	0.622

Alpha= Cronbach's alpha, CR= composite reliability, AVE= average variance extracted, VIF=variance inflation factor.

Total variance explained: 62.5%.

Model fit: $\chi^2 = 1789.864$ ($p < 0.05$); $df=1439$; $\chi^2/df = 1.244$; GFI=0.873; CFI = 0.976; IFI = 0.976; TLI = 0.975; RMSEA = 0.024.

Extraction Method: Maximum Likelihood.

Rotation Method: Varimax with Kaiser Normalisation.

Rotation converged in eight iterations.

Table 3.6: Discriminant validity for the first-order measurement model

Construct	AVE	MSV	FRM	TM	IEM	ED	IR	CSRC	CSRG	CSRE	CSRS	HRM
FRM	0.603	0.294	0.776									
TM	0.586	0.297	0.534	0.765								
IEM	0.643	0.366	0.542	0.545	0.802							
ED	0.600	0.366	0.511	0.489	0.605	0.775						
IR	0.573	0.315	0.433	0.364	0.527	0.561	0.757					
CSRC	0.591	0.251	0.427	0.347	0.479	0.501	0.394	0.769				
CSRG	0.637	0.245	0.474	0.38	0.495	0.397	0.308	0.569	0.798			
CSRE	0.594	0.329	0.477	0.483	0.563	0.574	0.472	0.536	0.499	0.771		
CSRS	0.613	0.264	0.503	0.455	0.514	0.449	0.39	0.526	0.524	0.569	0.783	
HRM	0.604	0.253	0.538	0.503	0.469	0.49	0.39	0.483	0.461	0.458	0.525	0.777

AVE= average variance extracted, MSV= maximum shared variance.

The values in bold are the square root of the AVEs.

Because there are multiple variables predicting the dependent variables in the model, multicollinearity may exist if the independent variables have a high correlation with others (Mason and Perreault Jr, 1991). Hence, the variance inflation factor (VIF) of each first-order construct was checked in order to

measure the correlations among predictors before testing the structural model. The VIF values displayed in Table 3.5 are all less than the suggested critical threshold of 3.0, confirming that there is no multicollinearity (Hair et al, 2019). Ultimately, from the above results, the measurement model was validated, and the next stage of structural model analysis could proceed.

3.5.2 Results of the structural equation model

First, the model of the second-order construct for CEP including IEM, ED, and IR was established. As reported in Table 3.7, the second-order construct model shows a good model fit: $\chi^2 = 184.437$ ($p < 0.05$); $\chi^2/df = 1.238$; GFI=0.958; CFI = 0.993; IFI = 0.993; TLI = 0.992; and RMSEA = 0.024. The weights of these three dimensions to the second-order construct are higher than 0.7, which presents a reliable relationship between IEM, ED, IR, and CEP (see Table 3.7). In addition, the VIF for each dimension is lower than the threshold of 3, indicating that there is no multicollinearity (Hair et al., 2019). Thus, the second-order construct can be applied in the structural equation model.

Table 3.7: The model fit and VIF for the second-order construct

Second-order construct		Dimensions	Loading	Weights	VIF
Circular economy practices (CEP)	Internal environment management (IEM)		0.57	0.754***	1.594

Eco-design (ED)	0.64	0.802***	1.490
Investment recovery (IR)	0.49	0.700***	1.808

Model fit: $\chi^2 = 184.437$ ($p < 0.05$); $\chi^2/df = 1.238$; GFI=0.958; CFI = 0.993; IFI = 0.993; TLI = 0.992; RMSEA = 0.024.

VIF=variance inflation factor

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, ns = not significant.

In comparing the first-order measurement model and structural equation models (see Table 3.8), it can be observed that the values of goodness of fit of the SEM remained strong as the first-order measurement model.

Table 3.8: Model fit of measurement model and structural equation model

	χ^2	χ^2/df	GFI	CFI	IFI	TLI	RMSEA
Measurement model	1789.864	1.244	0.873	0.976	0.976	0.975	0.024
Structural equation model	18.593	1.549	0.945	0.981	0.981	0.980	0.036

The structural equation model yielded a good model fit: $\chi^2 = 18.593$ ($p < 0.05$); $\chi^2/df = 1.549$; GFI=0.945; CFI = 0.981; IFI = 0.981; TLI = 0.980; and RMSEA = 0.036. As shown in Table 3.9, the model results presented that TM impact CSRS ($\beta = 0.137$; $p < 0.01$) and CSRE ($\beta = 0.236$; $p < 0.01$) significantly and positively. For the relationships between FRM and CSRS, CSRE, CSRC, and CSRG, as expected, FRM could significantly predict CSRS ($\beta = 0.297$; $p < 0.01$), CSRE ($\beta = 0.273$; $p < 0.01$), CSRC ($\beta = 0.256$; $p < 0.01$), and CSRG

($\beta = 0.355$; $p < 0.01$). Moreover, it was found that the relationships between HRM and CSRS, CSRE, CSRC, and CSRG were significant, with β values of 0.355, 0.201, 0.389, and 0.293, respectively, and all were significant at $p < 0.01$. Therefore, H1(a), H1(b), H2(a), H2(b), H2(c), H2(d), H3(a), H3(b), H3(c), and H3(d) are supported.

However, H1(c) and H1(d) are not supported because the relationships between TM and CSRC and TM and CSRG are non-significant ($p > 0.1$). In view of the condition that the relationship between the independent variable and the dependent variable can be hidden or suppressed by the assumptive mediator (Cheung and Lau, 2008), it could not be concluded that there are no relationships between these variables and, therefore, the mediating effects tests between TM and CSRC and TM and CSRG were suspended. When the indirect effect has an opposite sign to the direct effect between the independent variable and the dependent variable and both are significant, the total effect can be reduced and become even non-significant (Zhao et al., 2010). Thus, based on the non-significant influences, it is suggested that CEP may potentially have suppressing effects between TM and CSRC and TM and CSRG instead of mediating effects.

Table 3.9: Bootstrap test for the structural equation model

Hypothesis	Hypothesised paths	Bootstrap 95% CI	Indirect effects	Estimates
Hypothesis 4(a)	TM→CEP→CSRS	[0.111,0.212]	Direct effect	-0.020 ^{ns}
			Indirect effect	0.157***

Hypothesis 1(a)	TM→CSRS		Total effect	0.137***
Hypothesis 4(b)	TM→CEP→CSRE	[0.227,0.355]	Direct effect	-0.050 ^{ns}
			Indirect effect	0.286***
Hypothesis 1(b)	TM→CSRE		Total effect	0.236***
Hypothesis 4(c)	TM→CEP→CSRC	[0.189,0.308]	Direct effect	-0.226***
			Indirect effect	0.244***
Hypothesis 1(c)	TM→CSRC		Total effect	0.018 ^{ns}
Hypothesis 4(d)	TM→CEP→CSRG	[0.107,0.218]	Direct effect	-0.094*
			Indirect effect	0.158***
Hypothesis 1(d)	TM→CSRG		Total effect	0.064 ^{ns}
Hypothesis 5(a)	FRM→CEP→CSRS	[0.162,0.290]	Direct effect	0.075 ^{ns}
			Indirect effect	0.223***
Hypothesis 2(a)	FRM→CSRS		Total effect	0.297***
Hypothesis 5(b)	FRM→CEP→CSRE	[0.337,0.488]	Direct effect	-0.134***
			Indirect effect	0.407***
Hypothesis 2(b)	FRM→CSRE		Total effect	0.273***
Hypothesis 5(c)	FRM→CEP→CSRC	[0.154,0.310]	Direct effect	-0.092 ^{ns}
			Indirect effect	0.348***
Hypothesis 2(c)	FRM→CSRC		Total effect	0.256***
Hypothesis 5(d)	FRM→CEP→CSRG	[0.156,0.310]	Direct effect	0.131**
			Indirect effect	0.224***
Hypothesis 2(d)	FRM→CSRG		Total effect	0.355***
Hypothesis 6(a)	HRM→CEP→CSRS	[0.089,0.189]	Direct effect	0.202***
			Indirect effect	0.133***
Hypothesis 3(a)	HRM→CSRS		Total effect	0.355***
Hypothesis 6(b)	HRM→CEP→CSRE	[0.181,0.319]	Direct effect	-0.042 ^{ns}
			Indirect effect	0.244***
Hypothesis 3(b)	HRM→CSRE		Total effect	0.201***
Hypothesis 6(c)	HRM→CEP→CSRC	[0.154,0.271]	Direct effect	0.181***
			Indirect effect	0.208***

Hypothesis 3(c)	HRM→CSRC	Total effect	0.389***
Hypothesis 6(d)	HRM→CEP→CSRG [0.091,0.191]	Direct effect	0.159***
		Indirect effect	0.134***
Hypothesis 3(d)	HRM→CSRG	Total effect	0.293***

CI=confidence interval.

Model fit: $\chi^2 = 18.593$ ($p < 0.05$); $df=1439$; $\chi^2/df = 1.549$; $GFI=0.945$; $CFI = 0.981$; $IFI = 0.981$; $TLI = 0.980$; $RMSEA = 0.036$.

* $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, ns = not significant.

Next, the direct and indirect effects via bootstrap test method were analysed. Table 3.9 presents the results of the bootstrap test for mediating effects with a good model fit in the full model. Based on Hair et al. (2021), the mediating can be measured by comparing the direct and indirect effects between the independent and dependent effects' variables. As shown in Table 3.9, all 12 indirect effects were significant at $p < 0.01$ at 95% CI. To be specific, due to the non-significance of the paths of $TM \rightarrow CSRS$, $TM \rightarrow CSRE$, $FRM \rightarrow CEP \rightarrow CSRS$, $FRM \rightarrow CSRC$, and $HRM \rightarrow CSRE$, the indirect effects of paths $TM \rightarrow CEP \rightarrow CSRS$, $TM \rightarrow CEP \rightarrow CSRE$, $FRM \rightarrow CEP \rightarrow CSRS$, $FRM \rightarrow CEP \rightarrow CSRC$, and $HRM \rightarrow CEP \rightarrow CSRE$ have significant values of 0.157 ($p < 0.01$), 0.286 ($p < 0.01$), 0.223 ($p < 0.01$), 0.348 ($p < 0.01$), and 0.244 ($p < 0.01$), respectively. This means that H4(a), H4(b), H5(a), H5(c), and H6(b) are supported, and the proposed paths are found to be fully mediated For the indirect paths $FRM \rightarrow CEP \rightarrow CSRG$, $HRM \rightarrow CEP \rightarrow CSRS$, $HRM \rightarrow CEP \rightarrow CSRC$, and $HRM \rightarrow CEP \rightarrow CSRG$, it was found that they and the direct paths are significant with values of 0.131 ($p < 0.05$), 0.202 ($p < 0.01$), 0.181 ($p < 0.01$), and 0.159 ($p <$

0.01). Thus, the relationships between FRM and CSRG, HRM and CSRS, HRM and CSRC, and HRM and CSRG are partially mediated by CEP. In other words, H5(d), H6(a), H6(c), and H6(d) are empirically supported.

At the previous stage, it was supposed that the paths $TM \rightarrow CEP \rightarrow CSRC$ and $TM \rightarrow CEP \rightarrow CSRG$ were suppressing effects instead of mediating effects. As shown in Table 3.9, both the direct effects and the indirect effects are significant, while the signs of direct effects and indirect effects are opposite, and the total effects are non-significant. According to Zhao et al (2010), it is the opposite but significant direct effects and indirect effects working together that result in the failure of the $TM \rightarrow CSRC$ and $TM \rightarrow CSRG$ tests. Consequently, H4(c) and H4(d) are not supported.

Among the hypotheses, it was found that path $FRM \rightarrow CEP \rightarrow CSRE$ was a unique case. In this case, the indirect effect of FRM on CSRE through CEP is significant and positive with the value of 0.407 ($p < 0.01$), whereas the direct effect shows an opposite but also significant value of -0.134 ($p < 0.01$). This means that the relationship between FRM, CEP, and CSRE is supposed to have a suppressing effect rather than a mediating effect. Although the total effect of path $FRM \rightarrow CSRE$ is partially offset due to the opposite signs of direct and indirect effects, it is still significant with the value of 0.273 ($p < 0.01$) because the indirect effect ($\beta = 0.407$, $p < 0.01$) is much stronger than the direct effect ($\beta = -0.134$, $p < 0.01$). It is concluded that this hypothesis is supposed to have a suppressing

effect other than a mediating effect, and H5(b) is not supported. This is an unexpected result because the study failed to find this potential suppressing effect based on the total effects results.

In conclusion, H4(a), H4(b), H5(a), H5(c), and H6(b) are full mediating effects; H5(d), H6(a), H6(c), and H6(d) are partial mediating effects; and H4(c), H4(d), and H5(b) are suppressing effects. Table 3.10 and Table 3.11 present the results of the hypothesised paths and mediating effects.

Table 3.10: Results for hypothesised paths (Total effect)

Hypothesis	Hypothesised paths	Estimates	Results
Hypothesis 1(a)	TM→CSRS	0.137***	Supported.
Hypothesis 1(b)	TM→CSRE	0.236***	Supported.
Hypothesis 1(c)	TM→CSRC	0.018 ^{ns}	Not supported.
Hypothesis 1(d)	TM→CSRG	0.064 ^{ns}	Not supported.
Hypothesis 2(a)	FRM→CSRS	0.297***	Supported.
Hypothesis 2(b)	FRM→CSRE	0.273***	Supported.
Hypothesis 2(c)	FRM→CSRC	0.256***	Supported.
Hypothesis 2(d)	FRM→CSRG	0.355***	Supported.
Hypothesis 3(a)	HRM→CSRS	0.355***	Supported.
Hypothesis 3(b)	HRM→CSRE	0.201***	Supported.
Hypothesis 3(c)	HRM→CSRC	0.389***	Supported.
Hypothesis 3(d)	HRM→CSRG	0.293***	Supported.

Table 3.11: Results for mediating effects

Hypothesis	Hypothesis paths	Initial hypothesis	Potential effect after	Results
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		for effect	total effect analysis	
Hypothesis 4(a)	TM→CEP→CSRS	Mediating effect	Mediating effect	Supported. Mediating effect.
Hypothesis 4(b)	TM→CEP→CSRE	Mediating effect	Mediating effect	Supported. Mediating effect.
Hypothesis 4(c)	TM→CEP→CSRC	Mediating effect	Suppressing effect.	Not supported. Suppressing effect.
Hypothesis 5(d)	TM→CEP→CSRG	Mediating effect	Suppressing effect.	Not supported. Suppressing effect
Hypothesis 5(a)	FRM→CEP→CSRS	Mediating effect	Mediating effect	Supported. Mediating effect.
Hypothesis 5(b)	FRM→CEP→CSRE	Mediating effect	Mediating effect	Not supported. Suppressing effect.
Hypothesis 5(c)	FRM→CEP→CSRC	Mediating effect	Mediating effect	Supported. Mediating effect.
Hypothesis 6(d)	FRM→CEP→CSRG	Mediating effect	Mediating effect	Supported. Mediating effect.
Hypothesis 6(a)	HRM→CEP→CSRS	Mediating effect	Mediating effect	Supported. Mediating effect.
Hypothesis 6(b)	HRM→CEP→CSRE	Mediating effect	Mediating effect	Supported. Mediating effect.
Hypothesis 6(c)	HRM→CEP→CSRC	Mediating effect	Mediating effect	Supported. Mediating effect.
Hypothesis 6(d)	HRM→CEP→CSRG	Mediating effect	Mediating effect	Supported. Mediating effect.

3.6 Discussion and implications

This study investigates the influencing mechanisms among the application of Industry 4.0 technologies, CEP, and CSR, and proposes some main critical theoretical contributions. Specifically, this research advances the RBV theory by revealing how Industry 4.0 technologies interact with CEP to enhance CSR.

3.6.1 Theoretical contributions

The first key theoretical contribution is that this research investigates the impact paths from the application of Industry 4.0 technologies to CSR. Contrary to normal findings that technology always improves CSR, the study identifies the opposite situations that technology implementation may have no impact on CSR performance. Among most relationships between different dimensions of Industry 4.0 technology and CSR, the impacts are proven to be positive and are consistent with earlier research (Cyfert et al., 2021; Govindan, 2022; Cricelli et al., 2024; Hossain et al., 2024). However, it can be noticed that the relationship between TM and CSRC, and between TM and CSRG is non-significant. The results can be potentially interpreted as reflecting resource competition and price control from theoretical perspective. Specifically, although diverse Industry 4.0 technologies have been used in the whole oil and gas chain, customer-oriented results often hinge on pricing and regulations rather than technology application. Oil and gas price can be unfavourable for customers, as price control by government may prioritise short term profit. This will also weaken the cognition

of customers from technological upgrade to firms' efforts to social responsibility (Paltsev and Zhang, 2015). From the customer perspective, the fluctuations in oil price will impact customer costs and expectations (Wang, 2013), further weaken the feelings of customers that they are beneficial from new technologies. In the case that provided this study's research data, despite the continuous falling international oil price, China's oil price will not follow the changes in the international oil prices. China's oil price presents an asymmetric response to the international oil price with a dramatic response to the increase in the international oil price but a tardy and lingering response to the decrease in price (Chen and Sun, 2021). From the firm perspective, technology investment raises budget spending, which may lead to product price increases that consumers are forced to bear especially in short term. In emerging economies like China, short-term profitability pressure may impede possible CSR achievements from technological innovation. Regarding the relationship between TM and CSRG, these state-owned firms in the China's oil and gas industry are inherently operated under the direction and supervision of the government. The sensitivity of government and institutions to their use of Industry 4.0 technologies for achieving CSR is generally lower compared to NGOs, market, and consumers (Liu et al., 2014; Lin et al., 2020). Additionally, the implementation of Industry 4.0 can occasionally result in negative outcomes such as short-term benefits pressures and layoffs, which runs counter to the objectives of government of maintaining and promoting employment (Szabó-Szentgróti et al., 2021; Dieste et al., 2024). The statistical explanation for the insignificance of these paths

represents the second theoretical contribution of this research, which reveals the dual effect of CEP.

The second contribution is that this study responds to prior studies for the joint effects of Industry 4.0, CEP and CSR, and the critical dual role of mediator and suppressor of CEP is identified. Initially, based on previous literature (Jabbour et al., 2020; Awan et al., 2021; Govindan, 2022), it was expected that the relationships to be positive. Nevertheless, some unexpected results occurred in this study showing that there is no significant influence of TM on CSRC and CSRG. Specifically, as shown in the full model analysis in Table 3.11, the direct impacts of TM on CSRC and CSRG are negative and significant. However, upon being suppressed by CEP, the direct and indirect effects offset each other and result in non-significant total effects. Suppression occurs when the indirect and direct effects have opposing signs, marking the true relationship (Zhao et al., 2010). Path FRM→CEP→CSRE also exhibits a suppressing effect. Although it has been legislated in some countries such as Indonesia, China, Denmark, Sweden and Germany (Halkos and Nomikos, 2021) to require companies to perform their CSR, at this stage, the focus of these companies tends to be on how they can improve their CSR to stakeholders utilising government policies rather than on how they can make practical contributions to their employees, customers, and society (Bai et al., 2015). Under profit pressures and legitimacy concerns, the critics of CSR illustrated that firms should stick to profit maximisation as their only responsibility rather than social responsibility (Lin, 2020). As a result,

these companies may not treat the employees, society, customers, NGOs, communities, and government equally (Moon and Shen, 2010). Companies that proactively respond to improve CSR would also spend their budgets on sustainable economic aspects such as technology innovation, updated digital management systems, and green logistics while ignoring the responsibilities to their employees (Gao, 2009). In the view of the RBV, CEP act more than transmit value, as they help Industry 4.0 technologies convert into corporate social contributions. In the full model, paths such as $FRM \rightarrow CEP \rightarrow CSRE$, $TM \rightarrow CEP \rightarrow CSRC$, and $TM \rightarrow CEP \rightarrow CSRG$ show suppressing effects, suggesting that without effective CEP, technological investment may inadvertently undermine CSRE. These results indicate that applying merely technology cannot guarantee eminently satisfactory CSR and highlight the essential needs for the alignment of CEP. Ultimately, this study found that the application of Industry 4.0 technologies has an overall positive impact on CSR. However, part of the positive effect is not attributed to the direct effects of Industry 4.0 on CSR, which is caused by CEP acting as a suppressing variable that changes the relationship between Industry 4.0 and CSR to a certain extent. Here, the suppressing effect of CEP indicates that the positive impact of Industry 4.0 technologies on CSR is contingent on the implementation of CEP. Thus, this study reveals the critical point that effective CEP is required for Industry 4.0 technologies to transform into CSR performance.

Third, this study contributes methodologically on the suppressing effect by using

the Zhao et al. (2010) analysis methods. This study applies their method rather than Baron and Kenny's guidelines (1986). Many studies conducted a mediating effect test via Baron and Kenny's mediation test process. When the relationship path between the independent variables and the dependent variables is non-significant, previous studies tended to stop testing the mediating effects. If Baron and Kenny's method was followed in this current study, the existence of suppressing effects between TM and CSRC, TM and CSRG, and FRM and CSRE would not have been found between paths TM and CSRC, TM and CSRG, and FRM and CSR. As a result, the findings would incorrectly indicate that there are no mediating effects among these constructs. Therefore, the research results demonstrate that the typical first step in the mediation test of the significance between variables does not fit all mediation effects analyses. Departing from traditional mediation analysis approaches, the application of Zhao et al.'s (2010) method identifies a critical suppressing effect, providing a more nuanced understanding of CEP mechanisms in the process of the transformation of technologies to corporate social contributions. This study extends the scope of traditional mediation analysis.

3.6.2 Managerial implications

This study also provides several managerial implications. First, at the company operation and management level, the key implication is that the decision makers

can appropriately combine technology, management, and circular economy approaches during the process of technology introduction and innovation, thereby effectively improving CSR through the mediating and suppressing effects of CEP. The research results confirmed that the application of Industry 4.0 technologies positively promotes the firm's CSR, and CEP plays a pivotal role in the process of the implementation of Industry 4.0 technologies for CSR in firms. Given the firms' capacity and resources for investment is limited, it is still recommended that the various resources should be carefully allocated during the implementation of CE. This is because the core purpose of firms is to make commercial profits rather than focus on social responsibilities, which is also fundamental for all the economic entities. Firms in a state of profit declining will no longer have the willingness or the ability to improve their CSR. Thus, firms should integrate CEP into Industry 4.0 adoption to avoid harming their CSR.

Second, in terms of stakeholders, the key implication is that decision makers should clearly recognise that improving CSR should not be reduced to economic benefits alone. To improve CSR, the firm needs to transform from narrow shareholder-oriented to stakeholder-oriented. Specifically, while earning economic benefits, the company also needs to take the interests of society, communities, employees, customers, governments, and non-government organisations into account. CSR is often considered mandatory in the shareholder-oriented companies, resulting in much hesitation or even resistance from management because promoting CSR will inevitably consume the

company's resources (Lin, 2020). According to this study's findings, technology investment, fundings, and human resources related to Industry 4.0 will support their CSR performance. Thus, decision makers can incorporate the goals of improving CSR when formulating future plans and allocating budgets. This does not mean that all these resources should be diverted towards CSR. The key point is the willingness of decision makers to invest in promoting CSR instead of centring on economic interests. Firms should shift from shareholder-centric goals to metrics balancing both profit and CSR.

Third, in the aspect of government policies and legislation, the key implication that the government should recognise the value of promoting CSR, which is that companies can assume more social responsibilities for their stakeholders rather than merely providing job opportunities and seeking for commercial profits. On one hand, this is because the law does not provide an obvious definition of CSR and does not stipulate the obligations of firms on specific approaches (Luo, 2007). For instance, although the concept of CSR was written into China's Company Law as early as 2006, there is still no relevant law specifically targeting CSR (Gao, 2011; Lin, 2020). As a result, many firms are generally unable to perform CSR well in practice. On the other hand, many firms generally centralise the interests of shareholders through firm development and operations (Heath, 2006). These factors have hindered the CSR implementation. To tackle these issues at firm level, as mentioned above, decision makers can improve their firms' CSR by devoting more resources and integrating CEP with technology and internal

management. At the policy level, government can consider issuing CSR-targeted laws and regulations and propagating detailed CSR training to companies and public to raise awareness. Concurrently, they can also encourage firms to implement CSR with the adoption of Industry 4.0 and CEP through fiscal incentives such as tax reduction.

3.6.3 Limitations and future research

Although this study makes important contributions, it still has some limitations. First, the findings show that the implementation of Industry 4.0 technologies does not have positive impacts on all the dimensions of CSR. Therefore, one of the crucial directions for future research is to explore the impact and failure mechanisms of Industry 4.0 on specific dimensions of CSR. Future researchers can build a more detailed model to more comprehensively understand what factors reduce the effectiveness of Industry 4.0 on CSR. Second, it is unable to verify the knowledge level of the respondents, thus there is no guarantee that all respondents know about their firms' technology applications and CEP. Future researchers can conduct questionnaire surveys or interviews targeted at decision makers in the companies to optimise measurement validity. Third, the data for this study are collected from only one country. According to the above discussion, China has a distinctive understanding and treatment of CSR. Therefore, the China-specific data may limit generalisability, particularly for the negative paths,

which could reflect unique oil price policies in emerging countries. In all, there may be some threats to external validity in this research. Future research can extend to other industries or countries to obtain different insights and further enrich general practical managerial implications for improving CSR.

3.7 Conclusion

The application of Industry 4.0 technologies is a significant driver of firms' CSR, while organisations can obtain competitive abilities by jointly pursuing Industry 4.0 technologies, CSR, and CEP. Drawing on data collected from 155 Chinese companies in the oil and gas industry, this study identifies which aspects of the technology innovation and upgradation can have a positive or a negative influence when companies are using Industry 4.0 technologies to facilitate CSR. The findings demonstrate that, while Industry 4.0 technology adoption generally enhances CSR, this process has some critical contingencies. The dual role of CEP as a mediator and a suppressor is essential to realise CSR derived through technological investment. Moreover, some negative paths reflect profit-driven constraints in the oil and gas industry, implying that CSR outcomes require long-term and balanced resource reallocation. This study offers insightful managerial contributions for practitioners for integrating CEP with the implementation of Industry 4.0 technologies to improve CEP performance. These insights can be extended to other resource intensive industries such as manufacturing where

short-term profit pressure may similarly offset CSR achievements from technological innovations. Even so, this study has limitations derived from the selected industry type, geographic location, research questions, and research objectives, which future studies could address.

Chapter 4

The role of institutional pressure and sustainability strategies in the effects of circular economy practices on corporate social responsibility: An indirect moderation model

4.1 Introduction

The circular economy (CE) has evolved into a prominent paradigm, positioning itself as a systemic approach through which firms can decouple economic growth from resource use and advance toward sustainable development (Reike et al., 2018; Schroeder et al., 2019). CE refers to an industrial system designed to be restorative and regenerative (Ellen MacArthur Foundation, 2013). Its wide-ranging adoption of economic and environmental aspects has attained notable results in areas such as the impact of CE on carbon footprint reduction and renewable energy consumption (Cai et al., 2024), strategies for the logistics sector to transit to CE (Ruiz et al., 2020; Jayarathna et al., 2023). In fact, CE contributes not only economic and environmental outcomes but also social benefits of sustainability that support competitive advantage (Suchek et al., 2021).

Sustainability consists of three key dimensions: economic, environmental and social (Kuhlman and Farrington, 2010; Murray et al., 2017; Fischer et al., 2020). As a pathway from the linear to the circular economic model, the implementation of circular economy practices (CEP) can strengthen firm sustainability (Nayal et al., 2022; Le et al., 2024). The review of the literature revealed that firms also pursue sustainability by developing sustainability strategies (SS) rather than implementing CEP. Although both SS and CEP act as contributors to firms' sustainability goals, they differ in concepts, scope, and implementation. SS are plans at firm level that direct operations towards environmental, economic, and social sustainability goals including employee education, human rights protection, technological innovation, energy efficiency, emissions reduction, and biodiversity conservation, providing specific guidance for firms' operations towards sustainability (Wijethilake, 2017; Van Zanten and Van Tulder, 2021). CEP primarily focus on the technological tools to achieve circular production, circular design, recycling, and remanufacturing, representing operational actions and procedures undertaken by firms (Razzaq et al., 2021; Van Opstal and Borms, 2023). Although research on the impact of CEP on corporate sustainability has increased, most studies mainly focused on their economic or environmental benefits, with limited attention to social aspects (Korhonen et al., 2018; Nikolaou et al., 2021). These studies reveal that decision makers in the circular economy typically do not consider these three dimensions equally as the basis for their decisions, which are replaced by just the economic and environment aspects, while the social aspects represented by social equity and welfare are always

ignored (Kirchherr et al., 2017; Murray et al., 2017). In recent years, the perspective of balancing economic, environmental, and social goals for real sustainability is increasing (Van der Byl and Slawinski, 2015; Barbier and Burgess, 2017; Orieno et al., 2024). Recent studies call for balancing all three dimensions and point out that profit primacy may ruin the fundamental goals of CE (Pies, Schreck, and Homann, 2021; Fleurbaey and Ponthière, 2023). Ignoring the social dimension may harm CE legitimacy and stakeholder support, and both of which are the essential conditions for implementing CE (Eikelenboom and Long, 2023).

According to Baah et al. (2023), the adoption of CEP can result in higher participation of CSR via the improvement of innovation and collaboration capabilities. Firms can strengthen their social sustainability performance through the fulfilment of CSR, such as establishing a fair working conditions, offering more educational opportunities for employees, supporting social organisations, and maintaining legal compliance (Turker, 2009; Ali and Kaur, 2021). However, many organisations encounter difficulties in utilising CEP to achieve tangible CSR outcomes (Hong et al., 2024). These challenges may arise from the lack of effective, detailed long-term strategies that incorporate clearly defined and measurable sustainability objectives. For instance, at the initial stage of transition towards CE, firms may have to invest higher than expected. Since sustainability is a long-term goal, it is difficult for them to benefit from short-term operations, creating financial constraints in early stages. Without clear and adequate

planning, corporate resources may be misallocated, and the short-term economic performance may be harmed (Chen et al., 2020; Sharma et al., 2021). Thus, relying merely on CEP is unlikely to be sufficient to gain sustainability. To achieve long-term sustainable development and uphold CSR, firms need to craft operational SS including detailed approaches to signal intent and specify measures for guidance, providing a comprehensive internal strategic management framework and a balanced resource allocation plan (Reeves et al., 2015). In all, without SS that aligns goals, approaches and budgets, CEP become isolated projects and prove challenging to achieve corporate social contributions.

Drawing on the lens of the moral responsibility theory of corporate sustainability (MRCS), Ki et al. (2021) argue that corporate strategies that reflect the recognition of firm responsibilities and moral stance can help to build a CE framework. This perspective is consistent with Kauppi and Hannibal (2017). Similarly, Aragón-Correa et al. (2022) pointed out that institutional pressure (IP) can foster development strategies as it will drive firms to adopt practices. These insights suggest that both SS and IP have the potential to facilitate the implementation of CEP towards CSR performance. Although existing studies have investigated and highlighted the facilitating effect of CEP on CSR (Baah et al., 2023; Hong et al., 2024), to the best of the researcher's knowledge, no literature has systematically explored the role of sustainability strategies in the relationship between CEP and CSR, and only limited studies have examined the potential facilitating effect of IP in such relationships (Sancha et al., 2015; Zhou

et al., 2023). As mentioned above, the implementation of SS is critical for firms as it reflects their attitude towards sustainability and provides comprehensive guidelines for operations. Therefore, the study aims to fill this knowledge gap by investigating how SS and IP impact the relationships between CEP and CSR. This study focuses on the oil and gas industry because it combines high carbon emission, complex supply chains, and increasing regulatory, market, and social pressure, making it particularly suitable to examine how CEP contribute to CSR with the promotion of SS and IP. This raises the following research questions: *RQ1: How does CEP affect CSR? RQ2: How does SS affect the associations between CEP and CSR? RQ3: How does IP affect the relationships between SS, CEP and CSR?*

To address these questions, this study examines the relationships among CEP, CSR, SS, and IP using structural equation modelling (SEM) which best suits this research by providing a reliable estimation of multiple constructs and indirect effects. Drawing on the MRCS and institutional theory, a corresponding research framework was developed, and a survey was conducted among 155 companies covering upstream, midstream, and downstream sectors of the Chinese oil and gas industry. The results indicate that (i) SS can strengthen most paths from CEP to CSR, while IP promotes the adoption of SS and thereby indirectly contributes to the relationships between CEP and CSR. (ii) These effects vary across different dimensions of CSR, with no impact observed on the aspect of employees.

The rest of the paper is organised as follows. Section 2 presents a comprehensive literature review of the theoretical background and the hypotheses of this study. Section 3 provides an overview of data collection and measurement approaches. Section 4 conducts a preliminary test and two full model tests to verify the research hypotheses and present the results of empirical analysis. Section 5 and section 6 conclude by discussing the theoretical contributions, managerial implications, limitations, and suggest directions for future research.

4.2 Theoretical background and hypotheses development

4.2.1 Moral responsibility theory of corporate sustainability

The moral responsibility theory of corporate sustainability (Ha-Brookshire, 2017) argues that the core of achieving corporate sustainability lies in a firm's ability to proactively pursue sustainability within the scope of its moral responsibilities (Ki, Park, and Ha-Brookshire, 2021). Ha-Brookshire (2017) pointed out that the necessary condition for a corporation to realise true sustainable development is to first treat sustainability as a perfect duty. Subsequently, to fulfil this perfect duty, firms must establish clear goals and well-defined internal structures related to corporate sustainability. Based on the different degrees to which a firm considers sustainability a perfect duty to fulfil, firms can be classified as truly

sustainable corporation, occasionally unsustainable corporation, occasionally sustainable corporation, consistently sustainable corporation in selective areas, occasionally unsustainable corporation in selective areas, and occasionally sustainable corporation in selective areas (Ha-Brookshire, 2017). This classification is measured by whether a firm has clear goals and structure toward sustainability.

CEP represent an emerging strategic approach applied in many companies to transform from traditional linear to circular economy (Ciliberto et al., 2021; Neves and Marques, 2022). However, the adoption of CE is merely the starting point of a broader transition (Sarja et al., 2021). As Reeves et al. (2015) argue, successful implementation of this transition requires support from specific operational strategies. From the perspective of the MRCS, firms develop such routines through complementary strategies such as sustainable supply chain management and sustainability strategies (Blomsma et al., 2019). The degree of emphasis on sustainability or the extent of commitment to sustainability within a firm's moral responsibility spectrum determines the formulation of firm sustainability strategies, leading to variations from detailed and strict to simple and loose (Klettner et al., 2014; Ki et al., 2021). Support by corresponding strategies to fulfil the duty, firms can not only improve the economic and environmental performance but also include social contribution within their management and enhance it (Ha-Brookshire, 2017).

Based on the MRCS, this study posits that during the implementing of CEP, as firms tend to place greater emphasis on the interests of key stakeholders such as society, customers, employees, and government, they design and adopt stricter and more detailed SS including more explicit guidance for enhancing the CSR. Therefore, this study adopts the MRCS as the primary theoretical lens as it provides a suitable framework for evaluating and explaining the varying impacts of SS on the relationships between CEP and CSR. Treating sustainability as perfect duty means that firms should turn their values into clear strategies. Put differently, firms establish SS to guide their CEP which in turn improve their CSR performance.

4.2.2 Institutional theory

Institutional theory is employed in this study as firms generally do not design SS independently but are significantly influenced by external factors such as government regulations, industrial standards, social requirements, and market competition (Poisson-de Haro and Bitektine, 2015; Arora and De, 2020). Within this study's research model, these factors are conceptualised as institutional pressures that act as external drivers of SS.

Meyer and Rowan (1977) proposed that rationalised institutional elements emerged and become taken for granted gradually in the process of the

modernisation of society. Under the interaction of complicated social activities, these institutional elements affect firm management to adopt environmental rules for legitimacy. They emphasised the significance of complying with institutions over technology level or market competition. DiMaggio and Powell (1983) extended the content of institutional theory with the supplement of institutional constraints and legitimacy as well as the concepts of organisational field, institutional isomorphism, and three types of isomorphic mechanisms, making the institutional theory a more concrete and applicable analytical framework. They identify three different types of isomorphic pressure on organisations including coercive pressure, mimetic pressure, and normative pressure. Institutional pressure has a crucial impact on the sustainability practices and innovation strategies within the energy sector. Studies have shown that regulatory and normative pressure significantly drive environmental innovations and sustainability performance, particularly in the oil and gas industry (Liao, 2018; Jain et al., 2022). The introduction of energy conservation systems is influenced by both formal and informal institutions, with large firms being more responsive to high regulatory pressure (Garrone et al., 2018).

Energy conservation behaviours in firms are enhanced by senior management support and sufficient funding (Zhang et al., 2018). In addition to internal management, external stakeholders such as environmental organisations and market competitors also play a significant role in the adoption of green innovations, although their impact on financial performance varies by the source

of pressure (Khan et al., 2020; Lui et al., 2021). As the attention of customers to CSR and corporate sustainability increases, firms are experiencing emerging pressure from customers in the context of market competition. Evidence proved that customers are increasingly inclined to opt for products and services that align with social equity, human rights, recycled materials and environmental protection (Hosta and Zabkar, 2021; Duarte et al., 2024). While IP is significant in promoting sustainability and innovation, their effectiveness often depends on the context and the specific pressure applied (Daddi et al., 2016). Scholars note that government authorities, competitors, media public opinions, industry associations, industry regulators, clients, and customers can put pressure on firms (DiMaggio and Powell, 1983; Delmas and Toffel, 2004; Bharati et al., 2014; Voinea and van Kranenburg, 2018; Mombeuil et al., 2023). The forms of IP mentioned above drive firms to formulate internal development strategies or adjust their current practices (Beckert, 1999; Zhu and Sarkis, 2007; Farrukh et al., 2022). Facing different forms of IP, firms typically also adopt various strategies to ensure the effective implementation of their plans. For instance, considerations of the economy, environment, and society are simultaneously integrated into the company's sustainability strategies to respond to external appeals and requirements for corporate sustainability and social performance (Ioannou and Serafeim, 2012; Zhu et al., 2013). This research focuses on the oil and gas industry, where big capital investments and rigorous regulations lead to strong institutional pressure. This increases the strategic value of developing comprehensive corporate internal strategies. As IP is vital for companies to take

initiatives in the process of CE (Arranz et al., 2022), the institutional theory is adapted as the second theory for guidance in this study.

4.2.3 Circular economy practices and corporate social responsibility

The 3R principles (reduction, reuse, and recycle) are the core of CE and drive firms to reduce waste, and reuse and recycle resources to decrease the negative impact on the environment (Geissdoerfer et al., 2017). In the era of the traditional economy, profit maximisation was considered as an independent system and the only purpose for a commercial organisation, focusing solely on economic performance (Jensen, 2002). CE extends the business mode scale and requires companies to embed themselves into the wider economic, environmental and social system. As raw materials for production are extracted from nature, firms should be accountable for environmental preservation (Sharma and Vredenburg, 1998; Büsche and Fletcher, 2015). Firms have adopted CEP to improve their performance, with extensive empirical evidence suggesting that CEP can help to reduce resource consumption and costs, decrease waste emissions, and boost profits and core competitiveness (Trumpf and Guenther, 2017; Xue et al., 2020; Bhatti et al., 2023; Junaid et al., 2024).

Research also indicates that firms should adopt CEP in terms of social responsibility, not just for economic and environmental enhancement

(Rodríguez-Espíndola et al., 2022; Baah et al., 2023; Hong et al., 2024). Turker (2009) categorised CSR into four dimensions based on the different stakeholders involved in CSR; these are CSR to social and non-social stakeholders (CSRS), CSR to employees (CSRE), CSR to customers (CSRC), and CSR to government (CSRG). CEP contribute to all these dimensions through innovative technology applications, eco-friendly product design, and human resource management related to sustainability (Apostol and Näsi, 2014; Junaid et al., 2024). For instance, through the application of Industry 4.0 technologies, firms can create new employment opportunities in product research and design, operation and process upgrades and market development (Nascimento et al., 2019; Awan et al., 2022). Eco-friendly products help firms reduce their resource consumption, improve energy utilisation, and lower waste emissions (Mendoza et al., 2017; Papparoidamis and Tran, 2019). Publicity for environmental protection and skills training for employees can increase their social participation, which is also a manifestation of improved staff welfare (Lamm et al., 2015). The implementation of CEP enables firms to fulfil more social responsibilities, and it helps firms to combine practical operations with societal goals, which is crucial to improve CSR (Hong et al., 2024; Zhang and Li, 2025).

The above discussion informs the study hypothesis on the relationships between CEP and CSR. Although previous research has confirmed a positive impact of CEP on CSR, SS has not been embedded into their models. It remains essential to examine the relationships between CEP and CSR in current research to

explore potential moderating effects. Therefore, the following hypothesis is posited.

H1: Circular economy practices positively affect the corporate social responsibility to (a) social and non-social stakeholders, (b) employees, (c) customers, and (d) government.

4.2.4 Moderation effect of sustainability strategies in the relationship between circular economy practices and corporate social responsibility

The previously mentioned duty, goals, and comprehensive corporate structure related to sustainability can be reflective via a sustainable strategy manifested in detailed plans and practical performance (Ha-Brookshire, 2017). In this framework, SS provides overall goals and directions, while CEP specify the operations that put these strategies into effect. As firms encounter various challenges and barriers in the adoption of CEP, integrating sustainability into corporate core strategy is a significant method to overcome obstacles such as insufficient financial support, lack of technical knowledge, low employee motivation, and weak consumer acceptance in the process of implementing CE for CSR, especially when firms are seeking to provide long-term value for both themselves and the society (Santos, 2011; Galpin et al., 2015; Kirchherr et al.,

2018; Palombi et al., 2024).

As Ha-Brookshire (2017) stated, the perception and stance towards social responsibilities reflect a firm's values and are ultimately integrated into corporate strategy. SS founded on these values provides a foundation for human resource management that acts as a significant driver of the successful adoption of CEP (Zhu et al., 2010; Galpin et al., 2015). In addition to management, SS also emphasises firms' economic performance. The detailed instruction within SS allows employees to implement key principles of CEP including waste reduction, materials recovery, and eco-design, thus reducing costs (Rodríguez-Espíndola et al., 2020; Takacs et al., 2022). Innovative eco-design products also match customers' preferences, strengthening firms' image towards sustainability and competitive advantage (Esty and Winston, 2009). These approaches enable companies to maintain economic benefits while ensuring corporate economic sustainability and to fulfil their commitments to the firms' stakeholders by enhancing CSR through CEP.

When developing sustainability strategies, firms tend to design strategies covering all three pillars of sustainability (Eslami et al., 2019). However, as highlighted by Ha-Brookshire (2017) in the MRCS, due to differences in the recognition of responsibilities and objectives, the promoting effect of SS varies. Specific goals and detailed sustainability strategies will result in clear plans and approaches, which finally contribute to improved firms' social

performance (Ha-Brookshire, 2017). In other words, firms with stronger duty recognition and clearer goals are more likely to undertake and fulfil greater CSR. Based on the above discussion, the second hypothesis is proposed:

H2: Sustainability strategies have moderating effects on the relationships between circular economy practices and corporate social responsibility to (a) social and non-social stakeholders, (b) employees, (c) customers, and (d) government.

4.2.5 Indirect moderation effect of institutional pressure in the relationship between circular economy practices and corporate social responsibility via sustainability strategies

According to institutional theory, organisations live in an institutional environment that impacts their strategies and future development direction (DiMaggio and Powell, 1983). Among the three forms of institutional pressure, the most influential one that drives firms to adopt sustainability strategies is coercive pressure from government and legal departments (Yin and Zhang, 2012; Sancha et al., 2015; Kauppi and Hannibal., 2017). Under coercive pressure to incorporate sustainability, firms usually respond with conformity and compromise, establishing or adjusting corporate strategies to meet external requirements. As Hyatt and Berente (2017) and Huq and Stevenson (2020) stated,

normative pressure that comes from social expectations guides firms to take action that can fulfil the values closely related to social moral standards. Additionally, in response to fierce market competition, mimetic pressure leads firms to maintain their competitive advantage by imitating successful industry leaders, managing to avoid uncertainty and decision-making mistakes (Lieberman and Asaba, 2006; Semadeni and Anderson, 2010). These approaches effectively strengthen corporate core competitiveness, enabling them to achieve corporate sustainability and better fulfil social duties, consequently meeting social expectations (Peng et al., 2021; Sun et al., 2021).

Previous research demonstrates a greater ability to develop and execute SS, especially for the firms under high institutional pressure (Dai et al., 2021; Gunarathne et al., 2021; Zhou et al., 2023; Lee et al., 2024). These studies show that firms will integrate SS into their long-term business models in situations when exposed to institutional pressure. Similarly, during or after the transition from a linear to a circular economy, sustainability oriented competitive strategy can also be integrated into overall corporate strategies to support the implementation of CEP (Osei et al., 2024; Girma et al., 2025). By harnessing the CEP on corporate sustainability, firms can further enhance their social responsibilities. In sum, this study proposes that IP indirectly strengthens the relationships between CEP and CSR through its influence on SS. Thus:

H3: Institutional pressure positively affects sustainability strategies.

H4: Institutional pressure indirectly moderates on the relationships between circular economy practices and corporate social responsibility via sustainability strategies for (a) social and non-social stakeholders, (b) employees, (c) customers, and (d) government.

Figure 4.1: presents the conceptual model with relationships among CEP, IP, SS, CSRS, CSRE, CSRC, and CSRG and the research hypotheses

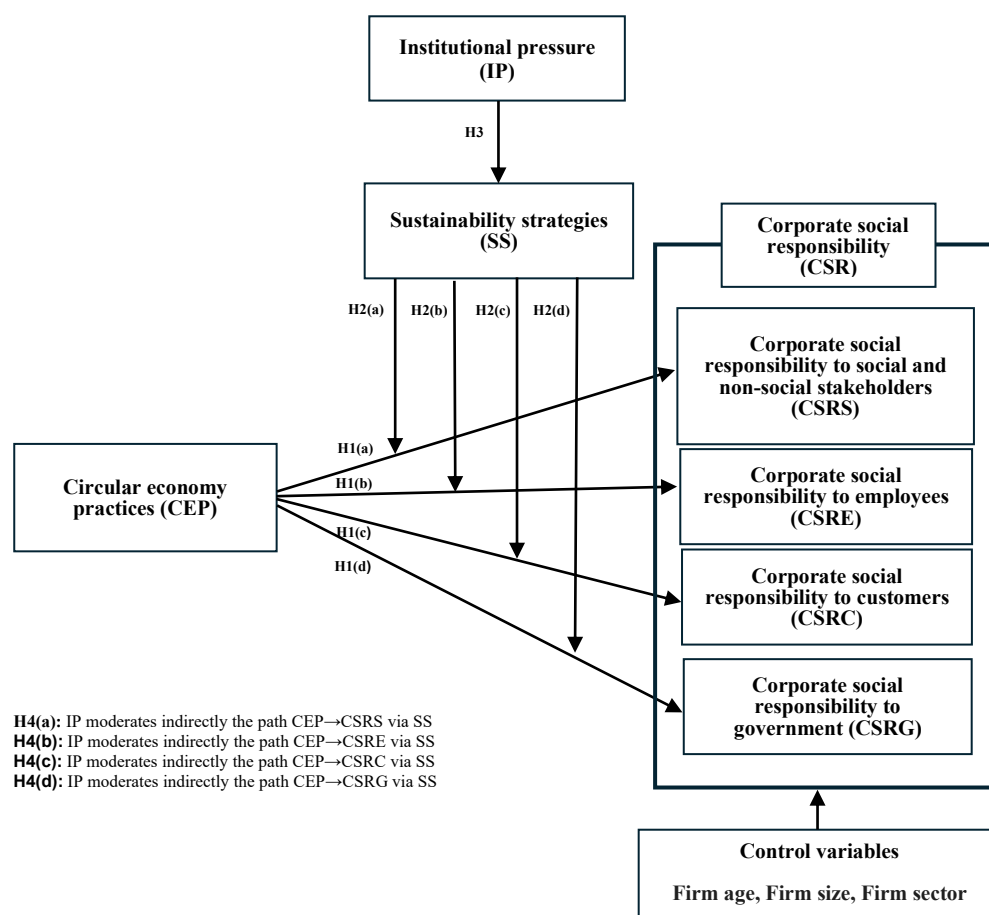


Figure 4.1: Conceptual model with relationships and hypotheses.

4.3 Research methodology

4.3.1 Pilot study

After drafting the initial questionnaire, two rounds of pilot study were held to test the clarity and acceptability of the questions. Pilot 1 lasted 14 days and involved 56 employees from the upstream sector of the oil and gas industry. Pilot 2 lasted 10 days and involved 47 employees from the midstream and downstream sectors. Both pilot tests were conducted in China. The questionnaire was delivered to the participants through firm managers via QR code and participants completed the survey using their mobile phones or laptops.

Meanwhile, managers were also requested to collect participants' feedback regarding the questionnaires. Both rounds of pilot studies successfully yielded constructive feedback that informed in the revisions to wording, the questionnaire layout, and additional brief explanations for some terms and questions, improving the overall validity of the questionnaire. Based on these revisions the questionnaire was updated and finalised for the main survey. Before launch, five managers working in the industry reviewed the wording to ensure that all questions were clear and easy to understand.

4.3.2 Sampling and data collection

The formal main survey targeted 155 companies randomly selected in the oil and gas industry in China. Since there are also foreign employees in the company, the questionnaire was prepared in both English and Chinese versions with supplementary short notes for some questions as suggested by Douglas and Craig (2007). The researcher then made some phone calls to these companies in sequence to confirm their willingness to participate and to arrange internal distribution of the survey (Dillman, 2011). In total, 155 companies that had an overall number of 11,412 employees replied that they were willing to be involved in the study. The questionnaire was delivered to these companies via email and QR code, followed by one reminder after one month. By the end of the survey in October 2024, 468 responses were received and recorded. After removing the unfinished questionnaires and others without consent, the final sample yielded 430 valid responses with a response rate of 4.1% (468 out of 11,412).

Table 4.1 summarises the demographics of the final sample. Most respondents (92.1%) had been working in large companies that had over 250 employees. Regarding company age, 236 (54.9%), 144 (33.5%), and 45 (10.5%) worked in companies aged over 50 years, 30–50 years, and 20–30 years, respectively. In terms of the sections of their companies in the oil and gas industry, a total of 55.8% of 430 respondents came from the upstream sector, 24.7% were from the downstream sector, 14.0 % worked in the midstream sector, and 5.6% worked

in other roles.

Table 4.1: Demographics of the sample

Category	Frequency(<i>f</i>)	Percentage (%)
Firm size		
Less than 10 employees	0	0
10–50 employees	9	2.1
50–250 employees	25	5.8
Over 250 employees	396	92.1
Total	430	100
Firm age		
Less than 10 years	2	0.5
10–20 years	3	0.7
20–30 years	45	10.5
30–50 years	144	33.5
Over 50 years	236	54.9
Total	430	100
Sector of the industry		
Upstream sector (explore, locate, and produce)	240	55.8
Midstream sector (transportation and storage)	60	14.0
Downstream sector (refining and chemical, petroleum products distribution, and product sales)	106	24.7
Others (accounting firm , audit centre, security firm, administration, human resource training centre, research institutions etc.)	24	5.6
Total	430	100

In this study, firm size, firm age, and sector of the industry were used as control

variables with different groups to account for their potential impact on the data analysis results. The variations among different groups could be huge, as various organisational characteristics could influence respondents' replies. To ensure these differences will not influence statistical analysis, they were introduced into the SEM model as exogenous variables to be controlled to assess their on impact on other latent variables.

4.3.3 Measurement items

Based on the literature review, a questionnaire was designed consisting of 58 items (see Table 4.2). All the constructs were measured with a 5-point Likert scale (1= strongly disagree, 2=disagree, 3= neutral, 4=agree, 5=strongly agree). All items were adapted from mature scales, with minor adjustments to suit the oil and gas industry background. The measurement items of circular economy practices consist of internal environment management, eco-design, and investment recovery (Zhu et al., 2010), sustainability strategies including environment strategy, economic strategy, and society strategy (Wijethilake, 2017), and institutional pressure comprised of coercive pressure, mimetic pressure, and normative pressure (Castro-Lopez et al., 2023) were primarily adapted from the previous literature. The scales adapted from Turker (2009) were used for the items of CSR dimensions including social and non-social stakeholders, employees, customers, and government. Following common studies on firm level, the study employed firm size, firm age, and sector as

control variables (Verwaal et al., 2010; Barba Navaretti et al., 2014; Roxas et al., 2014; Drempetic et al., 2020). Respondents could rate the degree to which they agreed with the listed questions covering social welfare, environmental contributions, sustainable strategies, and institutional pressure.

Table 4.2: Model constructs and measurement items

Second-order constructs	First-order constructs	Code	Measurement items	References
Circular economy practices (CEP)	Internal environment management (IEM)	IEM1	Senior managers commit to environmental management in my company	Zhu et al. (2010)
		IEM2	Mid-level managers support the environmental management in my company.	
		IEM3	There is cross-functional cooperation for environmental improvements in my company.	
		IEM4	My company provides special training for workers on environmental issues.	
		IEM5	My company has total quality environmental management.	
		IEM6	There are environmental auditing programmes such as ISO 14000 certification in my company.	
		IEM7	My company has eco-labelling of products.	
		IEM8	There are pollution prevention programmes such as cleaner production existing in my company.	
		IEM9	The internal performance evaluation system of my company incorporates	

			environmental factors.	
		IEM10	My company generates environmental reports for internal evaluation.	
Eco-design (ED)		ED1	My company designs the products for reduced consumption of material/energy.	
		ED2	My company designs the products for reuse, recycle, recovery of material, and component parts.	
		ED3	My company designs to avoid or reduce use of hazardous products.	
		ED4	My company designs the processes for waste reduction.	
Investment recovery (IR)		IR1	My company sells excess inventories/materials.	
		IR2	My company sells scrap and used materials.	
		IR3	My company sells excess capital equipment.	
		IR4	My company collects and recycles end-of-life products and materials.	
		IR5	My company has established a recycling system for used and defective products.	
Corporate social responsibility (CSR)	Corporate social responsibility to social and non-social stakeholders (CSRS)	CSRS1	My company participates in the activities which aim to protect and improve the quality of the natural environment.	Turker (2009)
		CSRS2	My company makes investments to create a better life for the future generations.	
		CSRS3	My company implements special programs to minimise its negative impact on the natural environment.	
		CSRS4	My company targets sustainable growth which considers the future generations.	
		CSRS5	My company supports the non-	

			governmental organisations to deal with problems.
	CSRS6		My company contributes to the campaigns and projects that promote the well-being of the society.
Corporate social responsibility to employees (CSRE)	CSRE1		My company encourages its employees to participate in the charity and voluntarily activities.
	CSRE2		My company policies encourage the employees to develop their skills and careers.
	CSRE3		The management of my company is primarily concerned with employees' needs and wants.
	CSRE4		My company implements flexible policies to provide a work-life balance for its employees.
	CSRE5		The managerial decisions related to the employees are usually fair in my company.
	CSRE6		My company supports employees who want to acquire additional education.
Corporate social responsibility to customers (CSRC)	CSRC1		My company checks the quality of products provided to customers.
	CSRC2		My company is helpful to customers and advises them about its products.
	CSRC3		My company respects its commitment to customers.
	CSRC4		My company invests in innovations which are to the advantage of customers.
	CSRC5		My company ensures that its products are accessible for all its customers.
Corporate social responsibility to	CSRG1		My company always pays its taxes on a regular and continuing basis.

	government (CSRG)	CSR2	My company always complies with the legal regulations.	
		CSR3	My company tries to help the government in solving social problems.	
Sustainability strategies (SS)	Environmental strategy (ENS)	ENS1	My company has a plan to promote sustainable resource management	Wijethilake (2017)
		ENS2	My company has a plan to reduce emissions into the air, water, and ground.	
		ENS3	My company has a plan to protect and preserve biodiversity.	
		ENS4	My company has a plan to reduce the environmental consequences of products and services.	
	Economic strategy (ECS)	ECS1	My company has a plan to introduce innovations on technology for sustainability.	
		ECS2	My company has a plan to organise employees for sustainability learning and knowledge management.	
		ECS3	My company has a plan to integrate the sustainability in the processes of production, transportation, storage. and sales.	
	Society strategy (SOS)	SOS1	My company has a plan to invest in human resource recruiting and training, and provide competitive salary and welfare for employees.	
		SOS2	My company has a plan to uphold ethical behaviour and protect human rights.	
		SOS3	My company has a plan to promote corporate citizenship (fulfil obligations to society, economy, and environment).	
Institutional	Coercive	CP1	The government requires CE practice from	Castro-Lopez et

pressure (IP)	pressure (CP)		my company.	al. (2023)
		CP2	Regulations require CE practice from my company.	
		CP3	Public organisations require CE practice from my company.	
	Normative pressure (NP)	NP1	Customers recognise the CE practice of my company.	
		NP2	Society expects my company to adapt to CE practice.	
		NP3	Suppliers participate in CE practice in my company.	
		NP4	Other potential partners can be attracted by the CE practice from my company for more collaboration.	
	Mimetic pressure (MP)	MP1	Our main competitors who have adopted CE are benefitted.	
		MP2	Our main competitors who have adopted CE are favourably perceived by other suppliers.	
		MP3	Our main competitors who have adopted CE are favourably perceived by their customers	

4.4 Data analysis and results

4.4.1 Results of the pilot study

4.4.1.1 Questionnaire feedback and modifications

Across the two rounds of pilot study, the questionnaire was distributed to 103 participants from three companies in the oil and gas industry (56 in Pilot 1 and 47 in Pilot 2). As seen in Table 4.3, there were 94 responses, of which 93 were valid (53 from Pilot 1 and 40 from Pilot 2), with an overall valid response rate of 90.3% (93 out of 103). Among all respondents, the completion rate was 98.9% (93 out of 94). Only one questionnaire was incomplete, while the remaining 93 contained no missing data, indicating satisfactory completeness. Moreover, very high or very low scores were not observed, indicating that they were distributed relatively evenly across different questions. This suggests that ideal engagement and the length and completion time of the questionnaire were appropriate.

Table 4.3: Responses in the pilot studies

Pilot study	Invited participants	Valid response	Valid response rate
Pilot 1	53	56	94.6%
Pilot 2	40	47	85.1%
Total	93	103	90.3%

Across the two pilot studies, 13 participants provided feedback via their managers. After removing duplicates, eight main issues related to the questionnaire were identified. As shown in Table 4.4, multiple comments concerned the clarity of some terms or the perceived complexity of some questions. Corresponding modifications were made by adding short explanations or definitions to clarify the questions. In addition to refining the questions, to

minimise potential response bias caused by the contextual framing of variables, the researcher did not specify which items measured independent or dependent variables and changed the order of some sections.

Table 4.4: Participants' feedback and solutions taken

Pilot study	Key issues raised by participants	Solutions
Pilot 1	<p>Terms 'internal environmental management', 'eco-design', and 'investment recovery' are difficult to understand</p> <p>The term 'institutional pressure' is difficult to understand.</p> <p>The term 'corporate social responsibility' is confusing.</p> <p>It is uncomfortable to answer personal information at the beginning.</p> <p>The sections 'circular economy practices' and 'corporate social responsibility' include too many questions and are too complex to complete.</p> <p>Questions 'My company complies with the legal regulations completely and promptly' and 'My company acts legally on all matters' are confusing. They seem to be the same.</p>	<p>Added short explanations to all sections.</p> <p>Added short definitions.</p> <p>Added short explanations to all sections.</p> <p>Moved basic demographic questions to the last section.</p> <p>Split long sections into smaller parts.</p> <p>Removed the latter question.</p>
Pilot 2	<p>The phrase 'promote corporate citizenship' is misunderstanding.</p>	<p>Added short explanations to this question.</p>

All parts of the section ‘corporate social responsibility’ are confusing.	Added short explanations to all parts of the section ‘corporate social responsibility’.
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4.4.2 Results of the main study: Preliminary analysis with measurement model

4.4.2.1 Reliability and validity tests

To examine the latent structure of measurement model, first, SPSS 28.0 was used to conduct an exploratory factor analysis (EFA). As shown in Table 4.5, using maximum likelihood and varimax rotation, the EFA produced a 13-factor solution. Meanwhile, the cumulative variance explained a total of 62.562% of the variance with all eigenvalues higher than 1, showing a positive explanatory power (Fabrigar, 1999). To test whether the sample size ($n=430$) is sufficient for a 13-factor solution, the Kaiser–Meyer–Olkin (KMO) score was checked and reached 0.955, which was well above the threshold of 0.5, indicating that the study’s sample is adequate for factor analysis (Kaiser, 1974). In addition, all the factor loadings in Table 4.5 were statistically significant, supporting the strong associations among the constructs.

	IR3	0.704	
	IR4	0.671	
	IR5	0.617	
Corporate social	CSRS1	0.710	
responsibility to	CSRS2	0.678	
social and non-social	CSRS3	0.680	
stakeholders	CSRS4	0.664	
(CSRS)	CSRS5	0.712	
	CSRS6	0.680	
Corporate social	CSRE1		0.667
responsibility to	CSRE2		0.638
employees (CSRE)	CSRE3		0.639
	CSRE4		0.704
	CSRE5		0.639
	CSRE6		0.627
Corporate social	CSRC1		0.662
responsibility to	CSRC2		0.666
customers (CSRC)	CSRC3		0.656
	CSRC4		0.693
	CSRC5		0.701
Corporate social	CSRG1		0.699

responsibility to	CSR2	0.670		
government (CSRG)	CSR3	0.623		
Environmental strategy (ENS)	ENS1		0.708	
	ENS2		0.656	
	ENS3		0.616	
	ENS4		0.685	
Economic strategy (ECS)	ECS1		0.686	
	ECS2		0.670	
	ECS3		0.588	
Society strategy (SOS)	SOS1			0.689
	SOS2			0.613
	SOS3			0.655
Coercive pressure (CP)	CP1			0.714
	CP2			0.624
	CP3			0.714
Mimetic pressure	MP1			0.667

(MP)													
	MP2												0.690
	MP3												0.681
	MP4												0.687
Normative pressure	NP1												0.682
(NP)													
	NP2												0.543
	NP3												0.700

Eigenvalue	6.889	3.971	3.624	3.207	3.153	2.570	2.433	2.363	2.200	1.933	1.795	1.758	1.642
% of Variance	11.481	6.618	6.039	5.345	5.255	4.284	4.055	3.938	3.667	3.221	2.992	2.930	2.737
Cumulative %	11.481	18.099	24.138	29.483	34.73	39.021	43.076	47.015	50.682	53.903	56.895	59.825	62.562

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Extraction Method: Maximum Likelihood.

Rotation Method: Varimax with Kaiser Normalisation.

Rotation converged in eight iterations.

Next, a confirmatory factor analysis (CFA) was conducted for convergent validity and the discriminant validity test of the model using Amos 29 (see Table 4.6 and Table 4.7). The Cronbach's alpha for all constructs ranged from 0.809 to 0.946, while the values of composite reliability (CR) ranged from 0.810 to 0.946, which were all over the cut-off point of 0.7 (Cronbach, 1951; Hair et al., 2010). Thus, the reliability and convergent validity were confirmed to be acceptable. The threshold of each index is as follows: The comparative fit index (CFI), the incremental fit index (IFI), the Tucker–Lewis index (TLI), and the goodness of fit index (GFI) should be all above 0.9, and the root mean square error of approximation (RMSEA) should be less than 0.05 to be considered good (Hu and Bentler, 1999). According to Table 4.6, CFI (0.986), IFI (0.987), and TLI (0.985) were all ideally higher than 0.9, and RMSEA (0.017) was less than 0.05. GFI (0.880) was less than 0.9 but still can be considered reasonable (Doll et al., 1994; Byrne, 2001). Overall, it can be concluded that the measurement model had a satisfactory model fit.

Table 4.6: Results of the confirmatory factor analysis for the first-order measurement model

Model construct	Items	Loadings	Cronbach's alpha
Internal environment management	IEM1	0.800	0.946
	IEM2	0.792	
	IEM3	0.808	
	IEM4	0.798	
	IEM5	0.811	

	IEM6	0.781	
	IEM7	0.815	
	IEM8	0.815	
	IEM9	0.792	
	IEM10	0.781	
Eco-design	ED1	0.784	0.856
	ED2	0.770	
	ED3	0.773	
	ED4	0.766	
Investment recovery	IR1	0.775	0.870
	IR2	0.747	
	IR3	0.757	
	IR4	0.766	
	IR5	0.738	
Corporate social responsibility to social and non-social stakeholders	CSRS1	0.791	0.904
	CSRS2	0.776	
	CSRS3	0.786	
	CSRS4	0.769	
	CSRS5	0.789	
	CSRS6	0.778	
Corporate social responsibility to employees	CSRE1	0.777	0.897
	CSRE2	0.772	
	CSRE3	0.759	
	CSRE4	0.775	
	CSRE5	0.769	
	CSRE6	0.762	
Corporate social responsibility to customers	CSRC1	0.762	0.876
	CSRC2	0.731	
	CSRC3	0.784	
	CSRC4	0.782	
	CSRC5	0.772	
Corporate social responsibility to government	CSRG1	0.789	0.839
	CSRG2	0.833	

	CSRG3	0.768	
Environmental strategy	ENS1	0.807	0.875
	ENS2	0.804	
	ENS3	0.781	
	ENS4	0.798	
Economic strategy	ECS1	0.765	0.809
	ECS2	0.817	
	ECS3	0.714	
Society strategy	SOS1	0.771	0.819
	SOS2	0.759	
	SOS3	0.794	
Coercive pressure	CP1	0.784	0.819
	CP2	0.739	
	CP3	0.805	
Mimetic pressure	MP1	0.770	0.857
	MP2	0.783	
	MP3	0.769	
	MP4	0.775	
Normative pressure	NP1	0.824	0.832
	NP2	0.741	
	NP3	0.809	
Model fit: $\chi^2 = 1773.104$ ($p < 0.05$); $df=1574$, $\chi^2/df = 1.126574$; $GFI=0.880$; $CFI = 0.986$; $IFI = 0.987$; $TLI = 0.985$; $RMSEA = 0.017$.			

The average variance extracted (AVE), and the maximum shared variance (MSV) were assessed to ensure the convergent validity and discriminant validity of the data. The AVE for each construct should be above the cut-off point of 0.5 and below the corresponding CR (Hair et al., 2011). Meanwhile, the square roots of AVE should be higher than the correlation coefficients, and all the values of AVE should be higher than corresponding MSV (Fornell and Larcker, 1981).

Based on these thresholds, as shown in Table 4.7, all AVEs met the criteria (higher than 0.5), while each square root of AVE was higher than its corresponding highest correlation coefficient. In addition, all AVEs were higher than their corresponding MSV. Consequently, the results of AVE, MSV, and the square root of AVE presented an acceptable discriminant validity (Fornell and Larcker, 1981; Tavakol and Dennick, 2011).

Table 4.7: Results of discriminant validity for the first-order measurement model

	CR	AVE	MSV	ED	CSRS	CSRE	CSRC	CSRG	ENS	ECS	SOS	NP	MP	CP	IR	IEM
ED	0.856	0.598	0.364	0.773												
CSRS	0.904	0.611	0.320	0.446	0.782											
CSRE	0.897	0.591	0.326	0.571	0.566	0.769										
CSRC	0.877	0.587	0.321	0.497	0.522	0.533	0.766									
CSRG	0.839	0.636	0.321	0.395	0.522	0.497	0.567	0.797								
ENS	0.875	0.636	0.301	0.480	0.546	0.502	0.506	0.549	0.798							
ECS	0.810	0.587	0.295	0.518	0.405	0.543	0.382	0.396	0.461	0.766						
SOS	0.818	0.600	0.292	0.501	0.522	0.484	0.516	0.486	0.540	0.509	0.775					
NP	0.834	0.627	0.297	0.532	0.502	0.473	0.428	0.450	0.478	0.404	0.476	0.792				
MP	0.857	0.600	0.291	0.433	0.481	0.511	0.392	0.380	0.501	0.496	0.480	0.539	0.775			
CP	0.820	0.603	0.291	0.442	0.420	0.422	0.341	0.398	0.439	0.465	0.505	0.539	0.469	0.777		
IR	0.870	0.573	0.312	0.559	0.387	0.469	0.390	0.304	0.461	0.478	0.364	0.441	0.384	0.297	0.757	
IEM	0.946	0.639	0.364	0.603	0.511	0.561	0.476	0.492	0.515	0.472	0.533	0.545	0.453	0.442	0.524	0.799

CR=Composite reliability, AVE=average variance extracted, MSV= maximum shared variance.

The values in bold are the square root of the AVEs.

4.4.2.2 Common method bias

To remedy potential common method bias (CMB), both procedural and statistical approaches were used in this study. Prior to formal data collection, two pilot studies were run to optimise the questionnaire design. First, at the beginning of each pilot study and the formal survey, all participants were clearly informed that the questionnaire would be anonymous, which could reduce their concerns and encourage honest responses. Second, feedback from the pilot studies indicated that the length and completion time of the questionnaire was appropriate and acceptable, showing no need to worry that the respondents may feel significantly impatient and provide random responses. Short explanations for some terms and questions were also added. These steps reduce the participants' concerns that may inflate CMB. For the statistical check, the CMB was tested with the Harman single factor method and the results showed that the first factor explained 11.481% of the total variance, which was well below the threshold of 50% (Harman, 1967; Kock et al., 2021). Thus, it can be concluded that the CMB was unlikely a serious issue in this study.

4.4.2.3 Assessment of multicollinearity

In this study, the second-order constructs of CEP, SS, and IP were established for subsequent SEM analysis. To test the validity of these higher-order constructs, it is

essential to examine the significance of the weights from all the first-order constructs, the second-order constructs, and multicollinearity (Hair et al., 2014).

As shown in Table 4.8, all weights from the various first-order constructs to the second-order constructs were significant ($p < 0.01$), while the variance inflation factor (VIF) showed that there was no multicollinearity between the first-order constructs and their corresponding second-order constructs as the VIF values were all less than the suggested critical threshold of 3.0, ranging from 1.494 to 1.795, 1.459 to 1.557, and 1.512 to 1.698, respectively (Hair et al., 2019). Furthermore, all the sets of indicators for second-order construct model fit met the conventional evaluation requirements in Table 4.8 (Hu and Bentler, 1999; Chatterjee and Hadi, 2015). Thus, all three second-order construct model fits are ideal and acceptable. Therefore, the next step was to use the second-order constructs of CEP, SS, and IP in the SEM.

Table 4.8: Assessment of multicollinearity for the second-order construct

Second-order construct	Dimensions/First-order construct	Weights	VIF
Circular economy practices (CEP)	Internal environment management (IEM)	0.752***	1.613
	Eco-design (ED)	0.801***	1.494
	Investment recovery (IR)	0.697***	1.795
Model fit: $\chi^2 = 185.743$ ($p < 0.05$); $df=149$, $\chi^2/df = 1.247$; $GFI=0.957$; $CFI = 0.993$; $IFI = 0.993$; $TLI = 0.992$; $RMSEA = 0.024$. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, ns = not significant.			
Sustainability strategies (SS)	Environmental strategy (ENS)	0.702***	1.513
	Economic strategy (ECS)	0.660***	1.557
	Society strategy (SOS)	0.771***	1.459

Model fit: $\chi^2 = 44.615$ ($p < 0.05$); $df=32$, $\chi^2/df = 1.394$; $GFI=0.980$; $CFI = 0.993$; $IFI = 0.994$; $TLI = 0.991$; $RMSEA = 0.030$. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, ns = not significant.

Institutional pressure (IP)	Coercive pressure (CP)	0.684***	1.632
	Mimetic pressure (MP)	0.685***	1.698
	Normative pressure (NP)	0.785***	1.512

Model fit: $\chi^2 = 40.151$ ($p < 0.05$); $df=32$, $\chi^2/df = 1.255$; $GFI=0.982$; $CFI = 0.996$; $IFI = 0.996$; $TLI = 0.994$; $RMSEA = 0.024$. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, ns = not significant.

4.4.3 Results of the main study: Main analysis with structural equation model

Two models were established to test the direct effects of CEP on CSR (SEM 1), the moderating effects of SS on CEP and CSR, and the indirect moderating effects of IP on CEP and CSR via SS (SEM 2). The SEM 1 yielded a good model fit: $\chi^2 = 16.616$ ($p < 0.05$; $\chi^2/df = 2.374$; $GFI=0.975$; $CFI = 0.994$; $IFI = 0.994$; $TLI = 0.974$; $RMSEA = 0.032$). The results of SEM 1 showed that there was a positive relationship between CEP and CSRS ($\beta=0.796$, $p<0.01$). Thus, H1(a) is supported. Moreover, CEP was positively associated with CSRE ($\beta=0.684$, $p<0.01$) which supports H1(b). The positive impact of CEP on CSRC ($\beta=0.687$, $p<0.01$) also indicated that H1(c) is supported. Finally, H1(d) was supported by the significant and positive path coefficients of CEP and CSRG ($\beta=0.640$, $p < 0.01$). These results confirmed the positive and significant impact of CEP on CSR and supported that CEP can contribute to the implementation of different dimensions of CSR. Table 4.9 shows the results of the SEM

models and the results of each hypothesis.

Table 4.9: Results of SEM models

Model	Hypothesis	Hypothesised paths	Estimates	Results
SEM 1	Hypothesis 1(a)	CEP→CSRS	0.796***	Supported.
	Hypothesis 1(b)	CEP→CSRE	0.684***	Supported.
	Hypothesis 1(c)	CEP→CSRC	0.687***	Supported.
	Hypothesis 1(d)	CEP→CSRG	0.640***	Supported.
Model fit for SEM 1: $\chi^2 = 16.616$ ($p < 0.05$); $df=7$; $\chi^2/df = 2.374$; $GFI=0.975$; $CFI = 0.994$; $IFI = 0.994$; $TLI = 0.974$; $RMSEA = 0.032$. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, ns = not significant.				
SEM 2	Hypothesis 2	IP→SS	0.973***	Supported.
	Hypothesis 3(a)	SS×CEP→CSRS	0.189**	Supported.
		SS×CEP→CSRE	-0.078 ^{ns}	Not supported.
		SS×CEP→CSRC	0.333***	Supported.
		SS×CEP→CSRG	0.347***	Supported.
	Hypothesis 4(a)	IP×CEP → CSRS	-0.182 ^{ns}	Supported.
		SS×CEP→CSRS	0.189**	
		IP→SS	0.973***	
	Hypothesis 4(b)	IP×CEP → CSRE	0.322 ^{ns}	Not supported.
		SS×CEP→CSRE	-0.078 ^{ns}	
		IP→SS	0.973***	
	Hypothesis 4(c)	IP×CEP → CSRC	0.131 ^{ns}	Supported.
		SS×CEP→CSRC	0.333***	
		IP→SS	0.973***	
	Hypothesis 4(d)	IP×CEP → CSRG	0.040 ^{ns}	Supported.
		SS×CEP→CSRG	0.347***	
IP→SS		0.973***		
Model fit for SEM 2: $\chi^2 = 65.046$ ($p < 0.05$); $df=23$; $\chi^2/df = 2.828$; $GFI=0.977$; $CFI = 0.993$; $IFI = 0.993$; $TLI = 0.980$; $RMSEA = 0.035$. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$, ns = not significant.				

The model fit for SEM 2 was also acceptable: $\chi^2 = 65.046$ ($p < 0.05$); $\chi^2/df = 2.828$; GFI=0.977; CFI = 0.993; IFI = 0.993; TLI = 0.980; RMSEA = 0.035. Based on Van Kollenburg and Croon (2017), as H4(a) (b) (c) and (d) assumed that the IP had indirect moderating effects on CEP to CSRS, CSRE, CSRC, and CSRG via SS, SS was the true moderator which influenced the relationships between CEP and CSRS, CSRE, and CSRC and CSRG. Thus, the moderation tests were carried out, focusing the significance of SS on the path of CEP to CSR first.

To assess the moderating effect of SS and the indirect moderating effect of IP, the interaction items of SS×CEP, IP×CEP, and direct effects of IP→SS were added in the structural equation model (SEM 2, see Table 4.9). The results of SEM 2 showed that the interaction item SS×CEP was positively and significantly related to CSRS ($\beta=0.189$, $p < 0.05$). Thus, Hypothesis 3(a) is supported. In terms of Hypothesis 3(c), the interaction item SS×CEP was positively and significantly related to CSRC ($\beta=0.333$, $p < 0.01$). Thus, Hypothesis 3(c) is supported. Similarly, the interaction item SS×CEP was positively and significantly related to CSRG ($\beta=0.347$, $p < 0.01$). Thus, Hypothesis 3(d) is supported. However, Hypothesis 3(b) is not supported as the interaction items SS×CEP was not significant ($\beta=-0.078$, $p > 0.1$). Specifically, simple slope analysis showed that the positive influence is steeper under high SS than that under low SS, while both high SS and low SS had positive influences. These findings demonstrate that the effect of high SS (strict and detailed SS) is greater than low SS (loose and simple SS). In addition, when firms adopted high SS or low SS, the relationships between CEP and

CSRS, CSRC, and CSRG were all positive (respectively, $\beta=0.189$, $p < 0.05$; $\beta=0.333$, $p < 0.01$; and $\beta=0.347$, $p < 0.01$). These results confirmed the above moderations. In other words, provided that SS could be adopted in the firms, the relationships between CEP and CSRS, CSRC, and CSRG can be positively moderated. These effects of CEP on these aspects of CSR increase when firms confirm their duty to social responsibilities and embed it into their SS. However, the relationship between CEP and CSRE was not significant regardless of the extent to which SS was implemented ($\beta=-0.078$, $p > 0.1$).

To further verify the interactions for the moderating effects of H3(a), H3(c), and H3(d), a simple slope analysis was conducted and displayed in Figures 4.2, 4.3, and 4.4. These figures show that all slopes from low SS to high SS are positive, and there was always a larger increase for the moderating effect of SS at a high level (strict and detailed) on the relationships between CEP and CSRS, CSRC, and CSRG than it was at low level. Except for this, it can also be observed from the figures that the influence of SS on CEP–CSRS was a little higher than the other two. Thus, all moderating effects of SS in H3(a), H3(c), and H3(d) were confirmed.

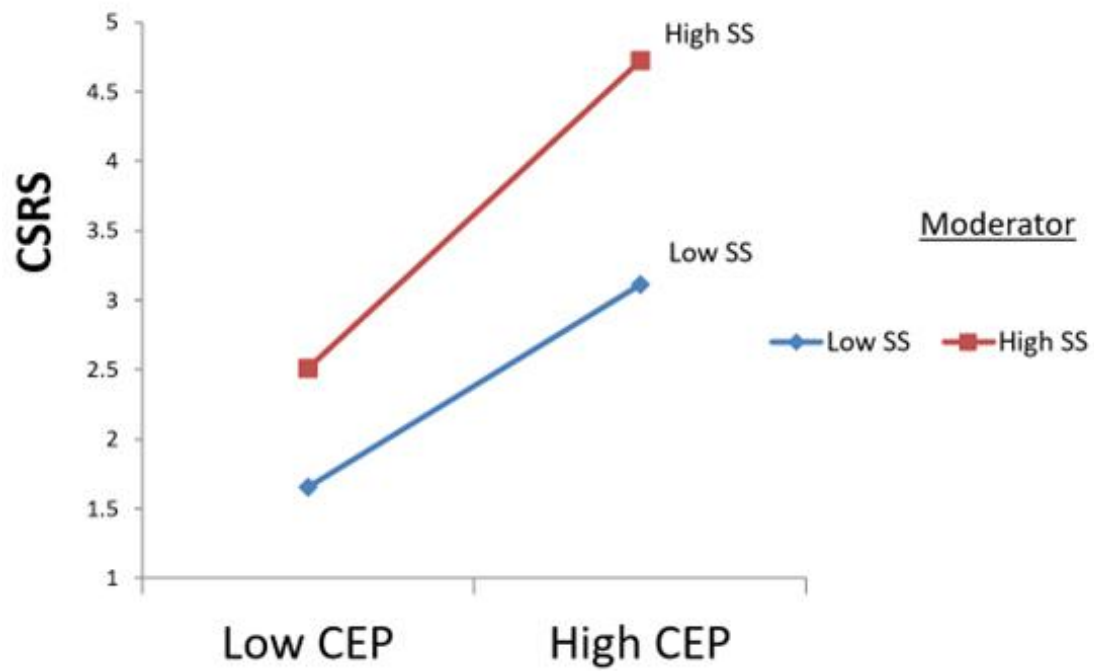


Figure 4.2: Moderating effect of SS between CEP and CSRS.

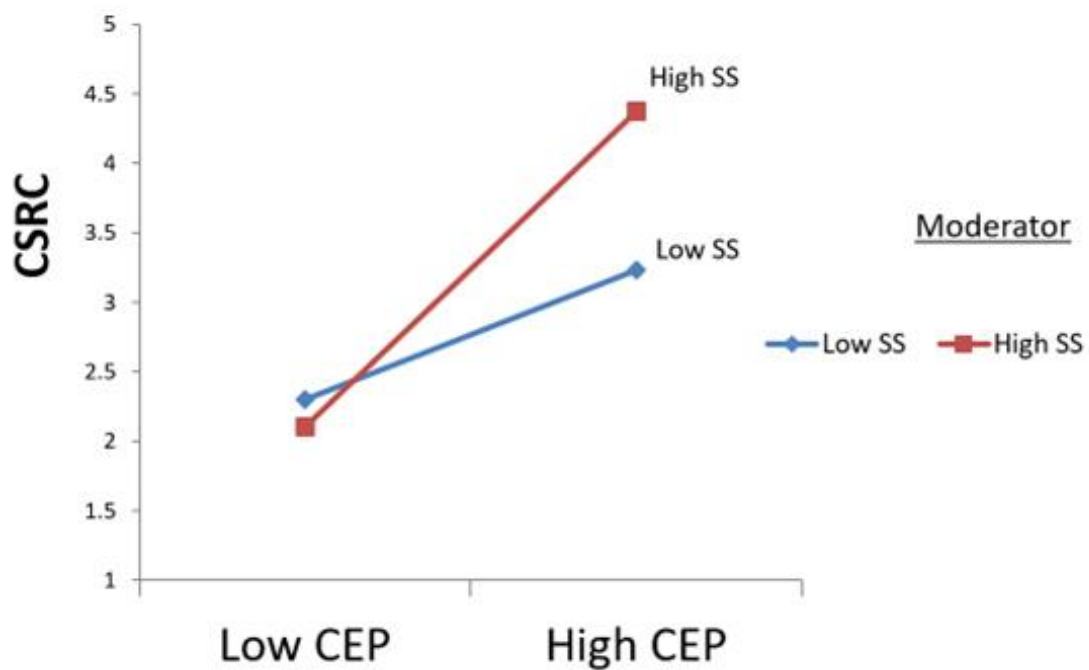


Figure 4.3: Moderating effect of SS between CEP and CSRC.

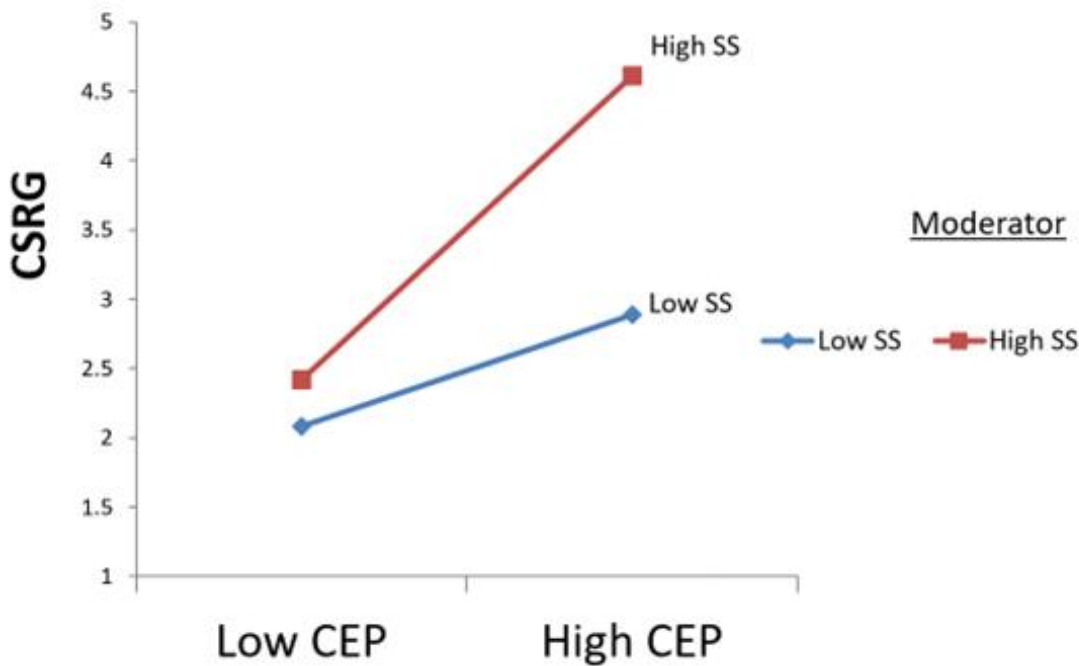


Figure 4.4: Moderating effect of SS between CEP and CSRG.

To test the indirect moderation of IP, the direct effect of IP→SS and two interactions of SS×CEP and IP×CEP was jointly analysed. Prior to analysing the interactions, it was noted that the IP was positively and significantly related to SS ($\beta=0.973$, $p<0.01$). Thus, H2 is supported. For H4(a), Table 4.9 indicated that IP had an indirect moderating effect on the relationship between CEP and CSRS. As can be seen from Table 4.9, whereas the interaction items SS×CEP of indirect moderating effect were significant ($\beta=0.189$, $p<0.01$) for their relationship, the interaction items IP×CEP of indirect moderating effect was not significant ($\beta=-0.182$, $p>0.1$). Regarding H4(c), the interaction items SS×CEP of indirect moderating effect was significant ($\beta=0.333$, $p<0.01$) for the relationship between CEP and CSRC, while the interaction items IP×CEP of indirect moderating effect were not significant ($\beta=0.131$, $p>0.1$). The results for

H4(d) yielded a similar significance for SS×CEP ($\beta=0.347$, $p < 0.01$) and IP×CEP ($\beta=0.040$, $p > 0.1$). However, IP had neither a direct moderating effect nor an indirect moderating effect on the relationship between CEP and CSRE as the model results do not present any significances for both interactions SS×CEP ($\beta=-0.078$, $p > 0.1$) and IP×CEP ($\beta=0.322$, $p > 0.1$), although the path from IP to SS is significant and positive ($\beta=0.973$, $p < 0.01$). Based on the above results, to sum up, H2, H4(a), H4(c), and H4(d) are supported, and H4(b) is not supported (see Table 4.9).

4.4.4 Discussion and findings

Guided by the MRCS and institutional theory, this research examines the mechanisms between CEP, SS, IP, and CSR. Specifically, it identifies the direct effects of CEP on four CSR dimensions and tested whether SS strengthens these effects and whether IP influences them indirectly via SS. Most of the research hypotheses are supported, while a few are unsupported, yielding several meaningful findings.

Hypothesis H1 explores the impact of CEP on CSR. The model results show that CEP can enhance CSR on all dimensions of social and non-social stakeholders (H1a), employees (H1b), customers (H1c), and government (H1d). The concrete practices such as providing training for employees, adopting internal environmental management, and designing eco-friendly products enable firms to fulfil their social responsibilities related to encouragement of education and skills, reduction of waste, and product innovation,

respectively. This finding aligns with previous studies demonstrating that CE initiatives contribute positively to CSR in various aspects (Hong et al., 2024; Zhang and Li., 2025).

Hypothesis H3 proposed that SS has a moderating effect on the relationships between CEP and CSR. The results indicate that SS strengthens the positive relationships between CEP and CSRS (H3a), CSRC (H3c), and CSRG (H3d). As specific practices that help firms in the transition process towards CE, CEP can be influenced by the firm's long-term sustainable development strategies. This helps them to better uphold CSR and improve their performance on economic, environmental, and social dimensions. Nevertheless, SS cannot strengthen all relationships as expected. Specifically, SS does not moderate the relationship between CEP and CSRE (H3b). This may be attributable to the latent tendencies within firms to prioritise external responsibilities. More specifically, firms may allocate limited resources to external responsibilities to enhance reputation and meet stronger external requirements instead of internal ones (Neubaum et al., 2012; Thomas et al., 2022; Siems et al., 2023). In the situations where resources and investments are limited, firms tend to prioritise meeting the needs of external stakeholders, as benefits such as enhancing external reputation, brand image, and legal compliance are greater compared to meeting the internal ones. Although this is a strategic decision, it also represents decoupling from the perspective of employees, as firms neglect to fulfil their commitment and responsibilities to the staff. By contrast, CSRE may depend more on internal human resource management rather than on SS. As a result, the needs from internal employees such as comfortable and supportive work environment, satisfactory welfare, and progressive education are not always prioritised,

and tend to be substituted with those from external stakeholders.

Hypothesis H3 posits that IP has a positive impact on SS. The evidence indicates that the pressures from regulations, laws, markets, and competitors encourage and promote the design and implementation of SS. H4 further tests the indirect moderating effect of IP on the relationships between CEP and CSR via SS. Although IP does not moderate the relationships directly, it has an indirect moderating effect on CSRS, CSRC, and CSRG via SS. This is also supported by previous studies that external pressures can be converted into internal strategies' response (Dai et al., 2021; Gunarathne et al., 2021; Zhou et al., 2023; Lee et al., 2024). SS acts as a lever during this process, especially when firms face strong external requirements and need to focus more on external stakeholders. Consistent with H2, IP indirectly moderates the positive relationships between CEP and CSRS (H4a), CSRC (H4c), and CSRG (H4d) via SS, while there is no indirect moderation between CEP and CSRE. This is because SS does not play a moderating role in the relationships between CEP and CSR. Consequently, IP cannot affect them indirectly through SS when the direct moderation is absent. As H2(a), H2(c), and H2(d) suggest, firms can independently develop SS by providing guidance on the implementation of CEP towards CSR even without IP. However, the existence of IP can drive firms to develop and adopt SS with higher efficiency, thereby accelerating this process.

4.5 Contributions

This study examines how SS and IP synergistically impact on the relationships between CEP and CSR in the Chinese oil and gas industry. Building on the MRCS and institutional theory, it proposes that firms embed their duty to sustainability into SS, and this process can be positively influenced by IP. To investigate the relationships among the variables and verify the initial hypotheses, two models are tested using 430 valid responses. The empirical analysis results show that (i) CEP is positively associated with all CSR aspects; (ii) SS directly moderates the effects of CEP on CSRS, CSRC, and CSRG; and (iii) IP does not directly moderate the relationships between CEP and CSR but indirectly moderates these paths by promoting SS. Not all dimensions of CSR benefit, as the responsibility to employees fails to improve through the participation of the moderators. Hence, this study contributes to a more comprehensive understanding of the roles of CEP and SS on CSR under IP. Next, managerial implications are provided for decision makers who apply SS, building the foundation for further research on the influence of strategies on overall CSR at the firm level. Theoretical contributions and managerial implications are discussed in Section 5.1 and Section 5.2, respectively.

4.5.1 Theoretical contributions

This study makes three primary theoretical contributions. First, the research adds to the current literature by identifying the mechanisms among IP and SS to CSR. Based on the analysis results, the performance of CSR can be noticeably improved through the SS

formed from the pressure of institutions. Firms manage to improve their ability to fulfil their social responsibilities by adopting CEP, and SS plays a positive moderating role during this process. The introduced SS can provide detailed guidance for corporate behaviour and urge management to gradually implement in the strategy context. This study fills that gap by examining the indirect moderating effect of IP on the relationships among SS, CEP and CSR. The results show that the indirect moderating effect of IP between CEP and CSR operates through its influence on SS. External pressures are converted into internal corporate strategies, which then promote the positive impact of CEP on CSR. This implies that the existence of IP first encourages companies to formulate sustainable strategies in the aspects of environment, economy, and society, and then through the practical implementation of these strategies to better fulfil the various responsibilities.

Second, this research extends the application of the MRCS to the fields of CE and CSR. It demonstrates that when firms treat sustainability as their duty and realise it through SS, CEP becomes more reliable to achieve CSR results. Regardless of whether the SS adopted by the firm is loose or detailed, the implementation of CEP will always help to enhance their CSR. The effects hold across most CSR aspects with external stakeholders. For companies seeking to improve their CSR, this research highlights the importance of converting clear goals into detailed SS during this process. So far, no literature has explored the role of SS in the relationships between CEP and CSR based on this theoretical lens, which makes the present findings valuable.

Third, the research reveals the heterogeneous effects of SS on the relationships between CEP and CSR. SS strengthens the impact of CEP on CSR on external aspects but not on internal aspects of employees. To the best of the author's knowledge, no studies identify the failure of SS or IP on CSRE in the fields. Thus, this research provides novel insights by locating the invalidation mechanism of SS and IP. When companies place more emphasis on the values from external stakeholders including society, customers, and government, they may overlook responsibilities to their own employees even under institutional pressure. In other words, current sustainable strategies focus on the external stakeholders and may draw resources away from internal staff, which will result in gaps of responsibilities to employees.

4.5.2 Managerial implications

This study also provides managerial implications for managers and decision makers on how to coordinate CEP, SS, and IP to more effectively achieve CSR. First, in terms of external stakeholders, due to the complexity of the institutional environment, firms face institutional pressure from markets, industries, media, and the public. The results show that, overall, IP and SS can help companies improve their CSR in the process of implementing CEP, but these effects do not extend to all CSR dimensions because no moderation is observed for CSRE. Since governments, regulations, and markets apply pressure on firms, decision makers may prioritise strategies that meet the needs and appeals of these external influencers for firms when designing future strategies and

subsequent implementation. Therefore, it is recommended that governments and regulators should include more indicators related to employees such as essential training projects, fair pay, welfare support, internal promotion rate, and anonymous feedback channels in disclosure rules and rating schemes, utilising their high visibility for firms as external stakeholders. This helps to shift firms away from only focusing on external stakeholders towards more engagement with internal employees.

Second, in terms of firms, decision makers should recognise their responsibility towards their employees. When institutional pressure is weak, companies can still adopt CEP to improve their responsibilities to employees such as via higher welfares benefits and more educational opportunities. However, when the institutional pressure increases, they fail to be pushed to improve their responsibility to employees under the influence of pressure. This should serve as a warning for decision makers, because employees are also a core part of CSR. This study suggests that firms should apply balanced SS that allocate resources to both external stakeholders and internal employees. In practice, firms can establish a separate budget program specially for employees, allowing continued fund support even when institutional pressure increases and firms' attention turns to external stakeholders. Employees are a core resource for companies to gain benefits, transform, and even survive.

4.5.3 Limitations and future research

This study has some limitations that also provide new future research directions. The first limitation is related to external validity. As all the respondents are from the Chinese oil and gas industry, the corporate ownership structure and unique regulatory framework may influence employees' understanding of CEP, SS, IP, and CSR. Future studies should expand the sample scale with multiple industries or countries to generalise the findings. Second, the findings show that, although CEP is positively associated with all four dimensions of CSR, the moderation of SS or IP cannot be observed for CSRE. The responsibilities to employees such as payment, welfare, education opportunities, and equities are one of the most important aspects of CSR (Bučiūnienė and Kazlauskaitė, 2012; Liu et al., 2019; Asante Boadi et al., 2020). A limitation of this study is that it does not explore the reasons why SS and IP have no influence on CEP and CSRE. Thus, future studies can further investigate the failure of SS and IP to influence CEP and CSR. Third, the research focuses on the IP and SS but does not model other internal factors such as organisational culture (Kwarteng et al., 2022), company systems (Marco-Fondevila et al., 2018), and innovation and collaboration capabilities (Baah et al., 2023) as which may also influence CEP and CSR. Given the complexity of the impact mechanism, such internal pressure may exist and affect decisions regarding CSR. Future studies can include more potential factors to investigate additional influences. Finally, the results show that CSRE cannot be enhanced by SS, while firms tend to place more emphasis on external stakeholders. When external stakeholders are prioritised, attention and resources towards employees may be relocated away, which is the direct opposite of the original purpose of CSR. Accordingly, another meaningful avenue for future studies is to explore how firms can achieve balance in different stakeholders to promote

sustainable development.

Chapter 5

Conclusion

5.1 Summary of this thesis

This research focuses on the current state of the implementation of Industry 4.0 technologies, CE and CSR in the oil and gas industry. More specifically, this thesis consists of three different studies, with a SLR on the application of Industry 4.0 technologies for CE, two empirical studies on the relationships among the application of Industry 4.0 technologies, CEP and CSR, and how SS and IP play their roles between CEP and CSR in the oil and gas sector in China.

Chapter 2 reviews the extant literature systematically in the field of Industry 4.0 and CE, with a pool of 60 eligible papers from 2013 to 2024 in the oil and gas sector. These included papers are selected following a structured series of approaches including keywords, publication year, titles, abstract and detailed content analysis along with the core concepts of Industry 4.0 and CE. We provide both descriptive and in-depth assessment of the topic related to Industry 4.0 technologies applied in the oil and gas industry. Although some previous studies have investigated the application of Industry 4.0 technologies and CE, none of them explored it in the oil and gas industry. Thus, our study fills in this literature gap.

The chapter provides a holistic overview on how Industry 4.0 technologies like artificial

intelligence and the Internet of Things are applied in the oil and gas sector, with more comprehensive understand of definitions and explanations of each categorised Industry 4.0 technology. Additionally, we also uncover the challenges that the application of Industry 4.0 technologies is facing with, of those the central important obstacle is from institutions. Along the same lines, we find out that the Industry 4.0 technology adoption can benefit all economic, environmental and social aspects in the oil and gas industry.

In our analysis, we also identify several research directions based on the research gap analysis. For instance, researchers can go further targeted investigation on different segments of the sector, such as upstream and midstream, providing a more nuanced understand of dynamics of different streams. Also, from the perspective of technology, specific technology can be focused individually to investigate its contributions to the CE. Moreover, as most studies focused on the economic and environmental benefits of CE, scholars can attempt to examine the social contributions. This chapter provide insights for scholars and practitioners in the oil and gas industry, revealing the benefits of Industry 4.0 technologies for the economy, environment, and society for them.

Chapter 3 focuses on the relationships among the application of Industry 4.0 technologies, CEP and CSR. Based on the findings of literature review in chapter 2, it has been observed that the firm's economic, environmental and social performance can be enhanced through the support of Industry 4.0 technology applications and CE methods. Despite this, few studies considered the pathway that how Industry 4.0 technologies affect firm's CSR via CEP. To address this gap in the literature, this chapter

aims to conduct an empirical analysis of the impact of the application of Industry 4.0 technologies on the CSR through CEP.

To this end, we deliver a questionnaire to 155 companies in all different sectors in the oil and gas industry in China with the instruments adapted from established scales applied in extant studies, attempting to identify which aspects of the technology innovation and upgradation can have positive or negative influence when companies are using the Industry 4.0 technologies to facilitate the CSR. The findings indicate that the application of Industry 4.0 technologies exert a positively impact on firms' CSR, which is in line with previous studies (Govindan, 2022; Cricelli et al., 2024; Hossain et al., 2024). However, the impact cannot go across all aspects of CSR. Specifically, the impact of technology management on CSRS and CSRG is found to be insignificant. Also, the findings reveal that CEP plays both crucial mediating and suppressing role between the relationship of the application of Industry 4.0 technologies and CSR. This is inconsistent with our initial expectations during the hypothesis development stage. We further identify that some positive paths between Industry 4.0 technology application and CSR are not merely consequences of the direct effect of Industry 4.0 technology application on CSR but arise through a joint effect including both direct effect and the mediating of suppressing effect of CEP.

Chapter 4 shifts focus on the relationships between CEP and CSR, and two additional variables that IP and SS are introduced and embedded into the model to investigate the mechanisms deeply. Building upon the findings of the previous chapter, this chapter

extends the scope of the study by exploring the impact of SS and IP on the relationships between CEP and CSR. To investigate the relationships and verify our hypothesis, we design and collect data from 155 companies in the oil and gas industry in China. Our data analysis results demonstrate that CEP can affect CSR positively, and SS has positive moderating effect on the relationships between CEP and some dimensions of CSR. Meanwhile, IP has an indirect moderating effect on the relationships between CEP and CSR via SS.

However, as shown by the empirical evidence, SS cannot moderate all CEP-CSR relationships as we expect. Specifically, SS does not positively affect the relationship between CEP and CSRE. Likewise, IP fail to moderate indirectly the relationship between CEP and CSRE via SS. As external stakeholders such as customers, non-governmental organizations and government are emphasized more significantly to firms' external reputation, they tend to prioritize investment into these rather than employees. This research argues that CEP, as a specific set of initiatives that help firms in the transition process towards CE, can be influenced by the mediation of firm's long-term sustainable development strategies under the pressure of institutions, and contribute to the promotion of CSR.

This thesis provides insights on the mechanisms of the application of Industry 4.0 technologies, CEP and CSR, and contributes to a more comprehensive understanding of the roles of CEP with the mediation of SS and IP. Our findings suggest several managerial implications. Practitioners should align Industry 4.0 technologies with CEP

to better uphold CSR and improve their performance on economic, environmental and social dimensions. Meanwhile, to support this transition effectively, adopting long-term strict and detailed sustainable strategies is essential. Notwithstanding the value of our contributions, this study still has some limitations. Due to the constraints of the selected industry type, geographic location, research questions and objectives, the findings of this study may not be generalizable to other countries or industries. Subsequent studies can be built upon this research to explore further.

5.2 Limitation and future directions

Despite significant findings and contributions, this thesis has limitations that also provide directions for future research. First, the SLR in this thesis is only based on two databases Scopus and Web of Science, and only journal papers are included for analysis. Although there may be duplicated records from different databases, it is possible that some other relevant research exists beyond those included ones. Grey literature or technical papers are excluded from the analysis, potentially missing some valuable practical insights. In addition, some relevant search strings such as ‘close loop economy’ or ‘reverse supply chain’ are not included, which may limit the scope of the literature. Hence, opportunities remain to strengthen this study with other databases and types of sources.

Second, this thesis focuses merely on the firms in China’s oil and gas industry, which

may lead to threats to external validity for this research. Regarding the questionnaire responses, although the industry experts have been invited to review and edit and two pilot studies have been conducted to refine the understanding, it is difficult to avoid the possibility that Chinese corporate ownership structure and unique regulatory framework may influence employees' understanding of different constructs. In other words, the China-specific data may limit generalisability. Given the variance of research results in different countries, regions, and industries, further research can therefore expand the sample scale with multiple industries or countries to generalise the findings. These can provide a more comprehensive understanding of the mechanisms among Industry 4.0, CEP, and CSR.

Third, this thesis investigates external factors such as SS and IP to further discuss the mechanisms between CEP and CSR, reinforcing the joint effect of Industry 4.0, CEP, and CSR. However, other factors such as organisational culture (Kwarteng et al., 2022), company systems (Marco-Fondevila et al., 2018), and innovation and collaboration capabilities (Baah et al., 2023) may also potentially influence such relationships. Thus, another extension is to further conduct research with other external factors to broaden the findings of this study. Additionally, future studies could explore the reasons of the failure of SS and IP influencing CEP and CSR on the aspects of CSRE, as responsibility to employees is also core of CSR (Bučiūnienė and Kazlauskaitė, 2012; Liu et al., 2019; Asante Boadi et al., 2020).

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