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Article

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A proposed hierarchical framework for Prioritizing Industry 4.0 technologies to improve environmental performance of manufacturing companies and environmental SDGs

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ABSTRACT

This study draws insights from the dynamic capabilities theory about industry 4.0 and sustainability as critical issues for maintaining firms' competitiveness in international markets. There is still a scarcity of literature about the environmental impacts of adopting Industry 4.0 technologies (I4.0T) and their contribution towards enhancing environmental management accounting systems and attaining sustainable development goals (SDGs). Although companies' managers are aware of environmental issues which have forced them to adopt I4.0T, they hesitate to invest in these technologies because of limited financial resources. The research objectives are exploring the positive environmental impacts of I4.0T and their contribution towards the environmental SDGs and developing a hierarchical framework to prioritize I4.0T. To achieve these objectives, three phases of research methodology were followed. First, we review the extant literature to identify commonly utilized I4.0T, their positive environmental impacts, and their contribution towards attaining SDGs. Second, a hierarchical framework using an analytical hierarchical process was proposed. Third, the proposed framework is applied to five leather firms to test its applicability. The findings indicate that waste management is the most important environmental aspect, and the Internet of Things is the most important technology, followed by big data and cloud computing technologies. This study offers significant theoretical and practical implications, and significant opportunities for future research.

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SUBJECTS

Accounting; Management Accounting; Corporate Social Responsibility & Business Ethics

1. Introduction

Industries face many challenges in meeting customer demands and minimizing negative social and environmental impacts (Pour et al., 2023). The business world witnessed many industrial revolutions that resulted in significant technological changes, such as the Fourth Industrial Revolution 'Industry 4.0' (I4.0). However, it also has negative environmental impacts that result in paying significant attention to EP (Bai et al., 2020).

Recently, companies' managers are aware of environmental issues such as climate change, resource scarcity, and pollution, which have forced companies to work on corporate social and environmental responsibility, set proactive environmental strategies such as pollution prevention, eco-efficiency, product development, and corporate social responsibility, and adopt appropriate environmental management accounting (EMA) systems to enhance their environmental performance (EP) and attain a sustained competitive advantage (Bresciani, 2022; Solovida & Latan, 2017).

EMA is considered a valuable tool to provide environmental accounting information (EAI) about material, energy, and water usage, emissions, and waste resulting from firms' activities. EAI is required for implementing different environmental strategies and supporting managers to make decisions (Nguyen, 2022). So, it is confirmed that EMA systems can overcome the limitations of conventional management

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accounting, quantify environmental issues for making decisions, and support organizations in achieving sustainable competitive advantage (Burritt & Schaltegger, 2010).

Although organizations implement EMA systems to improve their EP, these systems do not provide sufficient real-time EAI to help managers in their decision-making process, as stated by Solovida and Latan (2017), Deb et al. (2023), and Gunarathne et al. (2023). Consequently, companies consider the importance of the transition towards I4.0 to modify EMA systems and provide real-time EAI, as recommended by Luoma et al. (2023) and Chen and Hao (2022).

I4.0 was introduced by the German government in 2011 (Chiarini, 2021), involving integrated technologies such as the Internet of Things (IOT), cyber physical systems (CPS), cloud computing (CC), big data and analytics (BDA), additive manufacturing (AM), virtual reality (VR) and augmented reality (AR), intelligent robotics, and simulation (Beltrami et al., 2021; Jamwal et al., 2021). Recently, the environmental impacts of industry 4.0 technologies (I4.0T) have gained significant attention, such as resource efficiency, reduction of pollution levels, waste, and emissions (El Baz et al., 2022; Malik et al., 2024). Regarding the potential impacts of I4.0T adoption on sustainability dimensions, I4.0T can contribute to the achievement of sustainable development goals (SDGs). Kluczek et al. (2023) and Indana and Pahlevi (2023) highlighted that Agenda 2030 has 17 goals, 169 targets, and 231 indicators. Only SDGs 7, 8, 12, and 13 will be the focus of this study, as they are related to EP.

This study focuses on addressing the potential impacts of I4.0T adoption on manufacturing companies' EP for several reasons. First, significant attention is currently paid to EP owing to the consequences of industrialization, such as air and water pollution, emissions, and waste generation (Malik et al., 2024). Second, Chen et al. (2020) stated that manufacturing companies are required to prioritize environmental impacts' reduction because they contribute more than 35% of CO₂ emissions and utilize one-third of the energy on a large scale. Third, the application of EMA systems could not provide sufficient real-time EAI to support companies' managers in making decisions and improving their EP. Moreover, the intersection of EP and digitalization, involving the availability and utilization of EAI to modify EMA systems, has received significant attention (Cardinali & De Giovanni, 2022; Chen & Hao, 2022; Luoma et al., 2023; Nguyen, 2022). Fourth, Brozzi et al. (2020) stated that manufacturing companies prioritize economic aspects over environmental issues. In addition, Oláh et al. (2020) and Maisiri et al. (2021) have referred to the negative environmental impacts resulting from adopting I4.0T, such as increasing resource usage and emissions. Therefore, the environmental impacts of I4.0T remain unclear and require further research (Chen & Hao, 2022). Fifth, understanding the impact of adopting I4.0T on EP is crucial for managers, especially when capital investment decisions are made (Bai et al., 2020) given limited financial resources (Hughes et al., 2022). Thus, it can be concluded that I4.0T should be prioritized based on its impact on manufacturing companies' EP to adopt the most crucial technologies within a reasonable environmental budget.

Although the literature addresses the relationship between I4.0 and EP, it remains unclear due to the following reasons: First, Khan and Gupta (2023); Solovida and Latan (2017); and Gunarathne et al. (2023) only explored the conventional role of EMA systems in enhancing EP. To modify EMA systems and set appropriate environmental strategies, the environmental impacts of adopting I4.0T should be investigated. Second, Oláh et al. (2020), Sartal et al. (2020), Ghobakhloo (2020), Brozzi et al. (2020), and Bai et al. (2020) highlighted I4.0 as a general concept rather than as an umbrella of many diversified technologies. Third, because of the novelty of I4.0T, some authors have reported that the impacts of I4.0T on EP may be positive (Jena et al., 2020; Mourtzis et al., 2020; Tozanli et al., 2020) or negative (Chiarini, 2021; Nascimento et al., 2019). Consequently, the environmental impacts of I4.0T adoption are still unclear and require further research. Fourth, Kluczek et al. (2023) and Indana and Pahlevi (2023) only demonstrated the connection between I4.0 and sustainability at the industry level. Fifth, there is a scarcity of literature regarding the contribution of individual I4.0T toward attaining the SDGs. Sixth, due to the novelty of the I4.0 context, no studies have attempted to identify the intensity of the influence of each technology on the manufacturing firms' EP. Therefore, further research is required to identify this influence through the use of multi-criteria decision-making (MCDM) tools.

According to the above discussion, two research questions have been raised. First, what are the positive impacts of adopting I4.0T on the EP of manufacturing firms? Second, to what extent does the selected I4.0T impact the manufacturing firms' EP? Accordingly, the research objectives of this study are to identify the positive environmental impacts of the most commonly utilized I4.0T in the

literature and to use analytical hierarchical process (AHP) to develop a hierarchical framework to prioritize I4.0T.

Additionally, this study focuses on dynamic capabilities theory (DCT) to identify and prioritize the environmental impacts of I4.0T in the setting of manufacturing companies. The DCT offers insights into how the adoption of new dynamic capabilities can enhance a firm's EP (Teece, 2007). It can be noted that technological innovation like I4.0T can act as a dynamic capability, supporting firms to enhance their EP.

To fill the research gaps and achieve the research objectives, the related literature review is studied and analyzed to explore only the positive environmental impacts of adopting I4.0T and to what extent these technologies contribute to the environmental SDGs (7, 8, 12, and 13) that will be presented in Section 2.3 for answering the first research question. Then, to answer the second research question, a proposed hierarchical framework using AHP is constructed to rank I4.0T according to their relative importance toward enhancing EP, which will be presented in Section 3.2. Then, a case study methodology is utilized to assess the applicability of the proposed framework to a manufacturing company, which will be presented in Section 4.

The main contribution of this study is summarized as follows: first, this study answers the call of several scholars for more research on the environmental impacts of I4.0T adoption to enhance the understanding of the relationship between I4.0T and EP, extending the role of EMA in enhancing firms' EP; second, this study sheds light on how I4.0T adoption contributes to the SDGs agenda; and third, this study provides a novel framework for prioritizing I4.0T, aiding academics and practitioners to undertake substantial investments to adopt I4.0T, particularly for manufacturing companies with limited financial resources.

The rest of the paper is organized as follows: the theoretical background and literature review are presented in Section 2. Section 3 presents the research methodology and proposed hierarchical framework. A case study is conducted in Section 4. The study's findings are discussed and summarized in Section 5. Finally, conclusions, theoretical and practical implications, limitations, and future research are outlined in Section 6.

2. Theoretical background and literature review

This section presents the building blocks that support our investigation and provides a comprehensive exploration of fundamental concepts. Reviewing the literature aims at outlining the connection between I4.0T and EP of manufacturing companies, considering dynamic capability theory (DCT). This section starts with a general background about DCT, I4.0T, and the impact of adopting I4.0T on manufacturing companies' EP and their contribution towards attaining environmental SDGs.

2.1. Theories foundation

There are few studies that consider theories and viewpoints such as practice-based view (Bag et al., 2021b; Kamble & Gunasekaran, 2023), DCT (Kamble & Gunasekaran, 2023), and EMT (Tang et al., 2024). DCT is utilized by several researchers, particularly for making strategic choices or decisions in the light of different business scenarios (Bag et al., 2021b). Thus, to achieve the research objectives, it is relevant to consider DCT as a theoretical framework to identify and prioritize the environmental impacts of I4.0T in the setting of manufacturing companies. Teece (2007) stated that dynamic capabilities help firms address the challenges and issues associated with achieving the firms' sustainable goals. In the current study, I4.0T is considered as a set of valuable organizational resources providing a significant capability to integrate products and production processes. Thus, I4.0T acts as a dynamic capability that provides the ability to build and integrate internal and external competencies to cope with rapid changes in the business environment. Lahti et al. (2018) referred to the high implementation costs and uncertainty of adopting I4.0T. Therefore, the main objective of the current study is to advance the literature about DCT by identifying the potential impact of new dynamic capabilities such as I4.0T on firms' EP.

2.2. Environmental performance in manufacturing scope

EP is gaining significant attention because of external regulations and stakeholder demands. Customers desire environmentally friendly products, investors ask for more transparency and EAI, and regulators seek compliance with environmental regulations. Furthermore, these external pressures force manufacturing firms to adopt sustainable environmental strategies and implement EMA systems to enhance their EP (Luoma et al., 2023; Nguyen, 2022). Gunarathne et al. (2023) referred to the role of the EMA in managing, measuring, and improving companies' operating aspects to improve their EP and facilitate EAI collection and communication to support managers' decision-making processes. Latifah and Soewarno (2023) stated that EMA systems provide EAI about pollution and emissions from production and transportation, resource usage, renewable energy utilization, waste management, and circular economy practices (CEP) that are examples of EP aspects. According to DCT, the literature reveals the role of technology in improving the EP of manufacturing companies and modifying their EMA systems. Jabbour et al. (2018) and Brozzi et al. (2020) claimed that I4.0T offers significant environmental benefits through providing efficient solutions for controlling emissions, saving resources, and real-time monitoring. Therefore, understanding the relationship between I4.0T and EP is worthwhile, which is explored in the following section.

2.3. Environmental impacts of industry 4.0 technologies adoption

The first industrial revolution began in the 18th century with mechanical factories, followed by the 'Era of Mass Production' in the 1870s utilizing electricity in industrial processes (Malik et al., 2024; Ng et al., 2022) and the 'Digital Revolution' in the 1970s utilizing 'electronics and information technology' (Öztemel & Gürsev, 2018). The German government introduced I4.0 in 2011 as a high-technology strategy, with the first application proposal developed by the I4.0 Working Group in 2013 (Oláh et al., 2020; Öztemel & Gürsev, 2018). Therefore, I4.0 is not a sudden revolution because its appearance was based on previous revolutions. The various stages of the industrial revolution's progression are shown in Figure 1.

I4.0 has gained significant attention from academic researchers. The alignment between I4.0 and firms' strategic goals is essential to modify the EMA system through providing real-time EAI and improve their

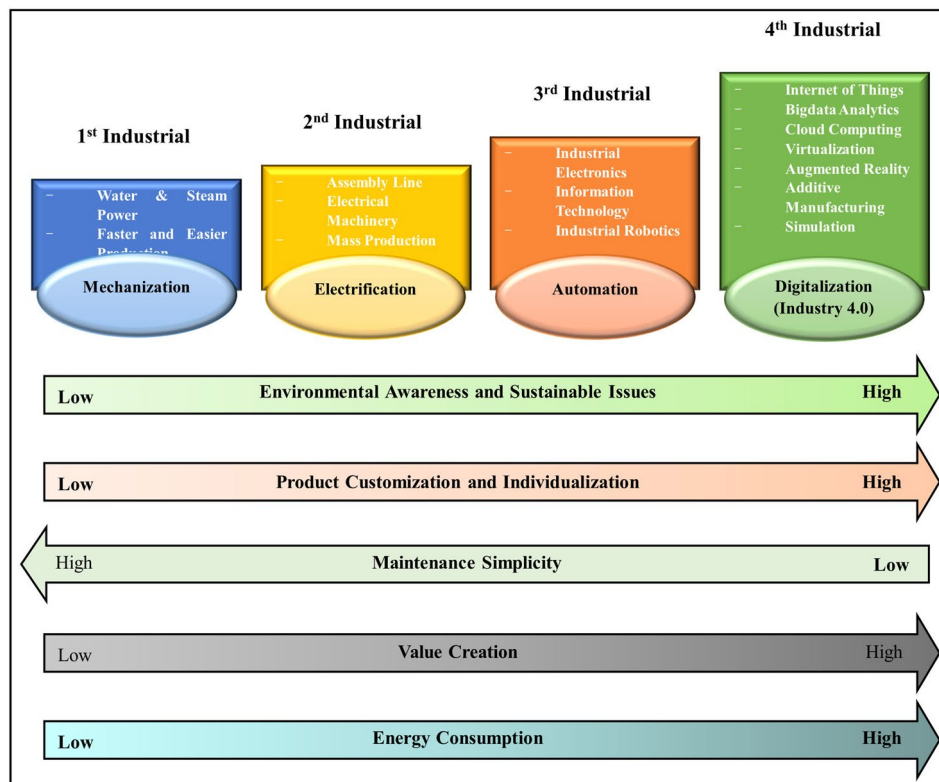


Figure 1. Stages of industrial revolutions (Source: The Author).

EP, as stated by Zheng et al. (2021) and Latifah and Soewarno (2023). According to DCT, Ghobakhloo et al. (2021) defined I4.0 as the integration of new technologies in manufacturing processes to ensure real-time connections between people, machines, and objects. I4.0T are known as technology trends, which are a set of advanced technologies that are considered the building blocks of manufacturing firms.

Although the literature highlights the EP of manufacturing firms in the I4.0 context, consensus on the environmental impacts of adopting technologies remains unclear (Malik et al., 2024; Nascimento et al., 2019). The study by Stock and Seliger (2016) is the first to highlight the role of I4.0T in promoting EP. Adopting I4.0T results in optimizing resource usage (Jena et al., 2020), utilizing renewable energy, reducing waste and emissions (Brozzi et al., 2020; Ching et al., 2022), and providing real-time EAI to modify the EMA system and set appropriate environmental strategies (Hanif et al., 2023; Indana & Pahlevi, 2023).

Some studies have indicated a linkage between I4.0 and CEP. Jabbour et al. (2018) proposed a road map to enhance EP through CEP adoption. CEP is adopted to improve EP by transitioning from a linear model to a maximized resource usage model, which also plays an essential role in attaining the SDGs (especially target 12.5) set by the United Nations in the Agenda 2030 for Sustainable Development (Dorado et al., 2022). Alayón et al. (2017) recommended reusing, recycling, and remanufacturing (3R) practices to optimize production, reduce waste, emissions, and resource usage. Chen et al. (2020) introduced a 6R methodology (reuse, recycle, remanufacture, reduce, recover, and redesign) to maximize resource utilization. Additionally, Khan et al. (2021) referred to the role of BD analytics, CPS, and AM technologies in supporting CEP, like reusing waste generation during the manufacturing stage or recovering energy from scraps or rejections, which in turn enhance EP.

Due to the novelty of the I4.0 context, this study focuses on DCT to identify the most utilized technologies in the literature to investigate their positive impacts on the EP of manufacturing firms such as IOT/CPS, BDA, CC, AM, simulation/digital twin, VR/AR, and intelligent robotics on environmental aspects like resource usage, waste management, emissions and pollution, and CEP. Furthermore, it is critical to present the contribution of each I4.0 technology toward attaining environmental SDGs (7, 8, 12, and 13) as presented in Figure 2. A summary of the literature review related to these technologies is shown in Table 1 and analyzed as follows:

2.3.1. Internet of Things and cyber physical system

Based on DCT, Zhou et al. (2016) and Beier et al. (2020) stated that the adoption of IOT technologies improves EP through reducing resource usage, waste generation, and emission releases. Jamwal et al. (2021) and Oláh et al. (2020) referred to the role of IOT in facilitating transparency in manufacturing processes via real-time monitoring of resource usage to help production management and facilitate necessary improvements. As stated by Chen et al. (2020), Beltrami et al. (2021), and Ghobakhloo (2020), IOT/CPS platforms enhance resource efficiency by enhancing communication with suppliers and customers, promoting eco-design, customizing products, reducing transportation frequency, and scheduling manufacturing resources flexibly. Consequently, the reduction of materials, energy, and water usage, substitution of hazardous or chemical resources, promotion of CEP, and reduction of waste and emissions can be achieved.

Also, IOT enables real-time data acquisition through sensors or RFID tags, enabling manufacturers to monitor resource usage, waste, and emissions, set proactive environmental strategies, and make relevant decisions (Jamwal et al., 2021; Vrchota et al., 2020). Sartal et al. (2020) stated that smart machines facilitate monitoring and predicting machine failures, enabling preventive and predictive maintenance, and resource efficiency, and waste reduction. Furthermore, IOT/CPS platforms enhance transparency, traceability, resource monitoring, and enabling closed-loop systems to reduce waste (Malik et al., 2024), and promoting reusing or recycling materials to optimize resource usage (Mastos et al., 2021).

2.3.2. Big data and analytics and cloud computing

BDA is a computing technology that analyzes vast amounts of data, enabling real-time monitoring of resource usage and predictive maintenance to avoid waste generation, breakdowns, or unscheduled downtimes and extend the life span of machines (Indana & Pahlevi, 2023). Uriarte-Gallastegi et al. (2022) asserted that BDA enables manufacturing firms to track production processes to avoid

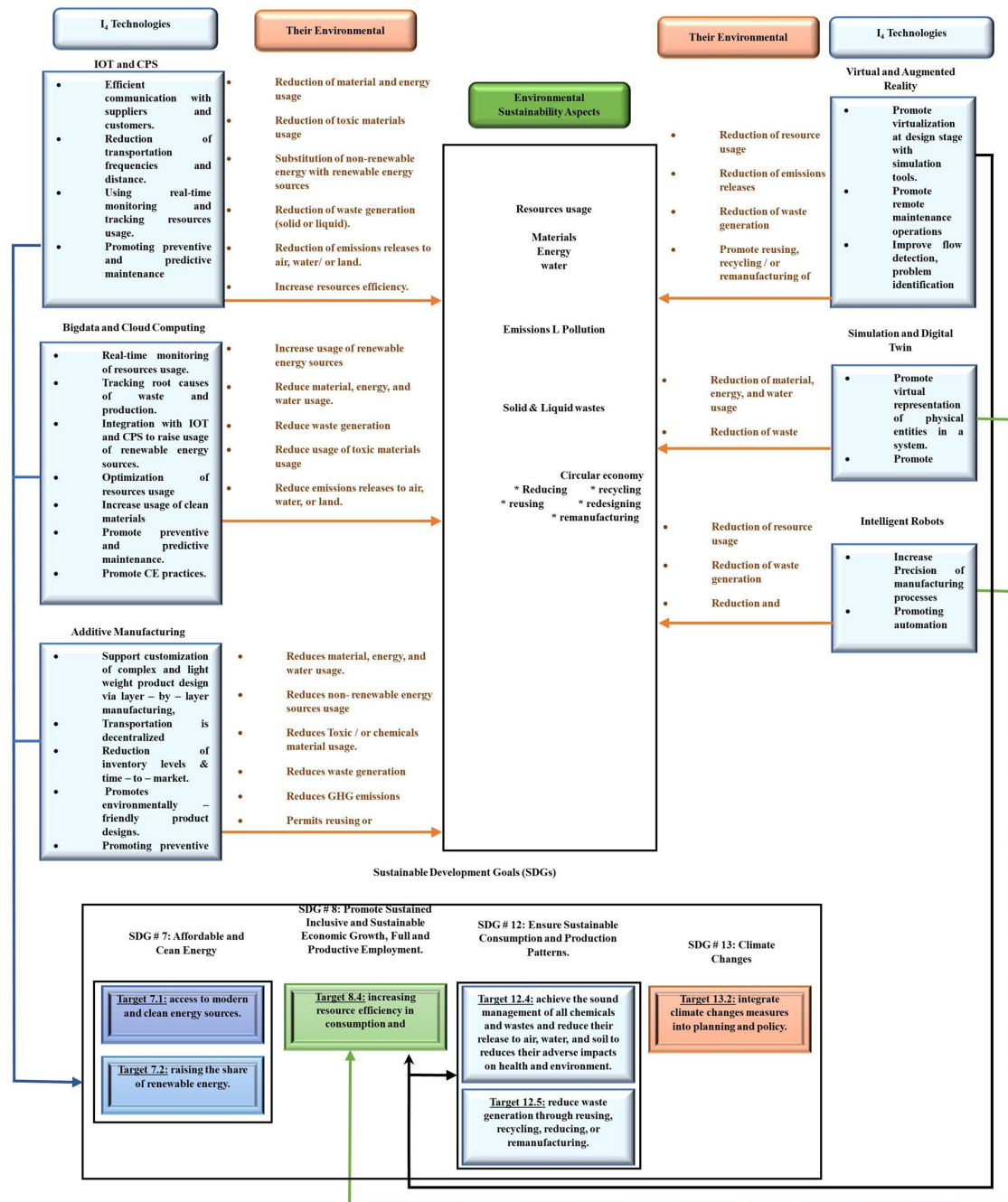


Figure 2. Potential environmental impacts of industry 4.0 technologies and their linkage with SDGs (Source: The Author).

overproduction and reduce resource usage and waste generation. According to Beier et al. (2020), adoption of BDA and CC technologies results in reduction of resource usage, waste generation, and emission releases. Based on DCT, it was argued by Bonilla et al. (2018) and Stock et al. (2018) that integration of IOT/CPS with BDA results in increasing renewable energy usage to meet increasing demand for energy and enhance EP.

Regarding cloud computing, it is a key enabler for adopting other technologies (Jamwal et al., 2021). Cloud computing can be combined with BDA to store data gathering until it is analyzed by BDA tools (Chen et al., 2020). As stated by Öztemel and Gürsev, (2018), cloud computing significantly reduces toxic material usage through real-time data support, thereby increasing the use of environmentally friendly materials.

Table 1. A summary of literature review.

| Authors | Digital technologies | Methodology | | Study's findings | | | | |
|---|----------------------|---------------------------------------|--------------|--|----------------|---------------------|-----------------|---------------|
| | | Qualitative | Quantitative | Resource optimization | Energy savings | Emissions reduction | Waste reduction | Promoting CEP |
| Jena et al. (2020); Saudi et al. (2019) | IOT/CPS, CC | Case study | | ✓ | ✓ | ✓ | ✓ | |
| Brozzi et al. (2020) | I4.0 | | Survey | ✓ | ✓ | ✓ | ✓ | |
| Khan et al. (2021) | BD, CPS, AM | | Survey | | | ✓ | ✓ | ✓ |
| Jamwal et al. (2021) | I4.0 | Systematic literature review (SLR) | | ✓ | ✓ | ✓ | ✓ | |
| Oláh et al. (2020) | I4.0 | SLR | | ✓ | | ✓ | | |
| Braccini and Margherita (2018) | I4.0 | Case study | | ✓ | | ✓ | | |
| Santos et al. (2019) | IOT/CPS, BD | Case study | | ✓ | ✓ | | | |
| Chiarini et al. (2020) | AM, BD, CPS | | Survey | ✓ | ✓ | ✓ | ✓ | ✓ |
| Zhang et al. (2019) | I4.0 | Case study | | ✓ | | ✓ | | |
| Nascimento et al. (2019) | CPS, AM | Case study | | ✓ | ✓ | ✓ | | |
| Stock et al. (2018) | CPS, AM | Simulation | | | ✓ | ✓ | | |
| Tozanli et al. (2020) | IOT | Simulation | | ✓ | | | | |
| Bonilla et al. (2018) | I4.0 | SLR | | ✓ | ✓ | ✓ | ✓ | ✓ |
| Bag et al. (2021a) | I4.0 | | Survey | ✓ | ✓ | ✓ | ✓ | ✓ |
| Pour et al. (2023) | I4.0T | Case study and Survey (mixed methods) | | This study proposed an industry 4.0 selection framework that focused on fuzzy analytical hierarchy process (FAHP) to rank different technologies towards enhancing three dimensions of sustainable performance of firms. | | | | |
| Evans et al. (2013) | I4.0T | Case study and Survey (mixed methods) | | This study utilized a fuzzy decision tree approach to compute the certainty index for different technologies to rank these technologies and selecting the most suitable tools for implementation. | | | | |

BDA and CC can promote CEP by utilizing real-time data. Based on DCT, these technologies can reduce resource usage and waste generation through reusing, recycling, and reducing materials and products, thereby reducing pollution and emissions (Beltrami et al., 2021; Chiarini, 2021).

2.3.3. Additive manufacturing

According to DCT, AM technology adoption has positive environmental impacts like reducing resource usage and enabling closed-loop material flows (Jamwal et al., 2021), reducing product weight, time-to-market, waste, and emissions (Ghobakhloo et al., 2021). Bonilla et al. (2018) and Oláh et al. (2020) highlighted the role of AM in decreasing transportation and carbon footprints by purchasing the right quantity of raw materials and decentralizing production geographically for customers.

Additionally, the adoption of AM technology promotes CEP. Uriarte-Gallastegi et al. (2022) argued that AM is a relevant technology for reusing or recycling parts or components rather than disposing or replacing them. Sartal et al. (2020) confirmed the role of AM technology in promoting CEP, improving resource efficiency, and reducing waste generation through product customization. Thus, the adoption of AM technology conserves natural resources and reduces emission releases, thereby enhancing EP.

2.3.4. Simulation/digital twin

Sartal et al. (2020) demonstrated that simulation systems can assess the consequences of changes in manufacturing variables, while Beltrami et al. (2021) highlighted their effectiveness in reducing energy usage and improving processes throughout the virtual simulation of new procedures or maintenance

activities without impacting their configuration. Jamwal et al. (2021) stated that digital twins promote preventive and predictive maintenance, which results in reducing waste generation and resource usage.

2.3.5. *Virtual reality/augmented reality*

Chiarini (2021) and Ghobakhloo et al. (2021) stated that VR and AR technologies can only enhance economic performance. But these opinions are criticized because AR/VR technologies can improve EP. Tao et al. (2018) stated that AR can be adopted at the design stage to support products' design with the help of simulation tools that can result in reducing design errors and resource usage. Also, Sartal et al. (2020) referred to the role of VR/AR in reducing resource usage and waste generation by minimizing the rate of production failures. In addition, AR/VR technologies promote CEP, supporting remanufacturing products at end-of-life stages, real-time product observation, data collection, and improved flaw detection across product life cycles (Kerin & Pham, 2019).

2.3.6. *Intelligent robotics*

Nowadays, several manufacturing firms are shifting toward automation, that results in increasing the utilization of intelligent robotics. Abdullah et al. (2023) referred to the benefits of adopting robots' technologies, such as self-optimization, self-diagnosis, self-automation, and intelligent decision-making. Ghobakhloo (2020) highlighted that the use of intelligent robotics enhances productivity, quality, and resource efficiency. Chen et al. (2020) stated that intelligent robotics enhance manufacturing processes' precision through reducing defects or errors. Also, Ching et al. (2022) confirmed that the utilization of robots enhances EP by reducing and controlling emissions, waste, and resource usage.

After exploring the impacts of adopting I4.0T on EP, it is critical to present the contribution of each technology toward attaining the SDG agenda because EP is promoted when I4.0T are aligned with the SDGs; otherwise, EP is negatively impacted. Jayashree et al. (2021) and Mabkhot et al. (2021) referred to the importance of observing the alignment between I4.0T and the SDGs to develop business models and map the positive and negative impacts of I4.0T on sustainability dimensions. Kluczek et al. (2023) and Jamwal et al. (2021) referred to the importance of incorporating sustainability with I4.0T as a key enabler to attain the SDGs. These studies focused only on revealing the role of BD, AM, CC, and simulation technologies in attaining decent work and economic growth (SDG 8), industry, innovation, and infrastructure (SDG 9), and responsible consumption and production (SDG 12).

Therefore, each I4.0 technology is aligned toward attaining environmental SDGs (7, 8, 12, and 13), as presented in Figure 2. Targets of SDG 7 related to environment (target 7.1: access to modern and clean energy sources; target 7.2: increasing renewable energy sources), targets of SDG 8 (target 8.4: increasing resource efficiency), targets of SDG 12 (target 12.4: management of chemicals and emission releases; target 12.5: waste reduction through promoting CE practices), and targets of SDG 13 (target 13.2: involving climate change measures into planning and policies).

It is noted from Figure 2 that IOT/CPS, BD/CC, and AM technologies can attain the SDGs 7, 8, 12, and 13 and their related targets. Based on DCT, these technologies support the utilization of clean and renewable energy sources, increasing resource efficiency, reducing pollution and emission releases, and promoting CEP. According to Bag et al. (2021a), IOT sensors can monitor the life cycle of materials and products, and AM technology enables firms to produce new products from recycled materials. Adoption of VR/AR technologies support the attainment of targets (8.4, 12.2, and 12.5) because they enhance resource efficiency and reduce waste and emission releases. Finally, the adoption of intelligent robotics and simulation technologies can only achieve targets (8.4 and 12.4) due to increasing resource efficiency and reducing waste generation and emission releases.

3. Research methodology

3.1. *Research design*

This study aims to investigate the positive impacts of adopting I4.0T on manufacturing firms' EP to modify their EMA systems, identify the contribution of each technology toward attaining environmental SDGs, and assess the intensity of the influence of each technology on each EP aspect. This study focused on

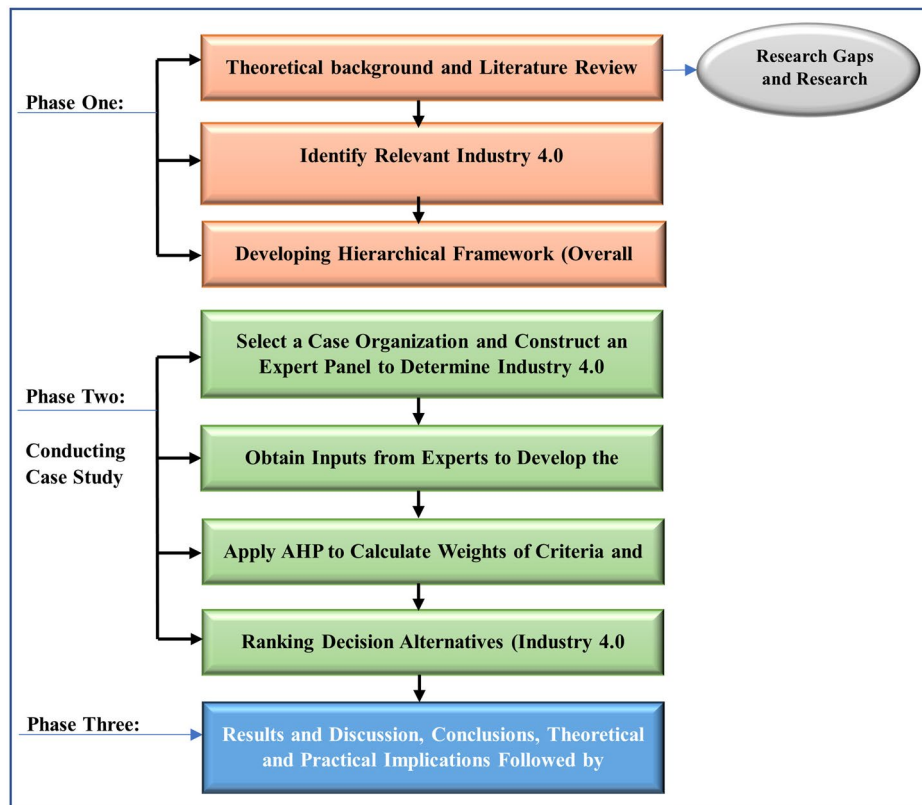


Figure 3. Flow of research methodology phases for the present study (Source: The Author).

sequential mixed research techniques involving qualitative and quantitative methods. The research design methodology is illustrated in Figure 3. The research process started with reviewing literature related to the research topic and addressing research gaps and questions. Considering the findings of this review, the first research question was answered. Then, to answer the second research question, a hierarchical framework using one of the MCDM tools was proposed that can be used by all types of firms, regardless of size or type of industry. Finally, a case study methodology was utilized to test the practical applicability of the proposed framework to five leather tanning firms as an example of a real-life case.

3.2. The proposed hierarchical framework

Although the transition toward I4.0 is a key enabler for firms to achieve sustainable development, manufacturing firms may face several challenges that hinder them from selecting the relevant technologies. Hughes et al. (2022) stated that the path toward I4.0 can't be achieved overnight. Ghobakhloo et al. (2021) asserted that the adoption rate of I4.0T is low because of the unpredictable nature of I4.0. Lack of financial resources (Kumar et al., 2021); lack of management support and commitment; high implementation costs (Prause, 2019); lack of expertise, data security, and employee resistance to change (Hughes et al., 2022) are examples of challenges that may hinder the transition toward I4.0. Ng et al. (2022) and Ghobakhloo et al. (2021) mentioned that financial resource availability and high implementation costs are critical challenges hindering firms' adoption of I4.0T. Therefore, investments in I4.0T have become a critical issue among firms.

A few studies have presented frameworks that are related to I4.0T selection. Hamzeh and Xu (2019) proposed a six-step framework for selecting I4.0T, whereas Evans et al. (2013) used a fuzzy decision tree approach to compute the certainty index for different technologies. Therefore, no study has presented approaches or frameworks to rank I4.0T according to its relative importance toward enhancing EP and modifying EMA systems.

This study proposes a novel hierarchical framework using AHP to rank I4.0T in manufacturing firms, addressing the lack of existing frameworks for assessing the intensity of the influence of individual I4.0T on firms' EP and modifying their EMA systems. This framework contributes to the literature and responds to calls for the I4.0T selection framework, which supports manufacturing firms to prioritize I4.0T considering limited financial resources.

Prioritizing I4.0T is a MCDM problem because I4.0T is ranked based on a given EP aspect. MCDM began in the 1970s and is used to find the most suitable options or rank them based on how they can satisfy their goals (Abdullah et al., 2023). Two studies utilized AHP in the literature. Luthra and Mangla (2018) used AHP to evaluate the challenges to I4.0T, and Erdogan et al. (2017) used AHP to support I4.0 application strategy evaluation. Therefore, no study in the literature utilizes AHP to rank I4.0T toward enhancing manufacturing firms' EP and modifying their EMA systems. AHP was developed by Saaty (2008) as a powerful tool for MCDM. So, AHP is used in this study to develop the proposed hierarchical framework through following AHP's steps as follows:

3.2.1. Step one is to structure the hierarchy of the AHP

A graphical representation of the problem is simplified by decomposing it in terms of the overall goal, criteria, sub-criteria, and alternatives. Typical hierarchical levels of the proposed framework are shown in Figure 4. **Level one** represents the overall goal, which is ranking I4.0T toward enhancing the manufacturing firms' EP and modifying their EMA systems. **Level two** represents the performance aspects of the EP, like material, energy, water usage, emissions, waste management, and CEP. **Level three** represents decision alternatives, which are I4.0T: IOT/CPS, BDA/CC, AM, simulation/digital twin, VR/AR, and intelligent robotics.

3.2.2. Step two is to construct pairwise comparison matrices

Pairwise comparisons were performed to determine the priorities for the criteria and alternatives. AHP involves qualitative considerations of human perception and provides a measurement scale to convert the verbal preferences of decision-makers into numerical values. Table 2 presents Saaty's 1-9 scale. Seven pairwise comparison matrices were constructed. A pairwise comparison matrix was established at the criteria level to compare the performance aspects of EP and determine the weights of each performance aspect in EP and modify EMA systems. Six pairwise comparison matrices were established at the alternative level with respect to the criteria level to make a comparison among I4.0T in terms of their corresponding performance aspects. This comparison determines the weight of each technology toward

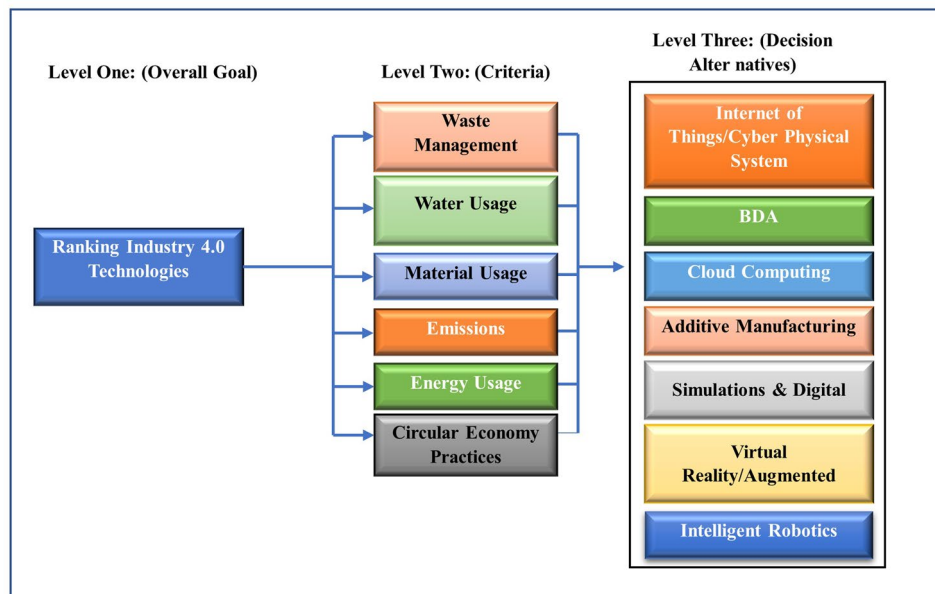


Figure 4. The proposed hierarchical framework (Source: The Author).

Table 2. Saaty's fundamental ratio measurement scale.

| Intensity of importance | Definition | Explanation |
|-------------------------|-------------------------|--|
| 1 | Equally important | Two elements contribute equally to the goal |
| 3 | Moderately important | Experience and judgment slightly favor one element over another |
| 5 | Strongly important | Experience and judgment strongly favor one element over another |
| 7 | Very strongly important | An element is strongly favored, and its dominance is demonstrated in practice |
| 9 | Extremely important | The importance of one element over another is affirmed on the highest possible order |
| 2,4,6,8 | Intermediate values | It is used when compromise is needed |

enhancing its related performance aspect. Therefore, the selected I4.0T can be ranked according to its relative importance toward enhancing related EP aspects.

3.2.3. Step three is synthesization

The global weights of each I4.0T are computed by multiplying its local weight by the importance of its related EP aspect, through which I4.0T can be ranked toward enhancing the manufacturing firms' EP and their EMA systems.

3.2.4. Step four is to calculate the consistency ratio (CR)

AHP provides a measure of consistency by computing CR. Therefore, if CR is 0.1 or less, the consistency of the pairwise comparisons is reasonable. However, if the CR is greater than 0.1, pairwise judgments are inconsistent.

4. Case study

The reasons for utilizing case study methodology are investigating a complex phenomenon in its real context, considering both quantitative and qualitative evidence sources (Yin, 2018), and considering the early stages of development and diffusion of I4.0T in ranking them toward enhancing companies' EP and modifying their EMA systems. The proposed hierarchical framework is applied to rank I4.0T by combining a case study and AHP to enhance its robustness.

4.1. Research setting and participants sampling

The main motivation for conducting this study in the leather industry is summarized as follows: First, this industry is one of the oldest and most polluting industries. Several chemical operations are conducted to collect raw hides and skins that result in huge environmental pollution (Dixit et al., 2015), thus, adoption of I4.0T to minimize and control these environmental pollutions is recommended. Second, no study has investigated or ranked the impacts of adopting I4.0T on leather tanning companies' environmental performance. Thus, the proposed framework helps leather companies' decision-makers make or re-evaluate investment decisions in critical technologies to reduce negative environmental impacts.

Five leather tanning companies were chosen based on the convenience sampling technique because of their accessibility and interest in ranking I4.0T towards enhancing the EP of these companies and modifying their EMA systems. To select a sample of companies with the same I4.0T and environmental problems, the companies have been selected based on some characteristics, such as their adoption of I4.0T in the previous five years, number of employees greater than 50, and their commitment to environmental management and the SDGs agenda with specific EMA systems to enhance EP. Additionally, an expert panel consisting of 15 experts was established and sampled from these selected companies. Although there are not many experts, the author decided to conduct the study with 15 experts because MCDM can be utilized with 5-10 experts, as stated by Saaty (2008). The experts were selected based on purposive sampling to ensure diversity of opinions and enhance the results' generalization. They were selected based on the following criteria: first, having sufficient knowledge about I4.0T and EMA systems for at least ten years to contribute significantly to the study; second, their current positions are as decision-makers or experts like general managers, department heads, and special engineers; and third, their companies have already adopted or are in the process of adopting I4.0T. The profile of the selected companies and experts is described in Table 3.

Table 3. Profile of the selected leather tanning companies and experts.

| Company | Turnover (millions) | Number of employees | Experts | Years of experience | Position |
|---------|---------------------|---------------------|----------------------------------|---------------------|--|
| A | 80 M | 220 | Production manager | 12 | Production and control |
| | | | Environmental management manager | 10 | Environmental and safety |
| | | | Technologist | 14 | Leather processing and quality control |
| B | 100 M | 350 | Production manager | 11 | Production and control |
| | | | Logistics manager | 10 | Transportation and distribution |
| | | | Environmental management manager | 13 | Environmental and safety |
| C | 150 M | 400 | Production manager | 12 | Production and control |
| | | | Supply chain manger | 10 | Procurement and distribution |
| | | | Logistics manager | 11 | Transportation and distribution |
| D | 60 M | 200 | Operations manager | 12 | Production and maintenance |
| | | | Logistics manager | 13 | Transportation and distribution |
| | | | Technologist | 10 | Digitalization and technology |
| E | 100 M | 300 | Production manager | 12 | Production and control |
| | | | Environmental management manager | 11 | Environmental and safety |
| | | | Technologist | 12 | Digitalization and technology |
| | | | Operations manager | 15 | Production and maintenance |

4.2. Data collection and analysis

During the qualitative phase of the research, semi-structured interviews were conducted with those experts across different time periods via Zoom meeting, telephone, or face-to-face based on their preferences, and each session lasted 30–45 minutes. The questions were designed to collect data about environmental strategies, EMA systems, and EP aspects considered within the company, environmental problems resulting from tanning processes and I4.0T which were adopted or are in the process of adoption and their potential contribution towards environmental SDGs (7, 8, 12, and 13), and challenges that may hinder the adoption of these technologies. The questions are shown in [Appendix A](#).

Although the sample used in this study is not representative, the composition of it is favorable to derive tendencies from it and discover real cases of companies to identify which I4.0T are adopted and their impacts on the EP of these selected companies because the percentage of large companies is 60% (more than 250 employees and turnover of at least \$100 million) and the percentage of medium-sized companies is 40% (number of employees ranged from 200 to 220 and turnover of at least \$60 million).

The analysis of the interview data revealed that all experts of the leather tanning companies considered material, energy, water usage, emissions, waste management, and CEP as EP aspects. The environmental problems resulting from tanning processes are summarized as follows: First, solid waste is a significant problem in companies that account for 15%–20% of raw material usage; second, there is a huge amount of water usage and pollutants discharged during tanning processes; and third, the tanning processes emit harmful volatile substances, such as amines, hydrocarbons, ammonia, and hydrogen sulfide, causing negative impacts on water and the atmosphere. Also, the companies' EMA systems do not provide sufficient real EAI to support managers in decision-making. Limited financial resources are the main challenges hindering the adoption of I4.0T. Thus, managers decided to adopt only IOT/CPS, BDA, and CC technologies, considering this challenge, because Indana and Pahlevi (2023) and Malik et al. (2024) referred to the integration and interconnection among these technologies to achieve a significant impact. After analyzing interviewees' responses, the quantitative phase of the research is conducted, during which an online AHP survey is created and sent to the same set of experts to be filled out to provide their judgments about the relative importance of the components of the proposed framework through responding to a series of pairwise comparisons established at two levels: criteria and decision alternatives. It means that diversified decision-makers have filled out a single AHP survey. This survey is indicated in [Appendix B](#).

Consequently, the proposed framework is tested in the selected leather companies to support decision-makers and managers making investment decisions in these technologies according to their relative importance toward enhancing the companies' EP and modifying EMA systems.

4.3. Application of proposed framework on the leather tanning companies

According to the interviewees' responses, material, energy, water usage, emissions, waste management, and CEP are considered EP aspects (criteria), and only IOT/CPS, BDA, and CC technologies are at the

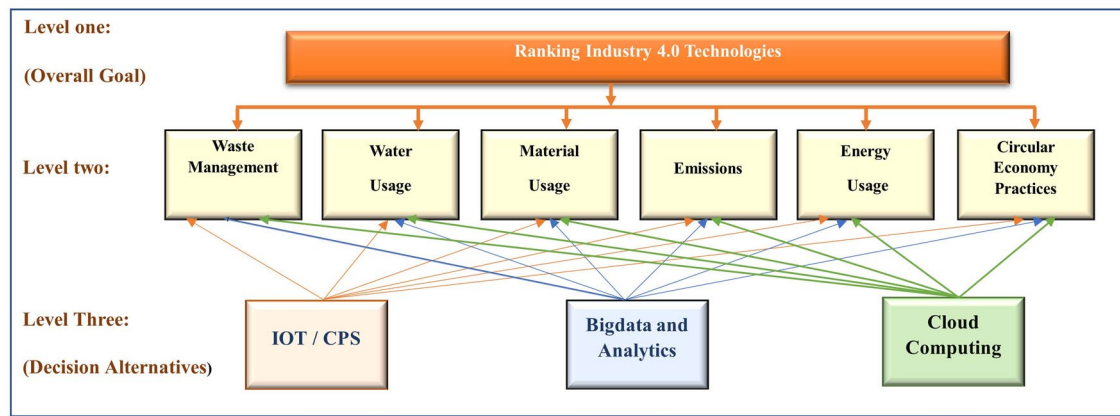


Figure 5. Proposed hierarchical framework for the selected leather tanning firms (Source: The Author).

Table 4. Comparison among environmental performance aspects.

| Pairwise comparison matrix | | | | | | | Average weights |
|----------------------------|-------|-------------|----------------|-----------|--------------|------------------|-----------------|
| | Waste | Water usage | Material usage | Emissions | Energy usage | Circular economy | |
| Waste | 1 | 4 | 5 | 5 | 6 | 5 | 0.437 |
| Water usage | 0.25 | 1 | 5 | 3 | 5 | 3 | 0.228 |
| Material usage | 0.2 | 0.2 | 1 | 0.5 | 4 | 0.5 | 0.078 |
| Emissions | 0.2 | 0.333 | 2 | 1 | 3 | 4 | 0.137 |
| Energy usage | 0.167 | 0.2 | 0.25 | 0.333 | 1 | 0.5 | 0.04 |
| Circular economy | 0.2 | 0.333 | 2 | 0.25 | 2 | 1 | 0.079 |

$$\lambda_{\max} = 6.4; \text{CI} = 0.08; \text{CR} = 0.09$$

beginning of their adoption process (decision alternatives). Figure 5 presents the proposed hierarchical framework for leather-tanning firms. A questionnaire in the form of pairwise comparisons was created to evaluate the relative importance of EP aspects and I4.0T. Also, Expert Choice Software was used to calculate the average weights of the criteria and alternatives using all experts' individual weights and the consistency ratio for each matrix.

- A pairwise comparison matrix was established at the **criteria level** to determine the weights of each aspect in enhancing EP. The matrix is listed in Table 4, which notes that waste management and water usage are given the highest importance, with weights of 43.7% and 22.8%, respectively. On the other hand, energy usage was given the lowest importance, with weights of 4%. Also, the CR is calculated to determine the degree of consistency in the decision-maker's judgments.
- Six pairwise comparison matrices were established at the **alternatives level** to determine the average weights of each technology toward achieving its related performance. The matrices are listed in Table 5, which notes that IOT/CPS are given the highest importance toward enhancing all EP aspects. However, CC has the lowest importance toward enhancing all EP aspects.

The final global weights for I4.0T were computed by multiplying its average local weights by the importance of its related EP aspect. The average global weights of I4.0T are listed in Table 6. The overall priority of each technology is computed as follows: for example, waste management has a priority of 0.437, and IOT/CPS technology has a priority of 0.48 in terms of the waste management criterion. Thus, (0.437×0.48) is the priority value of the IOT/CPS technology based on the waste criterion. To obtain the overall priority of IOT/CPS technology, it is necessary to perform similar computations for the water, energy, material, emissions, and CEP criteria and then add these values to obtain the overall priority. The calculation is as follows:

Overall Priority of IOT/CPS:

$$(0.437 * 0.48) + (0.228 * 0.55) + (0.078 * 0.54) + (0.137 * 0.66) + (0.04 * 0.69) + (0.079 * 0.62) = 0.54$$

Table 5. Comparison among industry 4.0 technologies under each performance aspect.

| a. Comparison Among Industry 4.0 Technologies Under Waste Aspect | | | | |
|---|---------|-----|----|-----------------|
| | IOT/CPS | BDA | CC | Average Weights |
| IOT/CPS | 1 | 1 | 4 | 0.48 |
| BDA | 1 | 1 | 2 | 0.37 |
| CC | 0.25 | 0.5 | 1 | 0.15 |
| $\lambda_{\max} = 3.09$; CI = 0.04; CR = 0.045 | | | | |
| b. Comparison Among Industry 4.0 Technologies Under Water Aspect | | | | |
| | IOT/CPS | BDA | CC | Average Weights |
| IOT/CPS | 1 | 2 | 5 | 0.55 |
| BDA | 0.5 | 1 | 5 | 0.35 |
| CC | 0.2 | 0.2 | 1 | 0.10 |
| $\lambda_{\max} = 3.09$; CI = 0.05; CR = 0.056 | | | | |
| c. Comparison Among Industry 4.0 Technologies Under Material Aspect | | | | |
| | IOT/CPS | BDA | CC | Average Weights |
| IOT/CPS | 1 | 2 | 3 | 0.54 |
| BDA | 0.5 | 1 | 2 | 0.30 |
| CC | 0.33 | 0.5 | 1 | 0.16 |
| $\lambda_{\max} = 3.02$; CI = 0.01; CR = 0.028 | | | | |
| d. Comparison Among Industry 4.0 Technologies Under Emission Aspect | | | | |
| | IOT/CPS | BDA | CC | Average Weights |
| IOT/CPS | 1 | 4 | 4 | 0.66 |
| BDA | 0.25 | 1 | 2 | 0.20 |
| CC | 0.25 | 0.5 | 1 | 0.14 |
| $\lambda_{\max} = 3.03$; CI = 0.015; CR = 0.06 | | | | |
| e. Comparison Among Industry 4.0 Technologies Under Energy Aspect | | | | |
| | IOT/CPS | BDA | CC | Average Weights |
| IOT/CPS | 1 | 5 | 4 | 0.69 |
| BDA | 0.2 | 1 | 2 | 0.18 |
| CC | 0.25 | 0.5 | 1 | 0.13 |
| $\lambda_{\max} = 3.02$; CI = 0.01; CR = 0.07 | | | | |
| f. Comparison Among Industry 4.0 Technologies Under Circular Economy Aspect | | | | |
| | IOT/CPS | BDA | CC | Average Weights |
| IOT/CPS | 1 | 3 | 4 | 0.62 |
| BDA | 0.33 | 1 | 2 | 0.23 |
| CC | 0.25 | 0.5 | 1 | 0.15 |
| $\lambda_{\max} = 3.11$; CI = 0.056; CR = 0.01 | | | | |

Table 6. Synthesized AHP table for the selected leather tanning companies.

| | Importance of level one | Average Local Weights for Level Two | Average Global Weights |
|----------------|-------------------------|-------------------------------------|------------------------|
| Waste | 0.437 | | |
| | IOT/CPS | 0.48 | 0.209 |
| | BDA | 0.37 | 0.162 |
| | CC | 0.15 | 0.065 |
| Water usage | 0.228 | | |
| | IOT/CPS | 0.55 | 0.126 |
| | BDA | 0.35 | 0.08 |
| | CC | 0.10 | 0.022 |
| Material usage | 0.078 | | |
| | IOT/CPS | 0.54 | 0.042 |
| | BDA | 0.30 | 0.024 |
| | CC | 0.16 | 0.012 |
| Emissions | 0.137 | | |
| | IOT/CPS | 0.66 | 0.09 |
| | BDA | 0.20 | 0.027 |
| | CC | 0.14 | 0.02 |
| Energy usage | 0.04 | | |
| | IOT/CPS | 0.69 | 0.028 |
| | BDA | 0.18 | 0.007 |
| | CC | 0.13 | 0.005 |
| CE practices | 0.079 | | |
| | IOT/CPS | 0.62 | 0.048 |
| | BDA | 0.23 | 0.018 |
| | CC | 0.15 | 0.013 |

Table 7. Overall priority for each industry 4.0 technology.

| Industry 4.0 technology | Priority | Ranking |
|-------------------------|----------|---------|
| IOT/CPS | 54% | 1 |
| BDA | 32% | 2 |
| CC | 14% | 3 |

Overall Priority of BDA:

$$(0.437 * 0.37) + (0.228 * 0.35) + (0.078 * 0.3) + (0.137 * 0.2) + (0.04 * 0.18) + (0.079 * 0.23) = 0.32$$

Overall Priority of CC:

$$(0.437 * 0.15) + (0.228 * 0.10) + (0.078 * 0.16) + (0.137 * 0.14) + (0.04 * 0.13) + (0.079 * 0.15) = 0.14$$

The final global weights for each technology and their corresponding rankings are presented in [Table 7](#).

5. Discussion and results

Oláh et al. (2020) referred to the importance of achieving sustainability for firms and communities because of the increasing environmental problems. I4.0 and its technologies are gaining popularity because they contribute to sustainable development, maintain organizations' competitiveness, and capture new markets.

Many studies have explored the implications of I4.0, such as the efficient utilization of resources (Bag et al., 2021a), reduction of harmful emissions and waste, and promotion of CEP (Ghobakhloo et al., 2021). To address the scarcity of literature and respond to the calls of Chen and Hao (2022), this study focused only on exploring the positive impacts of adopting common technologies in the literature on manufacturing firms' EP and demonstrated their contribution toward attaining environmental SDGs. To answer the first research question, the findings of the literature review are summarized and presented in [Figure 2](#), which also acts as a reference guide for companies' manufacturers.

Consistent with Nguyen (2022) and Luoma et al. (2023), the study's findings indicate that adopting I4.0T could provide relevant and real-time EAI to overcome the limitations of EMA systems, set appropriate environmental strategies, support capital investment decisions, and help stakeholders understand companies' willingness in terms of environmental governance.

The findings of this study confirm DCT that demonstrates I4.0T as new dynamic capabilities enhancing firms' EP. The findings of this study are aligned with the current literature indicating that the adoption of IOT/CPS (Beltrami et al., 2021; Mabkhot et al., 2021), BDA/CC (Gajdzik et al., 2020), and AM (Oláh et al., 2020) can achieve SDGs (7, 8, 12, and 13). The adoption of IOT/CPS (Jena et al., 2020; Tozanli et al., 2020), BDA/CC (Mourtzis et al., 2020; Uriarte-Gallastegi et al., 2022), and AM (Nascimento et al., 2019) results in reducing resource usage, waste, emissions, toxic material usage, increasing usage of renewable and clean energy sources, and promoting CEP. In addition, the study's findings revealed that the adoption of simulation/digital twin technologies attains SDGs (8 and 12), as presented in [Figure 2](#), which is consistent with the findings of Mourtzis et al. (2020) and Mabkhot et al. (2021). These technologies improve EP by reducing resource usage and waste, as confirmed by Chen et al. (2020) and Chiarini (2021).

Furthermore, the adoption of VR/AR and intelligent robotics technologies attains SDG 8 and SDG 12 (target 12.4), as asserted by Gajdzik et al. (2020). Waste and emission reduction, efficient utilization of resources, and promotion of CEP resulted from adopting VR/AR and intelligent robotics technologies (Chiarini, 2021; Uriarte-Gallastegi et al., 2022).

Additionally, manufacturing firms face critical challenges such as limited financial resources, which discourage them from investing in new technologies with uncertain costs or guaranteed returns (Ghobakhloo et al., 2021). There is still a scarcity of literature on frameworks that support companies in adopting critical technologies, considering these challenges. Therefore, to answer the second research question, this study proposes a hierarchical framework using AHP, which acts as a reference guide for decision makers and manufacturers to prioritize I4.0T toward enhancing EP and modifying EMA systems.

Then, the proposed framework was applied to five leather tanning companies to test the applicability of the proposed framework.

According to the interview sessions, the leather companies' managers decided to adopt IOT/CPS, BDA, and CC due to their expected environmental benefits. In the light of the AHP survey, the overall average weights for criteria and alternatives are presented in Table 6, and it was found that waste management is the most important performance aspect toward enhancing EP, with a weight of 43.7%. This result agrees with those obtained by Chen et al. (2020) and Malik et al. (2024), who stated that reduction of all types of waste (solid or liquid) can enhance EP. According to Table 7, IOT/CPS is the most important technology, with an average global weight of 54%. This result confirms the findings of previous studies (Chen et al., 2020; Khan et al., 2021). According to the interviewees' responses, they expected that adopting IOT would result in utilizing resources more efficiently through deploying sensors to monitor each tanning process. As stated by Indana and Pahlevi (2023), one participant stated that sensors are used for waste management, identifying waste bins and their contents by categories like waste material or chemicals. In addition, sensors can monitor the conditions of the tanning process, such as the heat, temperature, and humidity, as stated by Nagy et al. (2018). Moreover, smart sensors can aid real-time pollution monitoring systems to detect excessive pollution levels (Chiarini, 2021) or leaks from tanning processes, such as amines, ammonia, and hydrogen sulfide. Specifically, as stated by Laskurain-Iturbe et al. (2021), some participants expected that IOT adoption would support reusing or recycling solid and liquid waste generated before becoming unusable.

The BDA and CC technologies had global average weights of 32% and 14%, respectively, as presented in Table 7. As stated by Jamwal et al. (2021) and Uriarte-Gallastegi et al. (2022), participants asserted that BDA could reduce environmental risks and optimize resource usage by analyzing a large data pool. In addition, all participants anticipated the BDA's role in analyzing and predicting environmental problems, enabling real-time data collection, data analysis, and real-time decision-making for monitoring resource usage, emissions, waste generation, and promoting CEP, as mentioned by Chiarini (2021). Consistent with Chen et al. (2020) and Chiarini (2021), participants confirmed that the data gathered will not lead to a reduction in resource usage or waste generation unless data analytics tools are used to analyze the data gathered and provide decision-makers with real-time EAI. Additionally, participants anticipated the role of CC technology in storing and retrieving environmental data from IOT devices during tanning processes. Thus, the participants expected the joint contribution of BDA and CC technologies toward enhancing EP. However, this result is not consistent with those obtained by Wang et al. (2015), who stated that cloud services do not align with external data storage.

6. Conclusion, implications, limitations and future research

In the 21st century, technological advancements have necessitated manufacturing firms to adapt to changing business environments through transitioning toward I4.0 to address environmental problems resulting from traditional industrial activities (Luoma et al., 2023). Conventional EMA systems cannot consider environmental problems and should be modified to provide decision-makers with relevant and timely EAI by adopting I4.0T. Recently, I4.0 has been considered a technological revolution that has significant environmental benefits, as stated by Chen and Hao (2022). Companies face challenges such as limited financial resources, insufficient management support, and data security, which may hinder their I4.0 transition. High implementation costs and limited financial resources are identified as the most critical barriers (Kumar et al., 2021; Prause, 2019), which should be considered before starting the I4.0 transition.

Literature on the environmental impacts of I4.0T and their contribution to attaining environmental SDGs is limited. Accordingly, this study aims to answer these research questions and identify future research paths by analyzing literature reviews and applying the proposed hierarchical framework. The results of analyzing the literature review are summarized in Figure 2, which would contribute to filling this research gap and answering the first research question by exploring the positive environmental impacts of adopting commonly utilized technologies and their contribution toward attaining the SDGs (7, 8, 12, and 13).

Additionally, this study underpins the lack of frameworks in the literature that can support manufacturing firms' managers in making investment decisions in critical technologies. Therefore, a novel hierarchical framework is developed in Figure 4 using AHP to fill this research gap and answer the second research question. Subsequently, the proposed framework was applied to five leather-tanning companies. The results revealed that waste management is the most important performance aspect, and IOT/CPS is the most important technology. Finally, the current study provides significant theoretical and practical implications, which are discussed in the following sections.

6.1. Theoretical implications

This study provides significant theoretical implications as follows: first, this study contributes to the existing literature by addressing the ambiguity surrounding the contribution of I4.0T toward modifying EMA systems and enhancing the EP of manufacturing firms by endorsing principles of DCT. Besides, the proposed alignment between each technology and the environmental SDGs is an additional theoretical contribution, second, no studies in literature have demonstrated the influence of each I4.0 technology on EP. To the best of our knowledge, this study is the first attempt to propose a hierarchical framework using AHP to rank I4.0T toward enhancing EP and modifying EMA systems. Researchers can use this framework to assess the importance of other technologies that do not exist in the framework, third, the simultaneous adoption of all I4.0T is difficult, thus, the proposed framework aids firm managers in determining the weights of various technologies to make investment decisions regarding their adoption, fourth, the proposed framework enhances its applicability by combining case study and MCDM tools, unlike most frameworks in the literature that are validated only through case studies, and fifth, the case study results revealed that IOPT/CPS, BDA, and CC technologies would enhance the EP of the leather companies. These results vary significantly based on the technology adopted, industry type, and challenges of each firm.

6.2. Practical implications

This study analyzes the literature and proposes a framework that provides practical implications. First, the proposed framework acts as a reference guide for practitioners and managers on the environmental impacts of I4.0T and their contribution toward environmental SDGs achievement. Practitioners will recognize the significant role of I4.0T in driving sustainable trends within their organizations. Second, identifying the major determinants of adopting I4.0T provides opportunities for managers to pay more attention to them. Third, the proposed framework can support managers in many ways: (1) The proposed framework shows which technology can improve each environmental aspect, providing valuable insights, particularly for managers in polluting industries. (2) The proposed framework could help decision-makers prioritize and/or re-evaluate investments in I4.0T, considering limited financial resources. (3) The proposed framework can be used by companies in different industries by modifying its components based on their goals and policies. Fourth, public authorities and policymakers have established mechanisms of environmental governance monitoring to encourage firms to make their operations and processes environmentally sustainable and reward firms with modified EMA systems.

6.3. Limitations and future research

This study has some limitations and offers opportunities for future research. First, the interrelationships among I4.0T were not considered. Therefore, researchers could extend the present study by using an analytical network process to consider the interrelationships among them. Second, the results of this study are only valid at the company level. Therefore, future research should be conducted at an industrial level. Third, future research should consider the impacts of other technologies such as blockchain, artificial intelligence, cybersecurity, and mobile technology. Fourth, future research should consider the cost-benefit analysis of applying the proposed hierarchical framework.

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Data availability statement

Data is available upon request from the author.

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