

Industry 4.0 technologies and circular economy: Implications for sustainable development in manufacturing firms

Tecnologías de la industria 4.0 y economía circular: Implicaciones para el desarrollo sostenible en las empresas manufactureras

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Abstract: The objective of this study is to analyze the relationship between Industry 4.0 technologies, circular economy practices, and sustainable development activities implemented by manufacturing firms in the automotive and aerospace industries. Literature has shown inconclusive evidence connecting these three constructs, while the recent increase in environmental shocks due to climate change is forcing all industries to modify their production strategies. To achieve this objective, a survey was distributed to a sample of 378 manufacturing firms in the automotive and aerospace industries in Mexico, and the results were validated using PLS-SEM. The findings suggest that the adoption of Industry 4.0 technologies has significant positive effects, both on sustainable development and on circular economy practices. In addition, circular economy practices have a significant positive effect on sustainable development, and positively mediate the relationship between Industry 4.0 technologies and sustainable development. Therefore, it is concluded that the simultaneous adoption of Industry 4.0 technologies and circular economy practices in manufacturing firms increases the possibilities of significantly improving the level of sustainable development activities.

Keywords: Industry 4.0 technologies, circular economy, sustainable development, manufacturing firms.

Resumen: El objetivo principal de este estudio es analizar la relación entre las tecnologías de la Industria 4.0, las prácticas de economía circular y las actividades de desarrollo sostenible adoptadas e implementadas por empresas manufactureras de los sectores automotriz y aeroespacial. Esto se debe, en particular, a que, por un lado, la literatura ha demostrado que los resultados obtenidos son insuficientes e inconclusos para establecer una relación positiva entre estos tres constructos y, por otro lado, al aumento de desastres naturales en los últimos años, a causa del cambio climático, que obliga a todos los sectores de la actividad económica a modificar sus estrategias de producción. Para lograr este objetivo, se distribuyó una encuesta a una muestra de 378 empresas manufactureras de los sectores automotriz y aeroespacial en México, y los resultados se validaron mediante PLS-SEM. Los resultados obtenidos sugieren que la adopción de tecnologías de la Industria 4.0 tiene efectos positivos significativos, tanto en el desarrollo sostenible como en las prácticas de economía circular, del mismo modo que la economía circular tiene un efecto positivo significativo en el desarrollo sostenible,

además de desempeñar un papel mediador entre las tecnologías de la Industria 4.0 y el desarrollo sostenible. Por lo tanto, se concluye que existe una relación estrecha y positiva entre los tres constructos y, en particular, que la adopción simultánea de tecnologías de la Industria 4.0 y prácticas de economía circular en las empresas manufactureras aumenta las posibilidades de mejorar significativamente el nivel de actividades de desarrollo sostenible.

Palabras clave: Tecnologías de la Industria 4.0, economía circular, desarrollo sostenible, empresas manufactureras.

1. Introduction

The literature establishes that the last decade has been characterized by an increasing number of natural disasters caused by global warming, and it is expected that these types of phenomena will continue to increase in the following years (IPCC, 2023; WMO, 2024). From this perspective, drastically reducing the level of pollutant emissions into the atmosphere requires transformative changes across all sectors of the global economy (IPCC, 2022). Specifically, several international agencies, government agencies, and scientific community suggest that Industry 4.0 technologies (I4.0T), and circular economy practices (CE) represent a crucial strategy to significantly improve sustainable development (SD) by reducing greenhouse gas emissions, which will allow achieving net-zero emissions goals (European Commission, 2020; IEA, 2022; Saccani *et al.*, 2023; Sassanelli *et al.*, 2023; Acerbi *et al.*, 2024; Ciano *et al.*, 2025).

In the light of this scenario, the literature calls for manufacturing firms to adopt more digital, and efficient production processes (Gatell & Avella, 2024), through the simultaneous implementation of I4.0T, CE practices and SD strategies (Cannas *et al.*, 2025), particularly if we consider that I4.0T can be defined as “a combination of different technologies such as additive manufacturing, simulation, robots and autonomous vehicles, augmented and virtual reality, IoT, cloud and cybersecurity” (Rübmann *et al.*, 2015, p. 56); CE can be defined as “an economic system based on the reuse, reduction, recycling and extraction of end-of-life materials to achieve long-term sustainable development goals” (Kirchherr *et al.*, 2017, p. 222), and SD can be defined as “those activities that are oriented towards the production of eco-friendly products with the environment, in compliance with environmental protection and for the benefit of society, the economy and the environment (Singh *et al.*, 2022, p. 3)”.

However, even though theoretical and empirical evidence of the effects of I4.0T on CE and SD practices has been provided, there are still many doubts in the literature and among company managers about the results obtained (Varriale *et al.*, 2024). Particularly because while some studies have found a positive relationship between I4.0T and CE practices (e.g. Rosa *et al.*, 2020; Ciliberto *et al.*, 2021), others have found a negative relationship (e.g. Ghobakhloo & Fathi, 2020; Dieste *et al.*, 2023), while, theoretically, other studies are not clear how I4.0T and CE can potentiate research and other (e.g. Sehnem *et al.*, 2025; Ciano *et al.*, 2025). In this context, the link between I4.0T, CE and SD practices are open to debate in the literature (Cannas *et al.*, 2025), especially in the manufacturing industry of developing countries (Ciliberto *et al.*, 2021; Percin *et al.*, 2025).

Although recent studies have provided robust theoretical and empirical evidence of the link between I4.0T and CE and SD practices in developing countries (e.g. Kayikci *et al.*, 2022; Dwivedi *et al.*, 2022; Kumar *et al.*, 2024), especially in the manufacturing industry in Mexico (e.g. Mora-Contreras *et al.*, 2023; Rodríguez-González *et al.*, 2023; Maldonado-Guzmán & Garza-Reyes, 2023), which is one of the developing countries that have a total cost of depletion of environmental resources equivalent to 4.6% of GDP, with the manufacturing industry generating the greatest negative impact on the environment representing 15% of total GDP, and the automotive and aerospace industries contributing just over 5% of that total (INEGI, 2022), the full integration and potential of the relationship between these three concepts is still in the early stages of adoption and cannot be considered conclusive (Percin *et al.*, 2025).

Additionally, the digital transformation of companies is essential, especially after having adapted their work systems to the introduction of I4.0 digital technologies during the COVID-19 pandemic to become more competitive and survive (Lafuente et al., 2023; Escribá-Carda et al., 2024). Therefore, the adoption of I4.0 digital technologies such as big data, algorithms, cloud computing, and social networks not only helps companies improve their competitive advantages (Rojas-Segura et al., 2023) but is also an essential condition for their market participation (Lafuente et al., 2022). In this context, digital transformation contributes to the development of skills for adding value through customized solutions to specific problems in response to specific company challenges (Lafuente & Sallan, 2024), as well as greater cost efficiency for profitable customization of supplies (Vaillant et al., 2025).

In this context, digital transformation not only helps manufacturing companies align their processes to current business scenarios to obtain financial and economic benefits (Vaillant & Lafuente, 2024), but also to obtain non-financial benefits such as, for example, the benefits of customer orientation (Sjödin et al., 2019), operational and competitive performance (Vaillant & Lafuente, 2024), ecological benefits (Lafuente & Vaillant, 2023a) and competitive efficiency (Lafuente & Vaillant, 2023b). Therefore, digitalization provides I4.0 technologies that can be used to enhance value creation and appropriation by manufacturing firms (Wamba et al., 2017; Kohtamäki et al., 2019), providing them with both financial and economic benefits (Abou-Foul et al., 2021; Gebauer et al., 2021; Yang et al., 2023) and non-financial benefits (Lexutt, 2020).

Understanding digitalization processes in emerging contexts becomes essential for organizations to align their operations, business models, and strategic capabilities with corporate objectives of growth, efficiency, and competitiveness. This is noted by Ács et al (2022) in their article, where they highlight that the development of a digital ecosystem—measured through the Digital Ecosystem Index (DEI) in 16 Latin American and North American countries—allows companies to better connect with platforms, users, and governments, generating synergies that drive value creation in dynamic environments. In emerging markets, where technological, institutional, and infrastructure barriers are often more pronounced, this digitalization capacity not only improves internal processes but also enables new channels for development, geographic expansion, and adaptation to change. Consequently, integrating these digital processes into corporate strategy fosters improved organizational performance—greater agility, better data-driven decisions, and greater market reach—and, consequently, the achievement of corporate objectives in an increasingly digital and competitive environment.

The objective of this study is to analysis the connection between I4.0T and CE on SD of manufacturing firms in the automotive and aerospace industries in Mexico, and response the following research question: *What is the relationship between Industry 4.0 digital technologies in CE and SD practices in manufacturing firms?* a survey was used using a sample of 378 companies and the statistical technique of Partial Least Squares Structural Equation Modelling (PLS-SEM), with the use of SmartPLS 4.0 software (Ringle et al., 2024). Furthermore, from a theoretical point of view, this study adds significant value to the literature by offering an empirical analysis of the digital ecosystem in emerging economies, an area that has been little explored compared to the contexts developed by authors such as Agrawal et al (2022) and Ciano et al (2025), therefore, to complement and expand the limited body of knowledge, this paper addresses this gap in the literature.

2. Literature Review

2.1. Industry 4.0 Technologies and Sustainable Development

Despite the existence of a vast literature analyzing the importance of I4.0T in manufacturing firms (e.g. Centobelli et al., 2023; Chatterjee et al., 2023; Lepore et al., 2023; Vu et al., 2023), relatively few studies published in the current literature have analyzed the relationship between I4.0T and SD (Rifqi et al., 2024), particularly in developing countries (Percin et al., 2025). Therefore, it is essential that the scientific, academic and business community direct their future studies towards

providing empirical evidence of the relationship between both constructs (Percin *et al.*, 2025), especially because it has been shown in the literature that the adoption of I4.0T improves the capacity of manufacturing firms to manage data, information, and artificial intelligence systems, which will allow them not only to develop innovative capabilities (Lepore *et al.*, 2023), but also to substantially increase their level of SD (Dubey *et al.*, 2019).

Recent studies published in the literature have indicated that in the last decade the adoption of I4.0 in manufacturing firms has increased by 72%, which implies the existence of a growing environmental awareness, the adoption of SD objectives and the increasing accessibility of new I4.0 technologies (Kusuma *et al.*, 2020). By integrating new digital technologies, I4.0 is facilitating the incorporation of sustainable management practices in the manufacturing industry (Oláh *et al.*, 2020), which has enabled efficient utilization of natural resources, reduction of industrial waste, and adoption of longer technology life cycles (Adedokun-Shittu *et al.*, 2020). Furthermore, the adoption and implementation of I4.0T not only improves SD, but also generates multiple benefits in manufacturing firms, including cost savings in production processes (Singh & Srivastava, 2018).

Along these same lines, it has been established in the literature that the key to improving SD of manufacturing firms is the adoption of I4.0T (Percin *et al.*, 2025), for which cloud computing, Internet of Things, big data, blockchain, sensors and robotics, artificial intelligence, and manufacturing resourcing planning provide intelligent, connected, agile and autonomous systems for data management in decision-making in manufacturing firms (Lezoche *et al.*, 2020; Sutar *et al.*, 2024; Sharma *et al.*, 2024). Furthermore, blockchain, Internet of Things, and big data enable the identification, tracking, and traceability of more environmentally friendly products (Akyazi *et al.*, 2020), which is why these I4.0T help manufacturing firms increase productivity, reduce the level of industrial waste, reduce carbon and CO₂ emissions, and improve SD (Kayikci *et al.*, 2022). Therefore, I4.0T is considered in the literature as an essential component that improves the economic, social, and environmental performance of manufacturing firms (Belaud *et al.*, 2019).

Additionally, I4.0T provide several tangible economic, environmental, and social advantages by significantly reducing negative impacts on the environment (Zheng, 2022), which benefits not only manufacturing firms but also countries as a whole and the global community (Olabi *et al.*, 2022). Therefore, by fully harnessing the potential of I4.0T and integrating it with SD activities, manufacturing firms across sectors can achieve sustainable outcomes that positively impact both the economy and society (Obaideen *et al.*, 2022). Consequently, more manufacturing companies are transitioning to more sustainable production by employing I4.0T and adopting SD to produce eco-products that are more environmentally friendly (Osman *et al.*, 2021). In this context, the adoption of I4.0T helps manufacturing firms improve their organizational capabilities by exploring new opportunities and fully exploiting their resources (Vu *et al.*, 2023), which allows them their SD level (Bag & Christiaan, 2022).

Furthermore, the adoption and application of I4.0T has resulted in a substantial improvement in the efficiency, flexibility, and productivity of manufacturing firms' production processes (Zengin *et al.*, 2021), which not only allows for an improvement in production capacities (Beier *et al.*, 2021), but also at the SD level (Alhammadi *et al.*, 2024). In this context, instead of simply adopting new machinery and equipment, the integration of I4.0T allows manufacturing firms to quickly respond to market demand and improve SD activities (Sulaiman *et al.*, 2021). Thus, considering the information presented above, it is possible to propose the following research hypothesis.

H1: The adoption of Industry 4.0 technologies is positively correlated with firm's sustainable development practices.

2.2. Industry 4.0 Technologies and Circular Economy

The concept of I4.0 is very popular in the literature, and its diffusion has increased significantly since its inclusion in Germany in a high-tech strategy for 2020 (Suchek *et al.*, 2024), becoming since then a constantly growing field of research (Lu, 2017; Liao *et al.*, 2017; Birkel & Müller, 2021), mainly in the integration of new I4.0T into CE practices (Rosa *et al.*, 2020; Dantas *et al.*, 2021; Agrawal *et al.*, 2022). Thus, the adoption and implementation of I4.0T in manufacturing firms increases demand optimization, failure reduction, and a higher level of productivity (Müller *et al.*, 2018). There is also

evidence in the literature that I4.oT supports the adoption of CE in manufacturing firms and, consequently, the successful operational application of CE-based business practices (Rosa et al., 2020; Agrawal et al., 2022). Therefore, in terms of CE, I4.oT constitute a fundamental input to improve the innovative potential of firms, even though the role of I4.oT in CE remains little explored in the literature (Suchek et al., 2021).

Recently, research has been conducted in the literature on how to boost the adoption of CE practices in manufacturing firms (Ciano et al., 2025), and it has been found that I4.oT are widely recognized as facilitators of both value chain integration (e.g. Sassanelli et al., 2021; Awan et al., 2021; Basile et al., 2023; Schmidt et al., 2023) and CE adoption, which is considered as “natural” (Moktadir & Ren, 2023). A clear example of this is that Internet of Things and dig data analytics allow the establishment of circular supply chains, crucial for the adoption of CE practices (Patil et al., 2023) such as cooperation between the different departments or functional areas to improve the environmental practices of the organization, training program for the organization’s employees and workers on environmental issues, total environmental quality management program, program to prevent contamination of waste generated by the organization, such as clean production, among others (Ormazabal et al., 2018).

On the other hand, Internet of Things and big data analytics also facilitate the EC practice of reducing the use of materials in the production of eco-products, thereby allowing a more efficient exploitation of natural resources (Romero & Noran, 2017; Song et al., 2017; Esmaeilian et al., 2018). Other examples of I4.oT that improve CE practices are machine learning and artificial intelligence (Ahmed et al., 2023) that, for example, allow manufacturing firms to automate the sorting processes of recycling materials, thereby improving the CE recycling strategy (Chen, 2022; Namoun et al., 2022), or additive manufacturing that also improves the CE recycling strategy by allowing the use of recycled materials as new raw materials in the manufacture of eco-products (Mandil et al., 2016; Clemon & Zohdi, 2018; Urbinati et al., 2024). Many other studies on the enabling role of I4.oT can be found in the literature (Bressanelli et al., 2018; de Sousa Jabbour et al., 2018; Rosa et al., 2020).

All this evidence of the potential that I4.oT must boost CE practices has led the scientific and academic community to develop frameworks that could support the integration of I4.oT and CE practices (Ciano et al., 2025). Indeed, current literature highlights the existence of knowledge gaps on how manufacturing firms can integrate CE practices and I4.oT and the distance between theory and practice (Taddei et al., 2024a; Taddei et al., 2024b). In this sense, Bressanelli et al (2018), de Sousa Jabbour et al (2018), and Rosa et al (2020) suggested the development of more holistic models to guide manufacturing firms in such integration could be the solution. Therefore, after the first integration model carried out by de Sousa Jabbour et al (2018), followed by others in the literature (e.g. Kazancoglu et al., 2021; Liu et al., 2022; de Sousa Jabbour et al., 2023), however, all of them are characterized by having different types of limitations (Ciano et al., 2025).

However, the literature requires more studies that contribute to understanding the implementation of I4.oT in CE practices (Agrawal et al., 2022), basically because the analysis of the link between I4.oT and CE is in an initial phase (Dantas et al., 2021), and the contribution of empirical evidence on its adoption and implementation in manufacturing firms is relatively scarce (Rosa et al., 2020; Awan et al., 2021). Recently published studies in the literature have attempted to provide evidence of the relationship between I4.oT and CE, such as Ertz et al (2022), who conducted a literature review and found that I4.oT can help extend the shelf life of products, which is considered an efficient way to save CE resources. Tang et al (2022) analyzed manufacturing firms involved in supply chain operations and found that I4.oT had a significant positive impact on CE practices. Bai et al (2022) explored the impact of I4.oT on SD goals and found that CE practices play an essential role in connecting I4.oT and SD activities. Therefore, considering the information presented above, the following research hypothesis is proposed.

H2: The adoption of Industry 4.0 technologies is positively correlated with firms’ circular economy practices.

2.3. Circular Economy and Sustainable Development

There is a vast literature that has theoretically confirmed the relevance of CE practices in manufacturing firms (e.g. Prieto-Sandoval *et al.*, 2018; Khan *et al.*, 2020a; Matarneh *et al.*, 2024; Cannas *et al.*, 2025). However, relatively few studies have applied CE practices in a SD context (e.g. Ghobakhloo *et al.*, 2021; Elf *et al.*, 2021; Dieste *et al.*, 2023), and even fewer studies have analyzed the relationship between CE practices and SD in developing countries (Percin *et al.*, 2025). A possible explanation for this phenomenon could be that the adoption of CE practices in manufacturing firms requires the implementation of significant changes (Marrucci *et al.*, 2021), and various organizations have limited resources that hinder the application of this type of practices, particularly in manufacturing firms in developing countries (Percin *et al.*, 2025).

Therefore, in the last decade CE is increasingly gaining attention from scientific, academic, and business community, as well as from policymakers, who are approaching this issue from a more economic, environmental, and social perspective (Sonar *et al.*, 2024a). In this regard, Khan *et al.* (2020b) demonstrated that CE practices can help manufacturing firms identify and improve their SD activities, while Scapellini *et al.* (2020) found that manufacturing firms that adopted CE improved their SD. However, these contributions are not sufficient since it is essential to provide robust empirical evidence of the existing relationship between CE practices and SD (Percin *et al.*, 2025), particularly due to increasing environmental degradation, biodiversity loss, resource scarcity, high dependence on fossil fuels for energy generation, and the proliferation of air, water, and soil pollution (Geissdoerfer *et al.*, 2017; Horodytska *et al.*, 2020).

Additionally, CE practices play a fundamental role in facilitating the SD of manufacturing firms (Zhu *et al.*, 2019; Mishra *et al.*, 2022), particularly the practices of cooperation between the different departments or functional areas to improve the environmental practices of the organization, training program for the organization's employees and workers on environmental issues, total environmental quality management program, program to prevent contamination of waste generated by the organization, such as clean production (Ormazabal *et al.*, 2018). Therefore, the 4Rs that encompass CE practices (reduce, reuse, recycle, and recover) can contribute to the substantial improvement of the SD level through the preservation of natural resources and the reduction of greenhouse gas emissions (Kumar *et al.*, 2022; Kusumowardani *et al.*, 2022; Zhang *et al.*, 2022).

Essential CE practices include closing the loop, efficiency, and effectiveness in the use of resources, designing eco-products with a longer lifespan, recyclability and reuse of resources and eco-products, and a shift to a service-based model (Sonar *et al.*, 2024c). Furthermore, CE practices promote manufacturing firms to reduce the usage of materials discarded in municipal landfills and incinerators, and to reuse and recycle waste in production processes, which allows for an improvement in the organizations SD (Sonar *et al.*, 2024b). Therefore, recycling products and reusing industrial waste helps organizations conserve their resources, particularly energy and water, which significantly contributes to maintaining a cleaner and healthier environment (Chen *et al.*, 2024; Jayarathna *et al.*, 2024).

In this context, CE is undoubtedly one of the most effective strategies that can be adopted to make organizations more sustainable, as it can play different roles that improve the quality and SD in the industrial sector (Strippoli *et al.*, 2024). In addition, CE practices facilitate economic growth for manufacturing firms, as well as the well-being of the communities where the companies are located, by promoting labor insertion and more inclusive local value chains, which improves SD (Zhao & Li, 2018; Voukkali *et al.*, 2023). Therefore, CE is considered in the literature as the most effective strategy, not only to get out of the disastrous effects on the economy caused by the Covid-19 pandemic (Axhami *et al.*, 2023), but also to improve the level of SD (Strippoli *et al.*, 2024). Thus, considering the information presented above, the following research hypothesis is proposed.

H3: The adoption of circular economy practices is positively correlated with firm's sustainable development practices.

The circular economy acts as an essential bridge between Industry 4.0 technologies and sustainable development, transforming linear production models into regenerative, resource-efficient systems. Digital technologies—such as the Internet of Things (IoT), data analytics, smart automation, and additive manufacturing—enable the collection and processing of real-time information on materials, processes, and products, facilitating decision-making aimed at reducing waste and closing production cycles. Along these lines, [Ghobakhloo et al \(2021\)](#) highlight that Industry 4.0, by incorporating digitalization and automation capabilities, can serve as a catalyst for sustainable strategies if aligned with circular principles, while [Wamba et al \(2017\)](#) show that big data analytics strengthen the dynamic capabilities necessary to achieve superior environmental and operational performance. In this way, the circular economy mediates the relationship between technology and sustainability by offering a strategic framework that translates digital efficiency into environmental and social value.

Furthermore, the integration of the circular economy into Industry 4.0-enhanced value chains boosts resilience and the creation of new sustainable business models. [Kohtamäki et al \(2019\)](#) emphasize that digital servitization models foster collaboration in industrial ecosystems, facilitating resource reuse and product lifecycle extension, while [Centobelli et al \(2023\)](#) show how digitalization and resilience in the supply chain—such as in the naval sector—promote circular practices by optimizing material flows and minimizing waste. Together, these approaches reveal that the circular economy is not only a desirable outcome of Industry 4.0, but a key mediator that transforms technological innovation into practical sustainability, ensuring that digitalization effectively contributes to sustainable development and long-term competitiveness.

In this line, [Alcayaga et al \(2019\)](#) highlighted the need to develop a better understanding of how I4.oT facilitates SD through the successful implementation of CE practices, but few studies published in the literature have theoretically and empirically highlighted that CE practices can play a key role in the link between I4.oT and SD (e.g. [Dantas et al., 2021](#); [Akter et al., 2022](#)). Therefore, [Awan et al. \(2021\)](#) presented a literature review that provides a perspective of multiple activities that enhance the effects of I4.oT adoption and implementation on SD, through CE practices, while [Singh et al \(2024\)](#) found not only a significant positive relationship between I4.oT, CE practices, and SD activities, but also that the link between I4.oT and SD increases substantially when CE practices are incorporated as a mediating variable.

Additionally, [Massaro et al \(2021\)](#), through an extensive literature review, found that the adoption of I4.oT improves the SD outcomes of manufacturing firms, especially when CE practices act as a mediating variable ([Samadhiya et al., 2023](#)). In a more recent study, [Samadhiya et al \(2023\)](#) demonstrated that I4.oT significantly improves the SD of manufacturing firms when CE acts as a mediating variable. In this context, the adoption of CE practices in I4.oT has a great potential to improve outcomes in manufacturing firms, which increases the reliability of improving the SD in organizations ([Lim et al., 2021](#)). Moreover, the integration of CE into I4.oT has the potential to significantly improve the production systems of manufacturing firms, leading to a higher level of SD ([Boeing et al., 2022](#)).

However, integrating CE practices into the existing link between I4.oT and SD activities is not without challenges, especially in ensuring that the implementation of I4.oT does not lead to increased resource consumption or the generation of higher volumes of industrial waste ([Dolci et al., 2024](#)). Therefore, [Nascimento et al \(2019\)](#) highlighted the potential of big data, Internet of Things, artificial intelligence, and machine learning (I4.oT) technologies to improve the SD level of manufacturing companies through the implementation of CE practices such as efficient resource use, reduced industrial waste levels, and the use of renewable energy. Similar results were obtained by [Bressanelli et al \(2018\)](#) who argued that I4.oT such as big data and Internet of Things facilitates the improvement of SD activities through CE practices such as, for example, the reuse and recycling of materials that reduce the generation of industrial waste.

Recent studies have provided robust empirical evidence showing that the adoption of I4.0T substantially improves SD activities through CE practices (Dolci *et al.*, 2024). For example, Lei *et al.* (2023) found that the implementation of I4.0T such as the Internet of Things, big data analytics, artificial intelligence, and blockchain minimizes negative environmental impacts through CE practices such as waste reduction and material reuse, while Schöggel *et al.* (2023) found that the use of I4.0T such as additive manufacturing, 3D printing, the Internet of Things, computer-aided design, blockchain, and augmented reality minimizes negative environmental and sustainability impacts through the adoption of CE practices such as the design and development of eco-products that can be disassembled, repaired, and reused. Thus, considering the information presented above, the following research hypothesis is proposed.

H4: Circular economy practices positively mediate the relationship from Industry 4.0 technologies to sustainable development practices.

3. Methodology

3.1. Data

To answer the hypotheses posed in the research model, the business directories of the Mexican Automotive Industry Association (AMIA) were used, which had a record of 950 companies as of January 30, 2023, as well as the Mexican Federation of the Aerospace Industry (FEMIA), which had a record of 350 companies on the same date. It is important to establish that manufacturing companies in the automotive and aerospace industries belong to various regional, national, and international chambers and business organizations, which is why the study was not oriented toward a particular chamber or business organization. Likewise, a “Business Panel” was held in which 5 entrepreneurs from automotive and aerospace industry participated, 2 representatives of government agencies related to financial support to companies, and 3 academics from innovation area who were given the survey that would be applied for analysis and discussion. The results obtained in this Business Panel allowed the design of a survey to collect information, which was applied to a pilot sample of ten entrepreneurs from automotive and aerospace industry, in order to verify that the questions were correct and that there were no incorrect answers from the managers of the manufacturing SMEs surveyed, only making minor adjustments to the wording.

The selection of manufacturing firms in the automotive and aerospace industries (1,300 firms between both industries) was carried out using simple random sampling, with a maximum error of $\pm 4\%$ and a reliability of 95%, obtaining a sample of 320 companies. In addition, a survey was designed to collect the information and was distributed to 500 manufacturing firms in both industries in Mexico, achieving a response of 378 surveys, therefore the final error of the sample was 3.9%. In order for the sample to be representative of both industries and considering that there are no significant differences in the three constructs analyzed between both industries, the number of surveys to be applied was calculated according to the percentage of contribution of each industry to the total population (1,300), so the number of surveys to be applied in the automotive industry was 234 (73% of the total population) and in the aerospace industry it was 86 surveys (27% of the total population). Thus, of the 378 surveys applied, 260 surveys correspond to the automotive industry and 108 surveys to the aerospace industry, which indicates that the sample is representative of the population under study.

A market research firm was hired to administer the paper surveys, which then handed them out to SME managers for completion. The survey, administered from February to June 2023, was directed to firms’ managers, who, in turn, identified the most suitable individuals to respond to the various questionnaire sections. Given their pivotal role in decision-making, general managers, well-informed about the study, adeptly identified individuals with the requisite expertise to address the questionnaire’s diverse sets of questions (Kuo & Chang, 2021). Table 1 presents the most relevant descriptive statistics of the measurement items scales used in this study.

Table 1: Descriptive statistics of the items

Items	Mean	Standard Deviation
I4.0 Technologies (I4.0T)		
I4T.01 Computer-aided process planning (CAPP)	3.68	1.181
I4T.02 Automatic identification/bar code systems/RFID/industrial IoT	3.69	1.185
I4T.03 Smart ICT applications supporting collaboration, connectivity, data processing, information mining, modeling, simulation.	3.60	1.151
I4T.04 Manufacturing resource planning (MRP) and/or enterprise resource planning (ERP).	3.72	1.141
I4T.05 Advanced manufacturing technologies, additive manufacturing, 3D printing, high precision technologies (micro/nano-processing).	3.80	1.105
Sustainable development (SD)		
SD1 Expand the economy's productive potential	3.97	0.820
SD2 Foster economic growth to facilitate satisfaction of basic needs	3.93	0.910
SD3 Decouple economic growth and material consumption	3.82	0.945
SD4 Stabilize the economy's productive potential	3.76	1.003
SD5 Stabilize economic growth to safeguard ecological thresholds while redistributing Access.	3.77	0.987
SD6 Decouple economic growth and material consumption while taking rebound effects into account.	3.82	0.944
SD7 Limit and transform the economy's productive potential	3.86	0.933
SD8 Downscale economic growth while reducing inequalities and exploitation	3.83	0.933
SD9 Dematerialize society and economy through emphasizing the role of sufficiency, happiness, and equity.	3.81	1.120
Circular Economy (CE)		
CE1 There is an environmental commitment by senior management	4.12	0.780
CE2 There is support for environmental management by mid-level managers.	4.10	0.862
CE3 There is cooperation between the different departments or functional areas to improve the environmental practices of the organization.	4.07	0.865
CE4 There is a training program for the organization's employees and workers on environmental issues.	4.05	0.889
CE5 A total environmental quality management program is in place	4.01	0.911
CE6 There are permanent audit programs of the organization's environment, such as ISO 14000.	4.03	0.899
CE7 Eco-labels are used on most of the products generated by the organization.	3.99	0.969
CE8 There is a program to prevent contamination of waste generated by the organization, such as clean production.	4.09	0.862

Note: All the items were measured using a five-point Likert scale, with 1 = strongly disagree to 5 = strongly agree as limits.

3.2. Variables

Likewise, to measure the concepts of I4.0T, SD, and CE the literature was thoroughly reviewed, identifying the scale of [Gastaldi et al \(2022\)](#) as the most appropriate for measuring I4.0T, who measured this concept using 5 items. Regarding the measurement of SD, the scale of [D'Amato et al \(2017\)](#) was used, who measured it through 9 items. Finally, to measure CE, the scale proposed by [Ormazabal et al \(2018\)](#) was considered, who measured this concept using 8 items. All the items in the scales were measured using a five-point Likert scale, with 1 = strongly disagree to 5 = strongly agree as limits. [Table 2](#) displays the items of the measurement scales used in this study and indicates that all the items on the measurement scales used have a value higher than 0.6 recommended by [Hair et al \(2019\)](#).

Table 2: Measurement Model Assessment

Indicators	Constructs	Factor Loads (p-value)
Industry 4.0 Technologies (I4.0T) Cronbach's Alpha: 0.928; Dijkstra–Henseler's rho (ρ_A): 0.930; CRI (ρ_c): 0.945; AVE: 0.776		
I4T.01	Computer-aided process planning (CAPP)	0.871 (0.000)
I4T.02	Automatic identification/bar code systems/RFID/industrial IoT	0.907 (0.000)
I4T.03	Smart ICT applications supporting collaboration, connectivity, data processing, information mining, modeling, simulation.	0.883 (0.000)
I4T.04	Manufacturing resource planning (MRP) and/or enterprise resource planning (ERP).	0.876 (0.000)
I4T.05	Advanced manufacturing technologies, additive manufacturing, 3D printing, high precision technologies (micro/nano-processing).	0.867 (0.000)
Sustainable Development (SD) Cronbach's Alpha: 0.936; Dijkstra–Henseler's rho (ρ_A): 0.948; CRI (ρ_c): 0.949; AVE: 0.684		
SD1	Expand the economy's productive potential	0.842 (0.000)
SD2	Foster economic growth to facilitate satisfaction of basic needs	0.834 (0.000)
SD3	Decouple economic growth and material consumption	0.859 (0.000)
SD4	Stabilize the economy's productive potential	0.888 (0.000)
SD5	Stabilize economic growth to safeguard ecological thresholds while redistributing Access.	0.884 (0.000)
SD6	Decouple economic growth and material consumption while taking rebound effects into account.	0.905 (0.000)
SD7	Limit and transform the economy's productive potential	0.889 (0.000)
SD8	Downscale economic growth while reducing inequalities and exploitation	0.843 (0.000)
SD9	Dematerialize society and economy through emphasizing the role of sufficiency, happiness, and equity.	0.657 (0.000)
Circular Economy (CE) Cronbach's Alpha: 0.956; Dijkstra–Henseler's rho (ρ_A): 0.958; CRI (ρ_c): 0.963; AVE: 0.765		
CE1	There is an environmental commitment by senior management	0.827 (0.000)
CE2	There is support for environmental management by mid-level managers.	0.849 (0.000)
CE3	There is cooperation between the different departments or functional areas to improve the environmental practices of the organization.	0.899 (0.000)
CE4	There is a training program for the organization's employees and workers on environmental issues.	0.858 (0.000)
CE5	A total environmental quality management program is in place	0.912 (0.000)
CE6	There are permanent audit programs of the organization's environment, such as ISO 14000.	0.900 (0.000)
CE7	Eco-labels are used on most of the products generated by the organization.	0.853 (0.000)
CE8	There is a program to prevent contamination of waste generated by the organization, such as clean production.	0.895 (0.000)

3.3. Error Bias Test and Validity

Problems of common response bias exist in most cross-sectional and quantitative studies, when data are collected using a single source or by applying a self-report survey (Podsakoff *et al.*, 2003). Podsakoff *et al.* (2003) recommended two strategies to address the problems of common method bias (CMB). On one hand, managers were informed of the anonymous treatment of their correct and incorrect answers, so they should answer honestly each of the questions posed in the survey. On other hand, Harman's single factor was used (Podsakoff & Organ, 1986), which establishes that the factor analysis should have a common factor that explains at least 50% of the total variance. The results obtained of the exploratory factorial analysis show that KMO = 0.905, Bartlett's Test of Sphericity is significant ($X^2 = 8,475.12$, $gl = 231$, $p = 0.000$), and

42.92% of the total variance extracted is explained by a common factor, given that the total extracted factor was less than 50%, it is possible to affirm that there is no CMB problem.

3.4. Method

The data collected through the survey application were analyzed using PLS-SEM through the SmartPLS 4.0 software (Ringle et al., 2024). PLS-SEM was used because this study, on one hand, includes a research model with various indicators (Sarstedt et al., 2016; Rigdon et al., 2017), which are necessary in the operational definition of the emerging construct that mediates all its effects (Henseler et al., 2015). On other hand, because the indicators do not have a common error term, unlike what happens with research models that have causal formative indicators (Hair et al., 2021), which is why these types of indicators share the same results, even when they are not unidimensional and do not share the same conceptual unit (Henseler, 2017).

4. Results

The use of PLS-SEM statistical technique to respond to the hypotheses established in the research model is fundamentally due to two basic aspects. (1) It is the most appropriate statistical technique for the analysis of theories, which have not been widely developed in the literature in the various disciplines of knowledge (Hair et al., 2019). (2) It is the most appropriate statistical technique when the objective of the research is the prediction and explanation of the different concepts used in the research model (Hair et al., 2019). Therefore, the PLS-SEM statistical technique facilitates the explanation of the measurement error of the three concepts used in this study, as well as the multiple regression of the range of scores of the link between I4.0, SD, and CE in manufacturing firms (Hair et al., 2019).

4.1. Measurement Model

The reliability of I4.0, SD, and CE measurement scales was assessed using the four indicators recommended in the literature for the use of PLS-SEM: Cronbach's alpha, Dijkstra-Henseler rho, Composite Reliability Index (CRI), and Average Variance Extracted (AVE). Table 2 (Panel A) indicates that the values of Cronbach's alpha, Dijkstra-Henseler rho, and CRI are higher than the 0.80 recommended in the literature (Hair et al., 2021), while the AVE values are higher than the 0.50 recommended in the literature, which establishes the existence of reliability and validity of the concepts used (Hair et al., 2021). Additionally, discriminant validity was assessed using the two most used criteria in the PLS-SEM literature: Fornell and Larcker Criterion and Heterotrait-Monotrait ratio (HTMT).

Table 3 (Panel B) shows the results of the discriminant validity assessment and indicates that the square root of all AVE values is higher than the correlations with the other concepts in the respective rows and columns, which is an indicator of the existence of discriminant validity of the DTI4.0, SD, and CE concepts. Regarding the HTMT results, Henseler et al (2015) considered that an HTMT value within 0.1 to 1.0 would confirm the existence of discriminant validity, and the results obtained and presented in Table 3 (Panel B) show that HTMT values range between 0.254 and 0.473, which indicates the existence of discriminant validity of the scales of the I4.0, SD, and CE concepts, as well as a good statistical fit to the study data (Hair et al., 2021).

Table 3: Measurement Model. Reliability, Validity and Discriminant Validity

PANEL A. Reliability and Validity						
Variables	Cronbach's Alpha	Dijkstra-Henseler rho	CRI	AVE		
Industry 4.0 Technologies	0.928	0.930	0.945	0.776		
Sustainable Development	0.936	0.948	0.949	0.684		
Circular Economy	0.956	0.958	0.963	0.765		
PANEL B. Fornell-Larcker Criterion						
Variables				Heterotrait–Monotrait ratio (HTMT)		
	1	2	3	1	2	3
1. Industry 4.0 Technologies	0.881					
2. Sustainable Development	0.288	0.827		0.308		
3. Circular Economy	0.242	0.444	0.874	0.254	0.473	

Note: PANEL B: Fornell-Larcker Criterion: Diagonal elements (bold) are the square root of the variance shared between the constructs and their measures (AVE). For discriminant validity, diagonal elements should be larger than off-diagonal elements.

4.2. Structural Model

The structural model was evaluated through the most recommended indicators in the PLS-SEM literature: coefficient of determination (Adjusted R²), multicollinearity test (VIF), and p-value (Hair & Sarstedt, 2021). To obtain the values of these indicators, the bootstrapping procedure was carried out with 5,000 subsamples using SmartPLS 4.0 software (Ringle et al., 2024), and the results indicate the existence of an acceptable statistical level, obtaining Adjusted R² values (SD: 0.251; CE: 0.063) higher than the value recommended in the literature (Henseler et al., 2014; Hair & Sarstedt, 2021). Multicollinearity was assessed using VIF and the results obtained indicate that the minimum and maximum VIF values are 1.136 and 4.652, which confirms the non-existence of multicollinearity problems (Pallant, 2020).

The significance of the research model was assessed using the p-value, which are considered significantly acceptable if the p-value is less than 0.05 (Hair & Sarstedt, 2021). The results obtained indicate that the p-values (I4.0T-SD: 0.001; I4.0T-CE: 0.000; CE-SD: 0.000; I4.0T-CE-SD: 0.000) are less than 0.05, which indicates the acceptance of the hypotheses raised in the research model. Figure 1 shows these results in greater detail.

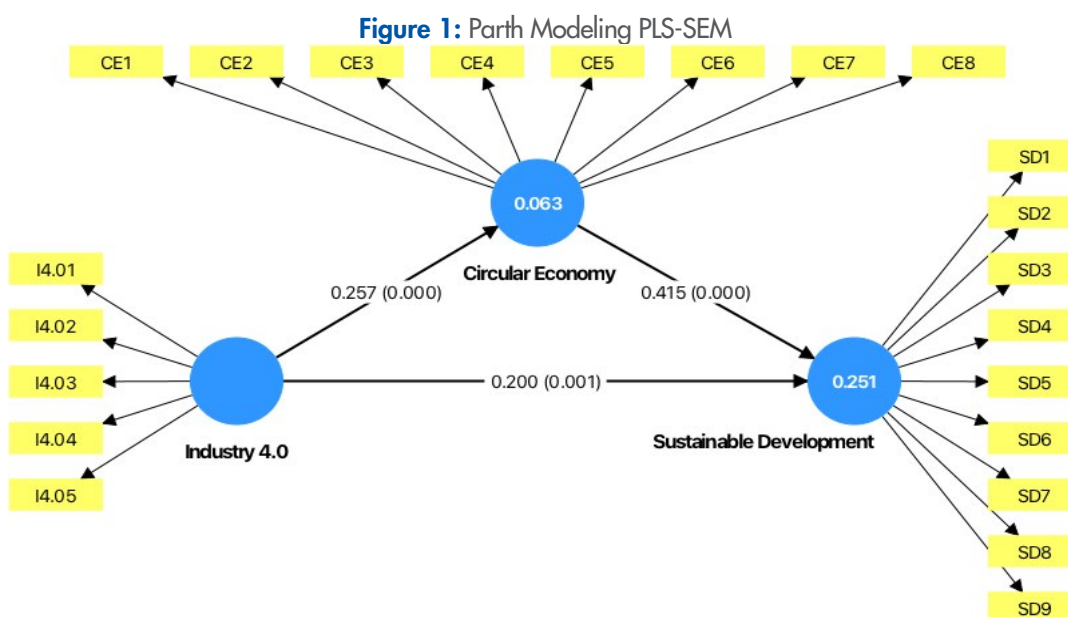


Figure 1 shows that the estimated data verify our argument that I4.oT has a significant positive effect on SD (0.200; p-value 0.001), which provides evidence in favor of hypothesis H1, these results being consistent with those found in recent studies by Rifqi et al. (2024) and Percin et al. (2025), which demonstrates the theoretical evidence found in the literature that I4.o digital technologies help manufacturing companies improve SD practices. Figure 1 also verifies our argument that I4oT has a positive effect on CE (0.257; p-value 0.000), these results showing evidence in favor of hypotheses H2 and are in line with both recent studies by Dantas et al (2021) and Agrawal et al (2022), as well as the theoretical evidence found in the literature that establishes a close connection between both constructs.

The Figure 1 results also show that CE practices have a positive effect on SD of manufacturing firms (0.415; p-value 0.000), which provides evidence in favor of hypothesis H3, These results are similar to those found in recent studies by Dieste et al (2023) and Sonar et al (2024a), which demonstrates the theoretical evidence found in the literature that establishes that CE practices are essential for improving the SD of manufacturing companies. Finally, Figure 1 also verifies our argument that CE practices can act as a variable mediator in the relationship between I4.oT and SD (I4.o→CE→SD 0.199; confidence intervals: 2.5% = 0.050; 97.5% = 0.154), thereby providing evidence in favor of hypothesis H4 and are in line with both recent studies by Singh et al (2024) and Samadhiya et al (2023), and with the theoretical evidence found in the recent literature establishing that the level of SD increases when CE practices act as a mediating variable between I4.oT and SD.

5. Discussion

The results obtained in this study support our argument of the existing link between I4.oT in SD activities, these results being in line with those found by Obaideen et al (2022), Bag and Christiaan (2022) and Vu et al (2023). The main reason that could explain these results is that the adoption of I4.oT promotes sustainable production practices and resource efficiency, which can help companies improve their level of sustainability, reduce waste and pressure on the use of natural resources. These results confirm the findings of Lezoche et al (2020), who demonstrated that by integrating I4oT such as wireless networks, cloud computing and the Internet of Things, agro-industrial companies can obtain additional data (e.g. water, soil, humidity, temperature and radiation) that can help them reduce negative impacts on the environment and SD. Therefore, I4.oT improve SD activities by increasing productivity, reducing industrial waste and ecological deterioration.

The results obtained also support our argument that I4.oT has a positive effect on CE practices, these results being like to those obtained by Rosa et al. (2020), Awan et al (2021) and Agrawal et al (2022). The essential reason that could explain this result is that the adoption of I4.oT, such technologies as big data, blockchain, the Internet of Things, artificial intelligence, and machine learning enhance business circularity. These results confirm the findings of studies by Sutar et al (2024) and Sharma et al (2024), who found that these types of I4.oT digital technologies significantly improve the traceability and transparency of material reuse, recycling, and remanufacturing, while reducing raw material use and industrial waste. Therefore, the results obtained in this study demonstrate the need for company managers to integrate I4.oT with CE practices and sustainability strategies to achieve SD objectives.

The results obtained also support our argument of the positive relationship that CE practices have on SD activities, these results being in line with those obtained by Voukkali et al (2023), Axhami et al (2023) and Strippoli et al (2024). The essential reason that could explain this result is that CE practices. They improve resource efficiency and productivity in circular production processes. These results confirm the findings of Islam and Zheng (2024), who demonstrated that CE practices are essential for improving SD activities, reducing industrial waste, using renewable energy, and adopting more sustainable consumption. Therefore, the results of this study provide robust empirical evidence demonstrating that the implementation of CE practices helps companies utilize renewable resources such as water and energy, as well as protecting the environment and terrestrial and marine ecosystems.

Finally, the results obtained also support our argument that CE practices play a mediating role between I4.0T and SD, these results being like those found by Lim *et al* (2021), Boeing *et al* (2022) and Samadhiya *et al* (2023). The main reason that could explain these results is that the integration of CE practices not only favors the improvement of SD through the adoption of I4.0T in production processes but also allows manufacturing companies to significantly reduce production costs. These results confirm the findings of the study conducted by Percin *et al* (2025), who found that the integration of I4.0 digital technologies such as sensors, RFID, remote sensing, big data, Internet of Things, and artificial intelligence contribute to real-time traceability and operational efficiency. By implementing CE practices at the same time. Therefore, I4.0T improves SD activities, when CE practices are applied simultaneously, which increases productivity and reduces industrial waste in manufacturing companies.

5.1. Practical Implications

The data estimated in our study is relevant for executives, policymakers, business practitioners, and public administration. First, the relationship between I4.0T, CE, and SD advocates the transition of manufacturing firms in the automotive and aerospace industries from a traditional linear economy based on *take-make-dispose* to a circular economy based on *reuse, recycling, and remanufacturing*. In today's dynamic business environment, the adoption of IoT 4.0 technologies such as big data, the Internet of Things, artificial intelligence, and blockchain allows manufacturing companies to create new market niches and develop new eco-products to become more competitive. Furthermore, as IoT 4.0 technologies help companies improve efficiency and increase process reliability and accuracy, it is essential to enhance workers' skills in the use of digital technologies such as big data, the Internet of Things, artificial intelligence, and blockchain, which will enable a reduction in industrial waste and environmental pollution.

Second, these findings support the notion that CE practices are essential to consolidate the achievement of manufacturing firms' long-term SD objectives, and therefore managers must consolidate the transition from a business model based on a traditional economy to a new business model based on CE. This relationship highlights the crucial role of CE practices in the imitative behavior of manufacturing companies, i.e. copying the successful actions of their competitors, so public administration should provide companies with favorable ecosystems by formulating appropriate legal frameworks that not only penalize organizations that do not carry out Russian, recycling and remanufacturing activities of materials (CE practices), but also incentivize those who do so in order for the country to comply with its international commitments to achieve the SD objectives.

Third, This study provides robust empirical evidence establishing that the adoption of I4.0T technologies such as big data, blockchain, the Internet of Things, artificial intelligence, and machine learning not only helps companies become more sustainable but also improves CE practices such as waste reduction and material recycling, essentially because new I4.0 digital technologies enable waste reduction, closing the loop, implementing sustainable purchasing, and improving resource use. Therefore, company executives should consider the life cycle of products and processes when adopting I4.0T, including digital technologies related to energy and natural resource inputs required for production and end-of-life disposal processes. This implies prioritizing the use of renewable energy sources and sustainable and recycled materials in their new product production operations.

6. Conclusions, Limitations and Future Research Directions

6.1. Conclusions

The objective of this study is to analyze and discuss the connection between I4.0T and CE on SD of manufacturing firms in the automotive and aerospace industries in Mexico. Based on this objective, the results obtained allow us to establish two

fundamental conclusions. First, managers of manufacturing companies in the automotive and aerospace industries must adopt strategies that facilitate the adoption of I4.0T by their staff, particularly because I4.0T will directly and indirectly impact all employees in the organization through the new dynamics adopted by companies. Therefore, I4.0T will allow manufacturing firms to optimize both their resources and capabilities, so that they can respond as quickly and efficiently as possible to the needs of their main suppliers, their customers, and an increasingly globalized and competitive market.

Second, by jointly adopting and implementing I4.0T and CE practices, manufacturing firms could generate unique competitive advantages that would help them improve not only their SD level but also their productivity and competitiveness. Furthermore, the joint application of I4.0T and CE practices facilitates teamwork and provides valuable information to management, facilitating the optimization of production processes, reducing work time, and increasing the productivity of the organization's staff. Additionally, the joint adoption and implementation of I4.0T and CE practices in manufacturing firms in the automotive and aerospace industries also facilitates and streamlines communication within the supply chain, which can significantly reduce work time and employee errors, thereby facilitating the acquisition of new skills, competencies, and knowledge.

6.2. Limitations and Future Research Directions

This study has several limitations that need to be considered in future research. The first limitation is the generalizability of the results, particularly because the study focused only on manufacturing companies in the automotive and aerospace industries in Mexico, which poses challenges for applying the results to a broader group of companies in other sectors or other countries. Therefore, to address this limitation, future research in other industries and countries could use this same survey to corroborate whether the results are similar. A second limitation is that in this study, we adopted a research model analyzed using the PLS-SEM statistical technique; however, the use of other types of statistical techniques could broaden our understanding of the link between I4.0T, CE practices, and SD activities. Therefore, future studies would be appropriate to use neural networks or logistic linear regression to corroborate the results obtained.

A third limitation is that the literature has analyzed and discussed the various sustainable benefits that the joint adoption and implementation of I4.0T and CE practices generate in manufacturing firms (Dantas et al., 2021). However, more studies that provide robust empirical evidence are needed to better understand the adoption of the new I4.0T and CE practices by manufacturing firms, particularly in developing countries, since these are the countries where the highest levels of pollution are generated due to the lack of environmental policies and programs. Therefore, in future studies, it would be appropriate to carry out studies in these types of countries with the aim of comparing the results obtained. Finally, a fourth limitation is the measurement scales used to measure I4.0T, CE, and SD, since only 5 items were used to measure I4.0T, 8 items for CE, and 9 items for SD. Therefore, in future studies it would be advisable to use other scales or hard data to verify whether the results obtained coincide or not with these results.

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