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Impact of Industry 4.0 Adoption on Eco-Innovation and Sustainable Development: The Automotive and Aerospace Manufacturing Sectors

Impacto de la adopción de la Industria 4.0 en la ecoinnovación y el desarrollo sostenible: sector manufacturero automotriz y aeroespacial

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ABSTRACT

This study aims to fill a gap in the literature and provide robust empirical evidence on the effects of IoT 4.0 on eco-innovation and the sustainable development of manufacturing companies by conducting a survey of 378 manufacturing companies in the automotive and aerospace industries in Mexico and validating the results using PLS-SEM. The results suggest that the adoption of Industry 4.0 has significant positive effects on both sustainable development and eco-innovation, that eco-innovation has a considerable positive impact on sustainable development, and that eco-innovation also serves as a mediating mechanism between Industry 4.0 and sustainable development.

Keywords: Industry 4.0, eco-innovation, sustainable development, automotive industry, aerospace industry.

Jel Code: M15

RESUMEN

Este estudio tiene como objetivo llenar el vacío existente en la literatura y aportar evidencia empírica robusta de los efectos que tiene la 4.0 en la eco-innovación y el desarrollo sustentable de las empresas manufactureras, mediante la aplicación de una encuesta a una muestra de 378 empresas manufactureras de la industria automotriz y aeroespacial de México, validando los resultados mediante el uso del PLS-SEM. Los resultados obtenidos sugieren que la adopción de la Industria 4.0 tiene efectos positivos significativos tanto en el desarrollo sustentable como en la ecoinnovación, y que la ecoinnovación tiene un efecto positivo significativo en el desarrollo sustentable, además de jugar un rol mediador entre la Industria 4.0 y el desarrollo sustentable.

Palabras clave: Industria 4.0, ecoinnovación, desarrollo sustentable, industria automotriz, industria aeroespacial.

Código JEL: M15

INTRODUCTION

The exponential growth of the global population, the surge in the consumption of goods and services, and the improvement in quality of life generated in recent decades have driven exponential increases in demand for natural resources (Strazzullo et al., 2022). However, the scarcity of natural resources is causing society, in general, and manufacturing firms in particular, to rethink their operational strategies and redesign production processes with a sustainable development (SD) perspective (Jawaad & Zafar, 2019). Furthermore, in accordance with the commitment signed by most countries to guide strategies towards sustainable consumption and production, not only as part of the United Nations 2030 Agenda to achieve the 17 Sustainable Development objectives (UN General Assembly, 2015), but also to reduce the planet's temperature by 1.5°C (UN, 2021).

To achieve this goal, the adoption and application of digital technologies in current production systems is necessary to promote the transition towards a cleaner economy that guarantees the reduction of the demand for natural resources, combined with an efficient use of consumer goods, and converges towards a regenerative economy (Strazzullo et al., 2022). The concept of Industry 4.0 (I4.0) is presented in the literature as a leading solution for harmonizing economic growth and ambitions to improve SD (Khan et al., 2023). Particularly, because I4.0 has proven to be a driver of eco-innovation (EI) of products and services derived from its rapid technological advances (Frank et al., 2019), as well as the improvement of processes (De Giovanni & Cariola, 2021), organizations (Dalenogare et al., 2018), and general business models (Ibarra et al., 2018) in different industrial sectors.

In this context, contemporary digital technologies used in I4.0, in conjunction with EI of environmentally friendly products, have proven to be a remarkable potential strategy in creating sustainable industrial value, by improving economic components of manufacturing firms such as resource efficiency, as well as overcoming environmental and social constraints necessary for SD (Bonilla et al., 2018). While I4.0 and EI are intertwined concepts, I4.0 and SD are relatively recent emerging trends in the literature that need to be analyzed more widely (Luthra & Mangla, 2018; Dubey et al., 2019; Bai et al., 2020). The relationship between I4.0 and the resulting EI, and its implications for SD, are recognized as both synergistic and overlapping concepts in the literature, but are also acknowledged as open to debate (Khan et al., 2023).

Additionally, there are recently published studies that have investigated the impact of I4.0 digital technologies and EI on different aspects of sustainability, such as I4.0 and the circular economy (Rosa et al., 2020), and SD (Dantas et al., 2021), sustainable production functions (Ching et al., 2022), maintenance management (Silvestri et al., 2020), and aspects of organizational and social sustainability (Ghobakhloo et al., 2021). However, given the importance, relevance and timeliness of this topic, recent studies suggest a careful evaluation of the link between I4.0 and EI and its influence on the impact of SD (e.g. Bai et al., 2020; Mubarak et al., 2021), basically because the strength of the relationship between I4.0, EI, and SD is still unknown (Piccarozzi et al., 2022). Its results are too ambiguous and open to debate (Khan et al., 2023).

Therefore, the objective of this study is to analyze the adoption of I4.0 digital technologies in manufacturing firms in the automotive and aerospace industries in Mexico, as well as their effect on EI and SD, using a sample of 378 companies and the statistical technique of Partial Least Squares Structural Equation Modelling (PLS-SEM), with the use of SmartPLS 4.10.9 software (Ringle et al., 2024). Likewise, this study contributes to filling the existing gap in the literature on the link between I4.0, EI, and SD (Bai et al., 2020; Mubarak et al., 2021; Piccarozzi et al., 2022), and in providing robust empirical evidence on the adoption of I4.0 digital technologies in manufacturing firms in the automotive and aerospace industries in a developing country, such as Mexico (Khan et al., 2023). The rest of the paper is structured as follows: Section 2 presents the literature review and hypotheses; Section 3 introduces the research methodology; the analysis and interpretation of esentthe results are included in Section 4; lastly, Section 5 provides the conclusions, limitations, and future research directions.

LITERATURE REVIEW

Industry 4.0 and Sustainable Development

In the last two decades, the concept of sustainability is gaining more interest in the scientific and academic community (Sadhukhan et al., 2020), mainly due to the implementation of global environmental protection policies promoted in various countries (Fuso Nerini et al., 2019; Zhang et al., 2019), as well as the establishment of the Sustainable Development Agenda by the United Nations, which guarantees the well-being of people and a more sustainable planet for the entire society (Rosa, 2017; Pollitzer, 2018). The concept of I4.0 appears in the literature as an approach and strategy that can significantly increase the wealth of manufacturing firms (Fakhrul et al., 2022), as well as industrial development linked to SD objectives (Hidayatno et al., 2019; Schroeder et al., 2019), and creativity that is a prerequisite for SD (Silvestre & Tirca, 2019).

Therefore, I4.0 substantially improves the SD of manufacturing firms through the automation and digitalization of production processes (Pacchini et al., 2019), as well as bulk customization and servitization (Oztemel & Gursev, 2020). Other benefits of I4.0 include real-time tracking and traceability of transactions in supply chains (Upadhyay et al., 2021), waste reduction and recycling, and the facilitation of circular economy outcomes (Nascimento et al., 2019). Therefore, by adopting I4.0, both production agility and production cost efficiency (Raj et al., 2020; Upadhyay et al., 2020) are exponentially improved, as is the SD of manufacturing firms (Mukhuty et al., 2022). Despite recognition of these benefits, adoption of I4.0 has been slow in the manufacturing industry (Fantini et al., 2020; Raj et al., 2020; Nankervis et al., 2021).

Additionally, the literature shows that the use of smart sensors extends product lifecycles and reduces the use of natural resources, thereby promoting both recycling and SD (Blömeke et al., 2020). In this sense, new sensor-based digital technologies of I4.0 help manufacturing firms constantly monitor the use of machinery and equipment and the organization's energy needs, thereby increasing the level of SD (Strazzullo et al., 2023). In addition, advanced digital technologies of I4.0 improve the efficiency of production processes and reduce the level of industrial waste (Strazzullo et al., 2023) by eliminating existing defects in production processes (Moeuf et al., 2018; Bigliardi et al., 2022), which increases the SD level of manufacturing firms by a high percentage (Strazzullo et al., 2023).

According to Ghobakhloo (2020), I4.0 enables companies to introduce new business models, such as crowd-sourced innovation, manufacturing as a service, and production as a service, which offer significant opportunities to improve the social and economic sustainability of SD (Åkerman et al., 2018; Birkel et al., 2019). In terms of improving the environmental aspect of SD, the adoption of I4.0 offers opportunities to reduce CO_2 emissions from manufacturing firms (Kamble et al., 2018), which accounted for a quarter of global emissions in 2021 (IEA, 2022). However, despite the above examples, relatively few studies published in the literature have analyzed and discussed the symbiosis between I4.0 and SD (Ghobakhloo, 2020; Beltrami et al., 2021). Thus, based on the information presented above, we propose the following research hypothesis.

H_1: The higher level of adoption of I4.0, the higher level of sustainable development

Industry 4.0 and Eco-innovation

The push towards sustainable production in the last decade stems from the increasing pressure that global manufacturing firms face from environmental groups, suppliers, public administration, and society in general, who demand environmental responsibility (Liu et al., 2021; Srhir et al., 2023). Therefore, manufacturing firms have to modify their current strategies to adapt them to the development of green capabilities that allow a reduction of their environmental impact (Sahoo et al., 2024), a transformation that is often challenging due to the changes required in production processes, supply chains, and eco-product innovation (Bag et al., 2021; Kannan et al., 2022), as well as the high costs of investment in technological transformation and unpredictable customer demand (Bai & Satir, 2020; Shokri et al., 2022).

These obstacles often lead to initial reluctance as manufacturing firms weigh the lack of a required return on investment against the long-term benefits the organization would gain (Kannan et al., 2022; Isensee et al., 2023). However, the lack of development of green product EI capabilities generates various risks for manufacturing firms, including environmental damage, competitive disadvantages, and neglect of lucrative business opportunities (Quintana-García et al., 2021; Jafari et al., 2022; Buadit et al., 2023). Therefore, to mitigate these risks, it is necessary for manufacturing firms to incorporate I4.0 digital technologies in the creation and development of EI activities of products and services (Nayal et al., 2021; Malacina & Teplov, 2022), which could minimize the carbon footprint and ensure sustainability (Bui et al., 2023).

Recently published studies in the literature argue that manufacturing firms that have adopted and applied I4.0 digital technologies as a strategic resource have significantly improved their value creation, visibility, supply chain transparency with their partners, and EI activities (e.g., Qader et al., 2022). Particularly because the adoption of I4.0 involves integrating advanced technologies into traditional production processes to create an intelligent production system, thereby improving efficiency, productivity, decision-making, and EI (Bag et al., 2021; Venanzi et al., 2023), in this sense, the literature suggests that the integration of digital technologies that make up I4.0 is a fundamental enabler for manufacturing firms to improve EI activities (Di Maria et al., 2022; Erboz et al., 2022).

Additionally, two main justifications in the literature have been proposed for analyzing the relationship between I4.0 and EI (Sahoo et al., 2024). First, with growing customer and consumer commitment to environmental care and protection, demand for environmentally friendly products is increasing (Bui et al., 2023; Luo et al., 2023). This trend is leading manufacturing firms to invest increasingly larger amounts of economic resources in the development of EI products, which requires new technologies and production processes (Nayal et al., 2021; Wang et al., 2022). Second, I4.0 is transforming production and supply chain processes, improving their efficiency, reducing industrial waste, and improving the development of EI in collaboration with supply chain partners (Patrucco et al., 2022). Therefore, considering the information presented above, the following research hypothesis is proposed.

H_2: The higher level of adoption of I4.0, the higher level of eco-innovation.

Eco-innovation and Sustainable Development

In the literature, innovation is considered a fundamental driver of SD, and the United Nations Sustainable Development Goals (SDGs) provide a comprehensive framework for addressing the different dimensions (people, planet, prosperity, partnerships, and peace) of global challenges (Dzhunushalieva & Teuber, 2024). Progress towards achieving some SDGs is lagging, particularly in developing countries (Dzhunushalieva & Teuber, 2024), but it is still possible to reach them (Sachs et al., 2023). However, Schot and Steinmueller (2018) argued that the complex nature of both SDGs and SD requires transformative solutions that go beyond adopting innovation activities, which require manufacturing firms to implement a combination of innovation activities and advanced technologies to develop eco-innovative products (Islam, 2025).

In this context, EI is considered essential in the literature for promoting and achieving the SDGs and the SD of manufacturing firms, because it plays a central role in promoting environmental sustainability and economic prosperity of companies (Islam, 2025). By focusing on green technologies and practices, EI helps manufacturing firms reduce greenhouse gas emissions and combat climate change, which are essential to significantly improving SD (Wang et al., 2021; Khan & Idrees, 2023). In addition, EI includes advances in energy efficiency, industrial waste reduction, and sustainable resource management, which together contribute to more sustainable economic growth and environmental management, substantially improving the level of SD (Islam, 2025).

Additionally, the synergy between EI and SD, together with technological advances, facilitates the progress of several SDGs, including those related to clean water and sanitation, affordable and clean energy, and sustainable cities and communities (Shahzad et al., 2022; Yikun et al., 2022). Therefore, the adoption and implementation of EI in manufacturing firms not only improves SD but also drives social development by creating new economic opportunities and improving the quality of life of society (Islam, 2025). However, to achieve the full potential of EI, manufacturing firms often also need to strengthen other complementary factors, such as sustainable performance levels and supporting policies, to effectively and in the long term obtain benefits (Younas et al., 2023).

In this regard, Calabrese et al. (2021) highlighted the mediating role of EI in manufacturing firms' SD achievement. Delving deeper into the community level, Imaz and Eizagirre (2020) analyzed how manufacturing firms can contribute to the SD agenda through enhancing EI activities. Meanwhile, Alarcón et al. (2021) and Nogueira et al. (2022) highlighted the pivotal role of EI activities in addressing and achieving the SDGs, particularly in rural firms. Meanwhile, Khan et al. (2022) found that EI moderates the correlation between financial performance and SD improvement. Zhou et al. (2020) and Wei et al. (2023) explored the promotion of EI in sustainable supply chains, while Wang et al. (2022) highlighted the role of EI knowledge management in improving the SD of organizations. Thus, considering the information presented above, the following research hypothesis is proposed.

H_3: The higher level of adoption of eco-innovation, the higher level of sustainable development

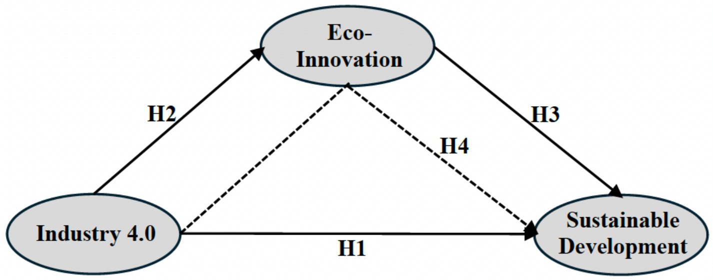
In the last decade, the scientific and academic community has not limited itself to analyzing the I4.0 paradigm and its link with EI activities. Still, it has gone a step further and is currently focusing on creating more sustainable industrial value (Khan et al., 2023). Thus, from an economic point of view, EI activities for products and services improve the relationship between I4.0 and SD by reducing social inequalities, climate change, and global environmental problems (UN DESA, 2020; UN News, 2021). Therefore, the adoption of EI in manufacturing firms has contributed to improving the results of new I4.0 technologies throughout the entire value chain, from the robustness of production processes (Sánchez et al., 2020; Tripathi et al., 2022) to the transformation of a more scalable and flexible supply chain (Hahn, 2020).

Additionally, Liu and De Giovanni (2019) demonstrated through mathematical models that I4.0 significantly improves SD by incorporating EI into production processes, while Dev et al. (2020) showed how I4.0 can simplify the supply chain in an environment of diffusion of SD-enhancing products. Chen et al. (2021) found that EI derived from implementing I4.0 technologies increased the energy efficiency and SD level of manufacturing firms. Ghobakhloo and Fathi (2021) found that EI activities can contribute to a greater adoption and implementation of I4.0 technological advances in manufacturing firms, which would significantly increase both energy sustainability and SD level.

In this context, current research trends in the literature show an essential interrelation of I4.0, EI of products, processes and management and SD from different perspectives such as, for example, the implications of sustainability for society, economy, and environment (Müller, 2021), sustainable supply chain (Luthra & Mangla, 2018), circular economy (Rajput & Singh, 2019; Yu et al., 2022), and sustainable business models (De Man & Strandhagen, 2017). However, the literature provides a limited view of the interaction and interpretation of EI, I4.0, and SD. It lacks a systematic analysis of the mediating role of EI in the implications of I4.0 and SD (Khan et al., 2023). Thus, considering the information presented above, the following research hypothesis is proposed.

H_4: Eco-innovation plays a mediating role between I4.0 and sustainable development.

Figure 1
Research Model



Source: Own elaboration.

METHODOLOGY

To respond to the hypotheses raised in the research model, the business directories of the Mexican Automotive Industry Association (AMIA), which had a registry of 950 companies, and the Mexican Aerospace Industry Federation (FEMIA), which had a registry of 350 companies, were considered as a reference framework as of January 30, 2023. It is important to note that the manufacturing firms of AMIA and FEMIA belong to different national and international business associations and chambers, which is why this study was not focused on a particular group or business chamber. In addition, this study focused exclusively on manufacturing firms in the automotive and aerospace industries, given that these industries have not received extensive attention in the literature relative to other sectors.

Manufacturing firms in the automotive and aerospace industries were selected through simple random sampling, with a maximum error of ±4% and a reliability level of 95%, obtaining a sample of 320 firms. The survey used to collect the data was distributed to 500 manufacturing firms in both industries in Mexico, and 378 responded. This ensured the final sample accurately represented both sectors. 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 (Yu & Tsai, 2018; Kuo & Chang, 2021).

Variables and Data Analysis

To measure the concepts of I4.0, SD, and EI, an extensive literature review was conducted, identifying the Gastaldi et al. (2022) scale as the most appropriate for measuring I4.0 digital technologies, which was measured using five items. To measure SD, the scale proposed by D’Amato et al. (2017), consisting of 9 items, was used. Finally, to measure EI, the scale proposed by Segarra-Oña et al. (2011) and Doran and Ryan (2012), comprising five items, was used. All items on the scales were measured using a five-point Likert scale, with 1 = strongly disagree and 5 = strongly agree as the limits.

Additionally, given that data were collected using the same instrument with the same informant (company manager), this can introduce bias that alters responses, potentially leading to Type I (false positive) or Type II (false negative) errors. The evaluation of standard method variance (CMV) was used, following the recommendations of Podsakoff et al. (2012). Traditionally, the method most used by researchers to verify the possible effect of CMV is Harman's one-factor test (Podsakoff et al., 2003), which consists of subjecting practically all the items of the scales to exploratory factorial analysis, forcing extraction to a single factor (Andersson & Bateman, 1997; Mossholder et al., 1998; Iverson & Maguire, 2000; Aulakh & Gencturk, 2000).

To verify the suitability of the data and the potential effect of CMV, an exploratory factorial analysis (EFA) was conducted using the principal components method with varimax rotation, and the Kaiser-Meyer-Olkin (KMO) coefficient and Bartlett's sphericity test were calculated. The results support the use of EFA with data from this sample, with a KMO value of 0.884 and a statistically significant Bartlett test [X2 (171) = 6,459.85, $p < 0.000$]. If there is a CMV problem, common factor extracted should have a value greater than 50% of the variance (Podsakoff et al., 2003), but common factor extracted from data is 41.96%, which is lower than the recommended value, which suggests that CMV is not a threat to sample data of this study, and does not seem to affect the relationships between variables of the research model significantly (Podsakoff et al., 2012).

Finally, the data collected through the survey application were analyzed using PLS-SEM with SmartPLS 4.10.9 (Ringle et al., 2024). Fundamentally, PLS-SEM was used because this study is based on a composite model of indicators (Sarstedt et al., 2016; Rigdon et al., 2017), which are essential in the operational definition of the emerging construct that mediates all its effects (Henseler et al., 2015). Furthermore, PLS-SEM was used because the indicators lack standard error terms, unlike studies with causal formative indicators (Hair et al., 2021). Commonly, these types of indicators yield the same results even when they are not unidimensional and do not share the same conceptual unit (Henseler, 2017), so composite indicators can represent different aspects of the concept (Hair et al., 2021).

RESULTS

The use of the PLS-SEM statistical technique to answer the research hypotheses raised in this study is primarily due to two essential issues: (1) it is the most appropriate statistical technique for the analysis of theories that have not been widely developed in the literature (Hair et al., 2019), in the different disciplines of knowledge (Sarstedt et al., 2014; do Valle & Assaker, 2015; Richter et al., 2016); (2) it is the most appropriate statistical technique when the essential objective of the study is the prediction and explanation of the concepts analyzed (Rigdon, 2012). In this sense, the PLS-SEM statistical technique facilitates the explanation of the measurement error of the concepts used in the study, as well as the multiple regression of the range of scores of the link between I4.0, SD, and EI of manufacturing firms (Hair *et al*., 2021).

Measurement Model

To assess the reliability of the measurement scales, the four indicators most commonly used in the literature were employed: Cronbach's alpha, Dijkstra-Henseler rho, Composite Reliability Index (CRI), and Average Variance Extracted (AVE). Table 1 (Panel A) indicates that the values of Cronbach's alpha, Dijkstra-Henseler rho, and CRI are higher than the value of 0.80 recommended in the literature. In comparison, the AVE values exceed the 0.50 recommended in the literature, thereby ensuring the validity of the constructs used (Hair et al., 2021). Additionally, discriminant validity was assessed using the two most widely recommended criteria in the literature: the Fornell-Larcker criterion and the Heterotrait-Monotrait Ratio (HTMT).

Table 1
Measurement Model. Reliability, Validity, and Discriminant Validity

PANEL A. Reliability and Validity				
Variables	**Cronbach's Alpha**	**Dijkstra-Henseler rho**	**CRI**	**AVE**
Industry 4.0	0.928	0.933	0.945	0.776
Sustainable Development	0.936	0.948	0.949	0.684
Eco-innovation	0.873	0.871	0.910	0.671

PANEL B. Fornell-Larcker Criterion				**Heterotrait–Monotrait ratio (HTMT)**		
Variables	**1**	**2**	**3**	**1**	**2**	**3**
1. Industry 4.0	**0.881**					
2. Sustainable Development	0.288	**0.827**		0.308		
3. Eco-innovation	0.348	0.442	**0.819**	0.377	0.489	

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.

Source: Own elaboration.

Table 1 (Panel B) presents the results of the discriminant validity assessment, indicating that the square roots of the AVE values exceed the correlations with the other constructs in the respective rows and columns, suggesting discriminant validity for the three measurement scales. Additionally, Henseler *et al*. (2015) established that an HTMT value between 0.1 and 1.0 indicates discriminant validity. The results obtained from the discriminant validity using the HTMT ratio suggest that the minimum and maximum values range between 0.308 and 0.489, respectively, which confirms the existence of discriminant validity (Table 2 Panel B) and indicates that the study has an excellent fit to the data (Bagozzi & Yi, 1988; Hair *et al.*, 2019).

Evaluation of Outer Model/ Measurement Model

An outer model analysis was conducted to ensure the measurement was appropriate for use. Measurement model testing shows convergent and discriminant validity. If the reflexive correlation exceeds 0.70, it is considered high. However, for early-stage research in scale creation, an external filling value of 0.5–0.60 is considered sufficient (Chin et al., 2003).

Structural Model

The structural model was evaluated using the coefficient of determination (Adjusted R2), effect size (f2), multicollinearity tests (VIF), t-test statistics, and p-values (Hair & Sarstedt, 2021). In addition, the bootstrapping procedure was used with 5,000 subsamples with the support of the SmartPLS 4.10.9 software (Ringle et al., 2024), and the results indicate that the data obtained have acceptable statistical levels (Table 2), finding Adjusted R2 values (0.221 for SD and 0.124 for EI) higher than the recommended value of 0.10 (Henseler et al., 2014; Hair & Sarstedt, 2021). Regarding the f2 values, Cohen (2013) classified the effect into three groups: (1) between 0.02 and 0.14 as small; (2) between 0.15 and 0.34 as medium; and (3) greater than 0.35 as large. The results indicate that the effect sizes for the I4.0-SD (0.030) and I4.0-EO (0.146) relationships are small, whereas for the EI-SD (0.179) relationship, the effect size is medium (Table 2).

Multicollinearity was assessed using the internal VIF, and the results show that the minimum and maximum values were 1.246 and 4.979, respectively, confirming the absence of multicollinearity (Pallant, 2020). Regarding significance, it was assessed using the t-test and the p-value, which are considered significant when the t-statistic exceeds 1.96 and the p-value is less than 0.05 (Hair & Sarstedt, 2021).

The results obtained from the data analysis indicate that the values of the t statistics of all the relationships are greater than 1.96 (I4.0-SD: 2.791; I4.0-EI: 7.614; EI-SD: 7.175; I4.0-EI-SD: 5.412), while the p values (I4.0-SD: 0.005; I4.0-EI: 0.000; EI-SD: 0.000; I4.0-EI-SD: 0.000) are less than 0.05, which establishes the acceptance of the hypotheses of the research model. Table 2 shows these results in greater detail.

Table 2
Structural Equation Model

Paths	Path (*t-value; p-value*)	95% Confidence Interval	f^2	Support
I4.0 → SD (H1)	0.154 (2.791; 0.005)	[0.048 – 0.262]	0.030	Yes
I4.0 → EI (H2)	0.352 (7.614; 0.000)	[0.251 – 0.430]	0.146	Yes
EI → SD (H3)	0.392 (7.175; 0.000)	[0.286 – 0.494]	0.179	Yes
Indirect Effects				
I4.0 → EI → SD (H4)	0.238 (5.412; 0.000)	[0.091 – 0.191]		Yes
Endogenous Variables	**Adjusted R^2**	**Model Fit**	**Value**	**HI99**
		SRMR	0.037	0.044
SD	0.221	dULS	0.256	0.372
EI	0.124	dG	0.138	0.180
		NFI	0.809	

Source: Own elaboration.

Note: I4.0: Industry 4.0; SD: Sustainable Development; EI: Eco-innovation. One-tailed t-values and p-values in parentheses; bootstrapping 95% confidence intervals (based on n = 5,000 subsamples) SRMR: standardized root mean squared residual; dULS: unweighted least squares discrepancy; dG: geodesic discrepancy; HI99: bootstrap-based 99% percentiles

Table 2 also shows that the fit assessment of the structural model was carried out through the SRMR, unweighted least squares discrepancy (dULS), and geodesic discrepancy (dG), which if they have values lower than those obtained in HI99, indicate that the structural model has a good fit to the data (Dijkstra & Henseler, 2015), as well as through the NFI which suggests that if it has a value greater than 0.70 it is indicative of a good fit of the structural model (Hair & Sarstedt, 2021). The results indicate that the values of SRMR (0.037), dLUS (0.256), and dG (0.138) are lower than the values of HI99 (0.044; 0.372; 0.180, respectively), while the value of NFI (0.809) is higher than the value of 0.70, indicating that the adoption of I4.0 improved both SD and EI of manufacturing firms in the automotive and aerospace industries.

DISCUSSION

The results found in this study support our argument of the existence of a significant positive link between I4.0 and DS; these results are in line with those found by Ákerman et al. (2018), Birkel et al. (2019), and Ghobakhloo (2020), as well as with the level of EI; these results being similar to those found by Nayal et al. (2021), Malacina and Teplov (2022), and Bui et al. (2023). The main reasons that could explain these results are, on the one hand, that the executives of manufacturing firms in the automotive and aerospace industries are clear about the advantages generated by I4.0 and, on the other hand, that its adoption not only allows the production of eco-products, but also an improvement in the SD of organizations, which allows I4.0 to be characterized not only as a technological leap, but as a strategic asset that reconceptualizes the dynamics of production processes that promote automated and interactive relationships with the members of the supply chain.

Furthermore, the results support our argument that EI is closely related to SD, and they align with those reported by Wang et al. (2021), Khan and Idrees (2023), and Islam (2025). The main reasons that could explain the relationship between these two concepts are, on the one hand, the development of eco-products (vehicles and aircraft parts) that are more environmentally friendly, which would not only allow them to comply with environmental regulations but also to be recognized as green companies. On the other hand, the use of new I4.0 technologies would facilitate both the development of new eco-products, and the achievement of the SD objectives set by the United Nations, through the recycling, reuse, and repurposing of materials from vehicles and aircraft that have completed their useful life cycle in the remanufacturing of new eco-products, thereby reducing the generation of greenhouse gases.

Finally, the results also support our argument that EI plays a mediating role between I4.0 and SD, and they align with those reported by Dev et al. (2020), Chen et al. (2021), and Ghobakhloo and Fathi (2021). The main reasons that could explain these results are, on the one hand, the implementation of EI activities significantly conditions the interaction and outcomes of I4.0 and SD, which highlights the multifaceted nature of the role that EI plays in manufacturing firms. On the other hand, the complexity of these interdependencies demands a deeper analysis of the moderating EI activities that govern the relationship between advanced I4.0 technologies and SD outcomes, not only in organizations in the automotive and aerospace industries but also in other sectors of the economy.

Additionally, the main reason for the findings of this study could be that manufacturing firms in the automotive and aerospace industries are currently moving towards an innovative technological culture, particularly because, as most of the organizations are suppliers of the large vehicle and aircraft manufacturing firms, they are required to change their organizational culture to continue in the supply chain, thereby generating the adoption of I4.0 and EI as a strategy that facilitates the improvement of the SD level. Therefore, manufacturing firms in the automotive and aerospace industries are currently facing unique challenges that make the adoption of I4.0 and EI activities a necessary strategy, not only to remain in the supply chain but also to achieve SD objectives.

Practical Implications

The data estimated in our study is relevant for executives, policymakers, business practitioners, and public administration. Firstly, the link between I4.0, SD, and EI advocates transitioning manufacturing firms in the automotive and aerospace industries from a traditional business strategy to a new technology strategy, which poses a challenge for industrial organizations. However, the level of difficulty varies among manufacturing firms, so managers must implement a technologically sophisticated model in the search for organizational results, to meet the demands posed by large companies that allow them to continue in the supply chain, as well as to be more proactive and innovative in the inclusion of sustainability activities that improve their business strategies oriented towards recycling that generates sustainable production.

Secondly, these findings further support the notion that EI activities are essential to consolidate the long-term competitive position of manufacturing firms, and therefore, managers need to advocate for an innovative spirit that relentlessly seeks new applications of I4.0 digital technologies to amplify integration at all levels of the supply chain. However, company managers should consider that even when organizations face several barriers to the adoption of I4.0 technologies, this should not influence the results and benefits obtained, particularly because I4.0 digital technologies are not only facilitators, but enablers that intensify communication, collaboration, and coherence within the supply chain which allow for improved SD and EI levels.

Ultimately, the integration of I4.0 technologies into SD and EI generates greater transparency, adaptability, and resilience, which are essential requirements to foster trust and value creation throughout the supply chain (Parviziomran & Elliot, 2023; Prataviera et al., 2023). However, company managers should emphasize to their staff that I4.0 technologies are a means to an end, not an end in themselves. In this context, the adoption of I4.0 digital technologies should be a relevant topic for policymakers, business practitioners, and public administration, in the development of policies and support programs to encourage more manufacturing firms in all industrial sectors to adopt new I4.0 technologies, as well as provide the infrastructure and necessary policies to expedite the preparation of workers for the adoption and application of I4.0, SD and EI.

Theoretical Implications

This study offers critical theoretical implications by providing robust evidence that companies can enhance the capabilities that give them a competitive advantage and leverage the benefits of adopting I4.0 digital technologies. Therefore, this research advances the theory of resources and capabilities by demonstrating how the strategic alignment of manufacturing firms' resources and capabilities with organizational objectives can serve as the basis for achieving competitive advantage in a technologically complex business environment (Saghiri & Wilding, 2021). Therefore, the benefits of adopting I4.0 and EI activities in manufacturing firms outweigh the associated costs.

Furthermore, this study offers substantial theoretical evidence that bridges the existing gap in the literature by highlighting the indispensable role of adopting I4.0 digital technologies in manufacturing firms in achieving their organizational objectives, amid the accelerated pace of technological advancements and the relentless pursuit of environmental stewardship and sustainability. These findings reinforce the idea that the adoption of I4.0 and EI activities is essential to consolidating the long-term competitive position of manufacturing firms. In this sense, the findings of this study empirically validate the theory that advocates the relentless pursuit of new applications of I4.0 digital technologies and the adoption of innovations that are compatible with both firms' economic performance and improved sustainability.

Finally, the theoretical findings of this study also highlight the fundamental role of internal integration in strengthening collaborative relationships with suppliers and customers of manufacturing firms. Therefore, by delving beyond the traditional view, this study reveals that the adoption of I4.0 and EI digital technologies significantly impacts technological integration by aligning organizational economic objectives with environmental stewardship goals. This can lead manufacturing firms worldwide to greater transparency, adaptability, and resilience, fundamental prerequisites for fostering value creation throughout the entire supply chain (Parviziomran & Elliot, 2023; Prataviera et al., 2023).

CONCLUSIONS

The information obtained in this study allows us to draw several conclusions, among which the following stand out. Firstly, this study reveals that I4.0 exerts an implicit transformative effect on SD of manufacturing firms, which is mediated by EI activities, thus constituting a fundamental axis in the innovation activities of organizations, which allows companies to strengthen their innovation capacity in the field of sustainability, which will enable us to conclude that the scientific, academic, and business community needs to direct future studies that provide robust empirical evidence of the relationship between these three concepts, particularly in manufacturing firms in developing countries, where the adoption of new I4.0 technologies as well as the achievement of SD objectives is very slow.

Secondly, the findings of this study highlight the importance of adopting I4.0 not only to foster innovation-focused, sustainable production but also to develop new, eco-innovative products and processes. This knowledge is poised to serve as an invaluable precursor for manufacturing firms interested in expanding their sustainability outcomes and the scope of their innovation activities. Therefore, it is possible to conclude that the transition from a conventional industrial environment to an intelligent industry environment will allow manufacturing firms in the automotive and aerospace industries to develop sustainable production practices, as this will help organizations to more quickly improve their production capacity and develop eco-products, which will increase both their financial resources and care for the environment and sustainability.

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