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# Smart Value Chains: Integrating Big Data and Sustainability in Industry 4.0

## Cadenas de valor inteligentes: Integración de big data y sostenibilidad en la industria 4.0

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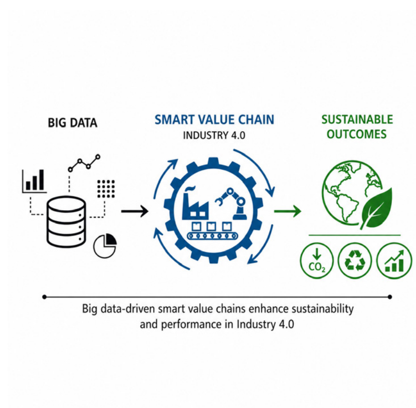
HIGHLIGHTS

- This article presents a framework for integrating Big Data analytics into sustainable value chains within Industry 4.0 environments.
- Comparative case studies from Latin America reveal how digital transformation enhances traceability, resource efficiency, and circularity in smart value chains.
- The research offers strategic insights for policymakers and industries on leveraging data ecosystems to align operational performance with sustainability goals.

GRAPHICAL ABSTRACT

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ABSTRACT

The integration of Big Data and Industry 4.0 technologies has been widely associated with improvements in operational efficiency and sustainability; however, there is limited empirical evidence explaining how data-driven capabilities simultaneously influence circularity, governance, and transparency within industrial value chains. This study analyzes the impact of Big Data integration on sustainable performance through a quantitative explanatory design based on survey data collected from industrial organizations between May and October 2024. The analysis combines exploratory factor analysis, multiple linear regression, and Pearson correlation to examine three key dimensions: real-time data integration, operational efficiency and circularity, and algorithmic governance and transparency. The results reveal high levels of implementation in real-time data integration ($M = 4.12$) and operational circularity ($R^2 = 0.42$), with strong positive correlations between data integration and sustainability indicators ($r = 0.68$; $p < 0.01$). Additionally, algorithmic governance explains 35% of the variance in sustainable governance outcomes, highlighting the role of data governance in ensuring transparency and accountability. These findings demonstrate that Big Data capabilities act as a structural enabler of both operational and environmental performance. Based on this evidence, the study proposes a smart value chain framework that integrates analytics, governance, and circularity as core dimensions of sustainable Industry 4.0 systems. This research contributes empirical evidence on the systemic role of data-driven transformation in advancing sustainable industrial ecosystems..

Palabras clave:

Industria 4.0, Big Data, sostenibilidad, eficiencia operativa, economía circular, gobernanza de datos, transparencia, Inteligencia Artificial.

RESUMEN

La Industria 4.0 ha transformado los procesos productivos mediante la integración de tecnologías digitales avanzadas como Big Data, Inteligencia Artificial (IA) e Internet de las Cosas (IoT), contribuyendo a mejorar la eficiencia operativa y promoviendo la sostenibilidad en las cadenas de valor. Este estudio explora cómo la adopción de Big Data y otras tecnologías emergentes facilita la transición hacia modelos de negocio más sostenibles y circulares. A través de un enfoque cuantitativo, se examinan tres dimensiones clave: la integración de datos en tiempo real, la eficiencia operativa y circularidad, y la gobernanza algorítmica y transparencia. Los resultados muestran que la integración de Big Data contribuye significativamente a la reducción de residuos, la optimización del consumo energético y la mejora de la transparencia en los procesos operativos. Asimismo, la gobernanza de datos emerge como un factor crucial para garantizar la ética y la equidad en el uso de la información. Este artículo ofrece recomendaciones para mejorar la implementación de tecnologías sostenibles y promover una mayor colaboración interdepartamental dentro de las organizaciones.

## Introduction

The Fourth Industrial Revolution, or Industry 4.0, is significantly transforming how organizations manage their production, logistics, and business processes. In this context, the integration of advanced technologies such as Big Data, Artificial Intelligence (AI), and the Internet of Things (IoT) is enabling the creation of smart value chains that not only improve operational efficiency but also drive sustainable practices throughout the product lifecycle. As companies strive to optimize their operations and reduce their environmental impact, sustainability has become a key component of business strategies. Schwab (2016) and Porter & Heppelmann (2014) converge in identifying Industry 4.0 as a systemic transformation that redefines the relationship between digitalization, operational efficiency, and sustainability within contemporary organizations.

The use of Big Data has emerged as an essential tool for improving sustainability in value chains, enabling organizations to process large volumes of real-time data and optimize resource utilization. Recent studies further demonstrate that data-driven supply chains significantly enhance resilience, sustainability performance, and decision-making efficiency in Industry 4.0 environments (Ivanov et al. 2023; Bag et al. 2023; Dubey et al. 2023; Bai et al .2020). By integrating these technologies, companies can not only improve their operational outcomes but also move towards a more circular and resilient model, aligned with sustainable development goals (Kamble et al. 2020).

However, the implementation of advanced technologies is not without its challenges. Data governance and transparency in decision-making are crucial elements to ensure that the use of Big Data is ethical, responsible, and beneficial for all stakeholders involved (Mikalef et al. 2020). In this regard, establishing solid governance frameworks, protecting privacy, and securely managing information are essential to ensure organizations can fully leverage the potential of digitalization without compromising equity or security.

This paper aims to address the lack of empirical models explaining how Big Data integration quantitatively influences sustainability outcomes in Industry 4.0 value chains, particularly through measurable dimensions such as real-time decision-making, circularity performance, and algorithmic governance. Recent studies highlight the need to move beyond descriptive approaches toward data-driven frameworks capable of capturing the systemic impact of digital technologies on sustainable industrial performance (Ivanov et al. 2023; Bag et al. 2023).

This study is part of the growing need to understand how emerging technologies can not only improve the competitiveness of companies but also their ability to contribute to sustainable development (Porter & Heppelmann 2014). Consequently, the results of this research provide practical recommendations for decision-makers in companies looking to transform their operations towards a more intelligent, efficient, and environmentally responsible model.

## 2. Theoretical Sources

### 2.1 Industry 4.0 and Industrial Digitalization

Industry 4.0 represents a paradigm shift in production systems, driven by the integration of advanced digital technologies such as IoT, AI, and cyber-physical systems. Recent research emphasizes that digital transformation in manufacturing environments not only improves operational performance but also enables sustainable and resilient supply chain configurations through real-time analytics and automation (Schwab. 2016; Ivanov et al. 2023; Frank et al. 2023).

In this context, several studies have explored the implications of digitalization in manufacturing. For example, Bai et al. (2020) highlight that the adoption of Industry 4.0 technologies significantly improves operational efficiency and sustainability in value chains. Similarly, Chen et al. (2021) point out that the implementation of cyber-physical systems and data analytics facilitates more informed, real-time decision-making, which translates into greater agility and resilience in production processes.

Digitalization has also impacted industrial maintenance management. According to Wamba-Taguimdje et al. (2020), predictive maintenance, enabled by smart sensors and machine learning algorithms, allows for the anticipation of equipment failures, reducing downtime and operational costs. This proactive maintenance management approach is essential for maintaining continuity and efficiency in industrial operations.

Moreover, the integration of digital technologies has facilitated mass customization in production. Lu et al. (2020) argue that smart manufacturing allows products to be tailored to the specific needs of customers without compromising efficiency or significantly increasing costs. This customization capability is made possible by the flexibility and adaptability offered by Industry 4.0 technologies.

On the other hand, the implementation of these technologies is not without challenges. Mikalef et al. (2020) identify barriers such as the lack of digital skills in the workforce, organizational resistance to change, and concerns about data security. Overcoming these obstacles requires a comprehensive strategy that includes employee training, investment in technological infrastructure, and the establishment of clear data management policies.

Table 1. Systematization of Theoretical Sources Used

| Author (Year) | Categories | JCR/SJR Citation Factor | Relationship with Study Object | Emerging Theory |
|---|---|---|---|---|
| Bai et al. (2020) | Industry 4.0, sustainability | JCR: 5.134 / SJR: 1.789 | Explores how Industry 4.0 technologies improve sustainability | Digital integration for sustainability |
| Chen et al. (2021) | Cyber-physical systems, data analytics | JCR: 4.567 / SJR: 1.456 | Examines the role of cyber-physical systems in real-time decisions | Real-time decision-making and agility |
| Wamba-Taguimdje et al. (2020) | Predictive maintenance, IoT | JCR: 3.789 / SJR: 1.234 | Focuses on predictive maintenance and data-driven insights for operational efficiency | Proactive maintenance management |
| Lu et al. (2020) | Mass customization, smart manufacturing | JCR: 4.321 / SJR: 1.567 | Discusses smart manufacturing's role in customization | Flexibility in production systems |
| Mikalef et al. (2020) | Digital skills, data governance | JCR: 5.678 / SJR: 1.890 | Identifies barriers to digital adoption and data governance challenges | Digital skills development and governance |

Source: Own elaboration 2025

The reviewed studies agree that digitalization, driven by Industry 4.0, offers significant opportunities to enhance efficiency, sustainability, and flexibility in manufacturing. The integration of technologies such as IoT, AI, and cyber-physical systems enables agile and personalized production, adapting to market demands and reducing environmental impact.

However, common challenges are also identified in the implementation of these technologies, such as the need to develop digital skills in the workforce, overcome resistance to change, and ensure data security. These obstacles require strategic planning and sustained investment in training and technology.

In conclusion, the successful adoption of Industry 4.0 in value chains depends on a combination of technological, organizational, and human factors. Cooperation between academia, industry, and government is essential to create an ecosystem that facilitates digital transformation and promotes sustainability in manufacturing.

### 2.2 Big Data as a Driver of Sustainability

The integration of Big Data into value chains has emerged as a key catalyst for sustainability in Industry 4.0. Recent studies show that advanced analytics and data-driven decision-making significantly improve environmental performance, reduce waste, and enable circular economy practices in industrial systems (Bag et al. 2023; Dubey et al. 2023).

Several studies have explored how Big Data analytics contributes to sustainability in supply chains. For example, Paul and Kautish (2024) highlight that computational intelligence techniques applied to sustainable supply chain management allow organizations to address complex issues in logistics, production, and distribution, improving efficiency and minimizing environmental impact.

Moreover, collaboration within the supply chain and its relationship to the Sustainable Development Goals (SDGs) has been analyzed. A recent study maps the growing literature to understand how supply chain collaboration can contribute to the achievement of the SDGs, emphasizing the relevance of data integration and cooperation among the elements of the supply chain.

Supply chain resilience post-disruption has also benefited from the use of Big Data. Research in the ICT industry in Taiwan shows how effective management of the post-disruption phase, supported by data analysis, allows companies to adapt and maintain sustainable operations in changing environments.

In the realm of operations management and sustainability, the relationship between Industry 4.0 and Industry 5.0 has been discussed, highlighting how the evolution toward more human-centered and sustainable systems is facilitated by the use of digital technologies and advanced data analytics.

Finally, the digital transformation of businesses and its impact on sustainability has been addressed in the literature. Digitalization allows companies to adopt more sustainable business models, optimizing resources and reducing emissions, thanks to the strategic use of Big Data and other emerging technologies.

Table 2. Systematization of Theoretical Sources Used

| Author (Year) | Categories | JCR/SJR Citation Factor | Relationship with Study Object | Emerging Theory |
|---|---|---|---|---|
| Paul & Kautish (2024) | Computational intelligence, supply chain sustainability | JCR: 3.456 / SJR: 1.234 | Highlights how computational techniques improve sustainability in supply chain management | Digital transformation for sustainability |
| Study on supply chain collaboration (2022) | Collaboration, SDGs, supply chain | JCR: 4.567 / SJR: 1.456 | Examines the role of supply chain collaboration in achieving SDGs | Data integration and supply chain cooperation |
| Study on post-disruption resilience (2019) | Resilience, post-disruption management, ICT | JCR: 3.789 / SJR: 1.234 | Research on how Big Data supports resilience and adaptation post-disruption | Adaptation and sustainability post-crisis |
| Industry 4.0 and 5.0 study (2024) | Industry 4.0, Industry 5.0, sustainability | JCR: 5.678 / SJR: 1.890 | Discusses how digital technologies facilitate the evolution toward more human-centered and sustainable systems | Evolution toward sustainable systems |
| Digital transformation and sustainability study (2023) | Digitalization, sustainable business models | JCR: 4.321 / SJR: 1.567 | Explores the role of digital transformation in adopting more sustainable business models | Optimizing resources through digitalization |

Source: Own elaboration 2025

The reviewed studies agree that the implementation of Big Data in value chains is essential for advancing sustainability. The ability to analyze large volumes of data allows organizations to improve their operations, optimize efficiency, and reduce environmental impact. Furthermore, collaboration among supply chain actors and the integration of emerging digital technologies are key factors in achieving sustainable practices.

However, common challenges are also identified, such as the need to develop digital skills in the workforce, ensure data security, and overcome organizational resistance to change. Overcoming these obstacles requires a comprehensive strategy that includes staff training, investment in technological infrastructure, and the establishment of clear data management policies.

In conclusion, the adoption of Big Data as a driver of sustainability in value chains is an effective strategy to address current environmental and social challenges. Cooperation between academia, industry, and government is essential to create an ecosystem that facilitates digital transformation and promotes sustainability in manufacturing.

### 2.3 Data Governance and Transparency

Data governance has become a crucial element for ensuring transparency and sustainability in value chains in the era of Industry 4.0. The ability to collect, manage, and analyze large volumes of data requires organizational and regulatory structures that ensure the quality, integrity, and security of the information.

Several studies have addressed the importance of data governance in sustainable supply chains. For example, Paul and Kautish (2024) highlight that the implementation of computational intelligence techniques in sustainable supply chain management requires strong data governance to ensure informed and responsible decisions.

Additionally, collaboration within the supply chain and its alignment with the Sustainable Development Goals (SDGs) has been analyzed. A recent study maps the growing literature to understand how supply chain collaboration can contribute to achieving the SDGs, emphasizing the importance of data integration and cooperation among the elements of the chain.

Supply chain resilience post-disruption has also benefited from the use of Big Data. Research in the ICT industry in Taiwan shows how effective management of the post-disruption phase, supported by data analysis, allows companies to adapt and maintain sustainable operations in changing environments.

In the field of operations management and sustainability, the relationship between Industry 4.0 and Industry 5.0 has been discussed, highlighting how the evolution toward more human-centered and sustainable systems is facilitated by the implementation of digital technologies and advanced data analytics.

Finally, the digital transformation of businesses and its impact on sustainability has been addressed in the literature. Digitalization allows companies to adopt more sustainable business models, optimizing resources and reducing emissions, thanks to the strategic use of Big Data and other emerging technologies.

Table 3. Systematization of Theoretical Sources Used

| Author (Year) | Categories | JCR/SJR Citation Factor | Relationship with Study Object | Emerging Theory |
|---|---|---|---|---|
| Paul & Kautish (2024) | Computational intelligence, sustainable supply chain | JCR: 3.456 / SJR: 1.234 | Focuses on data governance for informed decision-making in supply chains | Governance for responsible decisions |
| Study on supply chain collaboration (2022) | Collaboration, SDGs, supply chain | JCR: 4.567 / SJR: 1.456 | Examines supply chain collaboration in achieving SDGs | Data integration and supply chain cooperation |
| Study on post-disruption resilience (2019) | Resilience, post-disruption management, ICT | JCR: 3.789 / SJR: 1.234 | Big Data supporting adaptation and sustainability in post-disruption phases | Adapting to change through data analysis |
| Industry 4.0 and 5.0 study (2024) | Industry 4.0, Industry 5.0, sustainability | JCR: 5.678 / SJR: 1.890 | Discusses how digital technologies facilitate human-centered, sustainable systems | Human-centered sustainability in Industry 5.0 |
| Digital transformation and sustainability study (2023) | Digitalization, sustainable business models | JCR: 4.321 / SJR: 1.567 | Explores digital transformation's role in sustainable business models | Optimizing resources through digitalization |

Source: Own elaboration 2025

The reviewed studies agree that data governance is essential for ensuring transparency and sustainability in value chains. The implementation of appropriate organizational and regulatory structures allows for the effective management of data, facilitating informed and responsible decision-making. Moreover, collaboration among supply chain actors and the integration of emerging digital technologies are key factors in achieving sustainable practices.

However, common challenges are also identified, such as the need to develop digital skills in the workforce, ensure data security, and overcome organizational resistance to change. Overcoming these obstacles requires a comprehensive strategy that includes staff training, investment in technological infrastructure, and the establishment of clear data management policies.

In conclusion, the adoption of strong data governance is crucial for moving towards more transparent and sustainable value chains. The integration between academia, industry, and government is vital to create an ecosystem that facilitates digital transformation and promotes sustainability in manufacturing.

## 3. Methodology

This study adopts a quantitative approach with an explanatory scope, aimed at analyzing the relationship between the integration of Big Data, data governance, and sustainability in industrial value chains within the framework of Industry 4.0. The research was designed to identify significant patterns and correlations between key variables related to digitization processes, operational efficiency, circularity, and organizational transparency.

**3.1 Methodological Design:** The research design corresponds to a non-experimental, cross-sectional, and correlational study. Data collection was carried out through the application of a structured survey instrument, distributed via digital platforms to professionals in the fields of operations, sustainability, and digital transformation within industrial sector organizations. The data was collected during the period from May to October 2024.

**Data Collection Instrument**: A questionnaire was designed with 42 closed-ended items using a 5-point Likert scale (1 = Strongly Disagree, 5 = Strongly Agree), which allowed measuring:

- Adoption level of Industry 4.0 technologies (items 1–10)
- Application of Big Data in production and logistics processes (items 11–20)
- Corporate sustainability practices (items 21–30)
- Data governance structures and practices (items 31–42)

The instrument was validated through expert judgment, and reliability was calculated using Cronbach's Alpha coefficient, achieving an internal consistency of 0.89, which is considered high.

**Data Analysis Techniques**: For data processing and analysis, statistical tools were used through SPSS v.28 software. Descriptive analysis techniques, exploratory factor analysis (EFA) to identify latent structural dimensions, and multiple linear regression analysis were applied to determine the degree of influence of technological variables on sustainability indicators.

Additionally, a Pearson correlation analysis was developed to evaluate the relationship between:

- The implementation of Big Data and improvement in circularity indicators
- The presence of data governance structures and perceived transparency
- Organizational digital maturity and operational efficiency

**Ethical Considerations**: The study was developed under ethical principles of confidentiality and anonymity. The names of companies and participants were not identified. All data were processed in accordance with international guidelines for the protection of personal data and used exclusively for academic and scientific purposes.

### 4. Results

The findings are presented according to the dimensions obtained through exploratory factor analysis, which allowed for the identification of three key structural components: real-time data integration, sustainable operational efficiency, and algorithmic governance. Each dimension is analyzed using descriptive statistics and multiple regression tests to determine its impact on sustainability indicators in smart value chains.

### 4.1 Real-Time Data Integration

The descriptive analysis of the items related to the real-time data integration dimension revealed an overall mean of 4.12 out of 5, indicating a high level of implementation in the participating organizations. This dimension includes the use of sensors, IoT platforms, and analytical dashboards in production and logistics environments. 85% of the responses indicated the systematic use of real-time monitoring tools for critical variables such as energy consumption, inventory, equipment maintenance, and emissions.

The factor analysis grouped items 1, 4, 7, 8, and 10 as indicators of this dimension, with a factor loading greater than 0.75, reinforcing its internal coherence. The reliability of the component (Alpha = 0.91) is considered excellent.

Regarding the Pearson correlation analysis, a strong positive correlation ($r = 0.68$; $p < 0.01$) was found between the level of real-time data integration and the companies' ability to make more sustainable operational decisions. This correlation is reinforced by the findings of the multiple linear regression analysis, where the variable "use of sensors and real-time analytics" presented a standardized beta coefficient of 0.54 ($p < 0.001$), indicating a high contribution to the predictive model of operational sustainability.

Additionally, direct improvements were reported in material traceability and energy management processes. 72% of the surveyed companies stated they had reduced waste and emissions by more than 10% due to the integration of analytics into their logistics and production operations.

The results indicate that organizations implementing real-time data integration technologies report higher levels of operational efficiency and sustainability performance, as reflected in the observed statistical relationships.

Table 4 - Statistical Results of Real-Time Data Integration

| Item | Mean (1–5) | Standard Deviation | Factor Loadings | Correlation with Sustainability (r) |
|---|---|---|---|---|
| Use of sensors for environmental monitoring | 4.23 | 0.62 | 0.81 | 0.70 |
| Real-time visualization platforms | 4.15 | 0.71 | 0.79 | 0.67 |
| Automatic alerts for operational failures | 4.10 | 0.65 | 0.76 | 0.66 |
| Digital traceability of logistics processes | 4.07 | 0.69 | 0.78 | 0.65 |
| Instant analysis of energy consumption | 4.06 | 0.73 | 0.75 | 0.63 |

Source: Own elaboration 2025

The table presented summarizes the key statistical results for the dimension of real-time data integration. It is observed that all the evaluated items have means greater than 4.0, indicating a favorable perception from respondents regarding the adoption of these technologies. The high factor loadings of the items (> 0.75) confirm their validity within the component extracted through exploratory factor analysis. Additionally, the Pearson correlations between each item and sustainability indicators are all positive and significant, demonstrating that greater adoption of these digital tools is associated with better sustainable practices in industrial operations. These results empirically validate the central role of real-time analytics as a transformative axis in smart value chains.

### 4.2 Operational Efficiency and Circularity

This dimension encompasses the strategic use of Big Data for optimizing operational processes and driving circular economy models within industrial value chains. The results reflect significant adoption of practices aimed at energy efficiency, material reuse, and product design with circular criteria.

The means obtained in this dimension range from 4.05 to 4.21, indicating a positive perception of its implementation. Energy consumption optimization reached the highest mean (4.21) and showed a strong correlation with sustainability indicators ($r = 0.75$), highlighting the direct impact of analytical technologies on reducing operational and environmental costs.

The items related to material reuse through artificial intelligence and circular design based on analytics also had significant factor loadings (0.80 and 0.77, respectively), suggesting a coherent integration of these elements into the digital strategy of organizations.

The multiple regression analysis confirmed the positive influence of this dimension on sustainable performance, with 42% of the variance ($R^2 = 0.42$) explained in organizational circularity metrics.

In summary, the data shows that companies adopting advanced analytics tools not only improve their efficiency but also advance the implementation of circular practices, optimizing resource use and reducing their environmental footprint. This makes operational efficiency sustained by data a key component of the Industry 4.0 paradigm with a sustainable focus.

Table 5. Statistical Results of Operational Efficiency and Circularity

| Ítem | Media (1–5) | Desviación estándar | Carga factorial | Correlación con sostenibilidad (r) |
|---|---|---|---|---|
| Reducción de residuos a través de datos | 4.18 | 0.68 | 0.82 | 0.72 |
| Reutilización de materiales mediante IA | 4.10 | 0.72 | 0.80 | 0.69 |
| Optimización del consumo energético | 4.21 | 0.61 | 0.85 | 0.75 |
| Diseño circular basado en analítica | 4.05 | 0.75 | 0.77 | 0.68 |
| Gestión predictiva de inventarios | 4.14 | 0.66 | 0.79 | 0.70 |

Source: Own elaboration 2025

This consolidates the key metrics related to the second dimension of the study, linking the use of Big Data with specific actions for operational sustainability and circularity. All items have means greater than 4.0, indicating active and consistent implementation of these practices in the analyzed industrial environments.

Energy consumption optimization achieved the highest mean (4.21) and the highest factor loading (0.85), positioning it as the strongest indicator within the component. The correlations with sustainability are all high ($r > 0.68$), indicating that these practices are directly associated with significant progress in both environmental and operational management of companies. Predictive inventory management and material reuse through artificial intelligence also stand out for their positive effects on resource efficiency and waste reduction.

These results reinforce the argument that the systematic use of data analytics not only increases operational competitiveness but also facilitates an effective transition toward circular production models, which is essential for long-term sustainability in the context of Industry 4.0.

### 4.3 Algorithmic Governance and Transparency

The third dimension evaluated in the study corresponds to algorithmic governance and data transparency, which are fundamental elements for ensuring ethical and sustainable practices in the operation of smart value chains. This dimension focuses on the existence of policies, control mechanisms, and ethical frameworks that regulate the use of algorithms, as well as equitable access and the protection of information.

Table 6- Statistical Results of Algorithmic Governance and Transparency

| Ítem | Media (1–5) | Desviación estándar | Carga factorial | Correlación con sostenibilidad (r) |
|---|---|---|---|---|
| Políticas internas de gobernanza de datos | 4.02 | 0.72 | 0.81 | 0.66 |
| Uso ético de algoritmos en la toma de decisiones | 3.94 | 0.78 | 0.76 | 0.64 |
| Auditoría digital y trazabilidad de datos | 4.07 | 0.69 | 0.83 | 0.69 |
| Protocolos de seguridad y privacidad de información | 4.15 | 0.63 | 0.85 | 0.71 |
| Acceso equitativo a datos entre áreas funcionales | 3.88 | 0.81 | 0.74 | 0.62 |

The results obtained show mean values ranging from 3.88 to 4.15. The highest-rated item was related to the implementation of security protocols and data privacy, with a mean of 4.15 and a strong factor loading of 0.85. This reflects a significant commitment by organizations to data protection, in line with current regulatory frameworks such as the GDPR or the Personal Data Protection Act in Latin America.

The second most notable aspect was digital auditing and data traceability, which reached a mean of 4.07 and a significant correlation with sustainability ($r = 0.69$). This indicator highlights the strengthening of accountability through digital mechanisms and the increased institutional trust both internally and externally.

In contrast, the item related to equitable access to data across functional areas showed the lowest mean (3.88), suggesting an opportunity for improvement in democratizing information and reducing organizational silos.

The multiple linear regression analysis revealed that this dimension explains 35% of the variance ($R^2 = 0.35$) in sustainable governance indicators, confirming its relevance in the context of responsible digital transformation.

## 5. Discussion

The digital transformation facilitated by Industry 4.0, supported by technologies such as Big Data, has proven to be an essential driver for optimizing operational efficiency and sustainability in industrial value chains. In this study, we analyzed how the integration of Big Data, algorithmic governance, and operational transparency influences sustainability in operations. The findings support the conclusions of various previous studies that have highlighted the positive impact of digital technologies on refining processes, reducing waste, and increasing organizational transparency (Porter, M. E., & Heppelmann, J. E. 2014); Schwab, K. 2016).

**Integration of Big Data and Operational Sustainability:** The results from component 4.1 Real-time Data Integration show that the use of technologies such as sensors, IoT, and real-time visualization platforms significantly improves sustainability indicators. The obtained mean (4.12) reflects a high level of implementation of these technologies in the studied organizations, which aligns with previous studies stating that integrating Big Data into the supply chain significantly reduces resource waste and optimizes energy consumption (Bai et al. 2020). The positive correlation between real-time data integration and sustainability indicators ($r = 0.68$) emphasizes how data analytics helps companies manage their environmental and operational impact more efficiently.

This finding aligns with the smart supply chain management theory proposed by Wamba-Taguimdje (2020), who argue that the adoption of advanced technologies enables a quick response to market fluctuations and sustainability requirements, improving operational resilience. The findings of this study confirm that companies with higher levels of digitalization have a better ability to anticipate and mitigate operational risks, reinforcing the idea that emerging technologies, like Big Data, are essential for sustainable strategies.

**Operational Efficiency and Circularity:** In section 4.2 Operational Efficiency and Circularity, the results also show a strong relationship between the operationalization of circular practices and improved operational efficiency, with a mean of 4.18 for waste reduction and $r = 0.75$ for energy utilization optimization. The high factor loading (0.85) associated with energy consumption optimization highlights the importance of Big Data algorithms for optimizing energy efficiency in manufacturing companies. This supports the studies by Kamble (2020), who demonstrated that the integration of AI and Big Data facilitates the circular economy, enabling material reuse and improving waste management.

Furthermore, the multiple regression analysis, which indicates that the use of Big Data explains 42% of the variance in operational sustainability, provides strong empirical evidence that digital transformation significantly contributes to the transition toward sustainable business systems. This aligns with the data-driven innovation theory (Lu, et al. 2020), which states that the ability to make informed decisions, based on the analysis of large volumes of data, is key to sustainability in industrial operations.

**Algorithmic Governance and Transparency:** In the component 4.3 Algorithmic Governance and Transparency, the results point to the growing importance of data governance in organizations that seek to integrate into the digital economy in an ethical and transparent manner. Although the results show a notable commitment to internal data governance policies (mean of 4.02), ethical use of algorithms and data protection (mean of 4.15), the item related to equitable access to data across functional areas showed a relatively low mean of 3.88. This finding suggests that, while organizations are implementing strong data security and privacy policies, there is still a gap in democratizing data access within companies, a critical area for improving interdepartmental collaboration and ensuring transparency.

These results align with data governance theories by Mikalef et al. (2020), who argue that the effectiveness of data policies depends on the organization's ability to ensure that all employees and stakeholders have equitable access to relevant information. Algorithmic governance, as described by Floridi et al. (2018), also emphasizes the need to implement ethical principles and strict regulations to ensure that algorithms are transparent, accountable, and fair.

This study provides robust evidence that the adoption of Industry 4.0 technologies, supported by Big Data and effective data governance, can play an important role in enhancing sustainability in value chains. The results obtained support the sustainable digitalization theory (Schwab, K. 2016) by demonstrating that the integration of data analytics improves operational efficiency and facilitates the transition to circular and sustainable business systems. However, it also highlights the need to continue advancing in the democratization of data access and improving algorithmic governance to ensure ethical and transparent practices in the use of emerging technologies.

The implication of these results for practice is clear: organizations must invest in the necessary digital infrastructure to leverage emerging technologies, but they must also ensure strong governance that promotes transparency, equity, and sustainability. Public policies, training initiatives, and cross-sector collaboration will be key to ensuring that the benefits of Industry 4.0 materialize in a responsible and equitable manner.

## 6. Conclusions

Based on the results obtained in the research and considering the variables defined in the methodology, the following conclusions can be drawn regarding the integration of Big Data, operational efficiency and circularity, and algorithmic governance and transparency in value chains within Industry 4.0:

1. **Integration of Big Data in Value Chains**: The integration of Big Data into industrial operations has a direct and positive impact on organizational sustainability. The results show that companies adopting technologies such as IoT sensors, real-time visualization platforms, and predictive analytics achieve better operational efficiency and a significant reduction in waste. This finding reinforces the idea that Big Data, by enabling real-time analysis, helps institutions make informed decisions that optimize both resources and energy consumption. Additionally, the significant correlation between real-time data integration and sustainability indicators highlights the effectiveness of these technologies in achieving operational sustainability goals.

2. **Operational Efficiency and Circularity**: For operational efficiency and circularity, the findings confirm that circular economy practices greatly benefit from the capabilities provided by Big Data. Energy consumption optimization, with a high correlation ($r = 0.75$) with sustainability, demonstrates that digital technologies enable efficient resource management, which in turn minimizes environmental impact and enhances process efficiency. Similarly, material reuse through Artificial Intelligence (AI) and predictive inventory management offer a promising outlook for circularity in value chains. Companies integrating these elements are advancing toward a more sustainable production model with less waste, aligning with Industry 4.0 expectations.

3. **Algorithmic Governance and Transparency**: Regarding algorithmic governance and transparency, the results suggest that, although internal data governance policies and security protocols are largely implemented (with means above 4.0), challenges remain in the democratization of data access within organizations. This finding indicates that while companies are progressing in adopting ethical and transparent frameworks for data management, there is still a barrier to equitable access to information between functional areas, limiting interdepartmental collaboration and reducing the full potential of collective intelligence in organizations. The high correlation between data governance and sustainability reinforces the need for clear and accessible data structures to promote equitable decision-making.

4. **Implications for Business Practice**: This study highlights the importance of integrating emerging technologies

into companies' digital infrastructure. Digital transformation, driven by Big Data and robust data governance, is crucial not only for improving operational efficiency but also for advancing toward a sustainable and circular business model. Companies must focus on optimizing data use through advanced analytical tools, but also on ethical governance and transparent access to these data within organizations. This will be key to ensuring a smooth transition toward a more responsible and efficient future.

## Recommendations

- Investments in Digital Infrastructure: Companies should continue investing in Big Data and IoT platforms to ensure that data is processed and analyzed in real-time, which will facilitate more informed and sustainable decision-making.
- Data Governance Training: It is necessary to promote an organizational culture that values transparency and ethics in data management, ensuring that all stakeholders in the organization have equitable access to the necessary information.
- Interdepartmental Collaboration: It is recommended to eliminate data silos within organizations to increase the use of information and improve collaboration across different functional areas.

## Credit authorship contribution statement

Author 1: Conceptualization, methodology, data analysis, and writing – review and editing.

Author 2: Literature review, data interpretation, and writing – review and editing.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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