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The Impact of Digital Technologies and Sustainable Practices on Circular Supply Chain Management

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Abstract: *Background*: This study investigates how firms can enhance the functionality of their circular supply chains (CSCs) by adopting a portfolio of sustainable practices as well as digital technologies to increase performance. It analyzes the benefits that firms can obtain when investing in specific technologies to boost the impact of technologies and sustainable practices on CSCs, and further increase performance. *Methods:* We test several hypotheses by using structural equation modeling as well as multi-group analysis to verify whether CSCs can be achieved through sustainable practices and technologies and improve the firms' performance. *Results:* The empirical results partially support the research hypotheses. While the main research hypotheses are fully supported, the analysis of single digital technologies reveals that only a few solutions can contribute to both the management and the improvement of the CSC. *Conclusions:* Our findings demonstrate that the identification of green suppliers and ad hoc environmental regulations, combined with attention to the origin and provenance of raw materials, can promote a CSC. Moreover, transportation management systems (TMS) and the internet of things (IoT) are efficient technologies for managing transportation and product flow in the CSC. Furthermore, machine learning (ML) is effective in making positive green decisions, and 3D printing can extend product life.

Keywords: circular economy; circular supply chain; sustainable practices; digital technologies

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1. Introduction

According to [1], circular supply chain can be defined as follows: "the coordinated forward and reverse supply chains via purposeful business ecosystem integration for value creation from products/services, by-products and useful waste flows through prolonged life cycles that improve the economic, social and environmental sustainability of organizations." In general terms, a CSC seeks to achieve zero waste through collaboration between the producer's supply chain and secondary chains, thanks to which a company can easily restore and regenerate its primary resources [2]. Moreover, following the fundaments of industrial symbiosis, a real cross-chain and cross-sector collaboration can be achieved [3]. Stakeholders can realize several benefits with a CSC, which are outcomes obtained when collaborating, negotiating, and sharing the risks and resources with long-term perspectives [4,5]. In a CSC, firms can collaborate in an international framework to maximize the value of goods, returns, and materials, achieve efficiency and profitability while diminishing negative environmental, social, and economic impacts [3].

Different from linear supply chains, a CSC improves the firms' performance by collecting goods and packaging to recover their materials and use lower natural resources [4]. Although the CSC is—in principle—very appealing, it raises several operational issues and challenges due to the management of international forward and reverse flows. For example, CSCs collect a substantial amount of waste, which can result in being unrecyclable or non-reusable. In fact, the CSC implementation and management are followed by several barriers and constraints. Working in this direction, [5] discovered that circular systems face important technical and structural barriers, which are directly related to the core activities of CE models, specifically, the absence of collecting, sorting, and recycling. Missing these activities translates into a negligible capacity to implement CSCs. Furthermore, firms can be reluctant in accepting the CE models as well as be afraid of the lack of the returns' homogeneity and standardization [5]; these are important barriers in determining the firms' capacity to create a CSC, especially when linked to the uncertainty of the international backward flows. Similarly, the literature provided a comprehensive list of barriers and risks connected to the adoption of CSC, which deter its adoption and limit its functionality [3,6]. Considering the difficult balance existing between positive and negative aspects linked to CSC, a few questions still need to be answered: how can firms enable CSC? How can firms increase the CSC functionality? Does CSC contribute to business performance? How can the effect of CSC on business performance be leveraged?

This paper contributes to these directions by focusing on two main enablers, that are sustainable practices and digital technologies. In principle, the adoption of sustainable practices renders CSCs more effective [7] since the companies undertake a set of environmental management practices to enhance the value of circular activities. In fact, the implementation of non-sustainable practices could simply harm the effectiveness of any CSC system. Furthermore, digital technologies can surely enable CSC activities by connecting the ecosystem to the companies and supporting the decision-making process [8] and reduce the volatility of the whole supply chain system [9]. Specifically, digital technologies allow companies to obtain high-value information, which can then be used to improve the strategies around the circular systems [10]. Afterwards, the effects of both sustainable practices and digital technologies on CSC are also verified against the business performance to estimate the amplitude of the direct and the indirect benefits that these three strategic drivers offer to the firms' business economic sustainability. Finally, we test whether these relationships could be improved by focusing on some specific digital technologies and, consequently, appreciating their sole effects. To estimate all these effects, we test several research hypotheses using structural equation modeling and multi-group analysis. All developed models are tested by using a sample of 157 firms and dividing them into groups to run the multi-group analysis.

Our findings reveal that both the sustainable practices and the digital technologies help firms in achieving high capacity to implement and manage CSCs. However, the adoption of an ad hoc portfolio of sustainable practices turns out to be more effective than the implementation of digital technologies. Therefore, firms should first focus on supporting the CSC systems through sustainable practices and then through digital technologies. This result is corroborated by the indirect effect on business performance, for which sustainable practices offer a contribution, along with CSC. Hence, firms can improve their business performance by enhancing the CSC as well as by exploiting the benefits of sustainable practices. Furthermore, the direct effects that we estimated can be boosted when firms implement ad hoc digital technologies; specifically, we demonstrate that the adoption of some technologies can activate some positive effects by digitalization on CSC and business performance, informing on the directions that firms should undertake when allocating their budgets as well as on how to adjust their estimations.

Our research provides some new insights in the field, as it offers two additional strategic keys to boost the impact of CSC on performance. While this relationship has been investigated by other research works (e.g., [11,12]), none of them verifies the links between both the sustainable practices and the technologies, which are—de facto—two important antecedents for pursuing CSC. Furthermore, we extrapolate more insights from these relationships by testing both direct (short term) effects as well as the indirect (long term) effects of the antecedents on performance through CSC. Finally, we also verify whether the adoption of some specific digital technologies helps in increasing the value of some relationships, resulting in being extremely useful in deriving managerial insights and prescriptions on how companies can increase the functionality of CSC.

This paper is organized as follows. Section 2 introduces the literature review on the topics and helps to develop the research questions. Section 3 provides the details on the methodology, while Section 4 reports the findings. Section 5 displays the managerial implication, while Section 6 concludes.

2. Literature Review

In this section, the relevant literature is reviewed to clarify the research gap and devise hypotheses.

2.1. Sustainable Practices

When it comes to how the sustainability and greenness of a supply chain should be measured, different components should be considered. Being environmentally sustainable requires a company to be cautious about waste and pollution, which must be minimized [7]. CE implementation requires huge investments and cultural/organizational changes and offers economic benefits that are not always easily predictable and quantifiable. Therefore, there is a need for a clear company vision, shared between company owners and top management [13]. Thanks to the increasing awareness concerning ecological and social matters, companies are on the verge of finding effective and urgent alternative solutions, not only inside their specific organizations, but also across their entire logistic networks. At the same time, firms require a comprehensive analysis of the logistic networks that are composed of transport, geopolitical, regulatory, internal, and informational barriers [14]. Considering the guidelines elaborated by the Ellen MacArthur Foundation, it has become clear that in order to implement a CSC, firms should focus on three main targets.

The first aspect pertains to the rethinking of product design, given that it is essential in maximizing both its lifespan and its potential utilization. The aim is to increase the value extracted from items received from international networks before they are discarded. A real-life application of this wise approach may be seen in the fashion industry with the Service Shirt example, brilliantly described by [15]. With this new garment concept, it has been demonstrated that a simple shirt can be developed and adapted through a long sequence of redesign exchanges among the original purchasers and their friends. In fact, the Eco-Design or Design for the Environment is a kind of layout that focuses on minimizing the ecological impact of an article during its entire life cycle. It is indeed a design concept that is gaining increasing attention, especially in the packaging sector, due to the constant interest in strong, hygienic, and respectful solutions. Thanks to Eco-Design, businesses have begun to replace the usage of petrochemicals with mineral fillers and recycled materials, maintaining the same technical feasibility while reducing production expenditures.

The second perspective in deciding to create a CSC is the establishment of a reverse network. Planning this method along the entire production line renders it feasible to exploit many benefits through the recycling and upcycling of any product. The reuse, maintenance, refurbishment, and remanufacturing of products become salient elements in improving reverse capabilities, where the environmental efficiency can be achieved through a controlled return cycle [16]. They asserted that companies will even maximize their competitive advantage if they decide to address product returns through purposeful partnerships. Therefore, choosing the appropriate supplier and organizing international networks take on significant weight when circular policies must be put into place. Additionally, Ref. [17] stressed the importance of wisely screening potential suppliers by evaluating several variables, such as quality, design competency, process capability, preventive maintenance, flow distance, space, operator training, labor flexibility, and innovation of products and processes.

The third sustainable aspect is the creation of a complete pioneering business model that attentively adheres to the shift from a conventional linear system to a circular system. In recent years, alternative business structures and ad hoc strategies (such as sharing platforms and product-as-a-service (PaaS)) have enriched the extant literature.

The sharing platform is a typical business model that links product owners with potential final users. This kind of arrangement permits individuals and organizations to use an item without owning it. The integration of the sharing principle into a supply chain may create very useful commercial synergies, given that companies can collaborate by sharing human resources or physical assets to satisfy customers' needs in a timely fashion. An instructive example of this principle, practically applied, is represented by the partnership between Nestlé and Pepsi. Although they are strong competitors in the food market, they have decided to combine elements of their supply chains to produce and sell fresh and chilled products in Belgium. They have coordinated warehousing, packaging, and deliveries to fill their trucks. The outcome was a 44% reduction in transportation costs, a 55% reduction in gas emissions, and an overall greater level of customer satisfaction.

Product-as-a-service, also referred to as a product–service system, occurs when manufacturers sell products in combination with services. Goods are often sold via subscription, with pertinent options attached, such as repair or replacement contracts. This business model has been created not only to maximize the financial performance of products, but also to minimize the ecological sway of consumerism by planning precise material cycles and augmenting alternative possibilities for usage.

From the perspective of literature review, a consistent gap has emerged surrounding the identification of an extensive portfolio of practices that businesses can embrace to implement a circular economy (CE). In fact, the previous three perspectives can all be taken into consideration to build up a comprehensive portfolio of sustainable practices to support the CSC. The question that remains to be answered consists of the identification of which practices should be included in such a portfolio, knowing that the list emerging from the previous three perspectives can be extremely wide and heterogeneous. Beyond identifying such a portfolio, this research seeks to address the impact that it has on the creation of CSC systems, which will be tested by investigating the following hypothesis:

Hypothesis 1. *The adoption of an ad hoc portfolio of sustainable practices has a positive impact on the creation and management of CSC.*

2.2. Digital Technologies

The way we interact with the physical world around us is rapidly changing through advances in technology. Companies need to use the new technologies to support the achievement of economic, environmental, and social targets that are important to sustainable development and CE implementation [18]. CSC requires the application of digital technologies to successfully pursue its goals, especially when managing reverse flows linked to international frameworks. Digitalization constitutes an effective game-changing factor. In fact, as empirically proved by [19], digital protocols can ensure environmental, social, and economic benefits. Indeed, the circular approach strongly links with technology, especially when goods and their components are accurately designed to be reused and lessen waste. According to the proposed theoretical framework, modern CE systems include both hard and soft ingredients, which are clearly connected and influence each other [20]. A study by [21] has clearly identified various types of technologies and their potential application in a CSC.

The role of digital technologies is essential in obtaining information on the real value of returns. Through Industry 4.0 technologies, products communicate with consumers and send signals to firms regarding their performance, their usability, and their deterioration [22]. Certainly, one of the most relevant technologies is blockchain, because it ensures transparency and reliability. Moreover, it allows consumers to determine if sustainable production and transportation processes were used and even allows consumers to meticulously track, moment by moment, the geographical position of each article, maximizing reverse logistic operations. Finally, this advanced protocol can create real digital chains, assuming correct cooperation with other tokens and technologies [23].

Technology becomes highly effective when it complements the existing technologies used to manage the entire logistic system and integrates omnichannel solutions [24,25]. The adoption of blockchain technologies, combined with 4.0 logic, can improve the performance of different industries and sectors in terms of a circular economy [26,27]. The integration of blockchain with radio frequency identification (RFID) may be used to pinpoint material streams and strengthen a possible recovery policy, given the electromagnetic tags that identify and monitor every product [21]. Hence, RFID is another noticeable, emerging data-safety technology given its specific sensors and actuators. Logistic management very often exploits the associated benefits, such as cost cuts, process optimization, and enhanced service quality [28]. RFID represents advancements included in the internet of things (IoT) category, along with, for instance, quick response (QR) codes.

The IoT constitutes another relevant technology, especially if it is inserted into the reverse logistic management to enhance process-oriented performance while diminishing energy absorption [29]. IoT are electronic devices that are able to communicate with each other and direct the actions of objects or machines connected to a unique network. IoT apparatuses are particularly useful to supply chains because they can collect data and send information to diverse stakeholders and suppliers along the same value conglomerate [30]. In fact, operators may visualize possible hindrances and monitor indefinite queues or delays with real-time adherence [31].

In a study by [32], IoT protocol was applied to the scrap metal industry. The results reveal that IoT solutions improve the competitive advantage of both waste producers and waste management firms, while minimizing energy resources and CO_2 emissions.

Inventory management has always been a concern for small and large firms alike, and these firms always strive to find a solution or an ordering model that can minimize the total warehousing and inventory costs [33,34]. The research of Varriale et al. [35] construed two alternative scenarios: the first observed is the conventional scenario, without any employment of digital technologies; the second scenario described is a framework that simultaneously incorporates the use of blockchain, IoT, and RFID. A five-year simulation is offered, with the incidence of disruptive events included in both scenarios. Having focused on the second scenario, it is evident that the IoT infrastructure was successfully able to connect the brick-and-mortar warehouse with the virtual one in real time, that the inventory was managed second by second, and that when a disruptive event occurred, products were instantly withdrawn, reducing ineffectiveness by 3.2%. Additionally, using blockchain and smart contracts, operational efficiency was finally assured.

One additional, useful modern tool for the sake of this study is machine learning (ML). It utilizes programmed algorithms that can receive and examine input data to predict appropriate output data within a defined range. In this way, a machine truly learns from data rather than instructions set by a technician. Together with artificial intelligence (AI), it is feasible to evaluate large amounts of data, permitting organizations to quickly respond to unforeseen circumstances [36]. The introduction of AI into a CSC can support the design, monitoring, and daily management of the supply network and help in forming solid relationships with green partners to advance complete logistical effectiveness [37].

As suggested by that latter research, the combination of AI and ML in a CSC provides numerous benefits, such as the following:

- Speedy and cheap international shipping.
- Construction of autonomous vehicles to achieve better freight programming.
- More sustainable and green transport solutions that could reduce global pollution.
- Lower number of products discarded.
- Aggrandizement of the reverse logistic system.

An enlightening example of the use of AI in transnational businesses is Pirelli, one of the leading tire manufacturers, which employs RFID, sensors, actuators, and AI models to track the location of wheels and calculate the exact number of new items to be produced. Through a tailored-made fabrication, Pirelli decreases toxic emissions into the atmosphere and associated waste materials.

One enhancement solution that companies can practice is the optimization of container loading plans [38]. The efficiency of the transport service could be exponentially improved thanks to correctly scheduled loads, with the aim of minimizing environmental impact and diminishing the waiting times of drivers during pick-up and delivery stages. Following this reasoning, it is also advisable to combine orders from different customers arising from diverse locations but sharing partial routes of transport [39].

From the literature review, there clearly emerges a gap in the descriptions of various potential technologies that firms can implement in the creation of a CSC. In fact, most of the previous research tested the outcome of new advancements in a unique sector that is typically the manufacturing sector. Instead, this work seeks to identify the specific effect of technologies on supply chains operating in heterogeneous domains. Thus, with the objective of identifying a portfolio of useful tools for CSC, we propose the following hypothesis:

Hypothesis 2. *The adoption of an ad hoc selection of digital technologies has a positive impact on the creation and management of CSC.*

2.3. Firm Performance

The setup of a CSC, thanks to sustainable practices and digital technologies, also has consequences on corporate performance.

In general, firms' results are tested for efficiency, profitability, and financial ratios, but recently, the extant literature has also begun to analyze the impact of specific social and environmentally friendly protocols [40]. Organizations can measure sustainability performance, observing the economic, social, and environmental dimensions.

From an economic point of view, sustainable arrangements should be related to costs, investments, and profit control. For instance, if we apply this approach to cost monitoring in the manufacturing industry, it entails critically cutting unnecessary procurement expenditures and energy and water consumption.

Focusing on the social domain, the indicators associated with social sustainability pertain to good working conditions, societal commitment, customer satisfaction, turnover rate, inclusiveness, and diversity.

The last criterion is the ecological performance of companies. Practically, this means ensuring the reduction of noxious emissions, waste materials, and toxic chemicals used in production, as well as the wise recovery of used goods. It is reasonable to assert that if organizations do not embrace environmental solutions, they will not be able to enjoy the long-term benefits [41].

Analyzing the study by [42], the maintenance of a CSC may have both negative and positive outcomes. In the short term, the improvement of a CSC increases costs (due to huge initial investments related to the purchase of novel machinery or process modifications), while in the long term, savings originating from the use of recycled or reused materials, less waste, and lower energy consumption are certain.

On the other hand, [43] claimed that despite lower production burdens, CSC is related to poor corporate financial performance. Nevertheless, from a managerial point of view, it is worthwhile to stress the operational and cost-based improvements potentially attainable. Moreover, the CSC creates numerous additional revenue flows if purposefully managed. The first concrete example is given by the product-as-a-service business model. In this case, as previously explained, customers do not own the product but, rather, rent it for a certain period. The applicable contract then generates a long-term relationship between the client and the supplier, permitting durable revenue streams and the product's lifetime extension. Such a long-term deal also represents an opportunity for companies to experiment with their products and collect meaningful statistical data.

To assess the relationship between environmental and corporate financial performance, extant studies suggest specific indicators, which are broken down into two categories: accounting-based indicators and market-based indicators. The accounting-based indicators (such as ROE and ROA) stress the past- and short-term financial results that reveal internal decision-making appropriateness and the correct plan of resource allocation [44]. The market-based indicators are more closely related to future and long-term financial outcomes. The positive aspects of these business indicators are as follows: (1) they represent an external and objective perspective and are therefore less vulnerable to company manipulation, and (2) they embrace the expectations of investors regarding corporate profitability. Some examples are Tobin's Q and share prices [45].

In evaluating the extant literature, it is essential to affirm that there is no scientific research which investigates the performance consequences caused by the implementation of a CSC in a firm. The goal of this work is to purposefully analyze the effects on business performance (especially on financial ratios) following the establishment of a CSC. Hence, the following hypothesis is offered:

Hypothesis 3. *The adoption of a CSC has a positive influence on firm performance.*

Figure 1 summarizes the conceptual model, including both the direct relationships between the sustainable practices (H_1) and the technologies to CSC (H_2,), respectively, as well as the direct and the indirect impacts on firms' performance by CSC (H_3) as well as by sustainable practice (H_{3S}) and technologies (H_{3T}). Furthermore, we verify the effect that digital technologies have on the aforementioned relationships by analyzing whether a certain relationship can be improved by implementing specific digital technologies. Therefore, we explore the impact offered by internet-of-things (IoT), transportation management systems (TMS), machine learning, robotics, and 3D printing in enhancing the value of relationships. Therefore, we use the label "a" to signify that we test whether certain technologies improve some of the established relationships. For example, H_{1a} signifies that we test whether the adoption of IoT, TMS, machine learning, robotics, and 3D printing boosts the effect that sustainable practices have on CSC.

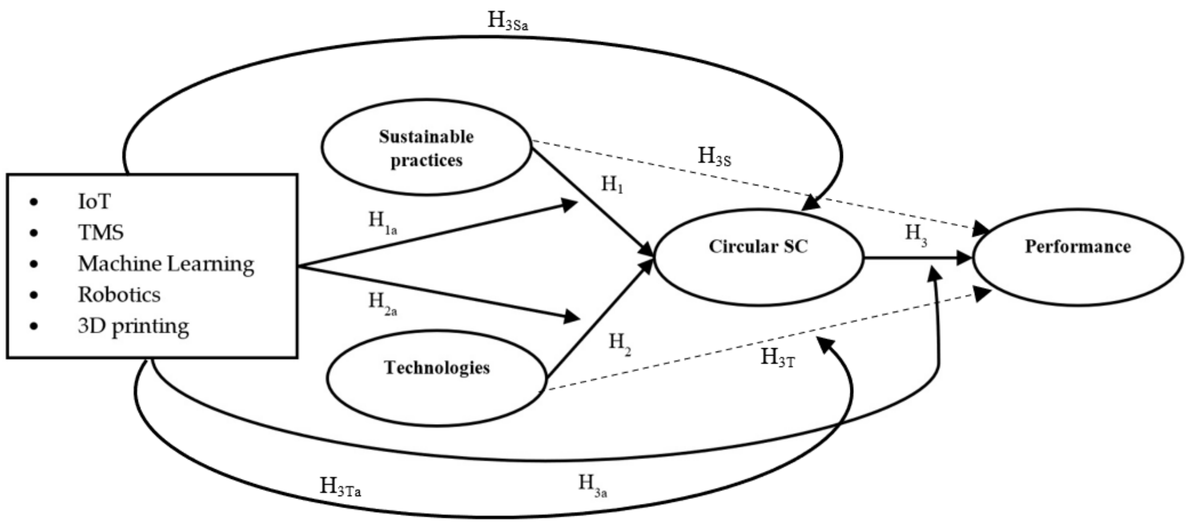

Figure 1. Conceptual model.

3. Methodology

To test our hypotheses, we designed a survey to collect information about the respondents concerning industry, company size, investments in blockchain, marketing strategies, logistic processes, and commercial performance. We then pre-tested the questionnaire conceived with a pool of experts (professors, students, professionals, and managers). We asked for feedback about wording, readability, and completeness. Finally, the survey was modified and improved accordingly.

The data-collection stage began by administering the survey to an initial sample of 120 firm managers. Obviously, for the purpose of our study, we decided to interview active experts in supply chain management. They were reached via email. Within two weeks, we received most of the responses. Meanwhile, the investigation was extended by contacting them via telephone. A total of 157 usable observations were obtained, excluding those excluded as invalid. This result represented about 12% of the entire company population we targeted (1200). The sample primarily represented large enterprises, both in terms of sales and number of employees. More than half of the organizations had an average sales turnover of more than 100 million (52%) and a workforce of more than 200 employees (53%). The data originated from European and American businesses, at 73% and 16%, respectively. Most of the interviewees were supply chain managers (52%), working primarily for manufacturers (36%) and retailers (23%). The results revealed a heterogeneous industrial panorama, with the food and beverage (22%) and the fashion (12%) sectors predominating. A more detailed representation of the distribution of interviewees and the exact composition of the sample is illustrated in Table 1. Several approaches were used to assess the non-response bias. The first approach consisted of comparing early and late respondents. A one-way analysis of variance (ANOVA) found no significant differences between the early and late answers for all items involved. Those findings supported the conclusion that non-response bias was not a significant concern. Moreover, we checked for non-response bias when evaluating the demographic variable size, number of employees, and sales. Once again, no relevant differences were discovered between the groups. All items included in the survey were measured using a 7-point Likert scale that indicates the level of accordance with a certain question (where 1 is not at all in agreement and 7 means full agreement).

To pursue the objective of this investigation, we used a technique called partial least squares path modeling (PLS-PM) and XL-Stat 2021.2.1 software. PLS-PM is a component-based estimation algorithm that calculates the links among theories by assigning scores to their original measure [46]. PLS-PM does not require any distributional postulate for the data inserted (in contrast with a maximum probability covariance-based approach). Furthermore, PLS-PM results in less biased assessments than other methods for treating equation modeling samples with fewer than 200 observations, while attaining the same effectiveness with examples above 200 observations [44]. The features of PLS-PM provided above coherently explain the usage in several business domains, such as operations management [47], supply chain management [48], sustainable supply chains [46], and closed-loop systems [49].

The first stage in our research was to identify the latent variables that are dimensions not directly observed but, rather, inferred from other variables that are instead directly measured. The latter are called manifest variables, and in our case, they were constituted by the possible choices in the survey. Conversely, the latent variables in this study were sustainable practices, technologies, circular supply chains, and performance. The final items list permits the detection of the cross-loadings associated with each construct, as displayed in Table 2, in which the bold values identify the items corresponding to the related construct.

The first relevant factors to evaluate are the composite reliability indexes, which entail an objective assessment of how much an ensemble of elements can be grouped together in the same category. In fact, if a group of elements targets the measurement of a certain construct, then the scores are expected to be similar. We focused on Chronbach's alpha and the eigenvalue. A high Chronbach's alpha value (close to 1) indicates that there is substantial reliability within the dimensions observed: the more the alpha value increases, the more the probability of error decreases. We considered a Chronbach's alpha higher than 0.8 acceptable, and to obtain this result for all of the latent variables, the challenging dimensions were reduced. Hence, it was evident that CSC and performance have a borderline Cronbach's alpha, but it is very close to 0.8, and for this reason, they were accepted. The eigenvalue indicates how many measurements of a definite concept are available. Each value that is higher than 1 represents a trustworthy dimension. As highlighted in Table 3, all of our latent variables achieved one-dimensionality. Therefore, we proceeded with the entire structural model evaluation.

Table 1. Sample description.

Sales	#	%	Employees	#	%	Country	#	%	Company Type	#	%	Professionals	#	%	Industry	Frequency	%
<10	11	7.0%	<50	14	8.9%	Europe	115	73.2%	Manufacturer	56	35.7%	SC Manager	82	52.2%	Food and Beverage	34	21.7%
10–50	38	24.2%	50–99	40	25.5%	USA	25	15.9%	Wholesaler	30	19.1%	Logistics Manager	12	7.6%	Fashion and Apparel	18	11.5%
50–100	26	16.6%	100–200	20	12.7%	Asia	4	2.5%	Distributor	14	8.9%	Operations Manager	13	8.3%	Medical and Healthcare	12	7.6%
>100	82	52.2%	>200	83	52.9%	Other	13	8.3%	Supplier	21	13.4%	Sales Manager	3	1.9%	Automobile	11	7.0%
									Retailer	36	22.9%	Production Manager	9	5.7%	Mechanic	7	4.5%
												Purchasing Manager	2	1.3%	Energy	7	4.5%
												Procurement Manager	8	5.1%	Furniture	6	3.8%
												Distribution manager	2	1.3%	E-commerce	5	3.2%
												Other	26	16.6%	Aerospace	4	2.5%
															Sport	4	2.5%
															Entertainment	4	2.5%
															Glass	3	1.9%
															Cement	3	1.9%
															Telecommunications	2	1.3%
															Luxury	2	1.3%
															Beauty and Cosmetics	2	1.3%
															Electrical and electronics	2	1.3%
															Chemical	1	0.6%
															Other	30	19.1%
Total	157	1		157	1		157	1		157	1		157	1		157	1

Table 2. Summary of the cross-loadings.

	Sustainable Practices	Technology	Performance	Circular SC
Identification of green suppliers	**0.867**	0.434	0.409	0.505
Environmental restrictions	**0.877**	0.473	0.429	0.563
Raw materials origin and provenance	**0.831**	0.486	0.460	0.541
Artificial intelligence	0.370	**0.765**	0.316	0.369
IOT sensors	0.340	**0.681**	0.458	0.444
RFID	0.368	**0.615**	0.545	0.472
Route optimization system	0.410	**0.731**	0.304	0.342
TMS	0.368	**0.721**	0.327	0.386
Mobile device monitoring of delivery people	0.402	**0.690**	0.283	0.313
Machine learning	0.396	**0.697**	0.355	0.357
Market share	0.357	0.439	**0.780**	0.454
Profits	0.420	0.393	**0.792**	0.504
ROI	0.448	0.478	**0.833**	0.463
Cost savings	0.356	0.398	**0.733**	0.477
Management of reverse logistics flows	0.492	0.414	0.447	**0.678**
Use of recycling material	0.408	0.321	0.337	**0.558**
Integration of forward and reverse logistics flows	0.269	0.373	0.280	**0.649**
Optimization of the logistics network	0.504	0.415	0.474	**0.797**
Optimization of the logistics loads	0.429	0.400	0.483	**0.757**
Logistics risks and safety	0.471	0.405	0.455	**0.720**

Table 3. Composite reliability indexes.

Latent variable	Dimensions	Cronbach's Alpha	Eigenvalues
Sustainable practices	3	0.821	2.213
Technology	7	0.828	3.476
Circular SC	6	0.786	2.927
Performance	4	0.792	2.467

4. Analysis and Results

This section provides the empirical results of the hypotheses testing by considering the complete sample; hence, no group was considered in this regard, while all the constructs were considered reflective. According to [50], the use of reflective scales allows one to verify the firms' capability on a certain field. Hereby, we wish to detect the firms' capability to make CSC function, to be technologically ahead, to be green by investing in sustainable practices, as well as to obtain business outcomes. The general outcomes showed a relative goodness-of-fit index of 0.940. All outcomes are displayed in Table 4, in which we report the result as "supported" when a research hypothesis was empirically confirmed or "not supported" in the opposite case. H1 was confirmed, because we calculated a coefficient (representing the direct effect) of 0.457, with a p-value <0.01. This impact proved that the adoption of sustainable practices positively influences the setup of a CSC. In particular, the ensemble of respective processes described in the first hypothesis were as follows:

- Correct identification of green suppliers.
- Ad hoc environmental regulations.
- Attention to the origin and provenance of raw materials.

H2 is supported because the coefficient is 0.314 and the p-value < 0.01. This empirical result shows that also the adoption of digital technologies has a favorable impact on the development of a CSC, but to a lesser extent than the adoption of sustainable practices.

H3 is also supported, given that the coefficient is 0.606 with p-value < 0.01. Therefore, the creation of a CSC has a positive impact on corporate performance, especially if the following indexes are considered: market share, profits, ROI, and cost savings.

Table 4. Results of the research hypotheses.

Research Hypotheses	Coefficients	Results	R^2	F Statistics	f^2
H1: The adoption of an ad hoc portfolio of sustainable practices has a positive impact on the creation and management of CSC	0.457 [1]	Supported	0.294	64.573	0.079
H2: The adoption of an ad hoc portfolio of digital technologies has a positive impact on the creation and management of CSC	0.314 [1]	Supported	0.460	65.619	0.015
H3: The adoption of CSC has a positive effect on firm's performance	0.606 [1]	Supported	0.436	39.369	0.136

[1] *p*-value < 0.01.

Overall, our findings suggest that both the adoption of a portfolio of digital technologies as well as the implementation of portfolios of sustainable practices activate the CSC and, hence, are effective drivers to leverage the potential and increase the capacity of CSC systems. However, the effect of sustainable practice is higher than the effect of digitalization, suggesting that firms should focus primarily on sustainable practices to enable CSC. Furthermore, our findings demonstrate that CSC can activate high business performance suggesting that circular systems are effective drivers to increase business sustainability. When estimating the indirect effects, it emerges that sustainable practices have a significant indirect impact on the business performance (the coefficient is 0.277 with *p*-value < 0.05), while digitalization is not statistically significant (the indirect coefficient is 0.190 with *p*-value < 0.1). Therefore, sustainable practices also exert a positive effect on business performance, being then a valid driver to enhance both the environmental and the economic sustainability of companies.

To improve upon this research and its methodology, a multigroup analysis was chosen, particularly focused on the digital technologies previously described. The multigroup analysis allows us to verify if predefined data groups show substantial dissimilarities in their group-specific criteria evaluations, and if this also allows for the collection of information pertaining to indirect effects. The multigroup analysis compared two groups: 1 and 0. Group 1 represents the set of companies that adopt a specific technology, while group 0 illustrates firms that do not use the same technology. To deploy the assessment, the results of which are summarized in Table 5, we measured the difference between the two groups, and subsequently, through standard deviation, we calculated the *p*-value and the level of significance.

Table 5. Results of the multigroup analysis.

Technology- > CSC	Technology- > Performance	Sustainable Practices- > CSC	Sustainable Practices- > Performance	Technology- > Sustainable Practices	Technology- > CSC
IoT	0.014 [2]	0.039 [2]			
TMS	0.004 [1]		0.024 [2]	0.041 [2]	
Machine Learning	0.005 [1]	0.033 [2]			
Robotics	0.037 [2]	0.031 [2]			
3D printing					0.030 [2]

[1] *p*-value < 0.01; [2] *p*-value < 0.05.

4.1. Internet of Things (IoT)

The first technological advancement tested was IoT, and, by using the data collection from the survey, 81 firms were counted in group 0 and 76 firms were counted in group 1. The empirical investigation demonstrates that technology has a positive effect on CSC. Therefore, if an enhancement of this relationship is required, businesses can invest in IoT to obtain superior outcomes (*p*-value = 0.014). As argued in the first section of this work, IoT unlocks the potentialities of CSC. In fact, via the usage of sensors and actuators, electronic devices can monitor and support the logistic system of products. It is also important to stress the indirect effect of the identified protocol on performance, given that the development of an IoT network has a strong impact (p-value = 0.039) on this variable. Thus, it is possible to conclude that IoT strongly leads to improvements, not only in the environmental aspect of supply chain, but also in its financial administration. Those benefits derive from an overall betterment of operational management (a benefit generally brought about by all of the technologies examined herein), but with IoT, firms gain real-time information from each operating unit concerning inventory, material flows, and customer demand. Following this approach, it is achievable to establish a more productive system that is able to better address clients' needs (and adjust production accordingly) and, at the same time, diminish waste, pollution, and resources employed.

4.2. Transportation Management System (TMS)

The results of the survey reveal that TMS was adopted by 88 companies, while 69 were not interested in this technology. TMS is one of the highest-performing technologies among those analyzed. It is a logistic platform that applies several protocols to a supply chain, with the objective of optimizing physical streams of products. It also strengthens the power of sustainable practices thanks to a controlled shipment, and without the typical issues related to transport, such as pollution and poor route scheduling. Moreover, it boosts warehouse efficiency and the degree of productivity; incoming and outgoing goods are constantly tracked, even in sectors where depositories are usually filled with products that tend to quickly deteriorate. In this way, assets are protected, and financial losses are wisely avoided. The meaningful performance enhancement is demonstrated in the analysis, with a p-value of 0.041.

4.3. Machine Learning (ML) and Robotics

The multigroup assessment, applied to ML and robotics, demonstrated similar influences. Both technologies lead to a positive impact on CSC, which means that their application in businesses depends on their ability to improve quality, find unusual solutions, and reduce operating costs. Notably, ML can anticipate the uncertain effects of various processes and detect flaws in circular systems, whereas robotics can facilitate the exchange of goods and carry out concurrent checks during subsequent stages of the production process.

4.4. 3D Printing

Three-dimensional printing is the only machinery studied that showed a substantial indirect outcome on sustainable practices, with a p-value of 0.30. Undoubtedly, 3D printers cut waste materials. In effect, with their usage, it is possible to take advantage of a close-to-demand arrangement, which reduces ordering and delivery times and lowers inventory costs.

5. Discussion and Managerial Insights

When considering the entire sample (Analysis 1), our findings indicate that the adoption of a portfolio of specific sustainable practices and technologies has a positive influence on the setup of a CSC. As explained above, the estimation found three protocols that usually promote CSC: correct identification of green suppliers, ad hoc environmental regulations, and significant attention to the origin and provenance of raw materials. As [51] affirmed, a central element of CSC is the prudent choice of suppliers since pollution depends on the production phases, and also on the logistic assemblage of final goods and their successive delivery to clients. In this matter, choosing a green operator diminishes environmental damage and fosters a more ecological logistic system, from procurement to final product sales. Furthermore, an essential feature of ensuring circularity is the attentive selection of raw resources through the criteria of durability and restoring possibility.

Finally, when public authorities potentiate ecofriendly collaborations through appropriate incentives, respectful manufacturing processes are strongly facilitated [2]. Undoubtedly, from a managerial point of view, the sustainable practices described in this study are not the only actions available to ensure the creation of a CSC; they reflect only the possibility for companies to create a new and fruitful business model. Other alternative options may be adopted according to companies' actual needs and problems. Green suppliers and raw materials selection may represent a starting point for subsequent actions that better fit the organization involved. By examining the results of Analysis 2, we identified the technologies capable of amplifying the benefits claimed by Analysis 1. The critical appraisal of indirect effects in turn made it clearly understandable as to which technologies simultaneously optimize corporate performance and sustainable practices.

From the combining of the two assessments, it emerged that the most effective technological development is TMS. In fact, TMS can achieve efficiency in logistics and international transport because it combines several novel enhancements. To reinforce this notion, our study found that TMS had effects on all three latent variables. We learned that TMS platforms, thanks to IoT networks, simultaneously ensure logistic improvements by removing queues and obstacles and support environment compliance by providing options for CO_2 reduction. To maximize their achievements, companies could combine TMS with other tools, such as ML and 3D printers. As illustrated in Table 5, those two latter developments act by strengthening the outcomes on CSC, business performance, and sustainable practices, because on the one hand, through ML, companies can train systems to take positive and green decisions, while on the other hand, 3D printers are able to extend the life cycle of products.

For the resolution of this study, it is fundamental to observe that both of the analyses conducted converge in one result: the adoption of CSC has a positive effect on companies' economic results. This appears to be in opposition to [43], which found that CSC is linked to poor financial achievements. This study's findings are notably evident in Table 5, whereby all of the technologies described, albeit indirectly, cause a substantial boost in business results, without overlooking the usual benefits originating from CSC on the last variable, as emerged from analysis 1. In our study, the following ratios were taken as economic indicators: market share, profits, ROI, and cost savings. They are the most used indexes in daily business management to measure company growth and the quality of investments. It has been elucidated that the indexes mentioned frequently do not yield considerable enrichments in the short run [42] due to high expenditures, although in subsequent stages, those indicators reveal progressive evolutions thanks to circularity, which is practically inserted into the business model.

6. Conclusions

This paper investigates how CSC functionality can be improved by adopting the portfolios of two main drivers, which are given by sustainable practices and digital technologies. The companies that implement sustainable practices acquire an important capacity to be sustainable from a social, an environmental, and an economic perspective, increasing the overall capacity to implement CSC systems in a responsible way. In fact, the capacity to be sustainable represents a considerable antecedent to create a CSC system. At the same time, the digital technologies play an important role in defining the connections between the companies and the related ecosystem, especially when organizing the logistics in an international framework; using digital technologies, the companies are able to gain high value of information and use them to improve their overall decision-making process at all levels of the companies and at all tiers of global supply chains. Therefore, the capacity to implement a CSC system increases thanks to the enabling technologies. When CSC systems are supported by sustainable practices and digital technologies, their capacity to be circular enables higher business performance, which contributes to making the overall business model economically sustainable. Inspired by this framework, we explore the impact that both sustainable practices and technologies have on increasing the CSC functionality, which impacts on the firms' performance. Afterwards, we verify whether such relationships can be improved when digital technologies are surely adopted by firms. We tested several hypotheses to verify the empirical association between sustainable practices and digital technologies with circular systems, along with the impact on business performance. At the same time, we analyzed if companies should focus on the same digital technologies with more details in order to improve the business performance even more.

Our empirical results show that both sustainable practices and digital technologies help companies in implementing circular supply chain systems; therefore, both of them represent effective drivers to pursue such types of circular systems. However, our empirical analysis demonstrates that sustainable practices are more effective than portfolios of digital technologies in enabling CSC systems. Therefore, companies should concentrate first on the creation of ad hoc portfolios of sustainable practices when aiming at implementing circular supply chain systems and then looking at digital technologies as a second investment opportunity. The creation of good circular economy systems allows companies to increase the business performance, leading to the results that the CSC system is sustainable not only from an environmental point of view, but also from an economic perspective. Furthermore, we discover that the sustainable practices have also an indirect and positive effect on their business performance, reinforcing the idea that the implementation of green practices can lead to improved economic results in the medium and long run.

Afterward, we complemented our empirical analysis with a deep analysis on the digital technologies to verify which of the technologies included in the portfolio gives a better contribution to the creation of circular economy systems and to the business performance. Our results show that companies can improve the impact that technologies have on performance as well as the links existing between sustainable practices and circular supply chain systems by implementing IoT, machine learning, and robotics. Similarly, transportation management systems, which optimize the international logistics networks, allow firms to improve the business performance with digitalization and sustainable practices while also reinforcing the links between technology and sustainable practices. Finally, 3D printing has a positive effect on the relationship between digital technologies and circular supply chain systems. These results help managers and practitioners to better drive their decisions and the allocation of their budget through investments in digital technologies, sustainable practices, and CSC systems.

This study has limitations that could be employed in subsequent avenues of research. For instance, only a small number of ecological practices and technologies were explored. This means that additional elements with an impact on the three latent variables could be identified in future research. For example, this research does not consider the digital supply chain twin technology to assess CSC. This technology is a digital representation of the physical supply chain relationships and flows, which allows supply chain managers to mimic the supply chain network and evaluate the operational and economic feasibility [52]. During the initial pre-testing of the questionnaire, digital supply chain twin emerged as not being currently used by experts; we imagine that this technology can be helpful in the future for better analyzing CSC. Finally, in forthcoming investigations, it may be useful to emphasize the opportunity for generous incentives, with the aim of encouraging the insertion of circularity within firms, as well as the possibility of exploiting the last mile concept to minimize the movement of goods and pursuing economic, environmental, and social outcomes. Moreover, disruptive events, such as the COVID-19 pandemic and the Russia–Ukraine war, could be taken into consideration to evaluate further challenges in the creation of CSC systems.

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