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# Industry 4.0 Technologies Promote Micro-Level Circular Economy but Neglect Strong Sustainability in Textile Industry

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**Abstract:** Large textile industries are deploying Industry 4.0 Technologies (I4.0T) aiming to develop a micro-level circular economy (CECP), considering cleaner production practices as a strategic tool. However, due to the environmental impact generated by the textile industry, it has not yet achieved Strong Sustainability (SS), denoting an important path to be pursued by managers and shareholders in view of meeting the 2030 agenda. With this, the objective of this study is to evaluate whether the adoption of I4.0T promotes CECP-driving SS actions in large textile industries located in Brazil. A survey was the research method adopted, and for data analysis, structural equation modeling was used to test the hypotheses and Pearson correlation between variables. It was concluded that the adoption of I4.0T promotes CECP. However, they neglect SS actions. Facilitators for CECP practices were big data, augmented reality, and autonomous robots. In terms of SS, I4.0T has a low impact on increasing resource consumption efficiency, reusing waste as input in other processes, and increasing access to commodities. This research contributes to the linking I4.0T, CECP, and SS theory. Moreover, with the dissemination of knowledge to managers about the I4.0T that generates the CECP, it is possible to develop sustainable strategies in operations. However, to move in this direction, it is essential that there is a collective effort of the government, companies, and society, starting by raising awareness about the importance of SS in the textile sector.

**Keywords:** Industry 4.0 Technologies; circular economy; cleaner production; SS; textile industry



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## 1. Introduction

The implementation of I4.0T in the textile production system has stimulated micro-level circular economy (CE) practices by considering cleaner production (CP) as an essential tool [1–4]. This phenomenon occurs mainly due to the textile industry being environmentally unfriendly, such as high consumption of energy, water, and chemicals [5], as well as generating a lot of waste at the end of the useful life of textile items [6]. Thus, CECPs are complementary to the adoption of I4.0T [7,8]. It is emphasized, based on UNEP, that CP, since its existence, already sought to close the cycle of the production system by not generating waste and promoting recycling to save raw materials, water, and energy [9]. Thus, CE originates from CP [10,11]. However, CE emerged in a radical way to eliminate linear flows and deployment of cyclical flows of productive resources aimed at the regeneration and use of materials from renewable sources [12].

As mentioned, the adoption of I4.0T in manufacturing stimulates CECP. For example, big data provided material regeneration through end-of-life clothing repair [13]; autonomous robots generated technological improvements in wastewater treatment and waste collection [14]; simulation favored post-consumer waste collection [15]; IoT promoted a circular business model of online apparel commerce [13,16]; Cloud Computing promoted renewable energy and dematerialization of products [13]. Additive manufacturing stimulated the use of by-products as raw materials and waste reduction [14]; augmented reality reduced waste by incorporating digital tools for selling and manufacturing apparel [17]. Cyberphysical Systems enabled energy and water optimization [18]; Cybersecurity Systems provided confidence to managers to share information between companies, promoting industrial symbiosis [6,13]; artificial intelligence played an important role in resource optimization [19].

It is emphasized that successful CECP implementation contributes to sustainability [20]. The definition of Strong Sustainability recognizes that the economy is an integrated subsystem within the system that includes society and the environment, which means that economic prosperity must be achieved without compromising social well-being and the health of the planet Oliveira Neto et al. [21]. Specifically, CECP can contribute to SS in terms of increasing resource consumption efficiency, limiting the consumption of renewable resources to their regeneration rate, reducing greenhouse gas emission, reusing waste as inputs in other processes, replacing toxic inputs with organic materials and non-replenishable energy resources with renewable ones, increasing access to commodities and sustainable manufacturing [21].

Thus, the textile industry can promote SS by installing more efficient engines and machines [18], producing dye pigments from by-products of various local, rapidly regenerating crops such as onion husks, artichoke leaves, walnut husks, and chestnut shells [22]; minimize material disposed of in landfills, which reduces methane gas and $CO_2$ emissions [23]; using textile waste as inputs in other sectors such as thermal and acoustic insulation in cars, in construction, coverings in agriculture and paper industry, filling of toys and seats of chairs and armchairs [6]; commercialize 100% biodegradable and non-toxic sewing threads [2]; explore the use of renewable energy [24]; donate clothing in good condition to charities [6]; produce bio-based materials that refer to sustainable manufacturing, lower environmental impact and better livelihoods of farmers, which causes positive socioeconomic impact [19].

It was identified only exploratory studies on the relationship between I4.0T and CECP in the textile industry. Evidence of SS was highlighted in the content analysis of the articles. Silva and Morais [15] (2022) performed a simulation to classify circular strategies in textile waste management outsourcing in Brazil. They considered the use of recycled raw materials. Kumar et al. [18] analyzed smart environmental management practices and CECP based on simulation technologies, augmented reality, and Cyberphysical Systems aimed at minimizing pollution in the supply chain of Pakistan. Agarwal and Singh [25] conducted a simulation that evaluated the performance of textile effluent treatment techniques in India. It showed improvement in water circularity and elimination of hazardous products. Shayganmehr et al. [13] evaluated I4.0T for the implementation of CECP practices and the readiness of the Iranian industry. Bai et al. [19] analyzed I4.0T related to sustainable performance in China, the main features of which were optimizing resources and increasing efficiency. Tsai [24] used a combination of simulation and sensing to perform CECP based on green production planning and control in Taiwan. Tsai considered industrial symbiosis of by-product exchange. Bloomfield and Borstrock [26] investigated the challenges of additive manufacturing to promote CECP in the UK and resource efficiency.

Evidence of a relationship between I4.0T, CECP, and SS was also verified by Jin et al. [16], who investigated circular business models based on product–service systems that use IoT in apparel companies targeting sustainable manufacturing. Chen et al. [27] proposed integrated strategies based on big data and IoT to promote green chemistry in CECP and eliminate toxic products. Shirvanimoghaddam et al. [6] discussed the use of IoT, additive manufacturing, Cyberphysical and Security Systems, and artificial intelligence for innovation and circular strategies in textile fashion and promote the exchange of by-products between companies. Jia et al. [28] mentioned IoT and Cyberphysical Systems in their survey of circular economy barriers and practices in the textile and apparel industry; they highlighted the reduction of pollutant gas emissions. Faria et al. [29] analyzed mobile applications that use IoT and cloud computing to support online apparel commerce with circular economy features and facilitate access to second-hand clothing. Alcayaga et al. [30] investigated big data, IoT, and Cyberphysical Systems in smart circular systems at the micro-production level, in which they stimulate sub-product exchange between firms.

Also, Angelis and Feola [22] addressed big data and Cyberphysical Systems in a case study in Italy on the characteristics of circular business models. They mentioned actions toward the use of non-toxic organic inputs. Franco [2] conducted a multi-case study in Austria and Italy on circular production based on IoT and Cyberphysical and Security Systems, which use rapidly regenerating renewable resources (Fatimah et al. [23]). A study applied a focus group to develop a sustainable and smart waste management system in Indonesia that minimizes methane gas emissions. Larsson [17] conducted action research that evaluated four augmented reality projects in Sweden, focusing on digital sales and manufacturing tools that minimize waste in the textile and apparel value chain. Oliveira Neto et al. [14] evaluated by survey the degree of sustainable resilience by the size of the textile industry to propose incremental changes from CP to CE, briefly mentioning additive manufacturing in product design and autonomous systems that improve working conditions. In this context, no confirmatory study was identified that has evaluated whether the implementation of I4.0T stimulates CECP actions in large textile industries located in Brazil, as well as whether the stimulation of CECP actions directs SS. Thus, based on this research gap, this study will answer the following question: Does the adoption of I4.0T supports CECP by promoting SS actions in large textile industries located in Brazil?

Thus, the objective of this study is to evaluate whether the adoption of I4.0T promotes CECP aimed at SS actions in large textile industries located in Brazil. This study presents a relevant theoretical contribution because it shows the I4.0T that promotes CECP actions, directing the SS. In addition to elucidating for business managers, the opportunity to invest in I4.0T to generate circularity in the production system is an important aspect of the fulfillment of the agenda for 2030.

## 2. Systematic Literature Review and Hypothesis Development

A systematic literature review was adopted to develop the conceptual model (Figure 1), using the keywords: "cleaner production" AND "circular economy" AND "textile" AND "Cloud Computer" OR "Internet of things" OR "Cyberphysical System" OR "Artificial Intelligence" OR "Augmented Reality" OR "Additive Manufacturing" OR "Industry 4.0" OR "System Integration" OR "sensors" OR "Autonomous Robots" OR "Big Data" OR "Simulation" OR "Cybersecurity System". The following databases were explored: Scopus, Compendex, Emerald, Science Direct, Willey, Taylor & Francis, and Sage. A total of 54 articles were analyzed to identify research that mentioned I4.0T, CECP, and actions to promote SS. After the analysis, 36 articles were excluded, which did not relate to the keywords, or these words were only in the references and literature review and not mentioned in the results and conclusion. Thus, 18 articles were used to build the conceptual model, enabling the identification of I4.0T, CECP, and actions to promote SS. The CECP practices were organized based on the ReSOLVE framework, and the SS evidence found in the articles considered the SS actions proposed by Oliveira Neto et al. [21].

### 2.1. Relationship between I4.0T, CECP, and SS in the Textile Industry

The studies found in the literature that addressed I4.0T, CECP in the textile industry used research methods with an exploratory approach. They were conducted through case studies, conceptual–theoretical research, action research, survey, and focus group.

Nine research were conducted by means of case studies. Silva and Morais [15] proposed a multi-criteria decision model based on simulation technology to rank CECP strategies in a textile factory in Brazil. The results indicated that the strategies of Regenerate, Share, Optimise, Loop, and Exchange stimulated SS actions such as finding sustainable alternatives for cotton, reusing water for washing to avoid industrial effluent, minimizing the use of toxic substances, using renewable energy and reducing the use of non-renewable energy sources, in addition to sustainable manufacturing aspects such as job creation, income generated from new jobs, improvement in job safety and being a socially responsible company. Kumar et al. [18] evaluated smart environmental management practices in five textile manufacturing facilities in Pakistan using simulation, augmented reality, and Cyberphysical Systems. The adoption of CECP practices resulted in reduced electricity consumption through the installation of more efficient motors and lamps, the use of chemicals in water treatment, lower fuel consumption and $CO_2$ emissions due to steam leakage control, the installation of new steam traps, and the replacement of steam pipelines.

Agarwal and Singh [25] implemented a simulation to integrate Fuzzy, Delphi, and Analytical Hierarchy Processes to select textile effluent treatment techniques in India. The results focused on SS were the reuse of treated effluent in irrigation or industrial use and the reuse of iodine extracted from effluent as fertilizer by composting. In addition, it presented sustainable manufacturing aspects that refer to economic gains associated with reduced environmental impact and improvement in the social dimension, such as employment generation and public safety for the local community and acoustic and thermal comfort for employees. Shayganmehr et al. [13] evaluated the importance of I4.0T for the implementation of CECP practices in Iran using Fuzzy Delphi and the Analytical Hierarchy Process method. The evaluation considered Big Data, Autonomous Robot, IoT, Cloud Computing, Additive Manufacturing, Cyberphysical Systems, Cybersecurity Systems, and Artificial Intelligence. It has resulted in operational efficiency in resource consumption, integration of industrial systems to exchange resources between production processes, the reduction of toxic inputs to facilitate material reuse, energy recovery, and sustainable manufacturing indicators.

Angelis and Feola [22] addressed the implementation of CECP in an Italian company that uses Big Data and Cyberphysical Systems for CECP practices, generating evidence in SS: (i) Big Data, automation and remote sensing increase resource efficiency and significantly reduce waste in the production process; (ii) production of color pigments from by-products of various local, rapidly regenerating crops such as onion husks, artichoke leaves, walnut shells and chestnut shells; (iii) production uses biological sources extracted from by-products of other agri-food processes, recovering waste; (iv) uses renewable biological inputs in the production process and plant residues are composted; (v) No toxic solvents are used in production; (vi) reduced energy consumption and use of renewable energy sources are part of the manufacturing strategy; (vii) reduced consumption of raw materials used; and (viii) sustainable manufacturing that adds economic value to harvest and processing byproducts.

Bai et al. [19] examined I4.0T and its implications for CECP in China. From the perspective of SS actions, resource consumption efficiency was evidenced by the use of IoT and soil sensors, which optimize the use of resources in the field, such as fertilizer, irrigation, harvesting time, and seed spacing. Also, autonomous robots increase energy and resource efficiency in the production of electronic components. Cloud computing has enabled a reduction in toxic materials and less impact on effluents and waste. The production of bio-based plastics and lightweight composites harks back to sustainable manufacturing by reducing environmental impact and improving the livelihoods of farmers, which causes a positive socioeconomic impact.

Tsai [24] analyzed green production planning and control in a Taiwanese textile industry, which combined mathematical programming with simulation and Cyberphysical Systems, influencing SS. The in-process material tracking increased the efficiency of resource consumption in manufacturing. In addition, the automatic monitoring system records all production process data in real-time, which encourages companies to control carbon emissions. Also, it has reused wastewater, waste heat, and ash produced from the combustion of coal in the boiler to produce eco-friendly bricks that are sold or used to replace asphalt surfaces in the company. The use of energy from renewable sources and its recycling in the process is a concern, not only for the green energy effect but also to reduce costs due to reduced energy consumption.

Bloomfield and Borstrock [26] addressed the challenges of employing Additive Manufacturing in the UK textile industry. The practices of CECP boosted SS. With this, additive manufacturing offers solutions in resource efficiency with the reuse of materials, reduction in the number of processes, and addresses energy and emissions concerns, as well as being continuously reused, rather than the end-of-life material being processed to be remade as something else. Also, he mentioned the need to reduce resources through localized manufacturing, product life extension, and demand-driven manufacturing. The benefits of localized manufacturing include employment of people from the local community, reduced transportation, and delivery times.

In Austria and Italy, Franco [2] identified through multiple cases a set of factors in the textile chain to develop circular products. IoT, Cyberphysical Systems, and Security were adopted, which impacted CECP, influencing SS through sourcing high-quality cellulose fibers sourced from reforested, renewable wood, generating the circular material cycle and, therefore, are suitable for biological metabolism; launching fiber made from post-industrial cotton waste sourced from one of the largest clothing retailers in the world; and trading 100% biodegradable, cellulosic, different color shades, and non-toxic sewing threads.

Six studies addressed I4.0T and CECP through a systematic literature review. Jin et al. [16] reviewed the business models of apparel companies. IoT drove CECP practices through product-service systems and online platforms. The findings indicated that the apparel industry turned its attention to life cycle sustainable development: ecodesign, sustainable manufacturing, and post-consumption and resource-efficient use and reuse of clothing through online platforms. Chen et al. [27] found that principles of green chemistry and the application of Big Data and IoT accelerated the transformation to an integrated CECP approach. The SS-directed results indicated: increased efficiency of natural resources and energy consumption; redesign of the production chain considering resource regeneration; recovery of $CO_2$ in synthesis gases to be used in steam conversion; recovery of biomaterials such as amino acids, carbohydrates, and nucleic acids by depolymerization process; substitution of hazardous chemicals by green chemistry; and significant advancement of renewable feedstock fuel development such as biodiesel from vegetable oils and algae. Faria et al. [29] reviewed mobile online apparel commerce applications based on IoT and Cloud Computing. CECP stimulated SS in reusing waste as inputs in other processes and increasing access to commodities and adopting web platforms and mobile apps that offer functionalities for buying, selling, and renting used clothing.

Jia et al. [28] identified drivers, barriers, practices, and indicators of sustainable CE performance in the textile industry. IoT and Cyberphysical Systems drove CECP practices, which drove SS through design for remanufacturing to promote circularity in the supply chain, textile waste defibration for fiber circularity, and recycling and reuse of textile materials. Shirvanimoghaddam et al. [6] reviewed the literature on approaches to reuse, recycling, and reuse of textile waste. IoT, Additive Manufacturing, Physical and Cyberphysical Systems, and Artificial Intelligence were part of the research that showed increased textile circularity contributing to SS through reuse and recycling of waste, raises resource consumption efficiency; use of bamboo and hemp as renewable textile raw materials; reuse of textile materials at end-of-life reduces carbon footprint; reuse of textile waste for use in other products, for example as thermal and acoustic insulation in cars; exclusive use of biodegradable materials and the replacement of chemical dyes with natural dyes; energy recovery (heat or electricity) in production; access to commodities; and sustainable manufacturing of textiles.

Alcayaga et al. [30] conducted a literature review to propose a conceptual framework of smart circular systems based on Big Data, IoT, and Cyberphysical Systems. Smart circular systems denote SS actions through CECP practices. Smart recycling, based on IoT and Big Data, has enabled more efficient waste collection, reorganizing collection routes and minimizing transportation costs. Analytics and business intelligence use large amounts of information generated during the product life about the phase and use, product operation, and user characteristics, which facilitates the provision of inputs for other processes.

In survey research, Oliveira Neto et al. [14] evaluated sustainable resilience to drive incremental changes in CECP practices in the textile industry. Autonomous Robots and Additive Manufacturing were the technologies highlighted by the study. The findings showed the resilience of companies in the efficient use of water, raw materials, and inputs and in the generation of emissions. In addition to reusing waste from the production process, co-generating energy, eliminating toxic materials, choosing raw materials and energy from renewable sources, and improving working conditions.

Fatimah et al. [23] conducted a focus group to propose a sustainable and intelligent waste management system in Indonesia based on the joint application of Big Data, IoT, and Cyberphysical Systems, driving CECP and SS. It was found that it improved the effectiveness of waste management because the generated waste is destined for proper treatment such as composting, recycling, pyrolysis gasification, incineration, and energy recovery; thus, the regeneration capacity is compatible with the generation rate; reduced methane gas and $CO_2$ emission due to minimization of material disposed of in landfill; reduced water and soil contamination; allowed the formalization of skilled jobs, which enhances their purchasing power and access to products; and improved aspects of sustainable manufacturing such as the level of safety and healthy living of people in the area of waste management.

In action research, Larsson [17] evaluated four innovation projects that used I4.0T for textile sales and manufacturing in Sweden. Augmented Reality leveraged CECP, driving SS by means of optimization of production resource use; digital service for new and used parts sales and maintenance, reducing $CO_2$ emissions and waste of materials, chemicals, and water; and job creation.

### 2.2. Hypothesis Development

Only qualitative evidence was identified in the literature indicating that the adoption of I4.0T drives CECP. Oliveira Neto et al. [14] concluded that large textile industries have invested in I4.0T connected to CECP practices, generating sustainable resilience. Shayganmehr et al. [13] mentioned that deploying I4.0T in the textile industry leveraged CECP practices to improve the quality of their products and services. Bai et al. [19] concluded that the adoption of I4.0T enabled CE strategies focused on sharing and optimization of textile resources. Rajput and Singh [7], Shayganmehr et al. [13], de Oliveira Neto et al. [31], and Luthra and Mangla [32] mentioned the relationship between industry 4.0 and CECP for achieving environmental, economic, and social gains in operations. In this context, the first hypothesis of this research is suggested:

**H1:** *The adoption of I4.0T promotes CECP in the large textile industry located in Brazil.*

There was also evidence of SS actions in the textile industry studies that addressed I4.0T directed toward CECP practices. The use of simulation supported circular strategies to promote actions such as finding sources of alternatives to cotton, maximizing recycling, minimizing toxic substances, using renewable energy, and sustainable manufacturing [15]. The integration of simulation, augmented reality, and Cyberphysical Systems to evaluate smart waste management practices resulted in increased resource consumption efficiency and reduced $CO_2$ emissions [18]. The integration of big data, IoT, and Cybersecurity Systems has improved the efficiency of sustainable waste management and CE by making regeneration capacity compatible with the waste generation rate, in addition to hiring waste pickers and improving access to commodities [23]. Also, several integrated I4.0Ts in CE showed reduced textile waste and increased efficiency, adoption of fast regenerating raw materials, reduced carbon footprint, use of textile waste as inputs in other sectors such as thermal and acoustic insulation in cars, exclusive use of biodegradable materials, energy recovery, donation of clothing to charities, and minimizing impacts of fast fashion and consumerism [6]. With this, it was found that the adoption of I4.0T stimulated CECP by promoting SS actions. It is emphasized that research on the subject presented only scientific evidence without confirmatory data. In this context, the second hypothesis of this study is suggested:

**H2:** *The adoption of I4.0T supports CECP promoting SS actions in large textile industries located in Brazil.*

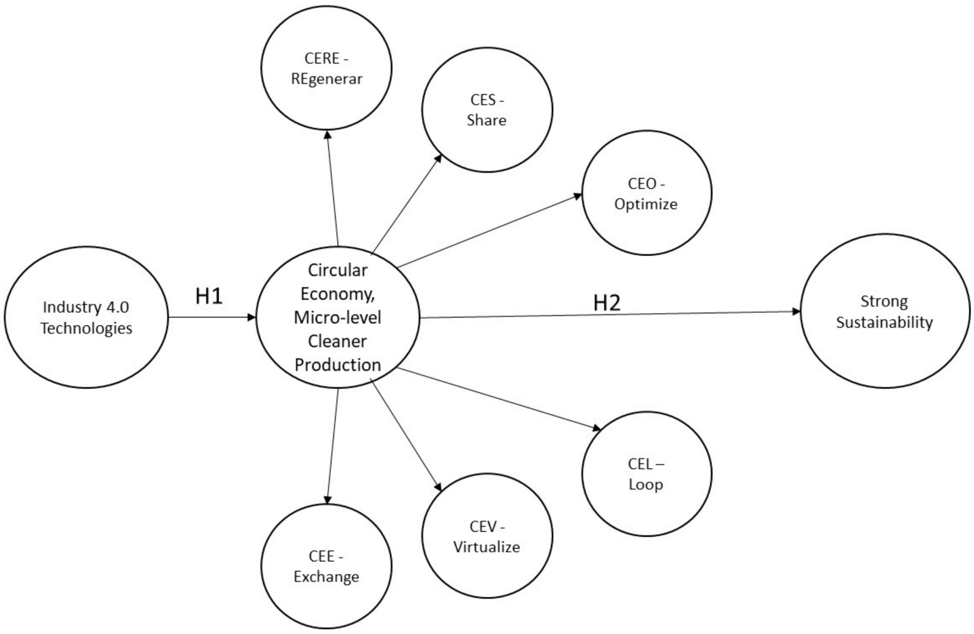


**Figure 1.** Conceptual Model.

## 3. Methodology

The research method used was a survey of large textile industries located in Brazil. A structured questionnaire was developed based on the systematic literature review, then evaluated by experts, and then sent to 150 companies [33]. The results were analyzed using structural equation modeling to test the hypotheses and Pearson-based analysis of the correlation between variables.

### *3.1. Data Collection Procedure*

After the identification of the variables (I4.0T, CECP, and SS actions—Table 2), an interview was scheduled with 10 specialists from the large textile industry to calibrate the research instrument based on organizational practice. These experts have worked in the textile industry for over 30 years and hold the positions of director, manager, and operations area coordinator. Forza [33] corroborates that it is important to develop surveys and expert analysis to correct and validate the structured questionnaire before applying it to other companies.

**Table 1.** I4.0T related to CECP and SS evidence.

| Author | Method | Country | Industry 4.0 Technologies | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | T_1 Big Data Analytics | T_2 Autonomous Robots | T_3 Simulation | T_4 Internet of Things | T_5 Cloud Computing | T_6 Additive Manufacturing | T_7 Augmented Reality | T_8 Cyberphysical Systems | T_9 Cybersecurity Systems | T_10 Artificial Intelligence |
| [15] | Case Study and Simulation | Brazil | | | X | | | | | | | |
| [18] | Case Study and Simulation | Pakistan | | | X | | | | X | X | | |
| [25] | Case Study and Simulation | India | | | X | | | | | | | |
| [14] | Survey | Brazil | | X | | | | X | | | | |
| [28] | Literature review | Null | | | | X | | | | | | |
| [13] | Case Study and Simulation | Iran | X | **X** | | X | **X** | **X** | | X | X | X |
| [27] | Literature review | Null | X | | | X | | | | | | |
| [22] | Case study | Italy | X | | | | | | | X | | |
| [23] | Focus Group | Indonesia | X | | | X | | | | X | | |
| [6] | Literature review | Null | | | | X | | X | | X | X | X |
| [19] | Case study | China | X | X | X | X | X | X | X | X | X | X |
| [28] | Literature review | Null | | | | X | | | | X | | |
| [29] | Literature review | Null | | | | X | X | | | | | |
| [30] | Literature review | Null | X | | | X | | | | X | | |
| [24] | Case Study and Simulation | Taiwan | | | X | | | | | X | | |
| [26] | Case Study and Simulation | UK | | | | | | X | | | | |
| [17] | Action Research | Sweden | | | | | | | X | | | |
| [2] | multiple case studies | Austria and Italy | | | | X | | | | X | X | |

| Author | Method | Country | CERE - REGENERATE - seeks regeneration through changes to renewable energy and material, allowing the circulation of energy and materials in a closed cycle. | | | | | CES - SHARE - Aims at the shared economy, goods and assets are shared between individuals. | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | CERE_1 - Seeks regeneration through renewable, reused, and recycled textile articles. | CERE_2 - Seeks regeneration through the adoption of clean technology supplied with energy from renewable sources. | CERE_3 - Seeks regeneration through the adoption of a closed-loop effluent treatment plant for water recovery, extracting hazardous products. | CERE_4 - Seeks regeneration by recovering textile articles at the end of their useful life. | CERE_5 - Seeks regeneration by reusing waste from other industries. | CES_1 - Seeks sharing through the implementation of a department in production to manage textile article recovery processes, even at third parties. | CES_2 - Seeks sharing through agreement with sewing workshops for post-consumption textile article recovery. | CES_3 - Seeks sharing with clothing merchants to sell recovered textile articles. |
| [15] | Case Study and Simulation | Brazil | | X | | X | | X | | |
| [18] | Case Study and Simulation | Pakistan | | | X | | | | | |
| [25] | Case Study and Simulation | India | | | X | | | | | |
| [14] | Survey | Brazil | X | X | X | X | X | X | | |
| [28] | Literature review | Null | | | | | | | X | |
| [13] | Case Study and Simulation | Iran | | X | | | | X | X | X |
| [27] | Literature review | Null | | | | | X | X | | X |
| [22] | Case study | Italy | X | | X | | X | X | | |
| [23] | Focus Group | Indonesia | | | | X | | | | |
| [6] | Literature review | Null | X | X | X | | X | | | X |
| [19] | Case study | China | X | X | | | | X | | |
| [28] | Literature review | Null | | | | | | X | X | |
| [29] | Literature review | Null | | | | | | | | X |
| [30] | Literature review | Null | | | | | | | X | |
| [24] | Case Study and Simulation | Taiwan | | | | | | | | |
| [26] | Case Study and Simulation | UK | | | | | | | | |
| [17] | Action Research | Sweden | | | | | | | | |
| [2] | multiple case studies | Austria and Italy | | | | X | | | | |

| Author | Method | Country | CEO - OPTIMISE - Optimize - aims to reduce waste in production systems and throughout the supply chain. | | | | | CEL - LOOP - Aims to recover the value from waste and restore the value of post-consumer products and packaging through repair, reuse, remanufacturing, and recycling. | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | CEO_1 - Seeks optimization through development and redesign of textile articles and packaging for reuse, repair, recycling, and remanufacturing and without hazardous components. | CEO_2 - Seeks optimization using renewable energy in production. | CEO_3 - Seeks optimization by reducing as much as possible the use of water in production. | CEO_4 - Seeks optimization by reducing as much as possible the generation of residues in the manufacturing process. | CEO_5 - Seeks optimization by adopting machines and equipment that do not emit greenhouse gases. | CEL_1 - Seeks circularity by recycling textile article waste. | CEL_2 - Seeks circularity by reusing waste textile articles. | CEL_3 - Seeks circularity by tracking post-consumer textile waste for recycling. | CEL_4 - Seeks circularity by reusing post-consumer textile packaging. | CEL_5 - Seeks circularity through reverse logistics aimingat remanufacturing, repair, recycling and/or reuse of post-consumption textile articles. |
| [15] | Case Study and Simulation | Brazil | | X | X | | | X | | | | X |
| [18] | Case Study and Simulation | Pakistan | | X | X | X | X | | | | | |
| [25] | Case Study and Simulation | India | | | X | | | | | | | |
| [14] | Survey | Brazil | X | X | X | X | X | X | X | | X | |
| [28] | Literature review | Null | | | | | | | | | | |
| [13] | Case Study and Simulation | Iran | | | | | | | | | | |
| [27] | Literature review | Null | | X | | | | X | | | | |
| [22] | Case study | Italy | | | X | X | | | | | | |
| [23] | Focus Group | Indonesia | | | | X | X | X | X | X | | X |
| [6] | Literature review | Null | | X | X | X | | X | | | | |
| [19] | Case study | China | | X | X | X | X | | | | | |
| [28] | Literature review | Null | X | X | X | X | | X | X | X | X | X |
| [29] | Literature review | Null | X | | | | | | | | | |
| [30] | Literature review | Null | | | | | | X | X | X | | |
| [24] | Case Study and Simulation | Taiwan | | X | X | X | X | X | X | | | |
| [26] | Case Study and Simulation | UK | X | | | X | | | X | | | |
| [17] | Action Research | Sweden | X | | | | | X | X | | | |
| [2] | multiple case studies | Austria and Italy | | | | | | X | X | X | | X |

| Author | Method | Country | CEV - VIRTUALISE - Formulate a strategy focused on services that replaces the physical with virtual and dematerialized products. | | | | CEE-EXCHANGE - Involves the replacement of old, non-renewable assets with advanced, renewable products. | | | STRONG SUSTAINABILITY | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | CEV_1 - Seeks virtualization through the deployment of the 3D printer, aiming dematerialization. | CEV _2 - Seeks virtualization with the use of virtual catalog of textile articles, aiming the dematerialization. | CEV_3 - Seeks virtualization using digital stylist services for the development of textile articles. | CEV_4 - Seeks virtualization through digital service for asset maintenance. | CEE_1 - Seeks the substitution of non-renewable productive resources by renewable ones. | CEE_2 - Search for the substitution of toxic components for non-toxic ones | CEE_3 - Search for the substitution of suppliers from non-renewable to renewable sources | SS_1 - Increase efficiency in resource consumption. | SS_2 - Limit consumption of renewable resources to their regeneration rate. | SS_3 - Reduce greenhouse gas emissions. | SS_4 - Reuse waste as an input in other processes. | SS_5 - Replace toxic inputs with organic materials. | SS_6 - Replace non-renewable energy resources with renewable alternatives. | SS_7 - Increase Access to Commodities. | SS_8 - Increase sustainable manufacturing. |
| [15] | Case Study and Simulation | Brazil | | | | | X | | | | X | | X | X | X | | X |
| [18] | Case Study and Simulation | Pakistan | | | X | | | | **X** | X | | X | | | | | |
| [25] | Case Study and Simulation | India | | | | | | | | X | | | X | | | | X |
| [14] | Survey | Brazil | X | | | | X | X | **X** | X | | X | X | X | X | | X |
| [28] | Literature review | Null | | X | | | | | | X | | | | | | X | X |
| [13] | Case Study and Simulation | Iran | X | X | | X | X | X | X | X | | | X | X | X | | X |
| [27] | Literature review | Null | | | | | X | X | X | X | X | X | X | X | X | | |
| [22] | Case study | Italy | | | | | | X | | X | X | X | X | X | X | X | X |
| [23] | Focus Group | Indonesia | | | | | | | | X | X | X | X | X | X | X | X |
| [6] | Literature review | Null | X | X | X | | X | X | | X | X | X | X | X | X | X | X |
| [19] | Case study | China | X | | | | | X | | X | | X | | X | | X | X |
| [28] | Literature review | Null | | | | | X | X | X | X | | X | X | X | | | X |
| [29] | Literature review | Null | | X | X | | | | | | | | X | | | X | |
| [30] | Literature review | Null | | | | | | | | X | | | X | | | | |
| [24] | Case Study and Simulation | Taiwan | | | | | | | | X | | X | X | | X | | |
| [26] | Case Study and Simulation | UK | X | | | | | | | X | | X | X | | | | X |
| [17] | Action Research | Sweden | | X | X | | | | | X | X | X | X | X | | | X |
| [2] | multiple case studies | Austria and Italy | | | | | | | | | X | | X | X | | | |

Then, the structured questionnaire was sent by e-mail to 150 managers of the operations and environmental management area of large textile industries in the period from September 2022 to January 2023. A total of 102 responses were returned, which completely answered the questionnaire. This amount of response was validated because the software G*Power 3.1.9.2 was used, considering the parameters' average effect size (f2) of 0.15 and test power of 0.80 [34,35], and thus it was found that 55 responses were sufficient to proceed with the data analysis procedure.

### 3.2. Data Analysis Procedure

For the data analysis, a structural equation modeling (SEM) by the partial least squares (PLS) method calculated by the cSEM module of the R project and with the R Studio console was used. This procedure was adopted because when analyzing the multivariate normality of the Mardia PK data [36] using the "mvnormalTest" module (also from the R project), it was found that the described condition was not met.

Thus, there are two groups of models: 1. covariance-based and 2. variance-based; those in the first case have the need to have data adherent to a multivariate normal distribution, and the second group does not have this assumption, the reason that originated the choice.

As commented in the previous item, the PK test of Madia resulted significant ($p \leq 0.05$), indicating that the data do not respect a multivariate normal distribution and so, for greater understanding, a partial least squares (PLS) measurement model was adopted because it does not need to meet the assumption (of the other models) analyzed by the indicated test.

Note that the SEM is important for developing confirmatory evaluation but requires many respondents and the normality of the data [37,38]. In conjunction, PLS is used to calculate regression coefficients, minimizing the conflict of unnecessary variables in model fitting [39,40]. However, PLS has some limitations due to the possibility of extrapolation of the findings by researchers [41,42]. Thus, it is necessary to stick to the main results when using PLS [43] as well as justify based on the scientific literature its application [44].

A relevant aspect is that to mitigate weaknesses, PLS-SEM is used together, a point noted in several high-impact publications [38,42]. It is also important to ground the constructs and variables of the model in the scientific literature [45]. In addition, to correctly ground based on the literature, the data analysis procedure, including explaining the validation metrics [38,45].

With the understanding of the limitations and the factors to mitigate them, this study adopted PLS-SEM to test the hypotheses and fit the model [46] and found it relevant to apply the correlation of Pearson between the variables of the constructs to assess the relationship between them. Thus, it is not possible to extrapolate the results because the explanations are made based on the correlations identified in the values of the factor loadings between the constructs of the model and their respective variables.

The metric adopted for correlation is values between −1 and +1, demonstrating negative or positive, lower, or higher intensity correlation [47–49]. The analysis of relationship intensity considered the criteria adopted by Dancey and Reidy [50]: weak correlation between 0.10 and 0.30, moderate between 0.40 and 0.60, and strong above 0.70.

For hypothesis testing and model fitting using PLS-SEM the following procedures were adopted: (1) assess the normality of the data distribution, being normal when Skewness values are between −1.0 and +1.0, at Kurtosis values less than 2.0; (2) assess the convergent validity of the model, in which all average variance extrated (AVE) should be greater than 0.50; (3) assess the discriminant validity, where the correlation values must be smaller than the square roots of the AVE; (4) assess the model reliability, being confirmed when the Composite Reliability (CR) and Cronbach's Alpha (CA) values are greater than 0.70; (5) evaluate correlations and regressions with Student's *t*-test, which must be equal or greater than 1.96; (6) evaluate the coefficient of Pearson (R2), which measures the effect of one construct on the other, where: 0.26 is a large effect, 0.13 a medium effect and 0.02 small effect; (7) evaluate predictive validity (Q2), where the number is greater than zero and the effect size (f2) is large for values near 0.35, medium for 0.15 and small for

0.02; (8) evaluate the accuracy of model fit, requiring a positive value of the Stone–Geisser indicator; (9) interpret the calculated path coefficients.

## 4. Results and Discussion

The indicators of the measurement model were obtained (AVE, R2, R2adj, Cronbach's Alpha, Composite Reliability), but the discriminant validity between the two constructs (SS and CEE) was not verified. For this purpose, the bivariate correlations of Pearson between all variables in the model were calculated. After evaluating the correlation values, the technology variable T_5 (Cybersecurity) was eliminated. The textile industry experts mentioned that the adoption of cloud computing generated the need for investment in Cybersecurity and justified that employees need training on information care in the digital transformation era. It is emphasized that in the correlation, it was found that the adoption of Cybersecurity is of little importance. Thus, large textile industries in Brazil have worked on the implementation of technologies essential for their operation without emphasizing the protection of intellectual property and risks to information systems. A significant increase in the use of information technology and connected systems in the textile industry, which includes process automation, production monitoring, supply chain management, and online sales, may encourage the industry to increase technology in defense against cyber threats such as hacker attacks, data theft, operational disruption, and industrial espionage. This result is at odds with the finding found in the case study conducted in the textile industry in Iran, which showed that I4.0 system security was one of the enablers with the strongest effect on CECP deployment [13]. In this regard, large textile industries in Brazil are lagging in employing security technologies, such as implementing firewalls, intrusion prevention and detection systems, data encryption, and network monitoring. The mentioned deficit can inhibit business with large corporations in the sector.

In a new round of the model, after the removal of variable T_5, variables SS_1 and SS_4, increase efficiency in resource consumption and reuse waste as inputs in other processes, respectively, were also extracted from the model for not presenting significant values. SS_1, which aims to increase efficiency in the consumption of resources, was removed because large textile industries located in Brazil have difficulties in optimizing energy, water, and production inputs because the machines are old and the manufacturing park has a low level of automation, which hinders the efficient use of production resources. For example, machines are turned on during idle periods, which reduces the efficiency of energy consumption. This also occurs with water, which is used on a large scale in dyeing. This finding is in line with what was mentioned by Silva and Morais [15] about the textile industry in developing countries whose operation is based on rudimentary low-efficiency technologies. The textile industry in Brazil faces significant challenges regarding the low efficiency level in the use of electricity, water, and other natural resources because it uses obsolete equipment and systems that consume a lot of energy and water, reuse of textile fibers, and waste of raw materials in production. In this sense, this research contributes to the theory by offering information on low efficiency in the use of resources in the textile industry in Brazil, which can be considered in future studies. In addition, managers can take the information from this study as a reference to develop appropriate strategies to raise the efficiency of operations, requiring investment in production machinery with lower energy consumption, water recirculation and treatment systems, and the adoption of circular economy practices, such as recycling textile waste. Furthermore, the research can make society aware of the importance of sustainability in this sector and its environmental and social impacts.

Also, the SS_4 that mentions the reuse of waste as inputs in other processes is not applied in the textile industry because it still lacks the integration more effectively with sewing workshops to reuse the scraps in the manufacture of products with their seams. The specialist mentioned that this is a very select public that buys textile articles made with scraps, such as bed sheets and bedspreads. Thus, the textile industry prefers to shred the waste and transform it back into cotton and thread for manufacturing in the company itself.

This finding is corroborated by the article by Oliveira Neto et al. [14], which concluded that the reuse of defibrated waste generates relevant economic and environmental gains, besides promoting circularity of more than 95%, denoting the reason why the textile industry prefers the reuse of textile waste internally instead of reusing it in other processes.

After re-spinning, the model discriminant validity was met.

At the end of the software calculation process, it was obtained values of the average variance extracted (AVE) greater than 0.50 (or 50%), indicating that the model meets the criteria of Fornell and Larker [51]. Also, Cronbach's alpha coefficients and Composite Reliability were above 0.70. Similarly, R2 and R2_adj (adjusted) show values considered large [51] (Table 3).

**Table 2.** Indicators of model fit quality.

| Constructs | AVE | Cronbachs alpha | Composite Reliability | R2 | R2_adj | f2 |
|---|---|---|---|---|---|---|
| I4.0T | 0.623 | 0.925 | 0.937 | | | 0.866 |
| SS | 0.732 | 0.926 | 0.942 | 0.658 | 0.654 | |
| CERE | 0.745 | 0.914 | 0.936 | 0.859 | 0.858 | |
| CES | 0.837 | 0.903 | 0.939 | 0.782 | 0.780 | |
| CEO | 0.816 | 0.943 | 0.957 | 0.772 | 0.770 | |
| CEL | 0.709 | 0.897 | 0.924 | 0.687 | 0.684 | |
| CEV | 0.645 | 0.816 | 0.875 | 0.713 | 0.710 | |
| CEE | 0.902 | 0.945 | 0.965 | 0.954 | 0.954 | |
| Valores Referenciais (*) | ≥0.50 | ≥0.70 | ≥0.70 | (**) | $R^2 \approx R^2$adj (***) | (****) |

* Hair et al. [51]. ** For the social and behavioral sciences, R2 = 2% be classified as small effect, R2 = 13% as medium effect and R2 = 26% as large effect [34]. *** R2 adj (adjusted) Should have values close to R2, as this "confirms" the quality of R2 [52]. **** Values of 0.02, 0.15, and 0.35 are considered small, medium, and large [52].

Finally, the effect size (explained by unexplained part—f2 = R2/(1 − R2)) "total" (from TI4—beginning of the model to all other constructs) is greater than 0.35, indicating relevant, i.e., it has great importance for the overall fit and its causal relationships.

Following the model fit, the square roots of the AVEs were calculated and compared with the correlations between the constructs to assess discriminant validity (DV) using the Fornell–Larcker criterion. This procedure is performed because the AVEs are the coefficient of (mean) Pearson determination or the mean squared correlations. Comparing the average correlation of a construct with the correlation with the other constructs assesses the independence of the construct from the others. Thus, to meet this requirement ("DV"), it is expected that the square roots of the AVEs will be higher than the correlations with the other constructs (Table 4).

**Table 3.** Discriminant validity by Fornell–Larcker criterion.

| | I4.0T | SS | CERE | CES | CEO | CEL | CEV | CEE |
|---|---|---|---|---|---|---|---|---|
| **I4.0T** | 0.623 | 0.435 | 0.273 | 0.361 | 0.312 | 0.382 | 0.389 | 0.348 |
| **SS** | 0.435 | 0.732 | 0.474 | 0.498 | 0.440 | 0.448 | 0.470 | 0.612 |
| **CERE** | 0.273 | 0.474 | 0.745 | 0.526 | 0.547 | 0.461 | 0.545 | 0.737 |
| **CES** | 0.361 | 0.498 | 0.526 | 0.837 | 0.395 | 0.400 | 0.546 | 0.679 |
| **CEO** | 0.312 | 0.440 | 0.547 | 0.395 | 0.816 | 0.343 | 0.350 | 0.655 |
| **CEL** | 0.382 | 0.448 | 0.461 | 0.400 | 0.343 | 0.709 | 0.323 | 0.489 |
| **CEV** | 0.389 | 0.470 | 0.545 | 0.546 | 0.350 | 0.323 | 0.645 | 0.649 |
| **CEE** | 0.348 | 0.612 | 0.737 | 0.679 | 0.655 | 0.489 | 0.649 | 0.902 |

Note: on the main diagonal are the square roots of the AVEs (or average correlations between each construct and its measured variables).

The analysis of Table 4 shows that the Fornell–Larcker criterion was met in all correlations, only between CEV, which relates virtualization and CEE and exchange (in gray in Table 4). The relationship gets higher in CEE of 0.003. Since this value is low, the decision was to leave the model without its removals. Also, the Heterotrace–Monotrace matrix was evaluated (Table 5) [53,54]. The non-presence of the value one (1) between the minimum and maximum values of the confidence intervals of the causal relationships also indicates that the model exhibits discriminant validity.

**Table 4.** Factorial loadings or Pearson correlation coefficients (loading) between constructs and their reflective variables.

| Correlations | Loading | Std_err | t_stat * | *p*_Value | CI_95%L ** | CI_95%U ** |
|---|---|---|---|---|---|---|
| I4.0T—T_1 | 0.790 | 0.026 | 30,896 | ≤0.001 | 0.759 | 0.802 |
| I4.0T—T_2 | 0.881 | 0.010 | 84,505 | ≤0.001 | 0.873 | 0.892 |
| I4.0T—T_3 | 0.794 | 0.057 | 13,823 | ≤0.001 | 0.766 | 0.864 |
| I4.0T—T_4 | 0.698 | 0.065 | 10,703 | ≤0.001 | 0.605 | 0.727 |
| I4.0T—T_6 | 0.748 | 0.076 | 9816 | ≤0.001 | 0.707 | 0.851 |
| I4.0T—T_7 | 0.869 | 0.010 | 82,805 | ≤0.001 | 0.812 | 0.831 |
| I4.0T—T_8 | 0.864 | 0.027 | 31,547 | ≤0.001 | 0.832 | 0.884 |
| I4.0T—T_9 | 0.756 | 0.058 | 13,044 | ≤0.001 | 0.758 | 0.854 |
| I4.0T—T_10 | 0.744 | 0.030 | 24,407 | ≤0.001 | 0.719 | 0.770 |
| SS—SS_2 | 0.748 | 0.057 | 13,089 | ≤0.001 | 0.692 | 0.801 |
| SS—SS_3 | 0.849 | 0.067 | 12,602 | ≤0.001 | 0.765 | 0.893 |
| SS—SS_5 | 0.915 | 0.007 | 139,919 | ≤0.001 | 0.919 | 0.930 |
| SS—SS_6 | 0.919 | 0.006 | 163,658 | ≤0.001 | 0.933 | 0.943 |
| SS—SS_7 | 0.870 | 0.008 | 107,912 | ≤0.001 | 0.886 | 0.901 |
| SS—SS_8 | 0.821 | 0.037 | 22,178 | ≤0.001 | 0.783 | 0.850 |
| CERE—CERE_1 | 0.868 | 0.021 | 40,565 | ≤0.001 | 0.844 | 0.883 |
| CERE—CERE_2 | 0.926 | 0.012 | 80,512 | ≤0.001 | 0.922 | 0.944 |
| CERE—CERE_3 | 0.818 | 0.032 | 25,793 | ≤0.001 | 0.790 | 0.844 |
| CERE—CERE_4 | 0.833 | 0.043 | 19,382 | ≤0.001 | 0.752 | 0.827 |
| CERE—CERE_5 | 0.865 | 0.021 | 41,122 | ≤0.001 | 0.823 | 0.863 |
| CES—CES_1 | 0.911 | 0.024 | 37,881 | ≤0.001 | 0.878 | 0.919 |
| CES—CES_2 | 0.916 | 0.008 | 112,024 | ≤0.001 | 0.885 | 0.900 |
| CES—CES_3 | 0.918 | 0.011 | 83,314 | ≤0.001 | 0.908 | 0.926 |
| CEO—CEO_1 | 0.923 | 0.009 | 106,525 | ≤0.001 | 0.918 | 0.934 |
| CEO—CEO_2 | 0.927 | 0.006 | 157,078 | ≤0.001 | 0.933 | 0.944 |
| CEO—CEO_3 | 0.838 | 0.019 | 44,005 | ≤0.001 | 0.843 | 0.879 |
| CEO—CEO_4 | 0.919 | 0.018 | 51,345 | ≤0.001 | 0.910 | 0.944 |
| CEO—CEO_5 | 0.905 | 0.013 | 69,929 | ≤0.001 | 0.914 | 0.938 |
| CEL—CEL_1 | 0.856 | 0.010 | 88,845 | ≤0.001 | 0.850 | 0.868 |
| CEL—CEL_2 | 0.883 | 0.013 | 68,894 | ≤0.001 | 0.884 | 0.908 |
| CEL—CEL_3 | 0.726 | 0.100 | 7267 | ≤0.001 | 0.636 | 0.817 |
| CEL—CEL_4 | 0.856 | 0.028 | 30,052 | ≤0.001 | 0.806 | 0.860 |
| CEL—CEL_5 | 0.879 | 0.021 | 42,738 | ≤0.001 | 0.878 | 0.917 |

**Table 4.** *Cont.*

| Correlations | Loading | Std_err | t_stat * | *p*_Value | CI_95%L ** | CI_95%U ** |
|---|---|---|---|---|---|---|
| CEV—CEV_1 | 0.536 | 0.071 | 7562 | ≤0.001 | 0.450 | 0.584 |
| CEV—CEV_2 | 0.901 | 0.017 | 51,988 | ≤0.001 | 0.881 | 0.911 |
| CEV—CEV_3 | 0.854 | 0.062 | 13,697 | ≤0.001 | 0.754 | 0.871 |
| CEV—CEV_4 | 0.868 | 0.028 | 30,753 | ≤0.001 | 0.844 | 0.896 |
| CEE—CEE_1 | 0.967 | 0.005 | 202,017 | ≤0.001 | 0.960 | 0.969 |
| CEE—CEE_2 | 0.925 | 0.007 | 140,794 | ≤0.001 | 0.927 | 0.939 |
| CEE—CEE_3 | 0.956 | 0.009 | 107,950 | ≤0.001 | 0.944 | 0.960 |

Note: CECP is not shown in the table because it consists of only one "totalizing" variable (CE), which represents the regression line of the CERE, CES, CEO, CEL, CEV, and CEE constructs. * t stat means t-statistic, i.e., the value on the *x*-axis of the Student's *t*-test probability area. The value that determines an area of 5% is 1.96. ** The absence of the zero in the Confidence interval (CI = confidence interval) also indicates the causal relationship is significant ($p < 0.05$).

Furthermore, the factor loadings or correlation of Pearson coefficients (loading) (Table 5) showed high and significant values ($p \leq 0.05$). This fact shows that the model was very well adjusted and that its variables are adequate to evaluate the constructs.

Finally, the analysis of causal relationships indicates that the path coefficients (or angular coefficients of the linear regression lines or betas) have values above 68%.

Table 6 shows the path coefficients to evaluate the hypotheses. With this, H1 was validated, considering that the adoption of I4.0T by large textile industries moderately (0.68) promotes CE at the micro-production level. This finding is justified because despite loadings above 0.70 of I4.0T in the model fit, three of them (additive manufacturing (T_6), Cybersecurity System (T_9), and artificial intelligence (T_10) showed correlation with no variable (Table 7), which directly reflects the lack of use of 3D technology for product development and redesign for resource efficiency (dematerialization) (CEV_1:0.54), which also showed no correlation. Additive manufacturing is not yet planned in textile production but could be applied in the apparel chain to promote personalization and personal style, even if with a higher added value, corroborated by Shirvanimoghaddam et al. [6] and Shayganmehr et al. [13]. While the adoption of the Cibersecuty System and T_5—cloud computing has a high cost, as mentioned earlier, and artificial intelligence consists of a later stage of implementation because, currently, the large textile industry is in the process of analyzing big data and applying machine learning techniques and have not yet applied autonomous systems based on artificial intelligence algorithms. This finding corroborates with Bai et al. [19] and Shayganmehr et al. [13], who identified the most relevant I4.0T for CECP that include Big Data and machine learning, with Cybersecurity and additive manufacturing in less significant positions due to acquisition cost. This result provides the basis for future studies to expand scientific knowledge in this field and enhance existing theoretical models because the incorporation of big data and machine learning in the Brazilian textile industry brings significant advantages. Managers of Brazilian textile companies can benefit from the information in this study when implementing additive manufacturing, Cybersecurity, and artificial intelligence to ensure a comprehensive approach and maximize the transformation potential and competitiveness of the Brazilian textile industry. In addition, the use of these technologies can generate positive impacts on society, such as reducing the consumption of natural resources, improving working conditions, producing more sustainable products, and promoting economic growth.

**Table 5.** Path coefficients (or angular coefficients of the linear regression lines.

| Causal Relation | Path Coefficients | Std_err | t_stat * | *p*_Value | CI_95%L ** | CI95%U ** |
|---|---|---|---|---|---|---|
| I4.0T-H1-> CECP | 0.68 | 0.02 | 42.72 | <0.001 | 0.68 | 0.71 |
| CECP-H2-> SS | 0.43 | 0.02 | 35.17 | <0.001 | 0.77 | 0.82 |
| CECP --> CERE | 0.93 | 0.00 | 266.75 | <0.001 | 0.90 | 0.90 |
| CECP --> CES | 0.88 | 0.01 | 105.26 | <0.001 | 0.87 | 0.89 |
| CECP --> CEO | 0.88 | 0.03 | 30.01 | <0.001 | 0.84 | 0.89 |
| CECP --> CEL | 0.83 | 0.01 | 83.16 | <0.001 | 0.80 | 0.82 |
| CECP --> CEV | 0.84 | 0.03 | 25.78 | <0.001 | 0.78 | 0.83 |
| CECP --> CEE | 0.98 | 0.01 | 100.06 | <0.001 | 0.93 | 0.95 |

Note: CECP indicates a second-order construct formed by obtaining the regression line of the CERE, CES, CEO, CEL, CEV, and CEE constructs, calculated with single factor (score creation) and varimax rotation. FIElD et al. [55] indicate using the "psych" package of the R project with forced single factor. This way, they develop a new variable that "represents all the factors since the software does not present the fit indicators for the relationships between first-order constructs with a second-order construct (consisting of first-order constructs). * t stat means t-statistic, that is, the value on the *x*-axis of the probability area of Student's *t*-test. The value that determines an area of 5% is 1.96. ** The absence of the zero in the Confidence interval (CI) also indicates the causal relationship is significant ($p < 0.05$). The non-inclusion of number one (1) indicates that the HTMT matrix (Heterotrace–Monotrace matrix) again confirms the discriminant validity of the model.

And other three technologies showed correlation with at most two variables, which are Simulation (T_3:0.73), IoT (T_4:0.69), and Cyberphysical System (T_8:0.86), denoting early stage of deployment in the textile industry because it is still little deployed Cyberphysical System to promote CE, which includes sensors and actuators, which are simpler technologies used in automation processes. In addition to low deployment with a focus on IoT CE, a primary aspect for managers is to use embedded technology for data-driven decision-making. Also, simulation is still little used to stimulate CE in production, denoting the low number of correlations; it only stimulated emission level reduction/elimination (CEO_5:0.90) but limited renewable resource consumption to its regeneration rate (SS_2:0.50) and reduced greenhouse gas emissions (SS_3:0.51). However, this finding is different from that found in the literature, denoting that there is potential for textile companies to leverage the use of simulation, IoT, and Cyberphysical Systems targeting economic and environmental gains provided by CECP practices, as was identified in the research of Shayganmehr et al. [13], Alcayaga et al. [30], and Bai et al. [19]. Thus, for future studies, it is important to study the application of simulation, IoT, and Cyberphysical Systems in the context of Brazilian textile industries. The practical contribution is to stimulate managers to explore the potential of IoT, simulation, and Cyberphysical Systems aimed at CECP practices, resulting in SS actions. Furthermore, the implementation of these technologies can generate qualified employment opportunities and boost the technological and economic development of the country.

**Table 6.** Correlation between each I4.0T, SS, and CECP action.

| T1 | CERE_1 | CERE_2 | CERE_3 | CERE_4 | CERE_5 | CES_1 | CES_2 | CES_3 | CEO_1 | CEO_2 | CEO_3 | CEO_4 | CEO_5 | CEL_1 | CEL_2 | CEL_3 | CEL_4 | CEL_5 | CEV_1 | CEV_2 | CEV_3 | CEV_4 | CEE_1 | CEE_2 | CEE_3 | Higher number |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SS_2 | 0.39 | 0.45 | 0.24 | 0.34 | 0.48 | 0.43 | 0.47 | 0.38 | 0.48 | 0.42 | 0.27 | 0.43 | 0.48 | 0.52 | 0.41 | 0.27 | 0.37 | 0.46 | 0.20 | 0.43 | 0.22 | 0.43 | 0.49 | 0.45 | 0.47 | 0.52 |
| SS_3 | 0.39 | 0.45 | 0.24 | 0.34 | 0.49 | 0.43 | 0.48 | 0.38 | 0.49 | 0.42 | 0.28 | 0.43 | 0.49 | 0.52 | 0.42 | 0.27 | 0.37 | 0.46 | 0.20 | 0.43 | 0.22 | 0.43 | 0.50 | 0.46 | 0.48 | 0.52 |
| SS_5 | 0.40 | 0.47 | 0.24 | 0.35 | 0.50 | 0.44 | 0.49 | 0.39 | 0.50 | 0.44 | 0.28 | 0.45 | 0.50 | 0.54 | 0.44 | 0.27 | 0.38 | 0.48 | 0.20 | 0.44 | 0.22 | 0.45 | 0.51 | 0.47 | 0.49 | 0.54 |
| SS_6 | 0.38 | 0.44 | 0.23 | 0.33 | 0.48 | 0.42 | 0.47 | 0.38 | 0.48 | 0.41 | 0.27 | 0.42 | 0.48 | 0.51 | 0.41 | 0.26 | 0.37 | 0.45 | 0.19 | 0.42 | 0.22 | 0.42 | 0.49 | 0.45 | 0.47 | 0.51 |
| SS_7 | 0.34 | 0.39 | 0.21 | 0.30 | 0.42 | 0.37 | 0.41 | 0.33 | 0.42 | 0.36 | 0.24 | 0.37 | 0.42 | 0.36 | 0.44 | 0.24 | 0.32 | 0.39 | 0.18 | 0.37 | 0.20 | 0.37 | 0.42 | 0.39 | 0.41 | 0.44 |
| SS_8 | 0.34 | 0.39 | 0.21 | 0.29 | 0.41 | 0.37 | 0.41 | 0.33 | 0.41 | 0.36 | 0.24 | 0.37 | 0.41 | 0.36 | 0.44 | 0.24 | 0.32 | 0.39 | 0.18 | 0.37 | 0.20 | 0.37 | 0.42 | 0.39 | 0.41 | 0.44 |
| T2 | CERE_1 | CERE_2 | CERE_3 | CERE_4 | CERE_5 | CES_1 | CES_2 | CES_3 | CEO_1 | 0.47 | CEO_3 | CEO_4 | CEO_5 | CEL_1 | CEL_2 | CEL_3 | CEL_4 | CEL_5 | CEV_1 | CEV_2 | CEV_3 | CEV_4 | CEE_1 | CEE_2 | CEE_3 | Higher number |
| SS_2 | 0.53 | 0.65 | 0.42 | 0.55 | 0.40 | 0.45 | 0.47 | 0.42 | 0.45 | 0.47 | 0.44 | 0.55 | 0.46 | 0.57 | 0.41 | 0.51 | 0.54 | 0.55 | 0.31 | 0.40 | 0.37 | 0.44 | 0.43 | 0.49 | 0.43 | 0.65 |
| SS_3 | 0.43 | 0.43 | 0.35 | 0.29 | 0.40 | 0.42 | 0.46 | 0.42 | 0.41 | 0.47 | 0.36 | 0.45 | 0.54 | 0.47 | 0.49 | 0.34 | 0.36 | 0.45 | 0.26 | 0.43 | 0.31 | 0.46 | 0.41 | 0.48 | 0.41 | 0.54 |
| SS_5 | 0.49 | 0.40 | 0.59 | 0.32 | 0.57 | 0.47 | 0.42 | 0.48 | 0.48 | 0.43 | 0.51 | 0.41 | 0.41 | 0.43 | 0.46 | 0.38 | 0.41 | 0.41 | 0.29 | 0.40 | 0.35 | 0.42 | 0.48 | 0.44 | 0.48 | 0.59 |
| SS_6 | 0.46 | 0.56 | 0.37 | 0.31 | 0.43 | 0.44 | 0.49 | 0.45 | 0.44 | 0.50 | 0.38 | 0.48 | 0.41 | 0.49 | 0.42 | 0.36 | 0.39 | 0.48 | 0.28 | 0.46 | 0.33 | 0.49 | 0.44 | 0.41 | 0.44 | 0.56 |
| SS_7 | 0.41 | 0.40 | 0.33 | 0.28 | 0.47 | 0.39 | 0.44 | 0.40 | 0.48 | 0.44 | 0.34 | 0.42 | 0.41 | 0.44 | 0.46 | 0.32 | 0.35 | 0.43 | 0.25 | 0.32 | 0.30 | 0.44 | 0.48 | 0.45 | 0.48 | 0.48 |
| SS_8 | 0.54 | 0.54 | 0.36 | 0.30 | 0.41 | 0.43 | 0.47 | 0.43 | 0.42 | 0.58 | 0.37 | 0.46 | 0.55 | 0.51 | 0.40 | 0.35 | 0.37 | 0.50 | 0.27 | 0.44 | 0.32 | 0.47 | 0.42 | 0.49 | 0.42 | 0.58 |
| T3 | CERE_1 | CERE_2 | CERE_3 | CERE_4 | CERE_5 | CES_1 | CES_2 | CES_3 | CEO_1 | CEO_2 | CEO_3 | CEO_4 | CEO_5 | CEL_1 | CEL_2 | CEL_3 | CEL_4 | CEL_5 | CEV_1 | CEV_2 | CEV_3 | CEV_4 | CEE_1 | CEE_2 | CEE_3 | Higher number |
| SS_2 | 0.28 | 0.31 | 0.18 | 0.24 | 0.28 | 0.31 | 0.32 | 0.33 | 0.37 | 0.27 | 0.22 | 0.29 | 0.50 | 0.25 | 0.32 | 0.16 | 0.28 | 0.35 | 0.22 | 0.34 | 0.27 | 0.29 | 0.31 | 0.25 | 0.30 | 0.50 |
| SS_3 | 0.27 | 0.30 | 0.18 | 0.24 | 0.28 | 0.30 | 0.31 | 0.32 | 0.36 | 0.27 | 0.21 | 0.28 | 0.51 | 0.25 | 0.31 | 0.16 | 0.27 | 0.34 | 0.22 | 0.33 | 0.26 | 0.28 | 0.30 | 0.25 | 0.30 | 0.51 |
| SS_5 | 0.21 | 0.23 | 0.15 | 0.19 | 0.22 | 0.23 | 0.24 | 0.24 | 0.27 | 0.21 | 0.17 | 0.22 | 0.31 | 0.20 | 0.24 | 0.14 | 0.21 | 0.26 | 0.18 | 0.25 | 0.21 | 0.22 | 0.23 | 0.20 | 0.23 | 0.31 |
| SS_6 | 0.24 | 0.26 | 0.16 | 0.21 | 0.24 | 0.26 | 0.27 | 0.28 | 0.31 | 0.24 | 0.19 | 0.25 | 0.36 | 0.22 | 0.27 | 0.15 | 0.24 | 0.29 | 0.19 | 0.29 | 0.23 | 0.25 | 0.26 | 0.22 | 0.26 | 0.36 |
| SS_7 | 0.22 | 0.24 | 0.15 | 0.19 | 0.22 | 0.24 | 0.25 | 0.25 | 0.28 | 0.22 | 0.18 | 0.23 | 0.32 | 0.20 | 0.24 | 0.14 | 0.22 | 0.26 | 0.18 | 0.26 | 0.21 | 0.23 | 0.24 | 0.20 | 0.23 | 0.32 |
| SS_8 | 0.23 | 0.25 | 0.16 | 0.20 | 0.24 | 0.25 | 0.26 | 0.27 | 0.30 | 0.23 | 0.19 | 0.24 | 0.35 | 0.21 | 0.26 | 0.15 | 0.23 | 0.28 | 0.19 | 0.28 | 0.22 | 0.24 | 0.26 | 0.21 | 0.25 | 0.35 |
| T4 | CERE_1 | CERE_2 | CERE_3 | CERE_4 | CERE_5 | CES_1 | CES_2 | CES_3 | CEO_1 | CEO_2 | CEO_3 | CEO_4 | CEO_5 | CEL_1 | CEL_2 | CEL_3 | CEL_4 | CEL_5 | CEV_1 | CEV_2 | CEV_3 | CEV_4 | CEE_1 | CEE_2 | CEE_3 | Higher number |
| SS_2 | 0.24 | 0.33 | 0.17 | 0.16 | 0.28 | 0.37 | 0.36 | 0.42 | 0.32 | 0.22 | 0.07 | 0.22 | 0.30 | 0.31 | 0.25 | 0.30 | 0.37 | 0.32 | 0.47 | 0.36 | 0.29 | 0.51 | 0.37 | 0.25 | 0.41 | 0.51 |
| SS_3 | 0.19 | 0.24 | 0.14 | 0.14 | 0.21 | 0.27 | 0.26 | 0.29 | 0.24 | 0.18 | 0.08 | 0.17 | 0.22 | 0.23 | 0.19 | 0.22 | 0.27 | 0.23 | 0.33 | 0.26 | 0.22 | 0.35 | 0.27 | 0.19 | 0.29 | 0.35 |
| SS_5 | 0.18 | 0.22 | 0.14 | 0.13 | 0.19 | 0.24 | 0.24 | 0.27 | 0.22 | 0.17 | 0.08 | 0.16 | 0.21 | 0.21 | 0.18 | 0.21 | 0.24 | 0.22 | 0.30 | 0.24 | 0.20 | 0.32 | 0.25 | 0.18 | 0.26 | 0.32 |
| SS_6 | 0.17 | 0.22 | 0.14 | 0.13 | 0.19 | 0.24 | 0.23 | 0.26 | 0.21 | 0.16 | 0.08 | 0.16 | 0.20 | 0.21 | 0.18 | 0.20 | 0.24 | 0.21 | 0.29 | 0.23 | 0.20 | 0.31 | 0.24 | 0.18 | 0.26 | 0.31 |
| SS_7 | 0.15 | 0.19 | 0.13 | 0.12 | 0.17 | 0.20 | 0.20 | 0.22 | 0.18 | 0.15 | 0.09 | 0.14 | 0.18 | 0.18 | 0.16 | 0.18 | 0.20 | 0.18 | 0.24 | 0.20 | 0.17 | 0.25 | 0.20 | 0.16 | 0.22 | 0.25 |
| SS_8 | 0.21 | 0.27 | 0.15 | 0.14 | 0.23 | 0.30 | 0.29 | 0.33 | 0.26 | 0.19 | 0.08 | 0.19 | 0.25 | 0.26 | 0.21 | 0.25 | 0.30 | 0.26 | 0.37 | 0.29 | 0.24 | 0.40 | 0.30 | 0.21 | 0.33 | 0.40 |
| T6 | CERE_1 | CERE_2 | CERE_3 | CERE_4 | CERE_5 | CES_1 | CES_2 | CES_3 | CEO_1 | CEO_2 | CEO_3 | CEO_4 | CEO_5 | CEL_1 | CEL_2 | CEL_3 | CEL_4 | CEL_5 | CEV_1 | CEV_2 | CEV_3 | CEV_4 | CEE_1 | CEE_2 | CEE_3 | Higher number |
| SS_2 | 0.25 | 0.24 | 0.16 | 0.15 | 0.21 | 0.25 | 0.25 | 0.27 | 0.27 | 0.19 | 0.12 | 0.21 | 0.24 | 0.17 | 0.22 | 0.17 | 0.23 | 0.25 | 0.25 | 0.27 | 0.21 | 0.25 | 0.24 | 0.21 | 0.26 | 0.27 |
| SS_3 | 0.20 | 0.19 | 0.14 | 0.13 | 0.17 | 0.20 | 0.20 | 0.21 | 0.21 | 0.16 | 0.12 | 0.17 | 0.19 | 0.14 | 0.18 | 0.14 | 0.18 | 0.20 | 0.20 | 0.21 | 0.17 | 0.20 | 0.19 | 0.17 | 0.21 | 0.21 |
| SS_5 | 0.16 | 0.15 | 0.12 | 0.12 | 0.14 | 0.16 | 0.15 | 0.16 | 0.17 | 0.13 | 0.11 | 0.14 | 0.15 | 0.12 | 0.15 | 0.12 | 0.15 | 0.16 | 0.16 | 0.16 | 0.14 | 0.16 | 0.15 | 0.14 | 0.16 | 0.17 |
| SS_6 | 0.21 | 0.20 | 0.14 | 0.13 | 0.17 | 0.21 | 0.20 | 0.22 | 0.22 | 0.16 | 0.12 | 0.18 | 0.20 | 0.15 | 0.19 | 0.15 | 0.19 | 0.20 | 0.20 | 0.22 | 0.18 | 0.21 | 0.20 | 0.18 | 0.21 | 0.22 |
| SS_7 | 0.24 | 0.23 | 0.16 | 0.14 | 0.20 | 0.24 | 0.24 | 0.26 | 0.26 | 0.18 | 0.12 | 0.20 | 0.23 | 0.16 | 0.22 | 0.16 | 0.22 | 0.24 | 0.24 | 0.26 | 0.20 | 0.24 | 0.23 | 0.20 | 0.25 | 0.26 |
| SS_8 | 0.23 | 0.22 | 0.16 | 0.14 | 0.19 | 0.24 | 0.23 | 0.25 | 0.25 | 0.18 | 0.12 | 0.20 | 0.22 | 0.16 | 0.21 | 0.16 | 0.21 | 0.23 | 0.23 | 0.25 | 0.20 | 0.24 | 0.22 | 0.20 | 0.24 | 0.25 |

**Table 6.** *Cont.*

| **T7** | CERE_1 | CERE_2 | CERE_3 | CERE_4 | CERE_5 | CES_1 | CES_2 | CES_3 | CEO_1 | CEO_2 | CEO_3 | CEO_4 | CEO_5 | CEL_1 | CEL_2 | CEL_3 | CEL_4 | CEL_5 | CEV_1 | CEV_2 | CEV_3 | CEV_4 | CEE_1 | CEE_2 | CEE_3 | Higher number |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| SS_2 | 0.42 | 0.49 | 0.37 | 0.42 | 0.43 | **0.58** | 0.44 | 0.42 | **0.61** | 0.48 | 0.33 | 0.47 | 0.40 | 0.42 | 0.49 | 0.33 | 0.42 | **0.61** | 0.49 | **0.59** | 0.35 | **0.51** | **0.55** | 0.44 | **0.54** | 0.61 |
| SS_3 | 0.47 | 0.44 | 0.34 | 0.38 | 0.48 | 0.43 | 0.49 | 0.47 | 0.46 | 0.44 | 0.31 | 0.43 | 0.44 | 0.48 | 0.43 | 0.31 | 0.47 | **0.55** | 0.28 | 0.43 | 0.32 | 0.46 | 0.40 | 0.49 | 0.49 | 0.55 |
| SS_5 | 0.49 | 0.45 | 0.35 | 0.39 | 0.49 | 0.45 | 0.41 | 0.49 | **0.58** | 0.45 | 0.32 | 0.45 | 0.46 | 0.49 | 0.45 | 0.32 | 0.49 | 0.47 | 0.28 | 0.45 | 0.33 | 0.48 | 0.42 | **0.50** | 0.41 | 0.58 |
| SS_6 | 0.42 | 0.49 | 0.37 | 0.42 | 0.44 | 0.49 | 0.44 | 0.42 | 0.42 | 0.48 | 0.33 | 0.47 | 0.47 | 0.42 | 0.39 | 0.33 | 0.42 | 0.44 | 0.30 | 0.49 | 0.35 | 0.41 | **0.55** | 0.44 | 0.44 | 0.55 |
| SS_7 | 0.40 | 0.46 | 0.35 | 0.40 | 0.30 | 0.46 | 0.42 | 0.30 | 0.48 | 0.46 | 0.32 | 0.45 | 0.48 | 0.40 | 0.36 | 0.32 | 0.49 | 0.48 | 0.29 | 0.46 | 0.33 | 0.48 | 0.42 | 0.41 | 0.42 | 0.49 |
| SS_8 | 0.43 | 0.48 | 0.31 | 0.35 | 0.43 | 0.48 | 0.44 | 0.43 | 0.40 | 0.40 | 0.28 | 0.39 | 0.49 | 0.43 | 0.48 | 0.28 | 0.42 | 0.45 | 0.25 | 0.48 | 0.29 | 0.42 | 0.45 | 0.44 | 0.44 | 0.49 |
| **T8** | CERE_1 | CERE_2 | CERE_3 | CERE_4 | CERE_5 | CES_1 | CES_2 | CES_3 | CEO_1 | CEO_2 | CEO_3 | CEO_4 | CEO_5 | CEL_1 | CEL_2 | CEL_3 | CEL_4 | CEL_5 | CEV_1 | CEV_2 | CEV_3 | CEV_4 | CEE_1 | CEE_2 | CEE_3 | Higher number |
| SS_2 | 0.37 | 0.41 | 0.24 | 0.25 | 0.41 | 0.44 | 0.37 | 0.29 | 0.43 | 0.31 | 0.13 | 0.31 | 0.41 | 0.42 | 0.39 | 0.22 | 0.35 | 0.45 | 0.37 | 0.46 | 0.37 | **0.54** | 0.42 | 0.38 | 0.38 | 0.54 |
| SS_3 | 0.32 | 0.35 | 0.22 | 0.22 | 0.36 | 0.38 | 0.32 | 0.26 | 0.37 | 0.27 | 0.12 | 0.27 | 0.35 | 0.37 | 0.34 | 0.20 | 0.30 | 0.39 | 0.32 | 0.39 | 0.32 | **0.57** | 0.37 | 0.33 | 0.33 | 0.57 |
| SS_5 | 0.28 | 0.31 | 0.19 | 0.20 | 0.31 | 0.32 | 0.28 | 0.23 | 0.32 | 0.24 | 0.12 | 0.24 | 0.31 | 0.32 | 0.29 | 0.18 | 0.27 | 0.33 | 0.28 | 0.34 | 0.28 | 0.39 | 0.32 | 0.29 | 0.29 | 0.39 |
| SS_6 | 0.29 | 0.32 | 0.20 | 0.21 | 0.32 | 0.34 | 0.30 | 0.24 | 0.34 | 0.25 | 0.12 | 0.25 | 0.32 | 0.33 | 0.31 | 0.18 | 0.28 | 0.35 | 0.29 | 0.35 | 0.29 | 0.42 | 0.33 | 0.30 | 0.30 | 0.42 |
| SS_7 | 0.24 | 0.26 | 0.17 | 0.18 | 0.27 | 0.28 | 0.24 | 0.20 | 0.28 | 0.21 | 0.12 | 0.21 | 0.26 | 0.27 | 0.25 | 0.16 | 0.23 | 0.28 | 0.24 | 0.29 | 0.24 | 0.33 | 0.27 | 0.25 | 0.25 | 0.33 |
| SS_8 | 0.23 | 0.25 | 0.17 | 0.17 | 0.25 | 0.26 | 0.23 | 0.19 | 0.26 | 0.20 | 0.11 | 0.20 | 0.25 | 0.25 | 0.24 | 0.16 | 0.22 | 0.27 | 0.23 | 0.27 | 0.23 | 0.31 | 0.25 | 0.23 | 0.24 | 0.31 |
| **T9** | CERE_1 | CERE_2 | CERE_3 | CERE_4 | CERE_5 | CES_1 | CES_2 | CES_3 | CEO_1 | CEO_2 | CEO_3 | CEO_4 | CEO_5 | CEL_1 | CEL_2 | CEL_3 | CEL_4 | CEL_5 | CEV_1 | CEV_2 | CEV_3 | CEV_4 | CEE_1 | CEE_2 | CEE_3 | Higher number |
| SS_2 | 0.24 | 0.23 | 0.18 | 0.25 | 0.23 | 0.30 | 0.23 | 0.17 | 0.30 | 0.16 | 0.11 | 0.21 | 0.36 | 0.21 | 0.29 | 0.10 | 0.28 | 0.38 | 0.17 | 0.30 | 0.25 | 0.30 | 0.27 | 0.20 | 0.23 | 0.38 |
| SS_3 | 0.22 | 0.22 | 0.17 | 0.23 | 0.21 | 0.28 | 0.21 | 0.16 | 0.27 | 0.15 | 0.11 | 0.19 | 0.32 | 0.20 | 0.26 | 0.10 | 0.25 | 0.34 | 0.16 | 0.28 | 0.22 | 0.27 | 0.24 | 0.19 | 0.21 | 0.34 |
| SS_5 | 0.17 | 0.17 | 0.14 | 0.18 | 0.16 | 0.20 | 0.16 | 0.14 | 0.20 | 0.13 | 0.11 | 0.15 | 0.23 | 0.16 | 0.20 | 0.10 | 0.19 | 0.24 | 0.13 | 0.20 | 0.17 | 0.20 | 0.18 | 0.15 | 0.16 | 0.24 |
| SS_6 | 0.20 | 0.19 | 0.16 | 0.20 | 0.19 | 0.24 | 0.19 | 0.15 | 0.24 | 0.14 | 0.11 | 0.17 | 0.27 | 0.18 | 0.23 | 0.10 | 0.22 | 0.29 | 0.14 | 0.24 | 0.20 | 0.23 | 0.21 | 0.17 | 0.19 | 0.29 |
| SS_7 | 0.18 | 0.17 | 0.15 | 0.18 | 0.17 | 0.21 | 0.17 | 0.14 | 0.21 | 0.13 | 0.11 | 0.16 | 0.24 | 0.16 | 0.20 | 0.10 | 0.19 | 0.25 | 0.13 | 0.21 | 0.18 | 0.21 | 0.19 | 0.16 | 0.17 | 0.25 |
| SS_8 | 0.16 | 0.16 | 0.13 | 0.16 | 0.15 | 0.18 | 0.15 | 0.13 | 0.18 | 0.13 | 0.11 | 0.14 | 0.21 | 0.15 | 0.18 | 0.10 | 0.17 | 0.22 | 0.13 | 0.18 | 0.16 | 0.18 | 0.17 | 0.14 | 0.15 | 0.22 |
| **T10** | CERE_1 | CERE_2 | CERE_3 | CERE_4 | CERE_5 | CES_1 | CES_2 | CES_3 | CEO_1 | CEO_2 | CEO_3 | CEO_4 | CEO_5 | CEL_1 | CEL_2 | CEL_3 | CEL_4 | CEL_5 | CEV_1 | CEV_2 | CEV_3 | CEV_4 | CEE_1 | CEE_2 | CEE_3 | Higher number |
| SS_2 | 0.26 | 0.28 | 0.17 | 0.24 | 0.26 | 0.34 | 0.33 | 0.33 | 0.31 | 0.26 | 0.13 | 0.26 | 0.27 | 0.23 | 0.26 | 0.16 | 0.24 | 0.36 | 0.27 | 0.29 | 0.22 | 0.33 | 0.31 | 0.25 | 0.30 | 0.36 |
| SS_3 | 0.22 | 0.25 | 0.16 | 0.21 | 0.23 | 0.29 | 0.29 | 0.28 | 0.27 | 0.23 | 0.13 | 0.23 | 0.24 | 0.21 | 0.23 | 0.15 | 0.22 | 0.31 | 0.24 | 0.25 | 0.19 | 0.28 | 0.27 | 0.22 | 0.26 | 0.31 |
| SS_5 | 0.23 | 0.25 | 0.16 | 0.21 | 0.23 | 0.30 | 0.29 | 0.28 | 0.27 | 0.23 | 0.13 | 0.23 | 0.24 | 0.21 | 0.23 | 0.15 | 0.22 | 0.31 | 0.24 | 0.25 | 0.19 | 0.28 | 0.27 | 0.22 | 0.26 | 0.31 |
| SS_6 | 0.26 | 0.29 | 0.17 | 0.24 | 0.27 | 0.35 | 0.34 | 0.33 | 0.31 | 0.27 | 0.13 | 0.26 | 0.28 | 0.24 | 0.26 | 0.16 | 0.25 | 0.36 | 0.28 | 0.30 | 0.22 | 0.33 | 0.31 | 0.26 | 0.31 | 0.36 |
| SS_7 | 0.26 | 0.29 | 0.17 | 0.24 | 0.26 | 0.34 | 0.33 | 0.33 | 0.31 | 0.27 | 0.13 | 0.26 | 0.27 | 0.24 | 0.26 | 0.16 | 0.25 | 0.36 | 0.27 | 0.29 | 0.22 | 0.33 | 0.31 | 0.26 | 0.30 | 0.36 |
| SS_8 | 0.24 | 0.27 | 0.16 | 0.23 | 0.25 | 0.32 | 0.31 | 0.31 | 0.29 | 0.25 | 0.13 | 0.25 | 0.26 | 0.22 | 0.25 | 0.15 | 0.23 | 0.34 | 0.26 | 0.28 | 0.21 | 0.31 | 0.29 | 0.24 | 0.28 | 0.34 |

Summarizing only three (30% of I4.0T) showed correlation with several variables, considering autonomous robots (T_2:0.88), augmented reality (T_7:0.80), and big data analytics (T_1:0.79). The adoption of autonomous robots positively influences the ability to operate independently by performing specific tasks, such as material handling, waste collection, sorting, and recycling, in a precise manner. This finding corroborates Alcayaga et al. [30], who indicated the use of robots in textile remanufacturing processes. Also, augmented reality has been used in the textile industry in Brazil in the design review of production processes and product prototypes and in employee training and capacity building. Larsson [17] corroborates the use of augmented reality to attract customers to redesign clothes instead of buying new ones. However, Bai et al. [19] mention that the application of augmented reality in the textile industry is understated. In this sense, this controversy indicates the opportunity for confirmatory research on this topic. In addition, big data analytics has been increased in the textile industry located in Brazil to collect, analyze and interpret data for more assertive decision-making in intelligent strategies. Chen et al. [27] indicated the use of big data analytics to define green chemistry strategies in the textile industry. Importantly, the number of textile industries located in Brazil that use autonomous robots, augmented reality, and big data is growing, denoting contribution to the theory. In practical terms, this study can encourage managers to consider the economic gains obtained through CECP practices in feasibility studies of the acquisition of I4.0T, despite the investment cost, the need to restructure production processes and personnel training. For society, this study shows technological advances that reduce environmental impact and risk to human health.

Also, it was found that the CECP actions present in large textile industries located in Brazil, resulting from the adoption of I4.0T, generated weak SS (H2:0.43). This result can be explained because two important variables (SS_1—increased efficiency in the consumption of resources and SS_4—reuse of waste as inputs in other processes) were excluded in the model adjustment, mainly because the large textile industries located in Brazil have an old manufacturing park, which makes it very difficult to optimize production resources and interact little with external companies to produce products with the remnants of fabrics, preferring to shred and transform into cotton again for manufacturing. This finding agrees with Larsson [17], who emphasized the need for textile chains to raise resource use efficiency, and Silva and Morais [15], who revealed the need to seek sustainable alternatives to cotton in Brazil. In this sense, the opportunity arises for studies to propose the use of I4.0T that optimize resources and promote the reuse of waste as inputs, aiming to increase SS, an important aspect for organizational practice as well, in addition to stimulating the awareness of society, the development of policies and the adoption of sustainable practices in industries.

Although the other variables of SS present loading above 0.74 in the adjusted model it cannot be considered SS because all these variables should have been supported, as guided by Oliveira Neto et al. [21]. Thus, the results are limited to consuming renewable resources (energy and materials), reducing greenhouse gas emissions, replacing hazardous products with organic ones, and increasing access to basic products to reduce hunger to promote sustainable manufacturing. Table 7 shows the Pearson correlation that details the correlations of each technology in relation to the actions of CECP and SS, making it possible to explain the results.

It was found that the most relevant I4.0T are autonomous robots (T_2:0.88) that drove 14 CECP actions, augmented reality (T_7:0.86), promoting 8 CECP and Cyberphysical System (T_8:0.86), generating 1 CECP.

With the implementation of autonomous robots in textile production, it began to reduce/eliminate waste generation (CEO_4), as well as recycle and reuse waste from textile articles and packaging (CEL_1, CEL_4), including the adoption of the tracking system of post-consumer textile waste at the end of useful life (CEL_3, CERE_4) with the use of reverse logistics (CEL_5). Thus, the textile industry started using reusable, recyclable, and biodegradable products, improving product quality (CERE_1), limiting resource use, and promoting regeneration (SS_2), contributing to sustainable manufacturing (SS_8). Oliveira Neto et al. [14] stated that autonomous robot contributes to the resilience of textile companies in the use of water, raw material, and input in sorting material for recycling, as well as improving working conditions. Also, Shayganmehr et al. [13] indicated that the use of this technology in the textile sector contributes to the achievement of sustainable manufacturing goals.

It was also found that the adoption of autonomous robots in the effluent treatment system is able to extract polluting residues from the water used in the finishing, dyeing, or washing process to promote closed cycle (CERE_3), optimizing water consumption (CEO_3), as well as using natural dye instead of chemical (CERE-5). Through this, it contributed to SS_5 by replacing toxic inputs with organic materials, contributing to sustainable manufacturing (SS_8). Bai et al. [19] mentioned that autonomous robots contribute to reducing the impact on effluents and waste generation, which reduces environmental impact and improves the livelihoods of farmers, which causes a positive socioeconomic impact.

Another finding is that the autonomous robot optimized energy consumption in the textile manufacturing process (CEO_2), including using renewable energy or cogenerating energy (CERE_2), replaces non-renewable energy resources with renewable alternatives (SS_6), favoring sustainable manufacturing (SS_8). Bai et al. [19] and Shayganmehr et al. [13] indicated that autonomous robot improves manufacturing performance through energy recovery. In addition, autonomous robots in textile production reduce emission levels (CEO_5), reduce greenhouse gas emissions (SS_3), and have a positive effect on reducing air pollution in the local community (SS_8). Oliveira Neto et al. [14] mentioned that autonomous robot also contributes to the high degree of resilience of companies in reducing the emission of pollutant gases.

Thus, this study sheds theoretical light to the knowledge about the relationship between autonomous robots and CECP practices, mainly focused on looping, optimizing, and regenerating the SS actions of replacing non-renewable sources of resources, reducing pollutant gases emission, and promoting sustainable manufacturing. Also, these findings may stimulate managers to adopt autonomous robots, as well as help overcome the acceptance barrier of this technology by machine operators, who see the robot as a threat to their jobs.

With the adoption of augmented reality, the large textile industry has created a department to design new business models for the recovery, reuse, and recycling of textile waste (CES_1), including in the creation process, without the need to develop physical prototypes, using only virtual data. Thus, it uses design for the virtual environment for the development or/and redesign of products and packaging, increasing durability and eliminating the use of toxic substances in the product and production system (CEO_1). It integrates suppliers for developing and selecting renewable and recyclable materials (CEE_3), substituting hazardous materials (CEE_2) and limiting the consumption of renewable resources to their regeneration rate (SS_2), as well as substituting toxic inputs for organic materials in product development (SS_5).

The use of augmented reality in manufacturing by the large textile industry has also directed efforts to online support services for machinery and equipment maintenance (CEV_4), as well as for virtualization of textile articles for customers (CEV_2). It is noteworthy that the development of textile articles based on the design for the virtual environment applied in product development and redesign allows the integration of augmented reality for virtual sales catalogs to customers. With this, it contributed to SS because it limits resource consumption by using virtualization, promoting system regeneration (SS_2).

Also, using augmented reality in product/production design replaced inputs (raw materials, water, and or energy) to increase the share of renewable and recyclable resources (CEE_1), generating a reduction in the consumption of non-renewable resources (SS_2), as well as replacing non-renewable energy resources with renewable alternatives (SS_6). Larsson [17] indicated that augmented reality was applied in a project supporting sustainable development in apparel value chains without extracting virgin natural resources or using toxic products, as well as showed weak evidence of virtualization.

No study was identified that confirms or shows a robust case study on the adoption of augmented reality in the textile industry, especially with a focus on CECP and SS. Thus, this study is the first to confirmatively emphasize that augmented reality is a facilitator of optimization, sharing, virtualization, and exchanges in the textile industry. With this, it is an important result and can shed light on future research. In this context, the implementation of augmented reality generates a high investment, but this study, in view of the gains with sustainability, can create incentives for its adoption. Additionally, promoting knowledge of services and products that improve the well-being of people to society.

The application of big data was important for the design of the environment in the development or/and redesign of the product/production and packaging aiming at recycling, repair, remanufacturing, maintenance, as well as developing new features for durable products and eliminating the use of toxic substances (CEO_1), changing to organic materials, for example, using natural paint extracted from waste from other manufacturing processes (artichoke) instead of using chemical dye (CERE_5, SS_5). The studies by Bai et al. [19] and Fatimah et al. [23] stated that big data technology enabled the reduction of toxic materials and less impact on effluents and waste, but without deep exploration, principally with the lens of SS.

Also, with big data analytics, it was possible to promote the recycling of monomers, oligomers, polymers, fibers, and fabrics (CEL_1), in addition to replacing production inputs (raw material, water and/or energy) to increase the share of renewable and recyclable resources (CEE_1) and used by-products from other processes for manufacturing (CERE_5), reducing emissions (CEO_5). In doing so, it limited the consumption of non-renewable resources (SS_2), replaced non-renewable energy resources with renewable alternatives (SS_6), reduced greenhouse gas emissions (SS_3), and replaced toxic inputs with organic ones (SS_5). Angelis and Feola [22] indicate that big data supported the production of dye pigments from by-products of various local, rapidly regenerating crops such as onion husks, artichoke leaves, walnut, and chestnut shells. It is emphasized that only this qualitative evidence was identified, without a confirmation, mainly not referring to SS. Thus, this study advances the knowledge of the potential of big data analytics to support CECP and SS practices, especially those aimed at reducing emissions, non-renewable resources, and toxic inputs. With digital transformation, textile industries are adopting technologies on machines, generating a large volume of data, and pushing operations managers on the role of the data scientist for this purpose. The role even of the data scientist goes beyond economic analysis; he needs to be concerned about the risks of the use of chemicals in textile production and the excessive volume of textile waste generated at the end of life for society.

The adoption of IoT (T_4) and Cyberphysical System (T_8) promoted the use of digital technician service for system configuration and online support service for machine and equipment maintenance (CEV_4), limiting the consumption of renewable resources to their regeneration rate (SS_2), as well as, reducing greenhouse gas emissions (SS_3). Tsai [24] presented the automatic monitoring system, based on IoT and Cyberphisical Systems, which records real-time data from the production process which encourages companies to control carbon emissions. Fatimah et al. [23] concluded that the intelligent waste management system has a regeneration capacity commensurate with the rate of waste generated. Although this research mentions the subject, they do not confirmatively explore the findings. Thus, this study confirms that virtualization promoted by IoT and Cyberphysical Systems reduces greenhouse gas emissions and limits resource consumption, providing a baseline that can be explored by investigations in other sectors to compare the benefits of virtualization and the technologies employed. The information raised also contributes to practice because it can stimulate the shift from physical processes to virtual environments, which reduces environmental impact and costs. In addition, society can benefit by having easier access to services and products through virtualization.

As previously mentioned, SS_4 was extracted in the model adjustment, which addresses the reuse of waste as inputs in other processes. In the Pearson correlation analysis

(Table 7), some variables recognized as important but did not generate correlation were found, which explains why SS_4 was excluded from the model, which is CES_2_3: 0.92 related to cooperation of sewing workshops to recover textile waste and other companies to market by-products with the fabric waste. Thus, the textile industry does not yet reuse materials (recycled fabrics, fiber) for new purposes, such as insulation, blanket, cloths, and others (CEL_2:0.88), and with that, it does not establish digital design/stylist service provision for collection creation and material development, cutting and modeling (CEV_3:0.85). With this, the lack of correlation of CES_2_3 denotes the lack of policies to generate jobs, reduce the informality of the textile sector, and not contribute to access to basic products (SS_7:0.87). It is noteworthy that SS_7, although important, did not generate a correlation in the analysis, a worrisome aspect. This finding is in line with what was presented in the studies of Silva and Morais [15] as well as Oliveira Neto et al. [14] carried out in the Brazilian textile industry, denoting the absence of industrial symbiosis focused on the exchange of materials and especially not mentioning SS aiming to increase access to basic products. The findings indicate that there is negligence by textile companies towards access to basic products for people, which may be driven by several factors, including excessive focus on profit, pressure for low prices, lack of supply chain transparency, and lack of awareness about corporate social responsibility, denoting an innovative theoretical contribution. Thus, industrial managers can use this information to seek industrial symbiosis networks in which participating agents benefit each other, whether recycling cooperatives or industries in other sectors, to optimize the use of closed-loop materials and avoid the consumption of virgin raw materials. For society, this study contributes by highlighting the importance of public authorities and companies taking measures to facilitate access to basic products for people in need, which can return as a gain in the brand image of the company.

## 5. Conclusions

This work found that the adoption of I4.0T promotes CECP; however, it neglects SS actions in large textile industries located in Brazil, denoting theoretical originality, in addition to guiding operational managers on I4.0T that promotes CECP, generating SS enables the development of sustainable strategies in operations.

The results highlighted the technologies of big data, augmented reality, and autonomous robots as the most significant enablers for CECP practices. Big data provides processed information for supply chain tracking and management, demand forecasting and inventory management, sustainable product design, recycling and waste management, and product customization and sharing. Data-driven decision support contributes to building a more circular and responsible textile industry. Augmented reality improves the consumer experience, extends product life, reduces waste, and encourages recycling and proper disposal practices. Thus, augmented reality shows itself as a promising technology to drive the circular economy in the textile industry and contribute to a more sustainable sector. Also, autonomous robots perform waste collection and segregation tasks, automated maintenance and repair, efficient transportation, and material recovery.

Another highlight refers to the low impact of I4.0T on SS actions aimed at increasing resource consumption efficiency, the reuse of waste as inputs in other processes, and increasing access to commodities. The lack of these actions can be attributed to several factors, including a lack of awareness, competitive pressures, and lack of adequate regulation. Many managers still do not fully understand the environmental and economic benefits obtained through sustainable technologies and methods, which reflects in the continuity of traditional and not very efficient practices. In addition, competitive pressures may discourage textile companies from investing in waste efficiency and reuse measures, prioritizing cost reduction and profit maximization over the implementation of sustainable practices. These companies may fear that investing in more efficient technologies will generate additional costs and put them at a disadvantage compared to competitors that do not adopt sustainable measures. Another factor is the lack of clear and strict government policies and international standards for SS actions, which allows some companies to neglect their social and environmental responsibilities.

To move in this direction, it is crucial that there is a collective effort of public authorities, companies, and society in general. Governments should implement regulations and policies that encourage sustainable and responsible practices in the textile industry. Companies should take responsibility for adopting sustainable measures, even in a competitive environment, recognizing the long-term benefits for the environment, people, and their own reputation. And society, in general, should demand more sustainable textile products by supporting companies that adopt responsible practices.

This study conducted a survey of large textile companies located in Brazil, which limits the power of generalization of the results. In this sense, future research in other countries and industrial sectors is recommended as a basis for comparison of the findings of correlation between I4.0T, CE practices, and SS actions, which will contribute to the dissemination of knowledge on this topic.

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