# How digital factors lead to sustainability through circular economy practices: empirical evidence from the textile sector

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## ABSTRACT – REZUMAT

### How digital factors lead to sustainability through circular economy practices: empirical evidence from the textile sector

*The transition toward sustainable manufacturing requires integrating digital innovation with environmental responsibility. In the textile sector, the adoption of Industry 4.0 technologies has become essential for achieving circular and sustainable operations. However, the mechanisms linking digitalisation to sustainability remain underexplored. This study examines how five Industry 4.0 technologies, Big Data (BD), Smart Factory (SF), Cyber-Physical Systems (CPS), Internet of Things (IoT), and Interoperability (IP) influence sustainability performance in China's textile industry, with Circular Economy Practices (CEP) acting as a mediating factor.*

*Adopting a quantitative, cross-sectional design, data were collected through structured questionnaires distributed to 523 professionals in textile manufacturing firms across mainland China. Using purposive sampling, firms that have either adopted or shown interest in adopting 4.0 technologies or circular practices are selected.*

*The analysis conducted using Structural Equation Modelling (SEM) reveals that BD and CPS exert significant direct effects on sustainability performance, while SF and IoT contribute indirectly through CEP. Interoperability shows no significant impact, indicating that integration does not lead to sustainability gains unless strategically aligned with circular principles. The results confirm that circular practices act as a key mechanism transforming digital capabilities into environmental benefits. These outcomes highlight the strategic role of digital technologies, guided by the Resource-Based View (RBV), in enabling a sustainable and circular transformation of China's textile industry.*

***Keywords:*** *Smart Factory, Big Data, IoT, Cyber-Physical Systems, Interoperability, Industry 4.0, circular economy, sustainability*

### Modul în care factorii digitali contribuie la sustenabilitate prin practicile economiei circulare: dovezi empirice din sectorul textil

*Tranziția către o producție durabilă necesită integrarea inovației digitale cu responsabilitatea față de mediu. În sectorul textil, adoptarea tehnologiilor Industriei 4.0 a devenit esențială pentru realizarea unor operațiuni circulare și durabile. Cu toate acestea, mecanismele care leagă digitalizarea de durabilitate rămân insuficient explorate. Acest studiu examinează modul în care cinci tehnologii din cadrul Industriei 4.0, Big Data (BD), Smart Factory (SF), Sistemelor ciber-fizice (CPS), Internetului obiectelor (IoT) și Interoperabilității (IP) influențează performanța în materie de sustenabilitate în industria textilă din China, cu Practicile economiei circulare (CEP) acționând ca factor de mediere.*

*Adoptând un design cantitativ, transversal, datele au fost colectate prin chestionare structurate distribuite către 523 de profesioniști din firme de producție textilă din China continentală. Folosind eșantionarea intenționată, sunt selectate firmele care au adoptat sau au manifestat interes în adoptarea tehnologiilor 4.0 sau a practicilor de economie circulară.*

*Analiza efectuată utilizând modelarea ecuațiilor structurale (SEM) relevă faptul că BD și CPS exercită efecte directe semnificative asupra performanței în materie de sustenabilitate, în timp ce SF și IoT contribuie indirect prin intermediul CEP. Interoperabilitatea nu are un impact semnificativ, ceea ce indică faptul că integrarea nu conduce la îmbunătățiri în materie de sustenabilitate decât dacă este aliniată strategic la principiile economiei circulare. Rezultatele confirmă faptul că practicile circulare acționează ca un mecanism-cheie de transformare a capacităților digitale în beneficii pentru mediu. Aceste concluzii evidențiază rolul strategic al tehnologiilor digitale, ghidate de perspectiva bazată pe resurse (RBV), în facilitarea unei transformări durabile și circulare a industriei textile din China.*

***Cuvinte-cheie****: Smart Factory, Big Data, Internetul obiectelor (IoT), Sisteme ciber-fizice, Interoperabilitate, Industria 4.0, Economia circulară, sustenabilitate*

## INTRODUCTION

The contemporary manufacturing landscape is undergoing a profound transformation, driven by the integration of advanced digital technologies and an escalating global focus on sustainable development. The global industries are also being pressured to strike a balance between economic growth and environmental responsibility, which makes them seek innovative solutions that can optimise the resources and reduce the waste [1]. The implementation of

Fourth Industrial Revolution (4.0) technologies can be considered one of the most promising answers to these demands. These are technologies, including smart manufacturing, data analytics, cloud computing, and real-time connectivity, that are revolutionising the functioning of industry, allowing new levels of efficiency, responsiveness, and sustainability [2]. With companies going digital in order to stay competitive, a similar focus on sustainability, especially in the form of the circular economy (CE), is transforming supply chains across the globe.

At the global level, 4.0 technologies are identified as potentially helpful in contributing to sustainability goals because they allow monitoring data in real-time and optimising resources [3]. These aspects are particularly important in industries such as textiles, which have a high environmental footprint, in terms of water and energy usage, pollution, and linear, wasteful operations that have long been the hallmark of such industries [4]. The CEP paradigm provides a way out of these problems, as it encourages recycling, reuse, remanufacturing, and minimising resource input throughout the supply chain processes [5]. The implementation of 4.0 technologies in CEP systems can support closed-loop supply chains, which would make sure that materials and products remain in use as long as possible, which will help reduce their environmental footprint [6].

These technological improvements are especially important in the textile industry. Being one of the largest producers of textiles in the world, China has a serious problem with environmental and operational issues in this industry [7]. The use of traditional manufacturing processes causes inefficiency and high ecological degradation in the industry, such as overconsumption of fossil fuels and dumping of chemicals in water bodies. Although the Chinese government is making efforts to make the industrial sector go digital and sustainable, as demonstrated by the digital China vision and green industrial policies, the uptake of 4.0 technologies in the textile industry is still small and scattered [8]. The majority of companies are still working with old systems and low technology integration, which prevents the attainment of sustainable and circular supply chain models.

Despite the increasing number of evidence of 4.0 technologies' potential to enhance the degree of circularity and sustainability in the world, the dynamics of this relationship within the framework of the Chinese textile industry have not been examined to a substantial degree [9]. The application of 4.0 technologies may have a significant beneficial impact on the sustainability of the supply chain, making it more visible, enabling it to be circular, and more efficient [10, 11]. These studies emphasise that 4.0 technologies may enable sustainable transitions, but also point out that other aspects, including CEP practices that enable the recycling of materials, influence such outcomes greatly. This has not been extensively covered by these previous studies, creating a gap in the empirical literature. This gap should be filled in, as the textile industry in China has a crucial strategic role in the economy and environment [12]. The industry not only makes a significant contribution to the GDP and the labour market of the country, but it also determines its environmental impact [13]. The inability to modernise and shift to sustainable and circular supply chains can undermine the competitiveness of the industry in the long term in the world market that is becoming more sustainability-focused. The textile supply chains in China can provide useful information to policymakers regarding how 4.0 technologies can be used to promote sustainable practices, to allow industry leaders and academics to facilitate the digitalisation of the textile industry and environmental change.

The proposed research aims to analyse the role of Industry 4.0 technologies in the sustainability performance of the Chinese textile industry, both directly and indirectly, as a result of the circular economy practices. This study is especially important as it takes a complex research model that places the circular economy as an intermediary variable in the correlation between 4.0 technologies and sustainability performance. This research will address five technological factors: Big Data (BD), Smart Factory (SF), Cyber-Physical Systems (CPS), Internet of Things (IoT), and Interoperability (IP). All these technologies have their peculiarities of opportunities, which could be utilised as far as the process of implementing the circular practices into manufacturing activities is concerned. The practical example of the BD analytics application in the work with big data to simplify the use of resources on the process and supply chain levels is practical [14, 15]. Creative factory arrangements make a highly dynamic, computerised manufacturing room to assist in setup in real-time and efficient flow of materials [16]. CPS is digital and physical in nature, which can dynamically control and monitor processes, which is essential to the circular operations. The IoT can also provide the connectivity infrastructure that allows machines, products, and nodes in the supply chain to communicate and exchange data in real time, enhancing the visibility of the supply chain and tracking material [17]. IP guarantees that various technological systems and platforms have the capability to share information with each other and increase the level of integration and effectiveness of circular strategies [18]. This study focuses on the overall effects of these technologies on sustainability performance in the textile industry, both directly and indirectly via the use of CEP. This research can help in understanding the impact of technological changes on the environment and sustainability by modelling the mediating role of CE. The literature has tended to assume that technology and sustainability are directly related in a linear form, but this paper suggests that the introduction of circular practices is an obligatory step through which the sustainability potential of 4.0 technologies can be achieved.

The study contributes to theory and practice. Theoretically, the work is well based on the Resource-Based View (RBV) that states that the internal resources and capabilities of an organisation play a central role in attaining sustained competitive advantage [19]. In this context, the 4.0 technologies, including BD, SF, CPS, IoT, and IP, may be theorised as valuable, rare, inimitable, and non-substitutable (VRIN) assets that enable companies to build unique capabilities. When these high-technological assets are properly combined with the use of the circular economy, they can become strategic resources that cannot be easily imitated by competitors. The RBV points out that having such technologies does not necessarily result in competitive advantage, but rather the capability of firms to use them in a manner that generates synergies with circular strategies results in high levels of sustainability performance [19, 20]. This view is specifically applicable to the textile industry in China, where the heterogeneity of technological usage and capability building among the companies can be attributed to the differences in the sustainability levels. This study identifies internal resource configuration as a strategic element of attaining circular and sustainable supply chains by integrating the RBV lens. In practice, the results will provide information to the managers and policymakers. The determination of the technologies that contribute to the strongest circularity and sustainability can be used to guide firms on the types of investments they should make (e.g., investing in IoT sensors or data analytics) and government agencies on the type of support programs they should prioritise. Effectively, the analysis will demonstrate how digital improvements and circular solutions can produce a greener production. A report on a digital and sustainable transformation in the textile industry can be used as an example to other textile-producing areas that need to modernise in a responsible way [21]. This paper is very useful in offering insights on how the textile industry and other industries in the emerging economies can use Industry 4.0 and circular strategies to have a more sustainable future.

## RESOURCE-BASED VIEW (RBV)

Resource-Based View (RBV) may be used to provide theoretical explanations that can help understand how the implementation of Industry 4.0 technologies may be associated with the sustainability of the textile industry. The RBV explains that a sustainable competitive advantage is achievable, and firms can be able to exploit viable, rare, inimitable and non-substitutable (VRIN) resources [19]. In this context, Big Data (BD), Smart Factory (SF), Cyber-Physical Systems (CPS), Internet of Things (IoT), and Interoperability (IP) may be viewed as essential internal resources that can empower the capacity of firms and enhance their general performance. The technologies would facilitate advanced processing of the data, predictable processes when empowered, and multiple functions throughout the production and supply chains [2]. With the effective integration, they can increase the resource utilization, minimize a waste, and stimulate the shift to more circular and sustainable production systems [1]. The significance of the RBV to this study is in the fact that these technological instruments are not just the tools of operation but rather the key internal resources of long-term performance that are considered in factory sustainability [22].

The translation of such technological resources into sustainability outcomes can be achieved successfully due to the complementary organisational capacity, namely, the application of the practices of the circular economy (CEPs). The role of CEPs in the context of the present study is as follows: CEPs are the channels through which the Industry 4.0 technologies are exerting their impact on the sustainability performance. These technologies, in combination with the cyclic processes such as recycling, remanufacturing, and reusing, allow companies to create closed-loop systems that minimise the quantity of waste and the recovery of resources [22]. This insight is consistent with the perception of natural resources, as developed by Hart (1995), which emphasises that a mixture of technological and environmental forces enhances sustainable competencies of firms. Digital technologies can help textile companies to improve the use of the circular production process, as they guarantee the optimal material management, waste reduction, and real-time control [6]. Based on the empirical evidence, the usage of technological capabilities coupled with the applications of the circular economy is far more likely to rise in both the environmental and economic performance [6]. The RBV indicates that the Chinese textile companies can be made sustainable by obtaining technology by combining it successfully with a circular economy practice.

## HYPOTHESES DEVELOPMENT

The emergence of Big Data as a core component of Industry 4.0 has transformed how firms manage operations, particularly in resource-intensive industries. Big Data analytics enables companies to collect, analyse, and determine huge quantities of organised and undefined data to optimise decision-making and improve the effectiveness of operations [23]. Within the textile manufacturing industry, in which lengthy and ecologically stressful production processes are involved, the application of BD can open up the possibility of real-time tracking of the use of energy and water, the minimisation of material waste, and supply chain streamlining [24]. Evidence-based information enables proactive maintenance, quality decrease, and improved inventory administration, all of which play a role in enhancing sustainability performance (Xi et al., 2025). According to the RBV, the ability to create and/or implement this technology might be regarded as a valuable and rare resource in increasing the competitiveness of a firm at the firm level, primarily as a consequence of sustainability [19]. According to Bag et al. (2023), companies using smart analytics will demonstrate better environmental performance because of resource-informed use and waste minimisation plans. Therefore, based on these insights, the following hypothesis is proposed:

***H1: Big Data has a significant positive impact on sustainability performance in the textile sector.***

The integration of smart factory systems within textile manufacturing processes is rapidly reshaping the landscape of industrial sustainability. A smart factory is a completely digitalised production area in which the machines, systems, and humans acquire a connection via cyber-physical infrastructure, facilitating the optimisation of the processes dynamically and autonomously [16]. Such settings allow real-time decision-making, adaptive control, and flexible manufacturing to become feasible and result in enormous efficiency of resources used and reduction of waste [25]. In textile industries, smart factories enable tracking and streamlining the process of dyeing, weaving and finishing, which could previously be characterised by the inefficient use of water, energy and chemicals. Such capability enables manufacturers to minimise the use of material and minimise emissions to the environment, which shape the goals of sustainability [26]. In the RBV, a smart factory system can be regarded as a worthy and inimitable source of competitive advantage in terms of increased performance in environmental responsibility [19].

Therefore, the following hypothesis is proposed:

***H2: Smart Factory systems have a significant positive impact on sustainability performance in the textile sector.***

CPS serve as the backbone of Industry 4.0 by tightly integrating physical production processes with computational control systems. These systems have embedded sensors, real-time communication, and an autonomous feedback loop that ensures constant monitoring and adjustment of the manufacturing operations [27]. In the textile industry, CPS allows the accurate control of temperature, humidity, and performance of machines as well as the flow of materials, reducing the inefficiencies that cause waste and gases. Spinning or dyeing machines fitted with smart sensors are able to sense the deviations and automatically adjust the spinning of the machine to prevent overusage of water or energy. CPS also helps in predictive maintenance, minimising the chances of sudden shutdown and loss of resources [28]. The functionalities will make the production environment more sustainable by improving the effectiveness of the system with regard to its reliability and responsiveness [29]. In terms of the RBV theory, CPS can easily be treated as an inimitable asset, which allows a firm to match its operational control to its sustainability ends [22]. Thus, the following hypothesis is posited:

***H3: Cyber-Physical Systems (CPS) have a significant positive impact on sustainability performance in the textile sector.***

The IoT has emerged as a transformative tool in enabling sustainable manufacturing. IoT brings together the machines, sensors, products, and humans in a networked infrastructure that enables the exchange of real-time data and vocational visibility across a system [30]. IoT technologies in the textile industry encourage the smooth tracking of water consumption, energy efficiency, emissions, and logistics of the supply chains. This can be done through the placement of sensors onto fabric dyeing systems that measure the amount and rate of chemicals and make finer adjustments that would decrease the unnecessary amount used and waste [12]. With IoT, the entire supply chain can be traced, which would enable responsible sourcing, reuse of material, and resourceful management of inventory [31]. According to RBV, when the IoT infrastructure is present in firm-specific systems that minimize resources consumption and environmental cost, the infrastructure turns out to be a strengthened capability that is hard to replicate [32]. Consequently, a hypothesis is presented:

***H4: Internet of Things (IoT) has a significant positive impact on sustainability performance in the textile sector.***

IP is an important facilitator of sustainable production. It makes sure that different technologies, including ERP systems, machines, cloud platforms, and analytics tools, can be used in synergy [33].

Interoperability can also be used in eliminating silos and promoting coordinated decision-making in the textile industry, where operations involve different functions that would include fibre processing, logistics, etc. One of them is to link the machine data with environmental tracking systems to enable firms to align the production specifications with sustainability indicators [34]. Interoperability provides real-time coordination and consequently enables effective scheduling, reduced downtimes and improved resource utilisation that contributes to the reduction of environmental footprints [35]. Interoperability in the RBV is not described as a technology capability but a strategic capability that can enhance the utility of available technology resources by maximising the synergistic nature of the resources [36]. It is often firm-specific and hard to imitate, hence it satisfies valuable RBV criteria [19]. Based on these insights, the following hypothesis is formulated:

***H5: Interoperability has a significant positive impact on sustainability performance in the textile sector.***

Recent discourse in sustainability and industrial innovation highlights that the relationship between Industry 4.0 technologies and sustainability outcomes is not merely direct but often occurs through enabling organisational capabilities, particularly CEP. A strategy that has the capacity to convert the technological potential into real sustainability is the circular economy principles, after stripping resources, reuse and recycle outputs [37]. CEP is not merely an environmental program but an active operating system to achieve an innovative use of technological resources, to reduce waste and emissions and to maximise efficiency and lifespan of used materials. Although 4.0 technologies can maximise valuable features of managing data intelligently, automated as well as machine integration, and having a system-wide visibility, the impact of the technology on sustainability is immense when applied in line with the circular processes matching the resource-conscious production and closed value chains [38].

Under the RBV, these technologies can be seen as valuable, rare, inimitable, and non-substitutable (VRIN) resources; however, to extract their full potential, firms must develop complementary capabilities [19, 22]. CEP acts as such a capability, integrating technological assets into routines and systems that deliver environmental benefits. BD analytics provides the insights needed to redesign processes for lower material usage; CPS and IoT enable real-time monitoring for efficient waste recovery and reuse; and SF systems, when combined with circular logic, can support flexible remanufacturing or energy optimisation. IP enhances CEP by facilitating communication across systems involved in reuse, recycling, or eco-design. Without such integration into circular frameworks, the environmental value of 4.0 technologies may remain underutilised [39]. Therefore, this research proposes that the circular economy mediates the relationship between these five industries' 4.0 technologies and sustainability performance, acting as the mechanism through which digital transformation leads to environmental improvement (figure 1). Based on the above discussion, the following hypotheses are proposed:

***H6–H10: Circular Economy mediates the relationship between industry 4.0 factors (Big Data, Smart Factory systems, Cyber-Physical Systems, Internet of Things and Interoperability) and sustainability performance in the textile sector.***

## METHODOLOGY

This study adopts a quantitative, cross-sectional research design to investigate how Industry 4.0 technologies influence sustainability performance in the textile sector of mainland China, with circular economy practices acting as a mediating variable (figure 2). The quantitative approach is suitable for testing theoretical hypotheses and generalising findings based on numerical data [40]. A cross-sectional design is chosen as it captures a snapshot of firms' technological and sustainability practices at a single point in time, which is appropriate given the stable nature of technological infrastructure and policy environment in China's textile industry during the data collection period. The textile sector in mainland China was selected for this study due to its substantial contribution to China's economy and its representation of the broader national textile landscape. Mainland China hosts a significant portion of textile manufacturing firms. These firms are currently facing mounting pressure to adopt sustainable and digital practices, making them ideal units of analysis for this study. The target population comprises operational managers, production heads, and sustainability officers in textile manufacturing firms across mainland China. Using purposive sampling, firms that have either adopted or shown interest in adopting 4.0 technologies or circular practices are selected. This technique is suitable for exploratory models involving emerging concepts, such as Industry 4.0 and CE, in developed economies [41].

To ensure statistical power and model robustness in Structural Equation Modelling (SEM), an appropriate sample size is crucial. Following recommendations by Hair et al. (2021), a minimum sample size of 10 times the number of indicators in the most complex construct is adequate. A 20-to-1 ratio has also been suggested [42]. In this study, the total number of items was 34 and 680 respondents were needed. However, to account for non-response and incomplete data, the survey will be distributed to 600 potential respondents, aiming for at least 523 usable responses. Two software tools will be used for data analysis. SPSS Version 26 will be employed for initial

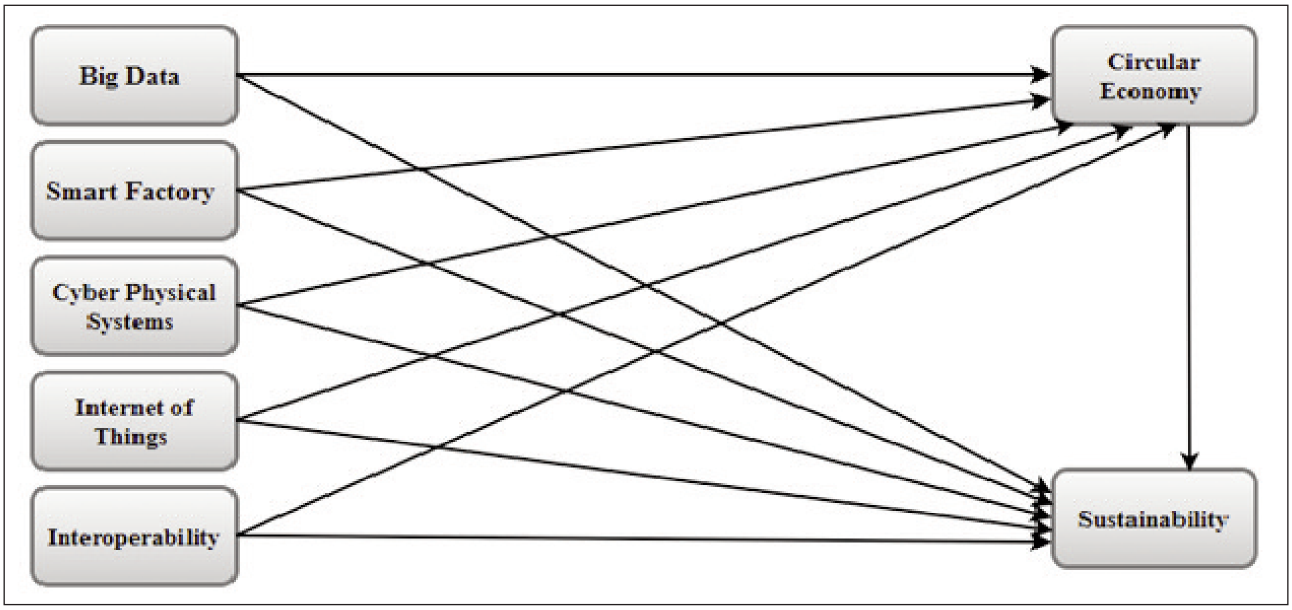

Fig. 1. The relations between the proposed hypothesis

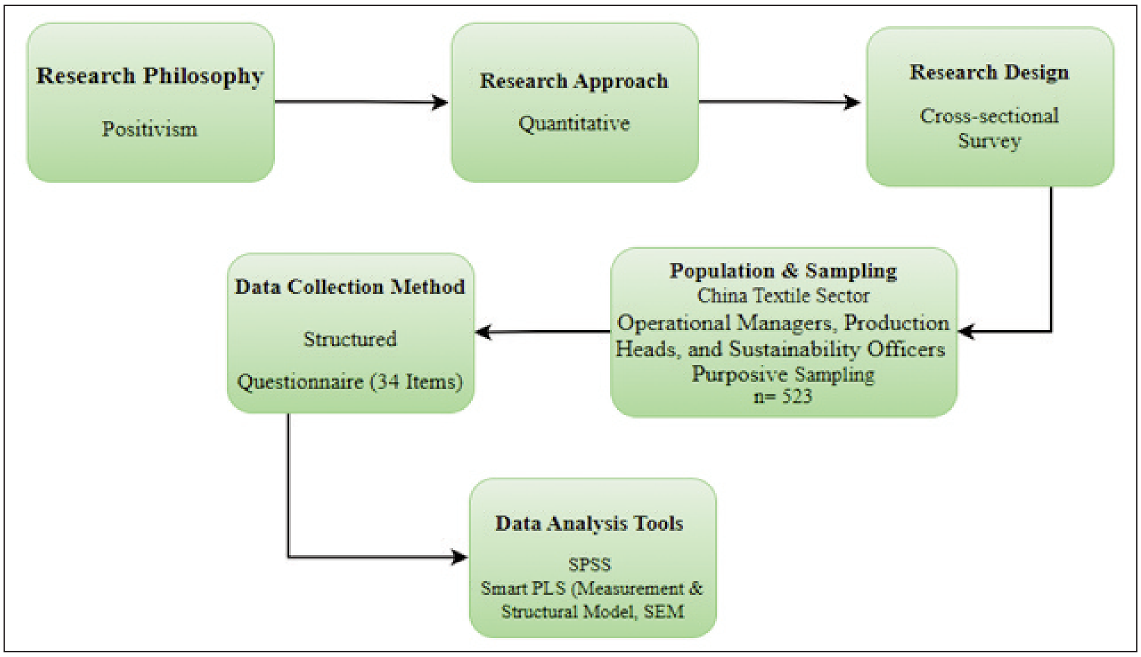

Fig. 2. Flow chart of methodology

data screening and descriptive statistics, while SmartPLS 4.0 will be used to test the structural model [43]. Data were collected using a 7-point Likert scale, ranging from “strongly disagree” (1) to “strongly agree” (7). A Likert scale is most suitable for examining the opinions and views of respondents [44].

## Data analysis

### *Primarily analysis*

The research conformed to the criteria provided by Sekaran (2003) and did not contain any missing values in the data. The CMV was measured using the single-factor test by Harman, and it was found that the single factor explained only 45.10 percent of the variance, which is lower than the standard value of 50 percent variance [45], therefore, the CMV issue was not considered serious. Hair et al. (2012) [46] and Bryne (2010) [47] are convinced that data is deemed normal when the skewness is between –2 and +2 and the kurtosis is between –7 and +7. Moreover, all the values are within range. The KMO value of 0.952 indicates an outstanding sampling adequacy for factor analysis, implying that the variables possess common factors [43]. To determine multicollinearity, the value of the variance inflation factor (VIF) is employed [48]. As the existence of multicollinearity is generally ignored when the value of the VIF is lower than 10 [48], it means that the independent variables do not reflect multicollinearity. All the values were lower than 10, hence no issue of multicollinearity.

## MEASUREMENT MODEL

The measurement model was assessed to get the reliability and validity of the constructs (table 1). First factor loadings of all the items in the model are adequate, having more than the minimum acceptable value of 0.50 [46]. Although a loading factor of above 0.7 is recommended [49], researchers usually obtain poorer outer loadings (<0.70) in social science research analysis. Instead of deleting the indicators blindly, the impacts of delinking the item on the reliability of the composite, content, and convergent validity should be checked. In general, the suggested criterion should be met; thus, items (outer loading is between 0.40 and 0.70) can be discussed only in those cases when deletion leads to composite reliability or the average variance extracted (AVE) being increased more than the recommended [46]. SS5 contains fewer factor loadings, and it was eliminated in order to improve the reliability statistics. Reliability was estimated by measuring Cronbach’s Alpha, rho_a are both greater than the recommended level of 0.700 [50]. An interval between values of Cronbach’s Alpha and composite reliability is presented as the value of rho a, and shows a value of more than 0.70, which indicates that it was a good reliability [51].

## Discriminant validity

Convergent validity also met expected levels because AVE was greater than 0.5. The Method to test the values of discriminant validity was to contrast the correlation rate of the latent variables with the square root of the AVE [52], heterotrait monotrait ratio of correlation [51], the value of which is lower than the 0.85 scores about discriminant validity, or it is conservative. Thus, the discriminant validity was established (table 2).

## Structural equation modelling (SEM)

The structural model results reveal the degrees of influence of different Industry 4.0 technologies factors on sustainability performance (table 3 and figure 3). BD shows a significant and positive relationship with sustainability performance (B=0.214,

Table 1

REGRESSION WEIGHTS AND RELIABILITY STATISTICS

| Variables | Items | Factor loadings | Cronbach's alpha | (rho_a) | (rho_c) | (AVE) |
|---|---|---|---|---|---|---|
| **Big Data (BD)** | | | 0.828 | 0.831 | 0.879 | 0.593 |
| | BD1 | 0.790 | | | | |
| | BD2 | 0.761 | | | | |
| | BD3 | 0.753 | | | | |
| | BD4 | 0.788 | | | | |
| | BD5 | 0.756 | | | | |
| **Circular Economy (CEP)** | | | 0.951 | 0.953 | 0.960 | 0.775 |
| | CEP1 | 0.898 | | | | |
| | CEP2 | 0.889 | | | | |
| | CEP3 | 0.803 | | | | |
| | CEP4 | 0.906 | | | | |
| | CEP5 | 0.856 | | | | |
| | CEP6 | 0.929 | | | | |
| | CEP7 | 0.877 | | | | |
| **Cyber-Physical Systems (CPS)** | | | 0.871 | 0.881 | 0.912 | 0.721 |
| | CPS1 | 0.801 | | | | |
| | CPS2 | 0.861 | | | | |
| | CPS3 | 0.893 | | | | |
| | CPS4 | 0.838 | | | | |
| **Internet of Things (IoT)** | | | 0.955 | 0.956 | 0.966 | 0.849 |
| | IoT1 | 0.914 | | | | |
| | IoT2 | 0.936 | | | | |
| | IoT3 | 0.897 | | | | |
| | IoT4 | 0.915 | | | | |
| | IoT5 | 0.943 | | | | |
| **Interoperability (IP)** | | | 0.960 | 0.963 | 0.974 | 0.926 |
| | IP1 | 0.960 | | | | |
| | IP2 | 0.965 | | | | |
| | IP3 | 0.963 | | | | |
| **Smart Factory (SF)** | | | 0.922 | 0.930 | 0.942 | 0.764 |
| | SF1 | 0.891 | | | | |
| | SF2 | 0.925 | | | | |
| | SF3 | 0.923 | | | | |
| | SF4 | 0.829 | | | | |
| | SF5 | 0.797 | | | | |
| **Sustainability (SS)** | | | 0.945 | 0.948 | 0.961 | 0.860 |
| | SS1 | 0.955 | | | | |
| | SS2 | 0.953 | | | | |
| | SS3 | 0.954 | | | | |

$p<0.000$), indicating that data-driven insights strongly contribute to sustainable operations in textile firms. CPS also showed a positive and statistically significant impact (B=0.178, $p<0.000$), reinforcing the role of real-time automation and intelligent process control in enhancing environmental outcomes. SF systems showed an insignificant effect on sustainability (B=0.034, p=0.676). IoT also showed an insignificant relationship with sustainability (B= –0.048, p=0.570), while IP also has an insignificant impact (B=0.003, p=0.962).

To see whether the model is good or not, the strength of each structural path can be determined by the value of $R^2$ of the dependent variable, and the value of $R^2$ is expected to be at least 0.1. Table 4 results indicate that all the $R^2$ exceed 0.1. Therefore, predictive ability is attained. $F^2$ value must be varied at $\geq 0.02$, $\geq 0.15$ and $\geq 0.35$, which indicates small, medium, and huge effect sizes of exogenous construct on endogenous [53]. Table 4 shows that BD and CPS had an impact not large (>0.02) on sustainability. Whereas SF, IoT and IP did not influence

Table 2

FORNELL LARCKER AND HTMT RATIO

| Constructs | BD | CEP | CPS | IOT | IP | SF | SS |
|---|---|---|---|---|---|---|---|
| **Fornell Larcker** | | | | | | | |
| Big Data (BD) | ***0.770*** | | | | | | |
| Circular Economy (CEP) | 0.275 | ***0.881*** | | | | | |
| Cyber-Physical Systems (CPS) | 0.384 | 0.266 | ***0.849*** | | | | |
| Internet of Things (IOT) | 0.266 | 0.820 | 0.289 | ***0.921*** | | | |
| Interoperability (IP) | 0.237 | 0.573 | 0.434 | 0.658 | ***0.962*** | | |
| Smart Factory (SF) | 0.250 | 0.743 | 0.372 | 0.836 | 0.742 | ***0.874*** | |
| Sustainability (SS) | 0.405 | 0.552 | 0.382 | 0.466 | 0.387 | 0.456 | ***0.928*** |
| **HTMT (Heterotrait-Monotrait)** | | | | | | | |
| Big Data (BD) | | | | | | | |
| Circular Economy (CEP) | 0.308 | | | | | | |
| Cyber-Physical Systems (CPS) | 0.438 | 0.292 | | | | | |
| Internet of Things (IOT) | 0.296 | 0.858 | 0.320 | | | | |
| Interoperability (IP) | 0.260 | 0.602 | 0.479 | 0.687 | | | |
| Smart Factory (SF) | 0.282 | 0.785 | 0.427 | 0.883 | 0.799 | | |
| Sustainability (SS) | 0.455 | 0.581 | 0.418 | 0.490 | 0.407 | 0.487 | |

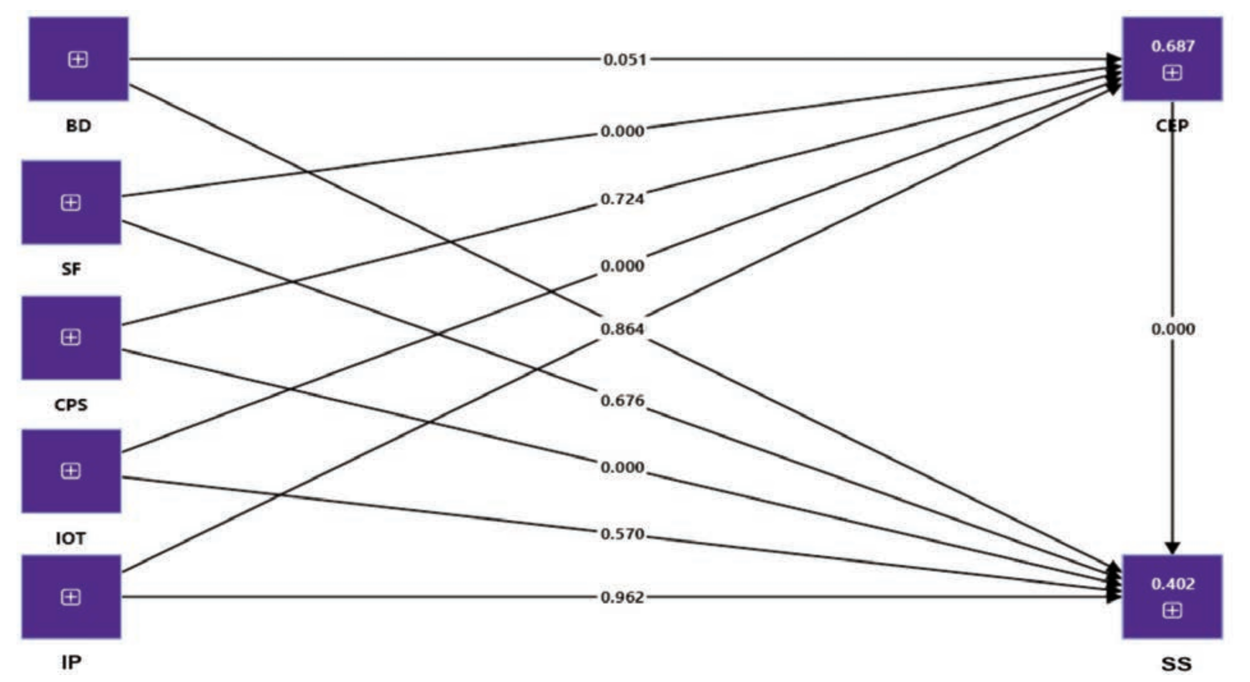

Fig. 3. Structural model results

Table 3

HYPOTHESES RESULTS

| | Original sample | (M) | Standard deviation | T statistics | P values |
|---|---|---|---|---|---|
| **BD → SS** | 0.214 | 0.215 | 0.040 | 5.296 | 0.000 |
| **SF → SS** | 0.034 | 0.034 | 0.082 | 0.418 | 0.676 |
| **CPS → SS** | 0.178 | 0.178 | 0.047 | 3.766 | 0.000 |
| **IOT → SS** | –0.048 | –0.048 | 0.085 | 0.568 | 0.570 |
| **IP → SS** | 0.003 | 0.003 | 0.059 | 0.048 | 0.962 |

*Note:* BD (Big Data), SS (Sustainability), SF (Smart Factory), CPS (Cyber-Physical Systems), IOT (Internet of Things), IP (Interoperability).

Table 4

| STRUCTURAL MODEL PREDICTIVE AND EXPLANATORY POWER | | | |
|---|---|---|---|
| **Variable** | **$R^2$** | **$F^2$** | **$Q^2$predict** |
| Circular Economy Practices (CEP) | 0.687 | | 0.679 |
| Sustainability (SS) | 0.402 | | 0.318 |
| Big Data (BD) | | 0.063 | |
| Cyber-Physical Systems (CPS) | | 0.038 | |
| Internet of Things (IOT) | | 0.001 | |
| Smart Factory (SF) | | 0.000 | |
| Interoperability (IP) | | 0.000 | |

sustainability. $Q^2$ determines how well the endogenous constructs are predictive. A $Q^2$ greater than 0 indicates that the model is relevant in prediction. The outcomes demonstrate that all the constructs have significance in their prediction (table 4). The model fitness was achieved by measuring the standardised root mean square residual. Standardised root square residual was equal to 0.065; it has the necessary value of 0.10, which reflects the suitability of the model [53].

## MEDIATION ANALYSIS

The mediation analysis examines how the Industry 4.0 technologies impacted the sustainability performance indirectly using CEP. The findings denote that the IoT has a statistically significant mediation value (B=0.297, p<0.000), indicating that the effect of IoT on the sustainability performance is enhanced by CEP. The effect of SF systems on sustainability is strong through CEP (B=0.090, p=0.001), indicating the role of the latter in the support of the resource-efficient and circular production tool. Another aspect of sustainability, BD has a significant impact regarding CEP (B=0.028, p=0.045), which suggests that its role in promoting sustainability is partly achieved with the help of the process of facilitating circular practices such as waste reduction and resource optimisation in real-time. While CPS demonstrate a negative and statistically non-significant indirect effect (B= –0.007, p=0.725) and IP shows a non-significant indirect impact (B=–0.004, p=0.866), indicating that technological integration alone does not enhance sustainability unless aligned with circular practices.

## DISCUSSION

The findings reveal a detailed and complex relationship between Industry 4.0 technologies and sustainability performance in China's textile sector. BD demonstrates a significant positive direct effect on sustainability, supporting the idea that data-driven insights enhance operational efficiency and reduce environmental burdens [54]. The ability to collect, process, and act on large volumes of production data facilitates real-time decision-making and resource optimisation, promoting greener manufacturing practices [24, 55]. The mediation analysis confirms that BD indirectly contributes to sustainability through CEP. This suggests that firms using analytics for material flow tracking, waste detection, and predictive maintenance are better equipped to implement CEP strategies like recycling and resource minimisation [6]. The dual direct and indirect effects of BD affirm its role as a strategic resource in line with the RBV [19, 22].

The direct effect that SF systems had on sustainability was not that significant, meaning that the sustainability of the environment cannot be secured in automated and digitised environments; there have to be other factors to consider. This result aligns with current insights that smart systems need to be deliberately associated with sustainability goals in order to create value. Nevertheless, the indirect effect of SF was significant and high, which means that by combining it with circular processes, including but not confined to the remanufacturing process, energy recapture or closed-loop material utilisation, smart factories can contribute to sustainability [16, 26]. This

Table 5

| INDIRECT EFFECT | | | | | |
|---|---|---|---|---|---|
| | **Original sample** | **(M)** | **Standard deviation** | **T statistics** | **P values** |
| BD → CEP → SS | 0.028 | 0.028 | 0.014 | 2.002 | 0.045 |
| SF → CEP → SS | 0.090 | 0.090 | 0.026 | 3.435 | 0.001 |
| CPS → CEP → SS | –0.007 | –0.007 | 0.019 | 0.352 | 0.725 |
| IOT → CEP → SS | 0.297 | 0.296 | 0.050 | 5.921 | 0.000 |
| IP → CEP → SS | –0.004 | –0.004 | 0.021 | 0.169 | 0.866 |

*Note:* BD (Big Data), SS (Sustainability), SF (Smart Factory), CPS (Cyber-Physical Systems), IOT (Internet of Things), IP (Interoperability).

affirms the perspective that technological possibilities should be powered by process-focused structures in a bid to release their potential on the environment.

The direct impact of CPS was high, although CEP did not have an influence on sustainability. This implies that CPS, as a means of providing real-time access to control over physical processes, influences the enhancement of production efficiency and minimises environmental damage even without a formal integration of CEP [27, 56]. Nevertheless, such limited mediation by CEP can suggest that there is a deficit in how the textile companies apply CPS to the higher-end circular processes, such as adaptive reuse or reverse logistics [22]. Therefore, CPS helps to sustain a business in the operating sense, but its capabilities related to circular change in the entire system are unexploited.

The IoT did not exert any direct impact but was highly mediated by CEP. This means that the sustainability advantages of IoT are achieved only when integrated into the models of circles. The ability of IoT to deliver real-time information throughout the supply chain, such as monitoring the use of water, energy, and materials, can be useful in the recycling process, eco-design, and lifecycle monitoring [11]. Thus, IoT itself might not be a sustainability driver, but its combination with CEP plays a key role in the achievement of resource circularity and environmental performance [12, 17].

IP did not have any significant direct or mediated effect on sustainability. Although it is viewed as a fundamental and necessary supporting factor of integrated systems, its ability to impact environmental outcomes seems to be minimal unless it is strategically connected to the idea of the circle or green. This finding indicates that companies can have interoperable platforms but fail to use them to drive sustainability-based cooperation, which is an aspect of maturity or implementation gap.

## CONCLUDING REMARKS

### Theoretical implications

This study makes several important contributions to the theoretical understanding of sustainability and digital transformation in the context of emerging economies, specifically within the textile industry. The research helps to prove that advanced technologies like BD, CPS, and IoT may be considered as useful, rare, inimitable, and non-substitutable (VRIN) resources due to the use of the RBV [19, 22]. The study builds upon RBV by showing that the entire potential of these technologies in creating sustainability is achieved when they are incorporated into complementary capabilities, which is CEP. This emphasises the fact that technology is not the only answer to high environmental performance, but organisational routines and systems, including those relating to circularity, are essential intermediaries. The substantial mediation of CEP in the connection between such technologies as IoT and sustainability also contributes to the development of knowledge regarding the interactions between the elements of Industry 4.0 in the organisational settings. Moreover, the paper contributes to the empirical complexity of the discussion on digital sustainability by examining an industry and a geographic area that has been under-researched, the textile industry in China. The previous research concentrated more on developed economies; therefore, the current research offers contextual information that can expand the applicability of digital-sustainability theories to developing economies. Though several studies have been conducted on Industry 4.0 and sustainability in the automotive, electronics, and energy sectors in China, the textile industry is a different scenario. The fact that textile manufacturing involves the intensive use of water, chemicals, and energy, and massive production of waste, is unlike these high-tech or capital-intensive industries. It is also characterised by a more fragmented supply chain that has many small and medium-sized businesses that do not always have developed digital infrastructure [7, 8]. The textile industry is both urgent and tricky to investigate the issue of how Industry 4.0 technologies can facilitate sustainable and circular change due to these structural and environmental issues.

This observation is in line with the more general evidence that the practices of the circular economy, especially recycling and the use of secondary raw materials, are significant processes that can be used to attain sustainable industrial development.

Vuckovski et al. (2025) [57] attest to the fact that the implementation of circular processes in the European industries is a highly effective way to increase the efficiency and sustainability outcomes of resources. This supports the conclusion of the current study that the combination of digital technologies and the practices of a circular economy can enhance environmental and operational performance in the manufacturing industries like textiles [58–60].

### Practical implications

The findings of the study are practical recommendations to the managers of the textile industries, technology suppliers, and policymakers who are interested in enhancing sustainability through the digital transformation. To begin with, the results indicate that the investment in technologies, including BD and CPS, can directly lead to changes in sustainability, in particular, when they are implemented in order to monitor the utilisation of resources, decrease the quantity of waste, and enhance real-time decision-making. It means that these technologies should be prioritised by the companies regarding budgetary allocation for digitalisation. However, the strategic integration is needed based on the indirect, yet beneficial effect of SF and IoT on CEP practices. Not only are managers expected to adopt technologies, but they are expected to redesign business processes in a way that will promote recycling, reuse, and management of products and product life cycles. This integration plays a critical role towards the achievement of the environmental goals and should be included in the training and operation planning. The lack of importance of interoperability demonstrates that simple linking of systems is not enough; the companies should ensure that digital linkage is aligned with sustainability goals. The policymakers can promote these changes by providing incentives, regulatory support, and digital infrastructure that would respond to the green industrial practices. This is especially true in the instance of developing economies like China, where the inefficiencies in resources and the outdated manufacturing systems are prevalent. The incentive to use technology with the help of subsidies or tax relief can accelerate the shift to the production that is circular and green production, and sustainability audits can help to accelerate this process. The suppliers of technology will have to develop solutions, which would not only make the productivity more productive, but also enable tracking the environment, and it will be easier to correlate the digital strategy of the firms with the indicators of sustainability.

### Limitations and future directions

Although the current research offers significant information on how Industry 4.0 technologies and CEP can be used to improve sustainability in the Chinese textile industry, several shortcomings must be acknowledged. The research was cross-sectional, and this limits the ability to establish a cause-and-effect relationship between variables. The longitudinal research would also give an additional perspective on the transformation of the technological adoption and sustainability performance. The study had only covered textile firms in mainland China, and this might have limited the extension of the findings to other regions or industries. Further research can expand the geographical scope or focus on other sectors with similar environmental and digitalisation concerns, such as the leather, ceramics, or agro-processing sectors. Although the study has covered five key Industry 4.0 technologies, it has not taken into account the other emerging digital technologies, such as blockchain, artificial intelligence, or digital twins, which can also make a more significant contribution to sustainability. The digital transformation knowledge base would be improved through the introduction of more technologies in future models. The study was founded on self-reported survey data that may be influenced by response bias or social desirability. The reliability of the data would be enhanced by the mixed-method approach or by the third-party assessments. Even though the CEP was a mediator, other organisational capabilities such as green innovation, dynamic capabilities, or environmental leadership may be required as key mediators or moderators. These variables should be researched in the future to come up with a more comprehensive framework. The constraints will be discussed to advance the degree of theoretical understanding and applied research of digital sustainability, particularly in the context of the developed economies.

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