

Twin Transformation in SMEs: Integrating Digital Technologies and Circular Economy Principles

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Industry 4.0 (I4.0) based on the proliferation of emerging digital technologies like Internet of Things (IoT), AI, CPS, big data analytics and cloud is transforming manufacturing & production around the globe. Meanwhile, the Circular Economy (CE) paradigm has emerged as a driving force of sustainable industrial sectors which focuses on the improvement of resource optimization and waste generation minimization to ensure economy developed for sustainable benefit. Though significant industry has done a lot of work on the integration of I4.0 – the reality is that from a CE perspective, Small and Medium Enterprises (SMEs) are constrained by financial, structural as well as operational restrictions implicated in engaging with the concept. This paper explores literature regarding emerging diagnostics and assessment models for the nexus of Industry 4.0 with circular economy readiness in SMEs. The paper reviews common research methods, discusses critical gaps in the extant literature, and suggests a multi-level readiness framework based on technological, organizational, and environmental levels. The model is underpinned by fuzzy logic and MCDM methods. By integrating sustainability targets with digital transformation, the paper provides actionability for SME managers, policy makers and industry practitioners in search of competitive, agile and environmentally friendly production systems.

Keywords: Digital transformation, Industry 4.0, Readiness assessment, Small and medium enterprises, Sustainability

Introduction

Industry 4.0 refers to a seismic change from traditional manufacturing and industrial systems to that of automated analytics, machine learning and smart decision support that allows for self-adaptive run-time behaviours. Born in Europe, it is now a global movement that has the potential to shape industrial policy both in developed nations and in emerging economies such as India. It is the data-enabled, autonomous and intelligent systems driving production paradigm shift here. In a country like India where manufacturing contributes significantly to

GDP and large workforce is engaged in working on has launched national programmes under the banners Make in India, Digital India and Skill India to make industry competitive for digital fabrication. This is evidence that a successful evolution does not just hinge on technology innovation, but also having clear strategies, people who are trained an infrastructure in place.

Scrolling through the digital disruption, the circular economy has emerged as a sustainable response to linear “take–make–dispose” thinking. Its concern is resource efficiency and waste reduction: designing devices to last as long as possible, and to be used again in a “closed cycling loop” of reuse, repair, and refurbishment, remanufacturing or

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recycling. Combining Industry 4.0 with the circular economy can improve productivity, reduce environmental impact and increase market resilience. SMEs are frequently held back from adopting new technologies and practices by their lack of technical strength, tight budget or because they are not adequately prepared. The convergence of Industry 4.0 and circular economy principles, as shown in Fig. 1, explains SME readiness assessment by connecting technological integration with challenges and resulting benefits.

The remainder of this review nails this issue down at the level of SMEs by focusing on the requirement for readiness assessment frameworks. Present maturity models are created for and can be applied to large-enterprise scale which does not completely capture or consider its limitations, abilities, competitive factors of small organization. To mitigate this gap, the paper introduces a multi-dimensional readiness model for technological, organisational and environmental dimensions with the help of decision-support techniques such as fuzzy logic and Multi-Criteria Decision Analysis (MCDA). The framework provides the organization with a structured approach to identify strengths and weaknesses so that SMEs can be better prepared for

their digital and sustainable transformation.¹⁻³ These include resistance to change, no tech culture, lack of HR and low nuance regarding the long-term investment in this technology. Challenges such as poor IT infrastructure, shortage of monitoring tools and lack of a direction make transformation even more difficult. Most SMEs lack finance and expertise to invest heavily in digitalization leading to a high failure rate of digital adoption efforts.⁴⁻⁸ The only solution to such hurdles is special tools and frameworks more advanced than the common readiness evaluations. Accordingly, this research delivers a new readiness assessment model for the SME sector by integrating DT requirements and CE principles. With consideration of technology readiness, organization culture and environmental pressures, the model provides an integrated analysis on SME readiness. Besides indicating the gaps, the model gives strategic guidance for policy support, capacity building and investment planning. Finally, this work points to a further step towards bridging the void between I4.0 adoption and CE realisation, which offer implications to SMEs on how they can enhance their competitiveness, resilience and sustainability.⁹ The key dimensions influencing SME readiness for Industry 4.0-enabled circular economy adoption are summarized in Table 1, highlighting major factors, practical examples, existing barriers, and expected outcomes across technological, organizational, financial, external, and sustainability aspects.

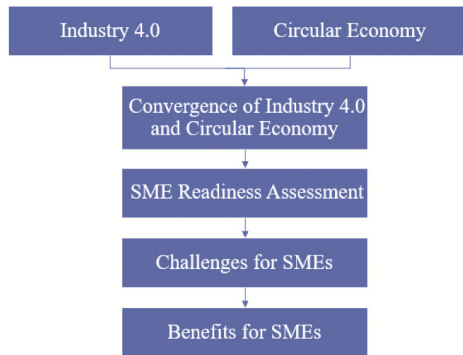


Fig. 1 — Convergence of Industry 4.0 and Circular Economy in SMEs

Scope of the Review

To increase transparency and rigour, the review could be enhanced with a brief account of the process for selecting literature. This section should briefly explain the databases searched (i.e., Scopus, Web of Science, Google Scholar), which period was considered and what were the main search terms combined with Industry 4.0, circular economy and

Table 1 — Dimensions of SME readiness for Industry 4.0 enabled circular economy adoption

Dimension	Key Factors	Examples in SMEs	Barriers/Challenges	Expected Outcomes
Technological	Automation, IoT, AI, Real-time monitoring	Smart machines, sensors, predictive analytics	Lack of IT infrastructure, limited technical skills	Improved efficiency, data-driven decisions
Organizational	Digital culture, Skilled workforce, Change mgmt.	Employee training, leadership support	Resistance to change, lack of digital mindset	Agile, adaptive workforce
Financial	Capital investment, Cost optimization, Funding	Govt. schemes, partnerships, subsidies	Limited access to capital, high upfront costs	Long-term cost savings, sustainable investment
External Environment	Policy, Infrastructure, Supply chain integration	Make in India, Digital India initiatives	Weak supply chains, inadequate infrastructure	Stronger networks, improved competitiveness
Sustainability	Resource efficiency, Recycling, Waste reduction	Closed-loop systems, eco-design	Low awareness, insufficient expertise	Reduced waste, greener operations, market edge

SMEs. Also, it would be useful for readers to know what inclusion and exclusion criteria were maintained (e.g., published in a peer-reviewed journal article, relevant to an SME context, involved readiness/integration frameworks) to have had studies identified and screened. Such clarification would provide additional methodological support to the review and contribute towards the trustworthiness of aggregated findings. As illustrated in Fig. 2, this structure highlights how the review links firm-level characteristics with digital–sustainability agendas while accounting for regional and contextual differences.

Focus on SMEs

"The Small and Medium-sized Enterprises (SMEs) face major scaling challenges due to limited financial resources, restricted market access, outdated infrastructure, and technical implementation issues such as system exceptions and improper background processing, which collectively hinder their digital transformation efforts. This enables them to better integrate Industry 4.0 practices with tasks related to Circular Economy (CE) activities. SMEs, in contrast, encounter more severe constraints.^{10–13} SMEs are cash poor and tend to have limited access to external capital when it comes to making large investments in technology. Digital technologies and automation systems have no-value/low value (high cost) return. These include IoT enabled machines, data analytics tools, Industry 4.0 applications etc, which are mostly above the available budgets.^{14–17} There are also technical hurdles that we need to overcome for these Establishment's. Most of the SMEs are equipped with antiquated facilities, outdated information systems and

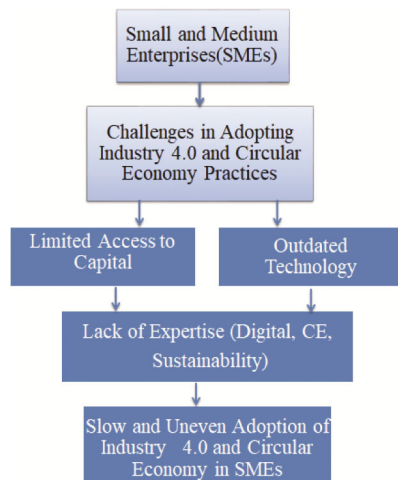


Fig. 2 — Challenges to Industry 4.0 and circular economy integration in SMEs

no compliance with the connectivity and interoperability standards central to I4.0.⁽¹⁸⁾ This condition of unpreparedness then impedes the development of digital integrated platforms for CE strategies, as waste reduction (resource-efficient closed-loop production and so on). Switching to a cryptic process/product undergoes an extensive investment but also potential production stops an especially important matter, taking into consideration the narrow margin and the competition where SMEs operate.

Uptake is also hindered by a lack of human resources. With many of the smaller workforces additionally holding varied roles, there is arguably limited scope for advancement and specialised training.¹⁹ A lack of inhouse expertise in digital technology, data analysis and sustainability management, for example, often means small businesses rely on external advisers at a cost. Dedicated staff, such as hydro champions and digital influencers is not enough to ensure operations that can be postponed in favour of day-to-day needs.²⁰ The process of such a transformation is greatly affected by the organizational culture and leadership style. These forms may be able to foster agility in some cases but are likely to promote risk-avoidance where there isn't an obvious (and near term) benefit for emerging technologies or business models.

In many emerging markets such as India, SMEs work under policy settings that have limited support for digital and sustainable transformation. Lack of regulation, low availability of public funds and weak awareness about available support mechanisms hamper the uptake of Industry 4.0 and circular economy practices. These challenges emphasize the necessity of customized readiness assessment approaches that consider factors beyond technology maturity. "Successful models will also consider financial capacity, workforce readiness, practice culture and jurisdictional regulation. But what they should do is provide several linear steps-by-step routes that enable SMEs to adopt digital and circular solutions without being burdened by the onerous costs or the risk of trying to change systems entirely."

Integration of Digital and Sustainable Agendas

This study relates to the I4.0 (where CE is not an individual or occasional subject, but two parallel fields that may exhibit stronger effects than can be reached by each field separately). I4.0 provides a digital ecosystem through increased level of automation, Internet of Things (IoT) connectivity, big

data analytics, artificial intelligence and cyber physical systems in which CE is sustainability driven framework that concentrates on optimizing resource use at minimum waste generation with closed loop production.” By aggregating such concepts these two paradigms can create intelligent and self-organizing systems that enable more energy/consumptions efficient, but at the same time less wasteful or non-productive material flows.²¹ However, both of these isolated paradigms have several drawbacks. Without digital bank-up, it’s still too common for circular economy programmes are without sight of data, traceability and predictive insights towards the optimal stewardship of resources. Concurrently, a sustainability-neutral uptake of technology may help lock in the linear model of production known as “take-make-dispose”. The integration of I4.0 with CE aims to overcome these barriers by combining sustainability in digital systems. So, time-based monitoring of energy/resource usage, predictive maintenance to enhance lifecycle of equipment’s and large scale analytics are possible on the development of close loop based dry regenerator value chain.²² It is evident that the fusion between Industry 4.0 and the circular economy brings value. It allows cost savings by decreasing use of raw materials, it enables new business models — remanufacturing, product-as-a-service and it helps to stay competitive by cooperating with increasing expectations of customers as well as regulatory circularity targets. Readiness assessment frameworks therefore must be able to gauge technical knowledge levels as well as how effectively sustainability is built into an organisation’s culture and in their decision making processes and the day to day routine of doing business.²³

Global Relevance with Local Adaptability

Although we have located our review within the context of Indian SMEs due to its overall economic importance, degree of complexity and maturity in digital adoption, there may or may not be anything particularly unique about this in terms of these principles, models or suggestions that they are not relevant elsewhere. The problems faced by SMEs in India — paucity of funds, shortage of skilled labour and infrastructure deficiencies — hold good for many developing regions such as Southeast Asia, Africa and Latin America. Furthermore, elements of the readiness model such as investigating organisational culture, leadership and sector specific barriers for example are also considered to be relevant for other

SMEs within advanced economies who are also negotiating transitions towards sustainability.²⁴ Our proposed architecture is with modularity and flexibility, it is practical. Instead of devising detailed criteria, it is a standard that is adaptable based on regional policy, industry structure and market maturity. For example, small businesses operating in highly regulated environments may initially focus on compliance and reporting systems, while businesses in less regulated contexts can begin with low-cost digital enhancements and building awareness. Similarly, manufacturing-SMEs need more attention for predictive maintenance and real-time resource monitoring to service logistics- and internal process-oriented SMEs could have more importance on digital platforms.²⁵ The model is designed to be general and applicable in a variety of regions, with opportunity for local tailoring. Its attention to global relevance and local particularities allows SMEs to draw on best practices developed elsewhere and at the same time pursue solutions tailored for their specific environments, further contributing to its ability adapt in an evolving industry environment.²⁶

The review also recognises sectoral variations. Product-oriented SMEs often need more automated production processes and preventive maintenance, service-oriented companies lean toward digital platforms that can monitor resources and make them more efficient. The objectives and scope of the review is detailed in Table 2 while key drivers, challenges and implications for SMEs have been considered to focus on the integration of Industry 4.0 technologies with circular economy principles to enable environmentally sustainable context-specific performance levels.

Need for the Study

The repeated discussion of SME barriers and readiness challenges throughout the manuscript is evident. For purposes of clarity and efficiency, these elements can then be combined into one topic-specific statement in the need-for-the-study or readiness dimensions section. Later sections can return to this composite discussion, thereby avoiding repetition but maintaining an analysis that is both deep and coherent. The inspiration for the work is both a technological opportunity and an ecological imperative. Industry 4.0 represents a crucial bridge between technological capability and environmental sustainability, as shown in Fig. 3, linking digital potential to the requirement of sustainability and innovative industrial development.

Table 2 — Scope of the Review: Key considerations for SMEs in Industry 4.0 and circular economy integration

Focus Area	Key Drivers	Challenges/Barriers	Implications for SMEs	Expected Outcomes
Focus on SMEs	Financial strength, Tech infrastructure, Managerial expertise	High capital costs, legacy machinery, lack of skills, centralized decision-making, weak policy support	Difficulty in digital-CE adoption, dependence on external consultants, resistance to change	Need for tailored frameworks, phased adoption, balanced financial & operational risks
Integration of Digital & Sustainable Agendas	I4.0 as enabler (IoT, AI, CPS), CE as sustainability framework	CE lacks visibility without digital tools, risk of linear 'take-make-dispose' without CE integration	Requires embedding sustainability metrics into digital systems & strategies	Cost savings, waste reduction, new business models, improved market competitiveness
Global Relevance with Local Adaptability	Indian SME ecosystem, cross-border benchmarking, sector-specific needs	Financial shortages, skill gaps, infrastructure issues in developing economies	Regional customization, modular framework adaptable to sector/policy context	Broader applicability, resilience to global trends, sectoral adoption pathways

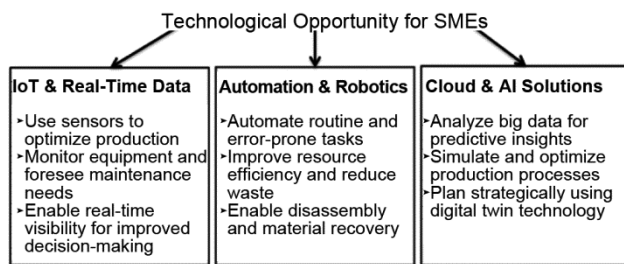


Fig. 3 — Digital technologies enabling Industry 4.0 opportunities for SMEs

Technological Opportunity

The connected, agile and sustainable industrial systems are served by Industry 4.0 as the digital business model in life. It gives SMEs an actual shot to add a competitive edge, even if they aren't at the scale and infrastructure-level of their large enterprise counterparts. IoT-enabled applications, cyber-physical systems, AI, big data analytics, cloud services and advanced robots are the disrupting enablers to automate deterministic tasks and map resource or frugality use in support of networked production environments with autonomous or semi-autonomous decision-making behaviour. One of the major benefits for SME's is to make data-driven decision in real-time. Since Sensor-based systems provide continuous monitoring of production processes, material flow or machine use. Preventative maintenance ultimately, preventative maintenance reduces unforeseen down times, extends life of the machine and minimises waste. Advanced analytics can also assist in the analysis of waste, demand forecasts and material asset recovery in accordance with circular economy concepts. It also continuous and makes the system even more reliable by minimizing watch dependent processing as in an automatic sorting or robotic un-assembly / disassembly within a closed loop production process. Cloud computing and digital twin technology allows SMEs to simulate production

cases, simulate life-cycle impact and choose the process with environmental advantages. The fact that the criteria of a circular economy are considered in the planning service and simulation phase ensures from right at the beginning already defined sustainability targets with Selection fulfilment, process optimization und so operating efficiency.²⁷

Environmental Necessity

Climate change is being manifested in increasing global mean temperature, an increase in the number of extreme weather events and the loss of environmental stability that threaten economic security and human health. Removal of natural resources on the other hand is still unsustainable; great pressure is put upon finite resources and ecological balance disturbed. The present linear model of production-consumption-disposal has become increasingly inconsistent with the demand on global perspective.²⁸ Transition toward sustainable patterns of production and consumption, not by CE among others, is already impossible but a matter of global demand no CE principles such as reducing, re-using and recycling could be seen as providing an organising framework for decoupling economic growth from environmental harm.

“The link with this sustainability scheme is particularly important for SMEs. In addition to the above regulation factor, a circular economy based on Industry 4.0 technologies is also designed to make supply base not susceptible to sudden price changes of material resources. Through embedding sustainability in business models, SMEs have chances to contribute to a global shift towards an economy based on low carbon and enhancing their competitiveness and long-term stability.

Strategic Gap in SME Transformation

However, due to the reality of Industry 4.0 (I4.0) tools within the context of Circular Economy (CE) it

is foreseen in a natural way, even though we can anticipate an impactful mature state there is still a significant strategic void on consolidated approaches supporting SMEs on its transition to a total CE. The majority of the current readiness assessment frameworks are largely designed for big corporations considering that companies were very well capitalized, with innovation department in place and most importantly already using the modern digital infrastructure as verified. These assumptions are rarely congruent with the real situation of SMEs, particularly in EMDE countries where capital and technical know-how as well as qualified HR are even scarcer. Employee Sense-making are limited in scope, and do not strongly consider the context of SMEs e.g., technological immaturity, challenge on funding digital adoption, focus on short-term operational performance on the expense of a long-term strategic transformation.^{29,30} Therefore, SMEs are generally forced to interpret basic digitalization guidelines that may not be tailored for an organization. Leaner, less skilled manpower; restrictions from full use of advanced production technology; shorter time horizons for investment and seriously bankable liquidity constraints are characteristic elements of their reality. In addition to million jobs creation potential in India if successfully scaled, alignment with global and national sustainability regimes such as the UN Sustainable Development Goals and India's National Action Plan on Climate Change accentuate the importance of scalable strategies considering resource constraints encountered by SMEs.³¹ The synergy of technological opportunities, environmental pressures and strategic voids in Table 3 highlights the need for tailor made Industry 4.0 & circular economy readiness models for SMEs.

Literature Review

Evolution of Industry 4.0 and CE Integration

This hybrid space sits between the intersection of Industry 4.0 technologies and Circular Economy concepts. Early exploratory works largely suggested conceptual models (e.g., where to apply IoT in the product lifecycle or applying AI for waste reduction).³² Recent works have moved to strategic level analyses, studying system-level circular transitions at the enterprise level enabled by data-driven Industry 4.0.⁽³³⁾ The combination of digital twins and block chain enhances transparency and traceability along the value chains, enabling efficient material recovery and remanufacturing.³⁴ These efforts demonstrate through empirical evidence how digitalisation enables value capture, product lifetime extension and reduced resource utilisation, which are essential to circular innovation.³⁵ That approach is especially applicable to SMEs because the money they have to work with in making their investments and operations decisions is always limited, so a gradualist approach just seems like a no-brainer. The interaction between I4.0 and CE have also triggered new business models like product as service achieved through smart product monitoring and advanced analytics.³⁶ The latest studies give evidences that companies are need to consider CE principles in their strategy making because of the environmental goals and government regulations.³⁷ This change is similar to that of the regenerative view of industry in the world, where materials are reused continuously and resource waste should be limited.³⁸ Digital technologies thus emerge as enablers in the mediatisation of material loop closure, lifecycle extension and resource efficiency for industry to help meet global demands for waste reduction.³⁹ Further research that is more systematic allowed to continue

Table 3 — Summary of the need for the study – technological opportunity, environmental necessity, and strategic gaps for SMEs

Section	Key Focus	Highlights	Implications for SMEs
Technological Opportunity	Role of Industry 4.0	Adoption of IoT, CPS, AI, big data analytics, robotics, and cloud platforms enables automation, predictive maintenance, and data-driven operations.	Improves operational efficiency, flexibility, and material recovery, while supporting closed-loop manufacturing and real-time decision-making.
Environmental Necessity	Climate and resource concerns	Rising concerns related to climate change, resource depletion, and waste generation require a shift toward circular economy practices.	Encourages SMEs to adopt CE-supported digital strategies to reduce waste, improve energy efficiency, and meet regulatory and market expectations.
Strategic Gap in SME Transformation	Barriers to adoption	Current readiness and maturity models are largely designed for large firms and do not adequately address SME-specific financial, skill, and infrastructure constraints.	SMEs lack tailored frameworks; need scalable, phased, and context-sensitive models aligned with SDGs and national climate policies.

the work of such unresolved issue regarding what is indeed possible with existing Industry 4.0 integration.⁴⁰⁻⁴² At this level, tool-path optimizations together with in-process measurement enable adaptive control at high spatial and temporal resolutions that translate into enhanced productivity and reduced loss.⁴³⁻⁴⁵ Industry 4.0-related use cases, such as predictive maintenance and analytics-driven resource efficiency support circular economy in the virtual elimination of costs and operational complexity.⁴⁶ Analogous methodology utilizing energy consumption and scope 1 and 2 emissions demonstrates that data-driven decision support and automated system optimization can make the system more resilient, at the same time as decreasing negative environmental performance.⁴⁷ From a supply chain point of view, the fact that the cyber-physical system could be used to reconfigure the traditional supply chain model into a smart and connected network. Other studies have linked I4.0 for business model innovation, that is collaborative, data driven models for CE outcomes. The application of IT systems in the supply chains is one way to improve eco-innovation processes and cheaper production of green goods.⁴⁸ These developments, taken together, show that I4.0 is guiding the direction toward smart self-organizing shop-floor composed of intelligence, accuracy and agility panels.^{49,50} Real time analysis and decision making will now enable to optimise production process and system performance more efficiently.⁵¹ In this digital-physical hybrid combination by IoT and CPS has created 'smart factories', where machines, products, or materials are able to communicate with each other for production control without human intervention.^{52,53} The concept of individual pursued decentralized self-optimized type production system is the newly presented model.^{54,55}

In general, the literature portrays a trajectory from token technological games playing to an integrative framework conceptualizing digitization and sustainability as mutually enforcing, rather than discrete, paths'. This emergent literature highlights the transformative nature of I4.0-CE convergence for supporting its greening, sustainability and competitiveness of industrial systems. On the other hand, Fig. 4, the development of Industry 4.0 and circular economy is presented, in which digital technologies like IoT (Internet of Thing), AI (Artificial Intelligence), blockchain and CPS have been corresponding to cleaner production, resource recovery, efficiency and transparency step by step.

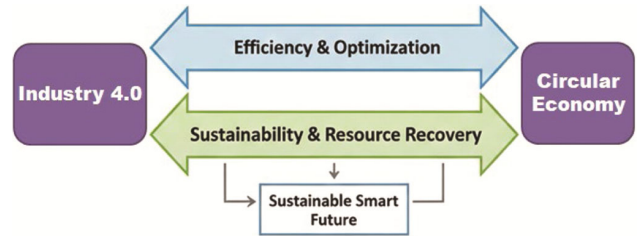


Fig. 4 — Evolutionary pathway of Industry 4.0 & circular economy integration

Common Themes of Literature

From a review of this literature, several common themes have emerged which delineate the isochoric 4-stream intersection I4.0 and CE in academic and industrial literature: Enabler Technology For the past decade, numerous technologies have emerged that enable IMS services to be open ended in term of the Qsupport and location transparency assuming there aren't restricts on RTT (Round Trip Time). Core I4.0, such as Internet of Things (IoT), artificial intelligence (AI), big data analytics, Cyber-Physical Systems (CPS) and cloud platforms are considered the fundamental enablers of CE integration. With such monitoring we need predictive analytics and automated decision making which can optimise the use of resources and not let them go waste when that infra has already been built. They also lead to linear to circular production models with the help of closed loop materials and product-as-a-service approaches.⁵⁶ It is this digital systems architecture that equally over time evolves existing models of supply chain management and typical volumetric chains into more sustainable and resilient circular economies commodity-type cycles which drive new economic growth from the basis of eco-conservation, resource effectiveness.⁵⁷

Sustainability Linkages

The intersection of Industry 4.0 and the Circular Economy enable superior sustainability performance, which is evidenced by improvements in resource utilization, waste generation, and energy consumption. These DTs allow the tracking of materials throughout their lifecycle in closed loops production systems thereby bring environmental benefits and operational flexibility. Automating such operations will also improve financial performance with streamlined use of resources and tightly controlled costs.⁵⁸ This loop feedback model shows that through decoupling economic growth from negative environmental consequences, the digital revolution itself can provide for a new kind of

Table 4 — Literature review on Industry 4.0 and circular economy (CE) integration

Focus Area	Key Contributions / Findings	Challenges / Gaps	Implications
Sustainable manufacturing with I4.0	Explored retrofitting existing equipment to achieve sustainability goals; introduced early I4.0-CE links.	Limited to incremental upgrades; less focus on systemic frameworks.	Relevant for SMEs with financial constraints, showing incremental paths toward CE.
Structured frameworks for I4.0 adoption	Proposed multi-layered frameworks; identified gap between current capabilities and I4.0 needs.	Lack of SME-specific roadmaps; highlights resource and skill shortages.	Need for targeted capacity building and phased adoption strategies.
Role of services in I4.0	Integrated service networks with manufacturing transformation; emphasized resource productivity across value chains.	Underexplored role of non-manufacturing sectors in CE integration.	Encourages holistic, cross-sectoral approach including logistics and services.
Supply chain integration	Showed role of CPS in enabling smart, interconnected supply chains for CE outcomes.	Cyber security and interoperability challenges.	Supports smart supply chains to drive CE practices.
Business model innovation	Advocated network-based, collaborative models leveraging data-driven decision-making.	Limited awareness and implementation in SMEs.	Demonstrates potential for CE-aligned, collaborative business ecosystems.
Twin Transformation (Digitalization + Sustainability)	Introduced concept of twin transformation in procurement; improved transparency and traceability.	Still conceptual; limited empirical applications in SMEs.	Promotes simultaneous pursuit of digital and sustainability agendas for competitive advantage.
Evolution of I4.0 & CE	Documented shift from technology-specific studies (IoT, AI, and blockchain) to systemic strategies enabling closed-loop manufacturing and CE.	Barriers: high costs, lack of skills, fragmented frameworks, SME neglect.	Highlights global trend toward synergistic I4.0-CE integration as a sustainability imperative.

development and an economy to be regenerated.⁵⁹ Therefore, a circular economy of efficient resources is to develop a-brand-new economic system by means of intentionally reducing the flows that are diluted, slow and closing based on its internal materials and energy; it is helpful to guide the solution for all kinds of problem along this or similar line track or economy; environmental sustainability. This is just the beginning of a concept in which waste is regarded as an energetic and material resource, promoting the recycling of products and materials in industrial processes instead of their mere treatment.

Barriers to Adoption

While the value has been demonstrated, take up is still impeded by long-standing barriers: high upfront capital costs; a workforce skills shortage in digital and sustainability related skills; lack of awareness in available solutions or business models. The problems raised above are even more significant in SMEs that face not only scarce resources but also the inability to experiment and scale up. Moreover, the difficulty to generate multiple I4.0 technologies and CE principles is great that had an expertise, which the most of SMEs did not have data privacy & security issues can complicate and limit the roll-out of digital circular use solutions for smaller companies.^{60,61} These types of barriers need to be addressed and reinforce the need for targeted supportive mechanisms such as policy drivers, training schemes, networking facilities etc. in change towards widespread implementation of I4.0

compliant CE practices in industry, and especially among Small and Medium Enterprises (SMEs). Additional regional digital innovation hubs and common data-sharing standards may also help address these barriers by providing training infrastructure and by encouraging secure, interoperable systems that are required for successful adoption of CE approaches.⁶² Furthermore, they should include knowledge transfer and skills upgrading mechanisms to overcome the dearth of technical knowledge and technological know-how typically found in innovation-poor SMEs⁶³ And the frameworks have to get better at realising and acknowledging that flexible, modular adaptation paths make sense for SMEs, who aren't likely to reshape their businesses from ground up just because they want something new presents an overview of research relating to how Industry 4.0 technologies and the principles associated with CE overlap in ways that contribute towards sustainability and barriers to, and implications for such development are identified, particularly at the SME level.^{64,65} The major research contributions, gaps, and implications related to Industry 4.0 and circular economy integration are presented in Table 4, which is positioned at mid to support a clear synthesis of SME-focused insights from the literature.

Future Directions

For intervention application, future work must move forward beyond theoretical reconciliation to

experimental examination of the framework for readiness we have suggested. It was necessary to begin by showing that case study research was relevant across a variety of SME sectors empirically and that local norms and paradoxes could be discovered. A second option that readiness dimensions could be assessed at great scale within survey projects using standardized questionnaires and the relative contribution of technological, organizational, and environmental determinants tested empirically. Third, as adopting digital and circular business practices is gradual, longitudinal research is necessary to reveal how the levels of SMEs' readiness change over time. Finally, decision support systems such as fuzzy logic, and/or multi criteria decision analysis can be linked to actual operational data to provide a benchmarking tool for the policy makers so that this framework becomes operational within SMEs and at policy making level.

Conclusions

The cross-sectoral converge between the Fourth Industrial Revolution and the Circular Economy is a game changer for SMEs inclined towards sustainability, resilience and long-term competitiveness under severe resources limitations. Advanced digital technologies, such as IoT, AI, cyber-physical systems, block chain and digital twin enable circular economy solutions with predictive maintenance, real-time monitoring and closed-loop production. Instead of seeking for interrelations between sustainability with digitalization, scientific output in this field has advanced from initial reductionist perspectives to a literal view where digital transformation is directly attached to the achievement of objectives to provide environmentally sustainable outcomes. Yet, SMEs continue to face major barriers for adopting digital technologies – financial constraints, skills shortages, lack of access to quality digital infrastructure and an uninspiring regulatory framework. In this concept, the twin-shift into digital and sustainability has competitive strategic direction that extends far beyond greenwash to investment in added-value economic success and operational efficiency. To support such a transformation, context sensitive and incremental readiness models are required that take into consideration the stages of SME maturity as well as its available resources. Furthermore, in the light of accelerating sustainability globally, it is rather

towards a sustainable approach to integrate circular economy indicators into the digital strategies and align these with SDGs, Climate action plans & compliance. Therefore, in short time readiness models' validation is a requirement to advocate large scale pilot deployment and policy co-design & steering of such good pay back factor potential that plays for wide adoption among SMEs.

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