Digital Technologies and Circular Economy Innovations:

Evidence from Manufacturing Firms in Emilia-Romagna and Veneto

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Abstract: The twin transition represents the concurrent advancement of digitalization and environmental sustainability across economies, compelling firms to innovate through technologies that are both green and digital. This convergence is transforming industrial structures and competitive dynamics, as companies increasingly need to align with the twin transition to maintain competitiveness, regulatory compliance, and long-term value creation (Calvino et al., 2025).

The literature examining the relationship between digital technologies and environmental innovation can be broadly divided into two strands. The first focuses on eco-innovation aimed at reducing the environmental footprint of information technology, the so-called green for IT perspective (Faucheux and Nicholai, 2011). The second, and the one this paper builds upon, emphasizes the enabling role of IT in fostering green innovation, referred to as the IT for green hypothesis.

Recent studies have underscored the central role of digital technologies as enablers of eco-innovation. Among these, Montresor and Vezzani (2023) offer one of the first comprehensive analyses. Using data from ISTAT's Permanent Census of Firms, they examine a large sample of over 150,000 Italian companies. Their results show that the eco-innovative contribution of digitalization is primarily driven by investments in artificial intelligence (AI) applications, while other digital technologies display more selective and context-dependent effects. Moreover, eco-innovative production processes and business models benefit from bundled digital investments, though the magnitude of these effects varies across firm sizes.

A complementary perspective is offered by Ning et al. (2023), who analyze 1,166 Chinese listed manufacturing firms between 2008 and 2019. Their findings demonstrate that enterprise digitalization positively affects green innovation, with this relationship mediated by the firm's absorptive capacity, i.e., its ability to acquire, assimilate, and apply external knowledge. In addition, green credit policies act as a moderator, strengthening the link between absorptive capacity and green innovation. These results highlight that both internal capability-building and supportive external financial and regulatory frameworks are essential for translating digitalization into environmental

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innovation.

However, existing studies tend to rely either on patent data or on simple binary indicators to capture whether firms have redesigned their production processes to mitigate environmental impacts. They provide limited consideration of circular economy principles or of the diverse strategies through which firms may reduce pollution and waste or enhance product reuse and resource efficiency.

On the second aspect, existing literature has largely examined the economic implications of green and digital innovations separately. Studies on green innovation (e.g., Chirico et al., 2025) show that market responses to green patenting depend on firm characteristics and patent attributes. For instance, in family firms, patents with longer approval times are perceived positively, signaling due diligence and a long-term sustainability orientation, whereas highly radical green innovations tend to generate negative reactions, possibly due to perceived risk aversion. Similarly, Perdichizzi et al. (2024) find a negative relationship between carbon emission intensity and firm market value among European listed firms, suggesting that environmental inefficiency diminishes investor confidence. The strength of this relationship varies across emission scopes and institutional contexts, echoing prior evidence that improvements in environmental performance can enhance financial outcomes (Clarkson et al., 2011; Ghisetti & Rennings, 2014).

On the digital side, research consistently highlights the productivity-enhancing role of Industry 4.0 and AI-related technologies. Cirillo et al. (2022) demonstrate that firms adopting digital technologies experience notable gains in productivity and sales, with stronger effects among SMEs and mature firms. This is consistent with evidence from Brynjolfsson and McElheran (2016) and Haskel and Westlake (2018) emphasizing the centrality of intangible digital assets in shaping competitiveness. Additionally, Cockburn et al. (2019) show that AI-related patents foster firm value and innovation spillovers. However, studies jointly assessing green and digital innovation remain scarce. An emerging perspective is offered by Biggi et al. (2025), who conceptualize “green intelligence” as the integration of AI into environmental technologies, demonstrating that AI acts as a general-purpose technology that amplifies green innovation potential. This insight underscores the growing interdependence between digital and environmental technological domains.

Building on this foundation, the present study provides novel firm-level evidence on the role of IT for the circular economy ,to do so, this paper investigates this synergistic evolution by examining how Digital Technology (DT) drives Circular Economy

Innovations (CEIs). Using a novel dataset of 1,549 manufacturing firms in the Emilia-Romagna and Veneto regions, we combine theoretical and empirical analyses to comprehensively describe the relationship between DT and CEIs. A key contribution of this study is that, by utilizing micro-survey data rather than relying solely on patents, we are able to capture the innovation performance of SMEs, thereby offering a more grounded and accurate reflection of their behaviors.

Specifically, this study examines the impact of DT on CEIs using Logit, OLS, and Negative Binomial models, complemented by an instrumental variable (IV) approach to address endogeneity concerns. Our empirical strategy mainly includes three steps:First, we assess how DT affects three distinct CEIs, Reduce, Reuse, and Recycle. Second, we decompose DT into eight technological categories (e.g., AI, IoT, and Big Data) to identify which digital technologies most effectively drive heterogeneous CEI. Third, we conduct subgroup analyses to explore whether these effects vary across firms with different levels of R&D intensity and GHG emissions.

Our findings indicate that DT significantly catalyzes CEIs, with the most pronounced impact observed in Reduce-type innovations, followed by Recycle and Reuse. Specifically, Internet of Things (IoT) and Big Data emerge as the most robust drivers, followed by Robotics. However, frontier technologies like Artificial Intelligence (AI) have yet to demonstrate a statistically significant effect in the current sample. These results reveal a clear technological and functional heterogeneity: while DT effectively optimizes resource efficiency (Reduce), its role in complex product life-extension (Reuse) remains limited.

Overall,this study contributes to a deeper understanding of the strategic role of digital technologies in advancing circular economic innovation, generating important implications for both firm-level innovation strategies and broader industrial policy design.

Keywords: Twin Transition, Circular Economy, Digitalization, Firm

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