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Digital-circular pathways for wine industry: Exploring evidence from multinational enterprises

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A B S T R A C T

The global shift toward the twin transition requires firms to integrate digital transformation and sustainability into a unified strategic framework. Within this context, the wine industry represents a particularly relevant field of observation due to its strong dependence on natural resources, high exposure to climate variability, and growing external pressure to enhance environmental performance. This study investigates the interplay between Industry 4.0 technologies and Circular Economy strategies in leading multinational wine enterprises, with the aim of understanding how such integration facilitates sustainable transformation. Through a multiple case study of three major Italian wine companies, this research investigates the technological and strategic mechanisms by which firms operationalize Circular Economy principles. A three-dimensional qualitative assessment was conducted through focus groups to evaluate each company's level of digital enablement, technological diversity, and alignment with the hierarchy of circular strategies. The findings reveal that the interaction between digitalization and circularity is not linear but strategically differentiated across firms. Three distinct digital-circular pathways are identified: data-driven prevention, automation-driven recovery, and governance-oriented efficiency. The study highlights that sustainable transformation emerges from strategic alignment between digital and circular initiatives rather than from the mere magnitude of technological adoption. These results provide novel insights into how technology, governance, and circular practices jointly shape sustainable competitiveness, offering actionable guidance for managers aiming to foster innovation and enhance environmental performance across industrial ecosystems.

1. Introduction

The global economic landscape is increasingly defined by the imperative of the "twin transition", demanding that firms simultaneously pursue rapid digitalization and the deep integration of sustainability principles [1]. This dual mandate requires a systemic redesign of operations, leveraging Industry 4.0 (I4.0) technologies to effectively enact the strategies of the Circular Economy (CE) [2]. The CE, defined by its comprehensive R-strategies hierarchy (R0-R9), provides the strategic blueprint for decoupling economic growth from resource consumption, while advanced digital technologies furnish the organizational tools to monitor, optimize and validate these efforts across complex value chains [3]. This framework, central to operationalizing CE objectives, provides a structured approach to implementing CE principles, guiding firms toward more regenerative systems [4,5]. It classifies strategies into short, medium and long loops, emphasizing prevention and resource minimization at the top of the hierarchy (R0-R2), prolonging product and component use (R3-R7), and recovering residual value through recycling or energy extraction when necessary (R8-R9). Applying these strategies allows companies to enhance resource efficiency, strengthen supply chain resilience and gain competitive advantages [6,7]. In this context, I4.0 provides the technological infrastructure to operationalize CE principles, with digital technologies acting as enablers that embed circular strategies directly into organizational processes and value chains [8–10]. By generating real-time data flows, supporting predictive modeling and guiding the

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redesign of production processes, these technologies make it possible to monitor material cycles, reduce waste, and optimize resource use, leading to enhanced traceability, operational efficiency and resilience across the value chain [1,11,12]. The wine industry offers a particularly compelling and critical context for examining the practical challenges and potentials of this twin transition, due to it being a resource-intensive sector critically dependent on natural resources and highly exposed to climate volatility [13,14].

Key sustainability challenges span the entire wine value chain, including the management of the water footprint [15], the complex valorization of vast volumes of agro-industrial by-products, and the optimization of global distribution and logistics [16]. The industry generates large volumes of diverse organic by-products such as grape pomace, vine trimmings and wine lees, that present both sustainability challenges and opportunities for circular valorization [17]. Furthermore, the sector's vulnerability to climate variability such as water scarcity, droughts and extreme weather events, makes the integration of sustainable and digital practices particularly urgent [18]. Multinational enterprises (MEs) in this sector, due to their organizational scale, expansive supply chains and global market influence, play a pivotal role in driving this transformation. Their ability to integrate advanced digital capabilities with robust CE strategies represents a key determinant of the entire ecosystem's sustainable future. As widely discussed in Section 2, while extensive literature details the theoretical potential of I4.0 technologies (e.g., Internet of Things (IoT), Big Data) to enable circularity [8] and explores the R-strategies framework [19], a crucial empirical and methodological gap persists regarding the real-world operationalization of the twin transition within major wine MEs. Specifically, research lacks a critical, evidence-based assessment of technology deployment, often remaining anecdotal rather than systematically quantifying the actual level of Digital Enablement and the Technological Variability supporting CE measures; this deficiency hinders understanding of whether technology is driving genuine transformation or merely incremental efficiency. Furthermore, existing research often fails to rigorously map operational sustainability initiatives into the structured R-strategies hierarchy, making it difficult to definitively assess a firm's strategic depth. The aim of this study is, therefore, to unveil the technological, strategic and organizational dimensions of the CE within wine ME. Specifically, the study seeks to address the following Research Question (RQ): *How do leading multinational wine enterprises strategically integrate Industry 4.0 technologies to implement Circular Economy principles?* To answer this question, the study is conducted through a multiple case study approach. This research contributes significantly to the body of knowledge on the technological, strategic and organizational dimensions of circularity by introducing a three-dimensional qualitative assessment (Digital Enablement, Technological Variability, R-Strategy Coverage) and three pathways of digital-circular transformation within the wine industry, offering a methodological tool for evaluating the true maturity of organizations undergoing the twin transition. The resulting findings offer critical practical insights for managers seeking to foster internal innovation ecosystems, redesign strategies and strengthen the overall sustainability performance of the wine industry. The remainder of the manuscript is structured as follows: Section 2 reviews the theoretical background. Section 3 details the multiple case study methodology, including the data collection process and the three-dimensional qualitative assessment. Section 4 presents the detailed case study findings. Section 5 discusses the results also in a comparative way. Finally, Section 6 outlines theoretical and managerial implications. Sections 7 concludes the paper explaining conclusions, limitations and avenues for future research.

2. Theoretical background

The twin transition provides a transformative lens for rethinking industrial value creation [1]. Within this context, the CE offers a conceptual framework to move beyond linear production models, guiding firms toward strategies that prevent waste, extend product life and recover value across the value chain [2]. Digital technologies, in particular those included in the I4.0 paradigm, act as enablers of this transformation, supporting the monitoring, optimization and redesign of operations in line with circular objectives [3,8,19]. In the wine sector, sustainable and circular principles are expressed through measures such as reducing energy and water consumption, repurposing grape by-products, and promoting the reuse of materials [20,21]. Therefore, the twin transition exemplifies how the integration of I4.0 technologies and CE approaches can create resilient, efficient and environmentally aligned industrial systems, providing a conceptual bridge to explore both the R-strategies framework and the role of digital enablers in practice [1,9].

2.1. R-strategies for circularity

The R-strategies framework is a cornerstone of the CE, providing a hierarchical approach that systematically moves beyond the linear "take-make-dispose" model toward a regenerative system [4]. This framework serves as a strategic roadmap for companies aiming to decouple economic growth from resource consumption [5]. As illustrated in Fig. 1, the framework is organized into three main loops: short, medium and long, each representing a different level of effectiveness in retaining resource value.

Short Loops (R0-R2): These are the most effective strategies as they prevent resource use from the outset.

- R0 - Refuse: The highest priority is to completely avoid a product or resource, saying "no" to unnecessary items to prevent their production and disposal.
- R1 - Rethink: This involves finding new ways to achieve the same function with fewer resources, such as through a service-based model where customers pay for a product's use rather than for its ownership.
- R2 - Reduce: This strategy focuses on minimizing resource consumption by using fewer materials or less energy during production and use.

Medium Loops (R3-R7): These strategies extend the life of products and components, keeping them in use for longer.

- R3 - Reuse: Using a product again for its original purpose (e.g., a refillable glass bottle).
- R4 - Repair: Fixing a broken product to restore its function.
- R5 - Refurbish: Upgrading or restoring a product to a "like new" condition.
- R6 - Remanufacture: Disassembling a product and rebuilding it with new and reconditioned parts.
- R7 - Repurpose: Using a product for a different function than its original one.

Long Loops (R8-R9): These are the last-resort strategies when a product can no longer be used. While still better than disposal, they result in the most significant loss of value.

- R8 - Recycle: Processing waste materials into new materials for new products. This often requires significant energy and can degrade material quality over time.
- R9 - Recover: The lowest priority, involving the recovery of energy from waste, for instance, through incineration.

The most impactful strategies are those at the top of the hierarchy, as they prevent waste generation at the source, thereby retaining the highest level of embodied energy and value in products and materials [6]. Therefore, the goal of implementing a CE is to shift from the bottom of the hierarchy (linear) to the top (circular). The application of these

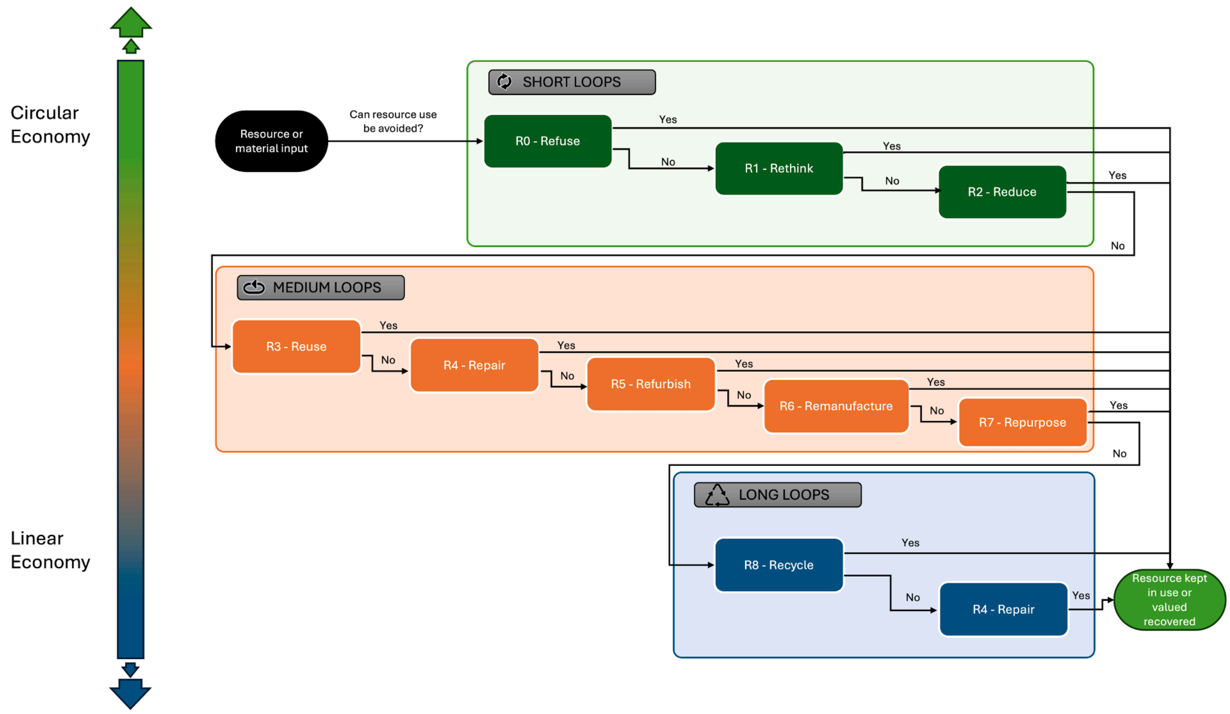

Fig. 1. R-strategies framework representation (own production).

strategies addresses environmental imperatives, while also conferring a significant competitive advantage. Given the high water and energy demands of viticulture and winemaking, a winery can Reduce its water and energy consumption through advanced irrigation and renewable energy systems [22]. Additionally, due to the large volumes of grape pomace generated during winemaking, a winery can Repurpose grape pomace into new products like grapeseed oil [23]. A specific application of Reuse helpful when considering the environmental impact and cost associated with producing new glass bottles, is the practice of collecting, sanitizing and reusing wine bottles which significantly reduces the demand for new glass [24]. Furthermore, among the environmental challenges faced by the wine industry, the resource demands of traditional glass packaging exacerbate the situation, prompting producers to explore alternative formats that could Reduce material use and waste, such as canned wine, which also represents a way to Rethink product packaging in a sector where glass bottles are a strongly established design [25]. From a regulatory standpoint, facing increasingly stringent environmental regulations and potential compliance risks, adopting R-strategies helps companies proactively comply with legal requirements, mitigate fines, and enhance overall sustainability performance [26].

Strategically, embracing circularity enhances a company's brand reputation, attracts environmentally conscious consumers and investors and fosters supply chain resilience by reducing dependency on volatile raw material markets [7]. This transition, from linear to circular, is heavily supported by digital transformation, with technologies like IoT and blockchain enabling the efficient tracking of materials, managing reverse logistics and optimizing resource flows [27]. For example, sensors can monitor the condition of reusable wine bottles, while blockchain can ensure the transparency of recycled materials, turning waste streams into valuable assets and unlocking new business models [28].

2.2. Industry 4.0 for circularity

The I4.0 paradigm offers the technological infrastructure to operationalize CE principles [1,30]. The complementarity between I4.0 and CE [31] is widely recognized, as digital technologies are increasingly framed as levers to sustain competitiveness while advancing environmental goals [32,3,33]. In this view, the nine technological pillars of I4.0 are described as enablers of circularity, since they provide the digital backbone for embedding CE principles into value chains [33–35]. Their main contribution lies in generating real-time information flows that connect material cycles with digital systems, thereby enabling monitoring, predictive modeling for waste reduction, and the redesign of production processes [8,19,33], guiding businesses towards sustainable objectives into a synergistic pathway in which digital infrastructures support circularity measures [10]. The agri-food sector offers a particularly compelling case, given its structural dependence on natural resources and high exposure to climate variability [11]. In such contexts, efficiency, waste minimization and traceability are not optional goals but structural requirements for resilience and long-term competitiveness [1]. Many technological applications support achieving sustainable and circular objectives also in a specific industry such as the wine industry [12], where I4.0 plays the role of a necessary lever for enhancing sustainability, competitiveness and innovation in the sector [12].

The primary contribution of digital technologies in this regard lies in their ability to enhance monitoring and control activities across production processes [36]. IoT-based sensor networks allow for real-time monitoring of production and critical product parameters, optimizing resource use and reducing losses while ensuring consistent product quality [20,21,29]. Automation and Robotics streamline processes from grape harvesting to bottling, minimizing waste and energy consumption [37]. The collection of multi-year agronomic and operational data, combined with Big Data analytics and AI, supports predictive decisions on harvest timing, disease management and process optimization, enhancing both efficiency and sustainability [20]. Simulation-based decision support systems are sometimes employed by winemakers to anticipate environmental and market variability, promoting circular resource flows [21], while Cloud Computing platforms enable the integration of vineyard and cellar data, ensuring traceability, lifecycle management and efficient reverse logistics [35].

Collectively, these I4.0 applications illustrate how digital enablers translate CE objectives into concrete practices, fostering sustainability and competitiveness beyond the boundaries of a specific industrial sector of application [12]. However, while existing studies illustrate how individual I4.0 technologies can enhance monitoring, resource efficiency and circular practices in the wine sector, a higher-level perspective reveals that these contributions are largely fragmented. Most research focuses on isolated applications or specific stages of the value chain, without systematically exploring how the coordinated deployment of multiple technological families can drive a holistic circular transformation. Furthermore, the limited evidence on how such technologies are integrated into organizational processes to fully enable the twin transition represents a clear gap, highlighting the need for empirical investigations that assess the combined technological and strategic dimensions of circularity in practice, thereby providing the foundation for the present study.

3. Methodology

3.1. Rationale for a multiple case study approach

To investigate how wine ME deploy digital technologies to implement circular strategies, this study adopts a multiple case study approach. This methodological choice is particularly suitable for examining complex and contemporary phenomena within their real-life context, where the boundaries between phenomenon and context are not always clearly defined [38–40].

By focusing on more than one case, the design enables cross-case comparison, allowing patterns and divergences to emerge and thereby strengthening both the validity and depth of the findings [41–43]. The selection of the multiple case study method is motivated by the need to explore the interplay between sustainability strategies, digital transformation and circular practices in organizations that operate in a highly globalized and competitive industry. Unlike single case studies, which can provide rich but context-specific insights, a multiple case strategy supports analytical generalization, offering broader evidence to frame theoretical contributions [44]. This approach is especially valuable in underexplored research domains such as the intersection of CE and digitalization in the wine sector.

3.2. Research setting

In multiple case study research, case selection is carried out strategically rather than randomly, ensuring alignment with the study's objectives. In this research, the cases were chosen specifically to enable meaningful comparison and contrast [44].

Within the multiple case study methodology, the number of cases is not determined by rigid sampling rules but rather by the specific objectives and design of the research. As highlighted by Lipsey [45] and Yin [40], a larger number of replications is generally required when the study aims to validate subtle or highly complex propositions, whereas a smaller set of well-chosen cases may be sufficient when each provides rich, in-depth evidence to generate robust analytical insights. In this study, three cases were purposefully selected - Mezzacorona Group, Caviro Group and Collis Veneto Wine Group – as they offer comprehensive and comparable insights into how I4.0 technologies enable sustainability and circularity in the wine sector. These cases share similar contextual features, including geographical setting, industrial domain, company typology, technological maturity and sustainability orientation (Table 1).

This design allows for the identification of common patterns and the exploration of nuanced differences in the ways digital technologies are leveraged to advance circular and sustainable practices within the sector.

The selection of the case studies focused on the Italian wine industry, which represents one of the most internationally recognized sectors of the national agri-food system. The wine sector in Italy plays a pivotal role not only from an economic perspective – being among the top contributors to agri-food exports – but also in terms of environmental and social sustainability due to the intensity of land use, water consumption and the complexity of its global value chains [13,15]. According to the Italian Wine Union [16], Italy has maintained its global leadership in wine exports, with over 22 million hectoliters exported in 2022, making sustainability and circularity strategic priorities to remain competitive on the international stage. The rationale for selecting an Italian winery with a global sales network was threefold: i) Italian wineries are at the forefront of combining tradition and innovation, increasingly adopting I4.0 technologies to enhance traceability and sustainability [14]; ii) the global distribution of Italian wine highlights the sector's exposure to international regulations, sustainability standards, and consumer preferences, thus offering a rich ground to study circular and sustainable practices; iii) wine production is often associated with challenges related to resource efficiency, climate change adaptation, and stakeholder engagement across complex international supply chains [46]. These factors justify the relevance of the Italian wine sector and support its selection as the context for this study.

Table 1
Case Study Selection - Comparison Features.

GEOGRAPHICAL CONTEXT	Headquarter in Italy, global selling
INDUSTRIAL SECTOR	Beverage - winery
COMPANY TYPOLOGY	Multinational, cooperative
TECHNOLOGICAL MATURITY	High level
SUSTAINABILITY ORIENTATION	Creating long-term value through a circular economy, and strengthening stakeholder trust with transparent and responsible reporting

The focus on MEs is particularly justified, as they represent a distinctive organizational form in the agri-food sector that combines global market presence with strong local embeddedness. In Italy, wine cooperatives account for nearly 50 % of national wine production and play a strategic role in export markets [14,16]. Their cooperative structure fosters collective action, resource sharing, and risk distribution among member producers, while their multinational dimension allows them to scale sustainability and digital transformation practices across global value chains [15,46]. Given their dual role as both economic drivers and sustainability enablers, MEs provide a particularly relevant context to investigate how CE principles and I4.0 technologies can be integrated into agri-food business models.

The selection of companies exhibiting advanced technological maturity and a clear sustainability vision – emphasizing the creation of long-term value through a CE and strengthening stakeholder trust via transparent and responsible reporting – is methodologically strategic for this study. Such companies are equipped to implement and scale digital technologies like IoT, data analytics and blockchain, which are pivotal in optimizing resource use, enhancing traceability and promoting transparency across operations and supply chains. Moreover, their commitment to sustainability ensures that these technological initiatives align with broader organizational goals and stakeholder expectations. This combination of technological readiness and sustainability commitment makes these companies particularly suitable for exploring how digital technologies can enable CE strategies and support sustainable business model innovation in the wine sector.

Recent studies underscore the importance of digital transformation in achieving sustainable business performance. For instance, a meta-analysis by Bindeeba et al. [47] demonstrates a positive association between digital transformation and sustainable business performance, highlighting the role of digital technologies in advancing sustainability goals across various sectors. Additionally, Moller et al. [34] discuss how digital transformation can enhance CE and circular business models, emphasizing the enabling role of digital technologies in achieving environmentally friendly production and profitability. These findings reinforce the relevance of selecting companies with high technological maturity and a sustainability vision for this research.

3.3. Conducting the multiple-case study

The methodology adopted in this research to conduct the multiple-case study represents an adaptation of the Digitalization & Sustainability Case Study (D&SC) Guideline proposed by Latino et al. [48] (Fig. 2). Specifically, the first three phases of the D&SC Guideline were inherited and tailored to the context of the wine industry, ensuring methodological coherence while allowing flexibility to address the specific objective of this study.

Phase A, named "*Identifying sustainable needs*", represents a preliminary step in the research process, aimed at understanding the specific sustainability and innovation needs of the wine sector and characterizing the types of companies considered in the study. This phase involved identifying the challenges, opportunities and market pressures that drive companies to adopt sustainable and circular practices, as well as assessing the technological readiness and strategic orientation of potential case study candidates. The analysis highlighted a clear need for structured approaches to evaluate and implement sustainable innovation, particularly in wine MEs that seek to integrate CE principles while maintaining competitiveness in global markets. These insights directly formed the study's objective: to develop a comprehensive framework to assess how I4.0 technologies can support sustainability and circularity initiatives, aligning business practices with stakeholder expectations and long-term value creation.

Phase B, named "*Mapping sustainability information*", focused on systematically collecting and analyzing publicly available information to map the sustainable and circular measures implemented by the selected companies, as well as the I4.0 technologies supporting these initiatives. The primary sources of data included the companies' sustainability reports, complemented by secondary data collected from corporate websites, social media profiles, and other publicly accessible platforms.

This phase allowed the research team to identify the types and scope of sustainability circular measures, and the technological solutions deployed to support them. The insights gained in this phase provided a detailed overview of how wine MEs integrate sustainability and digital transformation, establishing the foundation for the subsequent qualitative analyses in Phase C.

Phase C, named "*Data Analysis*", involved rigorous, evidence-based qualitative assessment founded on the results of the data collection. A Focus Group composed of five experts in twin transition and CE themes was convened to critically analyze the data and provide the necessary validation for the subsequent qualitative assessment. The group included two senior researchers with expertise in sustainable business models and I4.0, one junior researcher in organizational studies, one industry manager experienced in implementing circular practices in the wine sector, and one practitioner specializing in digital transformation and sustainability consulting. The evaluation followed an iterative, multi-step discussion protocol, with feedback loops ensuring that each qualitative judgment was reviewed and agreed upon by at least four of the five participants. This phase moved beyond simple mapping to a structured, critical evaluation designed to define the role of I4.0 in sustainable circular measures and gauge the firms' readiness to support these initiatives. The assessment established three core analytical dimensions, with final ratings assigned using a qualitative scale (High, Medium, Low and Absent):

1. Digital Enablement: This dimension determines the extent of I4.0′s role in circularity, thus establishing the level of digital enablement. It assesses the proportion of sustainable circular measures that are supported or driven by technology. We operationalize this dimension by (i) counting the proportion of circular measures with documented I4.0-based technological support, and (ii) assigning qualitative ratings as follows: High (≥75 % of the company's implemented measures are digitally supported), Medium (40–74 % digitally supported), Low (1–39 % digitally supported or only marginally supported), and Absent (no documented digital support).
2. Technological Variability: This analyzes the interplay of technology and circularity, specifically the relationship between a particular technology and a specific sustainable circular measure, to determine the level of technological variability. It assesses the breadth of the I4.0 technology portfolio used. We conducted this evaluation considering (i) the number of technological families adopted (out of the nine identified in the I4.0 paradigm), (ii) the diversity of

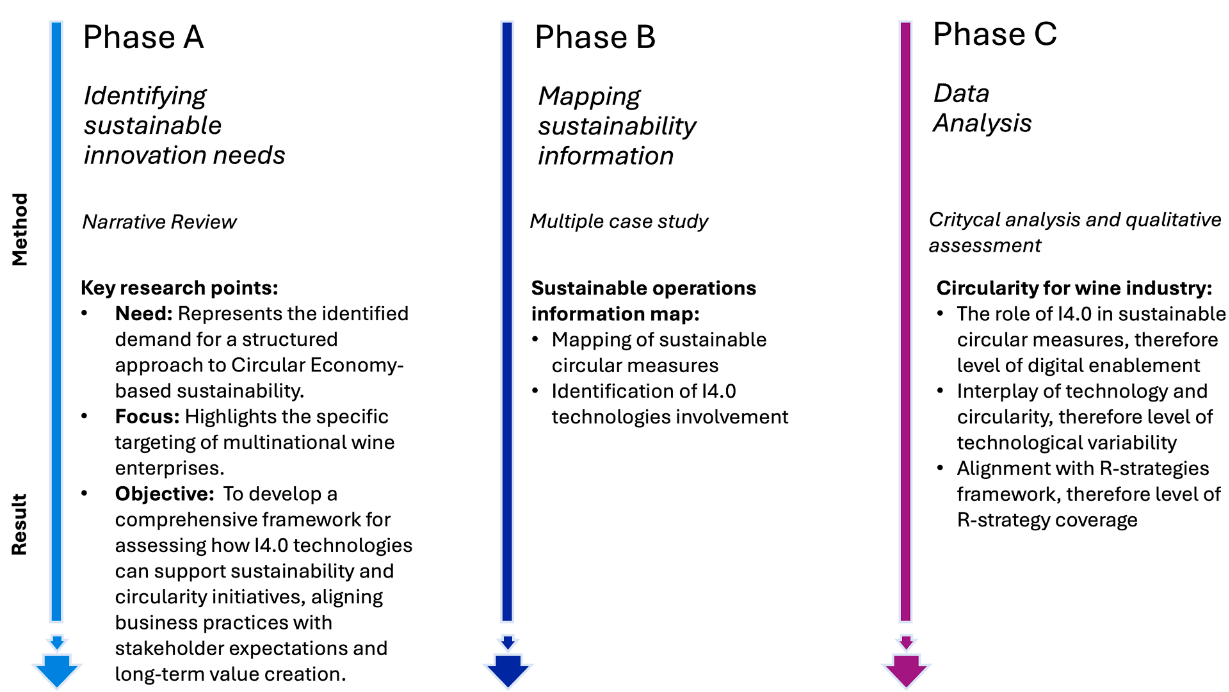

Fig. 2. Three-phase methodology: methods and results (own production).

application domains they address, and (iii) the presence of complementarity, where different technologies are jointly used to reinforce circular outcomes. A High rating corresponds to the use of at least 5 technological families with documented complementarities across multiple circular areas; Medium reflects the use of 3 or 4 technologies with limited interaction; Low indicates reliance on only 1 or 2 technologies; and Absent denotes no verified technological deployment.
3. R-Strategy Coverage: This evaluates the alignment extent of sustainable circular measures (both technology-enabled and traditional) with the R-strategies framework, establishing the level of R-strategy coverage. It measures how many of the ten R-strategies are addressed by the firm's practices. Qualitative ratings were assigned as follows: High when seven or more R-strategies are addressed, Medium for four to six strategies, Low for one to three strategies, and Absent when no R-strategy is clearly implemented.

To ensure robustness and reliability of the qualitative ratings, the evaluations for each dimension were subsequently discussed and validated through an additional focus group session with the same expert participants involved earlier in the study. This step enabled a collective examination of the evidence, promoting convergence of interpretations and resulting in consensual assessments for each firm and analytical dimension. The complete Data Collection Protocol, including illustrative examples for each research phase and specifically detailing Phases B and C of the methodology, is provided in Appendix (Table A1).

This structured, critical approach provided a comprehensive, evidence-based understanding of how sustainability and circularity are operationalized within the companies, moving the analysis from descriptive mapping to prescriptive assessment.

4. Results

4.1. Case study 1: Mezzacorona Group

Company overview and sustainability vision. Mezzacorona Group operations are focused primarily on wine production (encompassing still, sparkling and distilled products) and include fruit cultivation. With commercial activities extended to numerous international markets, the ME has consolidated its global presence. Its vision encompasses principles of collective governance, reciprocity, and community engagement, with sustainability embedded in its core values. Sustainability guides every step, from field to packaging, blending environmental care, safety and quality.

Sustainable circular measures. The company aligns with industry best practices, implementing circular measures and approaches that reflect the overall green and ecological footprint of its operations, covering multiple aspects of sustainability, including social and governance dimensions. Specifically:

- *Water management optimization.* The company has taken a leading role in Reduce (R2) strategies for water resource consumption, setting a 2024 target of achieving a 21 % reduction in water used for production and treatments. This required a comprehensive effort upstream in production and at a strategic level (Rethink R1) to intervene across the entire internal production cycle. The completion and commissioning of wastewater treatment facilities at all production sites enabled water recovery for reintegration into the production cycle, treating residues from washing and production processes for secondary uses such as irrigation (Recycle R8). The regenerative approach to water resources, combining strategic planning, optimized water management and reduced usage, is also reflected in the use of sub-irrigation, which allows for targeted water application while minimizing waste.
- *Water footprint assessment.* In addition to operational practices and interventions for water management, the Group demonstrates a strategic commitment to maintaining low resource consumption through continuous monitoring and performance control, in order to prevent unnecessary waste (Rethink R1, Reduce R2). Technology plays a key role in achieving these goals, particularly the use of digital tools such as Big Data, which enable the company to collect data on direct and indirect water consumption, analyze trends and plan reduction strategies from grape cultivation to winemaking and bottling.
- *Renewable and digital energy integration.* Energy procurement is one of the areas where the company most clearly demonstrates its commitment to sustainability, by integrating renewable sources and moving towards greater energy self-sufficiency (Rethink R1). Currently, >51 % of the company's total energy use comes from renewable sources self-generated through solar thermal and photovoltaic systems, thereby reducing reliance on the national energy grid (Reduce R2). The shift to renewable energy, replacing fossil-based sources, enables the company to lower the use of polluting raw materials as well as its overall emissions.
- *Energy monitoring.* As with water, integrated IoT and Big Data systems support energy management by monitoring the consumption of production machinery, collecting real-time data from each plant and production line. This enables quick detection and prevention of waste, inefficiencies or consumption peaks (Rethink R1, Reduce R2).
- *Sustainable logistics*. Internal logistics and material handling within plants and warehouses are managed using hybrid and electric vehicles, supporting grape transport from vineyards to the winery, internal operations, customer deliveries and local distribution (Rethink R1). This approach reduces overall emissions from activities (Reduce R2) and demonstrates a clear commitment to phasing out high-impact practices while consciously rejecting more harmful solutions (Refuse R0).
- *Circular valorization of by-products.* As in any production system, processing by-products account for a significant share of materials often destined for disposal. For the company, grape pomace, lees and stems from the early transformation stages are partly recovered and valorized as an additional resource, reused as inputs in subsequent processes. This approach, which primarily involves organic matter, optimizes resource use, reduces waste and generates new raw materials to be effectively valorized (Reuse R3, Recycle R7, Reduce R2). Beyond the direct ecological benefits of this circular strategy, reintegrating by-products into the production cycle also helps lower disposal costs.
- *Waste sorting and recovery.* All direct and indirect waste generated at production sites and company facilities is separated at the source into designated collection streams. This ensures that each type of waste is either properly disposed of or sent for recycling, preventing mixing and contamination, and promoting material recovery while reducing landfill-bound waste. The Recycle (R8) strategy, established across all industrial departments, begins with proper internal waste management, starting from the company's internal boundaries, and aims to ensure that materials at the end of their life cycle have a final opportunity for transformation. A proactive approach to this circular strategy not only reinforces the company's green foundation but also guides compliance with regulatory standards.
- *Sustainable packaging.* The company's approach to sustainability is also reflected in ethical choices that guide much of its operations, such as adopting sustainable packaging solutions (Rethink R1). The raw materials used in packaging production are optimized, reducing their quantity, weight and material complexity (Reduce R2). As a result, glass bottles are made lighter, cardboard containers are optimized in volume and thickness, and the use of additional secondary packaging materials, often plastic, is significantly reduced. These measures lead to a considerable reduction in carbon dioxide emissions, stemming from both packaging production and transportation. Furthermore, the use of recycled materials in packaging design further strengthens the Recycle (R8) strategy.

- *Low-Impact Agronomic Inputs.* Upstream in the value chain, before the production phase and in the management of raw materials, the company adopts low-risk agronomic inputs such as natural fertilizers and products with reduced chemical and biological impact (Refuse R0, Reduce R2). These practices mitigate environmental impacts from the earliest stages of operations while also enhancing the quality of the final products. At the same time, they ensure compliance with organic certification standards, making the supply chain more sustainable and certifiable (Rethink R1).
- *Sustainable Production Standards.* Applying protocol standards demonstrates the Group's tangible commitment to sustainability, requiring the adoption of agricultural and winemaking practices that comply with national guidelines and the careful oversight of every stage of the supply chain to ensure quality and safety. Integrating these protocols means, on the one hand, a comprehensive rethinking of production processes to enhance their sustainability (Rethink R1) and, on the other hand, the refusal of non-compliant practices or those with a high environmental impact (Refuse R0). The use of IoT technologies to monitor and adjust conditions in the winery and production areas ensures that environmental standards are consistently maintained over time.

For Case 1, the connections between the sustainable circular measures adopted and the principles of circularity defined by the R strategies, together with the I4.0 technologies applied to implement them, are illustrated in Fig. 3.

4.2. Case study 2: Caviro Group

Company overview and sustainability vision. Caviro Group is vertically integrated in the combination of agricultural production with industrial processing. Its operational model merges traditional viticulture with advanced technological and ecological practices, supported by a widespread network of growers. With a consolidated presence in both domestic and international markets, the company plays a significant role in connecting agriculture, industry and environmental innovation. Sustainability is a central pillar of the company's strategy, since the whole production cycle is designed to reduce waste and emissions, regenerate resources and return organic value to the soil.

Sustainable circular measures. The company has fully integrated circular approaches across all levels of its production and distribution, building its brand and mission around them. Its commitment to sustainability is operationalized through the following practices:

- *Water management optimization.* The company has implemented a water resource protection plan that enables the recovery of 621 million liters of water, equivalent to 42 % of its total demand. As a result, a significant portion of the water used in production processes is no longer extracted from aquifers but comes from recovery systems, reuse and optimized production cycles (Recover R9). This approach reduces pressure on natural water resources and enhances the overall sustainability of production processes.
- *Renewable & digital energy integration.* Extensive photovoltaic and agrivoltaics systems have been installed at multiple sites to produce

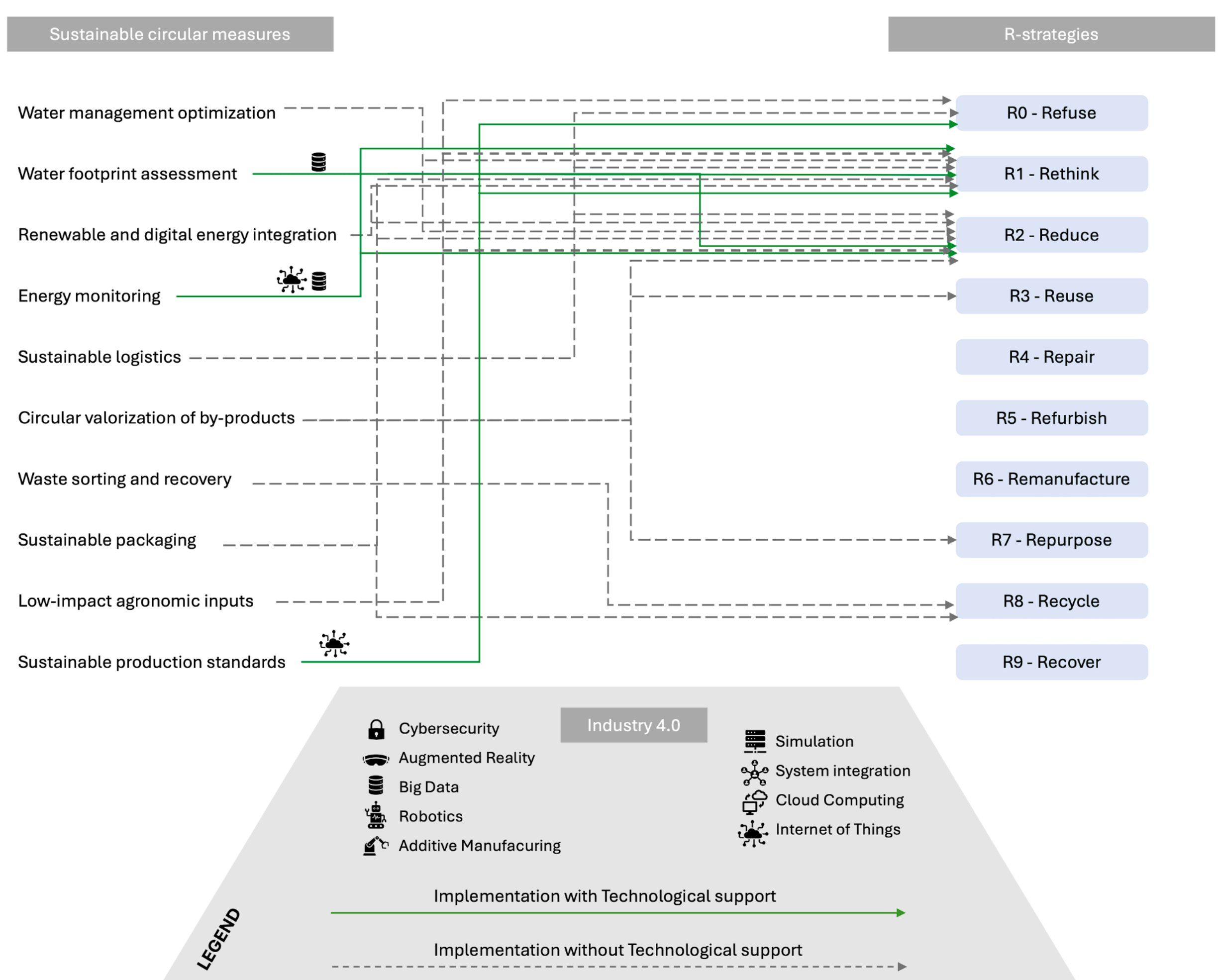

Fig. 3. Evidence from Case study 1.

renewable electricity, while energy consumption across operations is being actively reduced. These measures lower greenhouse gas emissions (Reduce R2) and support a transition to sustainable energy use through the redesign of energy management practices (Rethink R1). By integrating renewable energy production across different locations, the company enhances energy self-sufficiency and optimizes the efficiency of its operations.

- *Energy monitoring.* Across all production sites, machinery, tanks and filtration systems are interconnected in real time with the management system through IoT and Big Data technologies. This network enables continuous monitoring and control of operations, ensuring optimal performance, consistent quality and timely intervention in case of anomalies. By leveraging these digital capabilities, the company can rethink and optimize production processes, aligning with Rethink (R1) principles.
- *Sustainable logistics.* An automated warehouse has been implemented for the transport and storage of packaging materials (bottles, cartons, caps, etc.), equipped with digital systems that allow for fully automated movement from the packaging department to storage. This automation reduces handling times, errors, energy use and space waste (Rethink R1, Reduce R2). Robotic technologies have been essential in these operations, enabling efficient logistics and seamless warehouse management aligned with production systems.
- *Circular valorization of by-products.* Many production lines are dedicated to processing large volumes of by-products and residues from winemaking (pomace, lees, stems and other agro-industrial waste). Over 99 % of these materials are valorized: pomace and other residues are converted into biogas for renewable energy production (Repurpose R7), advanced biomethane suitable as vehicle fuel or for sale as green energy (Recover R9) and organic fertilizers that are reintroduced into the vineyards (Reuse R3). In this way, waste streams are transformed into secondary raw materials and energy, reducing disposal requirements (Recycle R8).
- *Carbon and climate footprint assessment.* A carbon footprint assessment is conducted to quantify greenhouse gas emissions across the company's entire production cycle, including vineyard management (fertilizers and machinery), winery operations (energy, water and materials), packaging, logistics and wine distribution. The aim is to identify key carbon sources and implement targeted strategies to effectively reduce overall emissions (Reduce R2).

For Case 2, the connections between the sustainable circular measures adopted and the principles of circularity defined by the R strategies, together with the I4.0 technologies applied to implement them, are illustrated i Fig. 4.

4.3. Case study 3: Collis Veneto Wine Group

Company overview and sustainability vision. Collis Veneto Wine Group corporate strategy is based on a model that integrates viticulture, industrial transformation and sustainable innovation. The enterprise combines traditional oenological practices with advanced technological solutions, with the aim of reducing environmental impacts and strengthening the resilience of the entire value chain. Sustainability

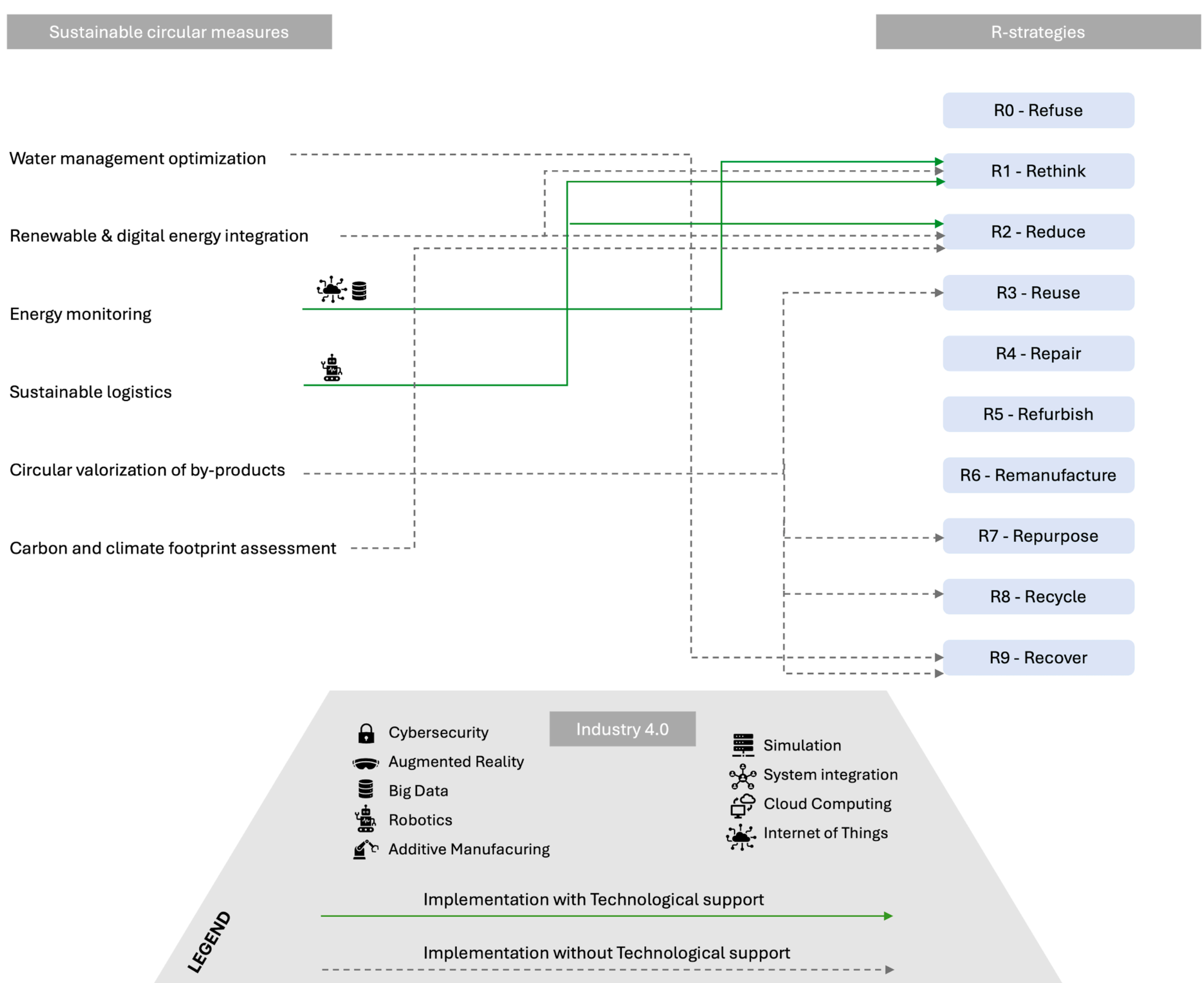

Fig. 4. Evidence from Case Study 2.

represents a cornerstone of the Group's vision: key initiatives include the transition towards the exclusive use of renewable energy, the optimization of water and energy resources and the valorization of winemaking by-products. Circular waste management and the National Quality System for Integrated Production (SQNPI) certification further underlines the efforts of the Group towards a low-impact, reuse-oriented economy.

Sustainable circular measures. The Group's sustainability strategy is based on the principles of resource efficiency, waste minimization and value regeneration, thereby positioning circularity as a structural component of its operational and strategic model. The following measures exemplify how circular practices are concretely implemented:

- *Water management optimization.* The optimization of water resources emerges as a central component of Group's sustainability strategy. The company has progressively introduced structured practices for the monitoring, treatment and reuse of water resources, embedding them into the broader governance of environmental performance. A distinctive element is the adoption of IoT-based solutions, which enable the real-time collection and transmission of data on water withdrawals, consumption points and wastewater generation. This digital infrastructure facilitates a more precise allocation of water across critical production stages, including vinification, cleaning and irrigation, thereby reducing inefficiencies that historically characterize the wine sector. The data-driven perspective also permits predictive management, anticipating anomalies and planning corrective interventions before critical thresholds are reached. In terms of CE strategies, these practices clearly align with Reduce R2, since they allow for substantial reductions in absolute consumption of water resources. At the same time, the integration of IoT contributes to the systemic rethinking of water as a regenerative resource within production cycles, reflecting a broader transition from linear extraction–use–discharge models towards closed-loop, resilient water management.
- *Renewable and digital energy integration.* Collis has undertaken a structural shift in its energy model through the progressive integration of renewable energy sources, particularly photovoltaic plants, into winery infrastructures. Although not supported by advanced digital technologies in the current phase, this strategy demonstrates a clear commitment to reducing dependency on non-renewable resources and to recovering the intrinsic potential of solar energy. By generating renewable electricity internally, the company strengthens its autonomy from external and fossil-based supplies, while simultaneously reducing greenhouse gas emissions across the life cycle of its products. From the perspective of circular strategies, this practice directly reflects Recover R9, as it leverages the recovery of natural energy fluxes that would otherwise remain unexploited. It further embodies the principle of ecological regeneration, transforming passive environmental flows into active contributors to production, and aligning the company with the European decarbonization agenda and the objectives of the Green Deal.
- *Energy monitoring.* The company complements its renewable energy commitment with a robust monitoring system designed to optimize overall energy efficiency. Here, the enabling role of digital transformation is particularly evident. The integration of system-level architectures and big data analytics allows for the continuous collection, aggregation and interpretation of data on energy consumption across all production facilities. This integration supports the development of a comprehensive energy baseline, facilitates the identification of high-intensity hotspots and enables benchmarking both internally and against sectoral best practices. The scientific relevance of this approach lies in its capacity to transform raw data into actionable insights, guiding managerial decisions towards efficiency improvements and decarbonization pathways. By ensuring a reduction in unnecessary energy losses and a rationalization of demand, energy monitoring strongly contributes to Reduce R2. Moreover, the embedding of digital technologies elevates the company's energy governance to a predictive and preventive paradigm, consistent with the principles of I4.0-enabled sustainability.
- *Sustainable logistics.* Within the downstream segment of its value chain, Collis has devoted increasing attention to logistics optimization, recognizing transport as a significant source of emissions and inefficiency in agri-food systems. The company has implemented strategies aimed at rationalizing delivery routes, consolidating shipments, and adopting packaging and distribution models that minimize environmental externalities. These measures exert a dual effect: on one hand, they support Reduce R2 by cutting fuel consumption and associated greenhouse gas emissions; on the other, they align with Recover R9, insofar as they favor the recovery and reuse of logistical assets (such as packaging materials and transport containers) and the optimization of return flows. From a systemic perspective, sustainable logistics underscores the importance of expanding circular principles beyond the production plant, embedding them into the wider network of supply chain relations and market interactions.
- *Circular valorization of by-products.* The management of vinification by-products represents a domain of high potential for circular transition in the wine sector. Collis has activated pathways for the reallocation of residues such as grape marc, lees and other fermentation by-products into secondary uses, preventing their classification as mere waste. This valorization process operates at different levels of the circular hierarchy. At the basic level, Reuse R3 is achieved when by-products are redirected to agronomic functions, for example as soil conditioners or organic amendments. At a more advanced stage, Recycle R8 is enacted through the transformation of these biomasses into new materials or compounds suitable for industrial applications. Finally, Recover R9 is mobilized when organic residues are used as feedstock for energy recovery processes, thereby re-entering the economic cycle in the form of renewable energy carriers. While the 2023 sustainability report indicates that these processes are still developing, the multi-layered approach reflects a strategic awareness of the bio-circular potential embedded in the wine production chain. From a research perspective, the valorization of wine by-products can be further strengthened by integrating biotechnological solutions, industrial symbiosis, and partnerships with bio-based industries, enhancing the economic and ecological value generated from what was once considered a disposal burden.
- *Waste sorting and recovery.* A mature and highly effective waste management system is evident across all Collis facilities. The company achieved a remarkable performance in 2023, with >96 % of total waste streams diverted from landfill and allocated to recovery or recycling channels, leaving only 3.4 % destined for disposal. Such a result signals a systemic integration of circular waste governance within daily operations. From a strategic standpoint, this practice embodies Recover R9, transforming waste into an input for new cycles and approaching the paradigm of "zero waste to landfill". This performance is particularly significant when assessed in comparison to broader sectoral averages, often characterized by higher landfill dependency. Scientifically, it highlights the capacity of cooperative organizational models to internalize environmental externalities and to coordinate large networks of suppliers and producers towards common sustainability objectives.
- *Low-impact agronomic inputs.* At the agricultural level, Collis has anchored its sustainability model in the progressive reduction of synthetic chemical inputs. The adherence of all 299 member farmers to National Integrated Production Quality System (SQNPI) and/or organic certification demonstrates a systematic alignment with integrated and ecological production practices. These certifications require the reduction of pesticide and fertilizer use, the adoption of integrated pest management, and the maintenance of soil fertility and biodiversity. Such practices are fully consistent with Reduce R2, as they directly minimize input intensity while safeguarding

ecosystem services. The scientific relevance of this measure lies in its upstream focus: interventions in the agricultural phase carry disproportionate weight in life-cycle environmental assessments of wine, and therefore represent a cornerstone of genuine sustainability transitions. By embedding low-impact practices at the base of the supply chain, Collis not only reduces its ecological footprint but also enhances product differentiation and market competitiveness.

- *Sustainable production standards.* Perhaps the most structural and institutionalized measure implemented by Collis is the adoption of Equalitas certification, which the group holds both at the organizational and product level. This certification embeds sustainability principles across environmental, social and governance dimensions, requiring compliance with strict performance indicators, traceability requirements and continuous improvement commitments. From the perspective of CE strategies, this institutional framework contributes to Rethink R1, as it necessitates a fundamental redesign of corporate governance and operational logic towards sustainability-driven value creation. It also reinforces Reduce R2, since adherence to Equalitas translates into verifiable reductions in resource consumption, waste generation and emissions. The certification, therefore, acts as a meta-instrument: it is not limited to individual practices but integrates and harmonizes the entire set of sustainability actions, ensuring systemic coherence and accountability.

For the Case 3, Fig. 5 represents the integration of sustainable circular measures with the R-strategies, while simultaneously illustrating the enabling role of I4.0 technologies in their implementation.

Table 2 summarizes all circular measures identified across the three cases, showing their associated R-strategies and whether I4.0 technologies are present or absent for each enterprise in a complete overview.

5. Discussion

The Mezzacorona Group demonstrates a medium integration of technology (digital enablement: medium), primarily leveraged for Short Loop efficiency and validation, aligning with the principles of the twin transition [1]. The Group's strategy prioritizes measurable performance in resource consumption, a core goal of the CE [5]. Digital tools, particularly IoT sensors and Big Data Analytics, are critical in supporting the highly prioritized Reduce R2 strategy through continuous Water Footprint Assessment and Energy Monitoring. This deployment transforms raw operational data into actionable insights for waste and inefficiency prevention, confirming the role of I4.0 in enhancing resource efficiency [8,19,33]. However, the analysis indicates that the technology portfolio shows limited variability (technological variability: low). Technological adoption is primarily focused on internal measurement and optimization, supporting incremental efficiency improvements. Advanced I4.0 technologies with potential to support systemic redesign, such as Simulation or Blockchain for external traceability and stakeholder engagement, are currently not explicitly applied to the core circular measures. This focus currently emphasizes protocol adoption and strategic goal-setting within Rethink R1, while offering significant opportunities to expand its impact across the value chain through operational redesign [3,8,19]. Mezzacorona demonstrates a strategically sound focus on both ends of the CE hierarchy (R-strategy coverage: high):

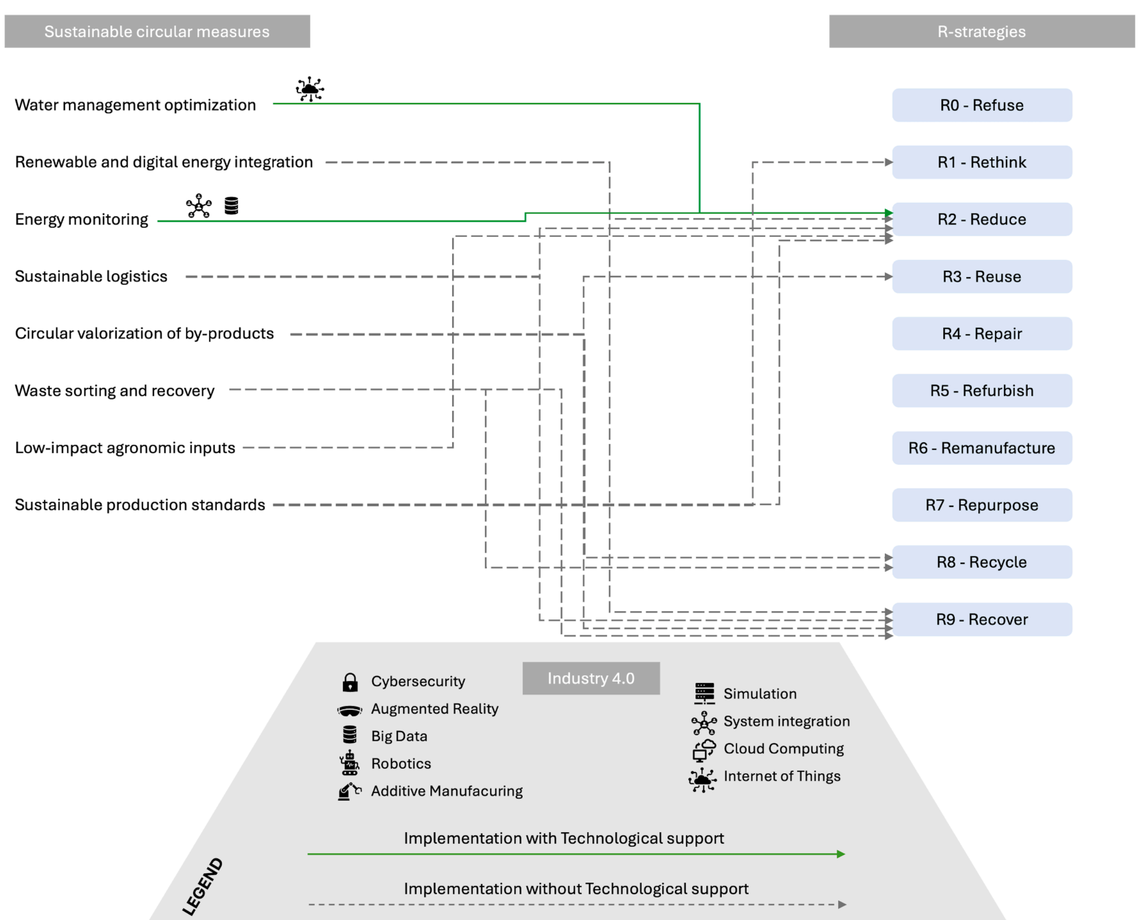

Fig. 5. Evidence from Case Study 3.

Table 2
Case Study evidence overview.

Circular measure	Associated R-strategies	Industry4.0 technologies		
		Mezzacorona Group	**Caviro Group**	**Collis Veneto Wine Group**
Water management optimization	R1, R2, R8, R9			Internet of Things
Water footprint assessment	R1, R2	Big Data		
Renewable digital energy integration	R1, R2, R9			
Energy monitoring	R1, R2	Internet of Things, Big Data	IoT, Big Data	System Integration, Big Data
Sustainable logistics	R0, R1, R2, R9		Robotics	
Circular valorization of by-products	R2, R3, R7, R8, R9			
Waste sorting and recovery	R8, R9			
Sustainable packaging	R1, R2, R8			
Low-impact agronomic inputs	R0, R1, R2			
Sustainable production standards	R0, R1, R2	Internet of Things		
Carbon & climate footprint assessment	R2			

- Short Loops (R0-R2): This area is robust, characterized by a commitment to minimizing resource consumption (Reduce R2) and the institutional rejection of harmful inputs (Refuse R0) via sustainable logistics and low-impact agronomic practices. Since Short Loops offer the highest value retention by preventing resource use, this prioritization is strategically sound.
- Long Loops (R7-R9): Effective long-loop activity is evident in Repurpose R7 by valorizing by-products (pomace) into secondary materials, and strong Recycle R8 for packaging materials. This addresses necessary end-of-life management.

The evidence indicates that while Mezzacorona effectively leverages technology to monitor and optimize its circular practices, advancing toward a truly regenerative system would require broadening its technological portfolio to support more radical Rethink strategies and enhance external transparency. In this context, digitalization functions as a tool for precision management and measurable impact verification, aligning with theoretical expectation that I4.0 technologies enhance efficiency by converting raw data into actionable insights [49,50].

The Caviro Group, with its specialized agri-industrial profile, demonstrates a strong emphasis on Recover R9, illustrating how technology can elevate long-loop circular strategies into a core, high-value business model. Its circular practices are supported by I4.0 technologies (digital enablement: medium). The vertically integrated model leverages advanced process control and automation, exemplifying how digital tools provide a robust backbone to operationalize circular principles. Notably, the use of Robotics in the automated warehouse for Sustainable Logistics highlights a clear connection between a specific I4.0 pillar and circular outcomes (Reduce R2). This industrial automation also supports the comprehensive Circular Valorization of By-products, enabling the conversion of over 99 % of residues into high-value derivatives. The technological adoption is focused on internal industrial automation and process optimization (e.g., Energy Monitoring via IoT and Big Data), effectively enhancing operational efficiency and performance (technological variability: medium). This specialization allows Caviro to consolidate its leadership in waste-centric operation while creating a strong foundation for future expansion toward broad collaborative or service-oriented circular initiatives, such as Rethink R1 or Reuse R3. Caviro demonstrates exceptional strategic strength in the Long Loops, making its circularity model waste-centric rather than prevention-centric (R-strategy coverage: medium):

- Long Loops (R7-R9): The Group excels in Repurpose R7 and Recover R9, converting residues into biogas, bio-methane, bioethanol, and high-value chemicals. This level of integration effectively closes the material and energy loops, maximizing the retention of material value (R7) and energy (R9). The large-scale water recovery (42 % of total demand) also contributes significantly to closing the Recover R9 loop.
- Short Loops (R0-R2): While committed to Reduce R2 through energy self-sufficiency and logistics optimization, the Group's primary competitive advantage is built on its technological investment in waste valorization.

Caviro exemplifies a pathway in which advanced I4.0 technologies elevate resource recovery into a core, high-value business model, with technological adoption primarily oriented toward industrial efficiency. The Group leverages digital tools not only for measurement but for automation and control, creating a technological architecture that integrates information and material flows. This configuration supports an effective industrial metabolism, demonstrating a clear and robust linkage between automation and circular valorization [51].

The Collis Veneto Wine Group presents a distinctive interpretation of circularity, emphasizing operational efficiency, renewable energy integration, and resource recovery. Its circular practices are supported by a focused, targeted use of I4.0 technologies (digital enablement: low). The Group's vertically coordinated but decentralized organization employs basic digital tools primarily for traceability, energy and water monitoring, and sustainability reporting under the Equalitas SOPD_004.1 framework. These tools provide a reliable informational infrastructure that ensures compliance and track environmental performance, supporting effective management of operational processes.

A central element of Collis's circular model is its strong focus on renewable energy adoption and process optimization, showing that substantial sustainability gains can be achieved through organizational coordination and disciplined operational management. The Group has progressively expanded the use of green energy across its facilities and implemented energy and water efficiency programs supported by continuous monitoring and improvement. These initiatives underpin Reduce R2 strategies, minimizing resource consumption and production inefficiencies, illustrating that circular value can be generated effectively even in contexts with lower digital intensity.

Technological variability is currently moderate (technological variability: low), reflecting a structure promotes standardization and uniform practices across member wineries. The adoption of I4.0 tools is focused on internal control systems and compliance management, supporting incremental improvements in operational performance. Advanced technologies such as automation, AI-based optimization or blockchain for extended traceability are not yet integrated, slowing down the innovation process and leading the Group to focus on consolidating efficiency and recovery strategies while maintaining a stable operational foundation (Rethink R1).

The Group's R-strategy coverage is medium, highlighting a consistent emphasis on efficiency and recovery. Collis exhibits high performance in Reduce R2 and Recover R9, medium engagement in Recycle R8, and limited focus on Rethink R1 and Reuse R3. This configuration reflects a balanced approach, where operational priorities are effectively distributed between short-loop efficiency measures and long-loop recovery mechanisms, supporting sustainable performance across the value chain:

- Long Loops (R7–R9): Collis demonstrates strong specialization in Recover R9 and Recycle R8, converting organic residues such as pomace, lees and grape seeds into secondary materials and bio-based products. Through well-established partnerships and valorization chains, the Group ensures that nearly all by-products are reintegrated into productive use, aligning with the principles of resource circularity and energy regeneration. In addition, the Group's engagement in carbon offset and reforestation initiatives reinforces its long-loop strategy, linking recovery practices with broader environmental stewardship goals.
- Short Loops (R0–R2): The Group maintains a firm commitment to Reduce R2 through renewable energy use, process efficiency and optimization of resource management. However, the limited technological diversification constrains the expansion of Rethink R1 and Reuse R3 strategies. Product eco-design, packaging reuse, or collaborative digital platforms are not yet core components of the operational model, and innovation remains primarily directed at reducing inputs and improving efficiency within existing structures.

Collis Veneto Wine Group achieves tangible environmental results through procedural coherence, renewable energy use, collective alignment and effective use of digital tools where applied.

A complete overview of the qualitative assessment on the three cases study is shown in Fig. 6.

The comparative examination of Mezzacorona, Caviro Group and Collis Veneto Wine Group reveals three different but complementary trajectories of digital-circular transformation within the wine industry, showing that the interplay between digitalization and circularity is far from linear. To move beyond a linear assessment of inputs, we introduce the concept of Digital Circularity Intensity (DCI). We define DCI as "the strategic intersection of the three core assessment dimensions - digital enablement, technological variability, and R-strategy coverage - together representing the integrated maturity level of a firm's twin transition". This concept provides a comprehensive lens to evaluate how firms synergistically combine digital capabilities and circular strategies to achieve sustainable transformation. Fig. 7 provides a complete overview of how the MEs in our multiple-case study position themselves along the three dimensions.

The assessment of the three core dimensions illustrates how each ME operationalizes the twin transition under different structural, technological and governance conditions. The comparison illustrates that DCI serves as a differentiator of implementation pathways rather than final outcomes: while technological intensity shapes the approach to circular practices, governance structures and process coherence guide the overall level of circular maturity attained [52,53].

When synthesized, the companies' three trajectories converge to define each firm's DCI profile, capturing how digital technologies and circular strategies are strategically aligned rather than merely co-present. Consequently, DCI is shaped not by the scale of technology investment, but by the strategic and organizational integration of digital tools with high-value R-strategies.

Mezzacorona Group and Caviro Group illustrate the complementarity between CE and I4.0 highlighted in the literature [1,9], while also demonstrating the differentiated ways in which alignment occurs: Mezzacorona leverages data analytics to reinforce preventive loops, whereas Caviro emphasizes automation to enhance recovery within the value chain. Collis Veneto Wine Group offers a contrasting pathway, showing that robust governance and procedural coordination can achieve tangible environmental outcomes even with a more selective deployment of digital technologies.

The three MEs thus represent a continuum in which the interaction between digitalization and circularity shaped primarily by managerial choices and governance capacity rather than technological intensity alone. Within this continuum, three distinct digital-circular pathways emerge (Fig. 8):

- *Data-driven prevention* (e.g., Mezzacorona Group).This pathway is characterized by a high degree of coherence and resilience on real time data-intensive approach oriented toward short-loop prevention and performance monitoring. Digital technologies such as IoT sensors, Big Data analytics and smart irrigation systems generate feedback loops that enable firms to actively Reduce (R2) resource consumption and Rethink (R1) strategic processes at the decision-making level. The emphasis on short-loop prevention is realized through proactive monitoring, which enables the firm to anticipate inefficiencies and implement corrective actions before waste occurs. By integrating technology across multiple stages of the production process, going from grape cultivation and fermentation to bottling and distribution, digital tools help synchronize operations, optimize resource use and enhance process flows. This systemic application of technology reinforces both operational efficiency and environmental performance, ensuring that data is transformed into actionable insights that support preventive measures and strategic sustainability objectives. This approach aligns with the CE literature, which emphasizes the importance of preventive strategies (R0-R2) in retaining

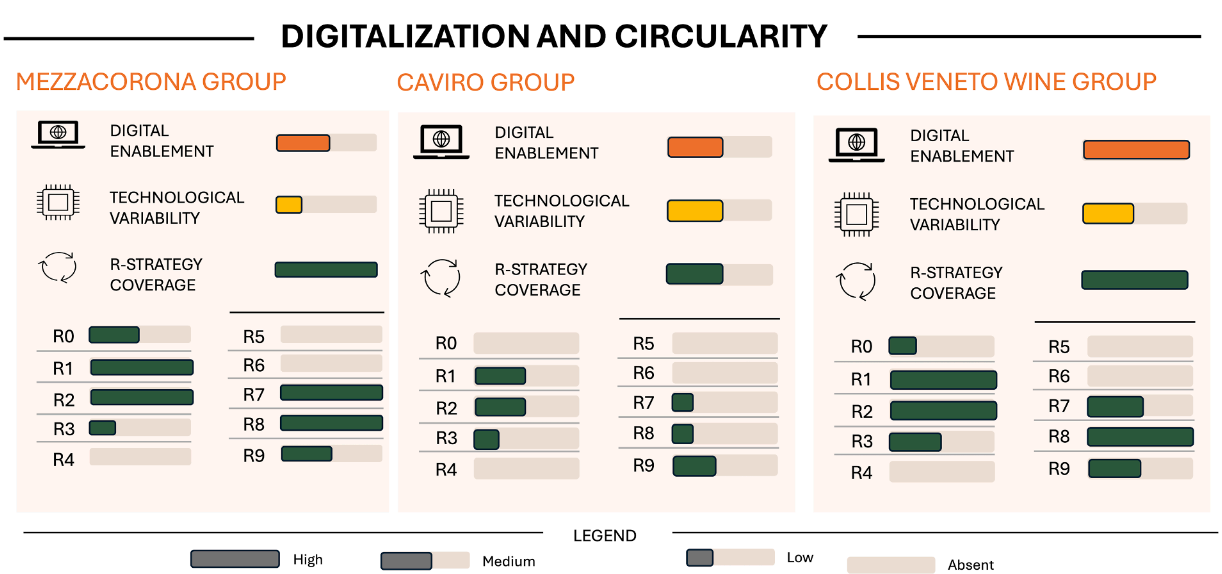

Fig. 6. Qualitative assessment for the three case studies.

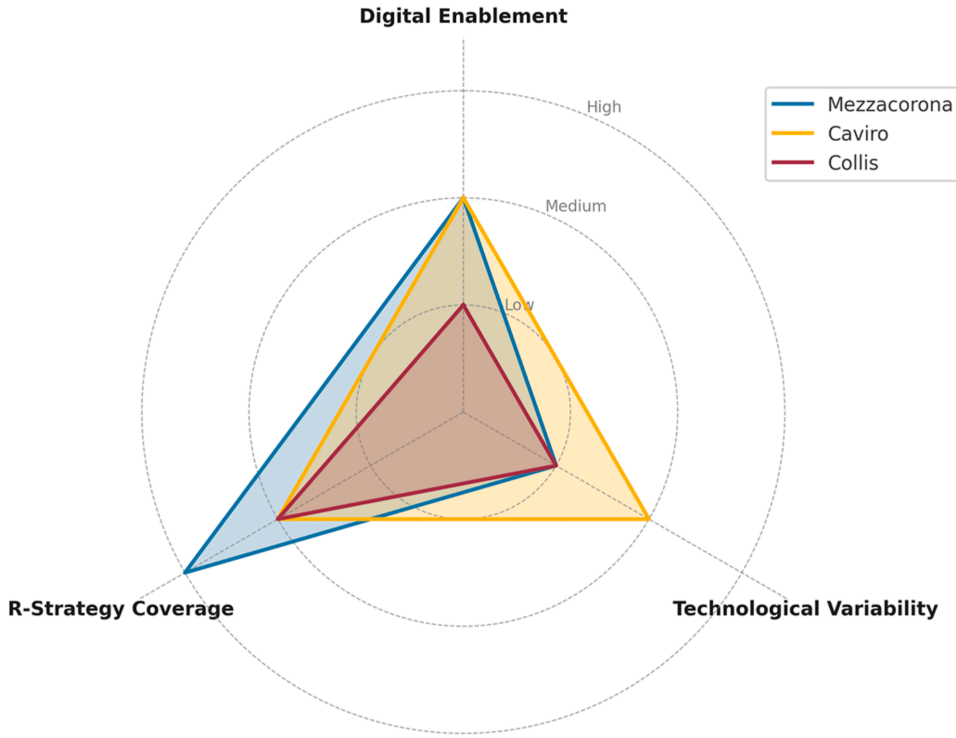

Fig. 7. Differentiator assessment for the three companies.

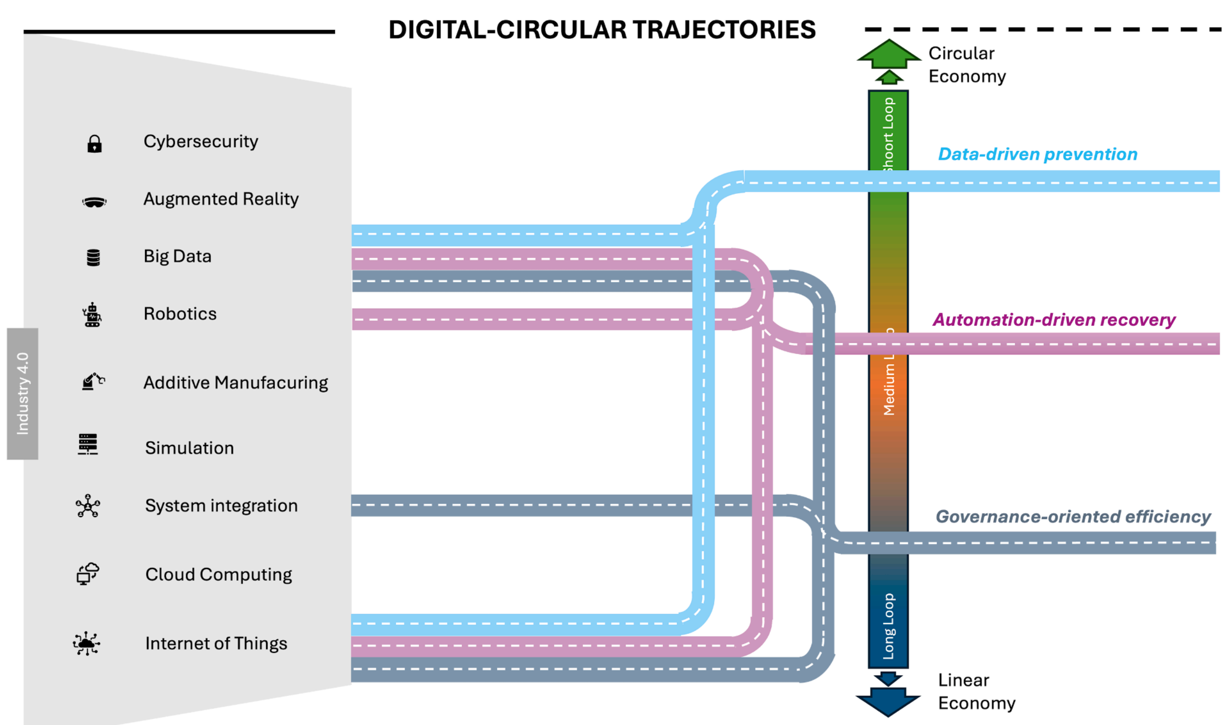

Fig. 8. Digital-circular pathways emerged from case studies.

resource value [2,4] and highlights the role of digital technologies in enabling real-time monitoring and process optimization [3,8,19].

- *Automation-driven recovery* (e.i.,Caviro Group). This pathway is characterized by a process-diverse, technology-intensive configuration focused on medium- and long-loop recovery strategies. Technologies - such as Robotics, bio-refinery integration and automated sorting systems generate synergistic interactions that enable firms to repurpose and recover by-products efficiently (Recover R9, Repurpose R7) as a core business model, while also complementing upstream strategies (e.g., Rethink R1 or Reuse R3). The strategic contribution of automation is maximized when deployed across multiple stages of production and post-production processes, allowing for consistent valorization of residual streams and the creation of new circular business opportunities. Through the coordination of automated systems, companies can systematically reduce material losses, enhance product lifecycle value, and ensure compliance with circularity objectives, demonstrating that recovery-focused strategies can be operationalized effectively even in complex industrial contexts. This pathway reflects the CE literature on medium- and long-loop strategies (R3-R9), which focus on extending product life and recovering value [2,4], and exemplifies how I4.0 technologies can act as enablers for valorization and reverse logistics [3,20,21].

- *Governance-oriented efficiency* (e.i., Collis Veneto Wine Group): This pathway emphasizes strong managerial oversight, procedural coherence, and collective alignment to implement circular outcomes, particularly those associated with long-loop strategies. Governance mechanisms, including formalized protocols, broad coordination and monitoring dashboards, ensure the systematic application of R-strategies and alignment with overarching sustainability objectives. By embedding circular principles into decision-making and operational routines, this approach facilitates efficiency improvements, renewable energy adoption, and the valorization of residual resources. The strategic value of this pathway lies in its capability to leverage organizational structures to generate measurable environmental performance, maintain resilient processes and reinforce organizational consistency. This approach is consistent with literature emphasizing the importance of organizational and managerial alignment in enabling circularity, particularly for long-loop strategies (R8-R9) where structural coordination complements technological enablers [2–4,27].

Taken together, these patterns illustrate that the three MEs exemplify different modes of digital–circular integration: data-intensive prevention optimizes resource input, automation strengthens material recovery, and governance ensures institutional coherence.

Rather than representing isolated trajectories, these modes can function as complementary logics within a shared circular innovation ecosystem. Consequently, DCI captures how varying combinations of digital, technological and governance capabilities can achieve comparable sustainability outcomes, highlighting that multiple strategic pathways can effectively operationalize circular principles.

6. Theoretical and practical implications

From a theoretical perspective, this study contributes to the advancement of CE research by offering a structured mapping of the connections between sustainability measures, R-strategies, and the enabling role of I4.0 technologies within the wine sector. By introducing the concept of DCI, we provide a single integrative indicator capable of capturing the strategic alignment of digital enablement, technological variability and R-strategy coverage. This allows for a nuanced assessment of how firms operationalize the twin transition beyond mere technological investment, highlighting the importance of strategic and organizational integration. Notably, the results illustrate moving beyond a purely technology-centric perspective, common in empirical studies mapping I4.0 applications [3,8], toward a strategy- and governance-oriented understanding of the twin transition. By connecting the deployment of digital technologies with the alignment to R-strategies and organizational decision-making [2,19], our findings show that managerial choices and governance mechanisms, rather than technology alone, drive circular outcomes. This shift from a technocentric to a strategic lens represents a first conceptual contribution, demonstrating that the effective implementation of CE principles requires integrating digital tools within broader organizational and strategic frameworks, consistent with prior research highlighting the role of circular strategies and digital enablers in fostering resilient, efficient, and environmentally aligned industrial systems [1,2,19]. Furthermore, the identification of three distinct digital-circular pathways – data-driven prevention, automation-driven recovery, and governance-oriented efficiency – offers a typology for understanding how wine MEs align technology and circular practices in distinct but complementary ways. These findings open several avenues for future research, including the exploration of additional digital-circular trajectories within the wine sector, the comparison of pathways across sectors where the twin transition is central, such as fashion or agri-food, and the investigation of how DCI relates to firm performance, market outcomes and broader ecosystem-level sustainability. Moreover, the study lays the groundwork for examining how organizational structures, governance mechanisms, and stakeholder engagement shape the effectiveness of digital-circular integration.

From a practical perspective, the cases provide actionable insights for managers, policymakers and stakeholders in the wine industry. The DCI framework emerges as a concrete tool for measuring and monitoring the performance of the twin transition, enabling firms to evaluate the strategic alignment of their digital and circular initiatives. The three pathways highlight different approaches that firms may adopt depending on their organizational characteristics and strategic priorities. Data-driven prevention demonstrates how short-loop efficiency and proactive resource management can be supported by advanced analytics and IoT technologies. Automation-driven recovery illustrates the potential of robotics and process automation to elevate waste valorization and integrate by-products into core business models. Governance-oriented efficiency emphasizes that procedural discipline, renewable energy adoption and strong coordination can achieve tangible environmental outcomes even in contexts with more selective digital deployment.

In addition, the study underscores the importance of institutional and regulatory factors in shaping the twin transition. Current public funding schemes are often concentrated on the development of precision agriculture technologies, such as IoT and Big Data monitoring systems, reflecting a focus on efficiency and control. The experiences of the three case companies mirror this trend, showing the predominance of monitoring technologies in their circular practices. At the same time, the findings suggest that broader regulatory and policy support could enable the integration of more systemic R-strategies, including collaborative, service-oriented and reuse initiatives. By combining these insights, the study provides practical guidance for managers seeking to navigate the twin transition, offering a roadmap for adopting effective digital-circular strategies, enhancing organizational alignment and leveraging policy instruments to scale sustainable practices across the industry.

7. Closing remarks, limitations and future research agenda

This study demonstrates that leading wine MEs strategically integrate I4.0 technologies to implement CE principles. While digital technologies do not underpin all circular measures, when they are deployed, the way I4.0 enables CE strategies is largely determined by managerial decisions and governance structures rather than by technological intensity alone, revealing how firms translate digital capabilities into strategic and operational circular practices. This interplay is manifested through three distinct digital-circular pathways which illustrate alternative yet complementary approaches to operationalizing the twin transition. Through a case study of three leading firms in the Italian wine industry, the research highlights the different pathways that companies can undertake toward a circular and sustainable transition that leverages the potential of I4.0 technologies. The study was built on solid methodological and conceptual foundations, yet some limitations are acknowledged, which may open future research directions and follow-ups (summarized in Table 3). While the selection of the three case study companies is robust given the key characteristics aligned with the research focus, extending the investigation to a larger sample of firms (beyond geographical and size constraints) would help eliminate any potential selection bias. This would also enhance the statistical representativeness of the sample and potentially lead to more diverse results, enabling richer comparative analyses. The purely qualitative approach, although rigorous, could be complemented by a quantitative study to confirm the generalizability of the findings and to numerically assess the

Table 3
Research Agenda.

NEW RESEARCH STREAM	FOLLOW-UPS
Investigate the link between I4.0 technologies and the achievement of sustainable circularity goals.	Extend the sample size of the case study within the wine sector and across other industrial sectors
Analyze the influence of stakeholders on the adoption and effectiveness of I4.0	Conduct quantitative validation of the findings to confirm generalizability and assess circularity outcomes numerically
Design a maturity model to assess circular and technological commitment, as well as the strategic alignment of MEs.	Develop a KPI-based framework to assess the efficiency of I4.0-enabled circular practices

sustainability and circularity outcomes achieved by firms in the sector through I4.0-enabled circular practices. For instance, developing a KPI-based framework could strengthen the results of the present study and validate their empirical and practical consistency from both a quantitative and mathematical perspective. A validation and results-deepening phase could be conducted by carrying out a series of interviews aimed at collecting feedback on the findings, in line with the objectives of Phase 4 of the D&SC methodology. Furthermore, while the study addresses the existing gap in the literature regarding the role of I4.0 technologies in implementing circular measures for the twin transition, the link between technology and sustainable circularity goals remains under-theorized. This suggests new avenues for research, including exploring the role of stakeholders in circular practices and understanding how their influence shapes the use of I4.0 technologies. Insights from such studies could help firms achieve both twin transition objectives and long-term competitive advantage.

CRediT authorship contribution statement

Marta Menegoli: Writing – review & editing, Writing – original draft, Visualization, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Maria Laura Giangrande:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Leonardo Agnusdei:** Writing – review & editing, Writing – original draft, Visualization, Investigation, Formal analysis, Data curation. **Federica De Leo:** Writing – review & editing, Writing – original draft, Supervision, Resources. **Maria Elena Latino:** Writing – review & editing, Writing – original draft, Visualization, Validation, Supervision, Resources, Methodology, Conceptualization.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Aknowledgments

none

Appendices

Table A1

Table A1
Data Collection Protocol and Illustrative Examples by Research Phase.

Case study	Phase B Primary data source (Mapping)	Example of retrieved primary information	Phase B Secondary data source (complementary)	Example of retrieved secondary information	Phase C Critical data source (analysis & validation	Example of final qualitative rating (*Digital Enablement*)
Mezzacorona Group	Company's sustainability report	Specific KPIs on resource efficiency; documented integration of circular initiatives and green solutions	Corporate Websites, Social Media Profiles, Publicly Accessible Platforms	Commitment to sustainability practices, sustainable development projects	Focus group with five experts	Rating assigned for the Digital Enablement dimension: *High* (e.g., nearly all sustainable circular measures leverage technology)
Caviro Group	Company's sustainability report	Data on recovery rate, valorization of by-products, responsible energy consuption and sustainable best practices	Corporate Websites, Social Media Profiles, Publicly Accessible Platforms	Sustainable development projects, environmental certifications, published corporate policies	Focus group with five experts	Rating assigned for the Technological Variability dimension: *Low* (e.g., circular practices rely consistently on only two I4.0 technology families)
Collis Veneto Wine Group	Company's sustainability report	Data on procurement processes, resource and waste management	Corporate Websites, Social Media Profiles, Publicly Accessible Platforms	Sustainable development projects, CE and regeneration initiatives	Focus group with five experts	Rating assigned for the R-Strategy Coverage dimension: *High* (e.g., practices converge across seven of the ten R-strategies)

Data availability

Data will be made available on request.

References

[1] A. Hofmann Trevisan, F. Acerbi, I. Dukovska-Popovska, S. Terzi, e C. Sassanelli, «Skills for the twin transition in manufacturing: a systematic literature review», J. Clean. Prod. 474 (2024) 143603 https://doi.org/10.1016/j.jclepro.2024.143603 ott.

[2] L. Liu, Y. Liang, Q. Song, e J. Li, «A review of waste prevention through 3R under the concept of circular economy in China», J. Mater. Cycles. Waste Manage 19 (4) (2017) 1314–1323, https://doi.org/10.1007/s10163-017-0606-4, fascott.

[3] C. Sassanelli, J.A. Garza-Reyes, Y. Liu, D.A. De Jesus Pacheco, e S. Luthra, «The disruptive action of industry 4.0 technologies cross-fertilizing Circular economy throughout society», Comput. Ind. Eng. 183 (2023) 109548 https://doi.org/10.1016/j.cie.2023.109548 set.

[4] W. McDonough, e M. Braungart, Cradle to cradle: remaking the way we make things, North point press, 2010.
[5] L. Montag, «Roadmap to a circular economy by 2030: a comparative review of circular business model visions in Germany and Japan», Sustainability. 15 (6) (2023) 5374, https://doi.org/10.3390/su15065374, fascmar.
[6] W.R. Stahel, «Sustainability and the performance economy». The performance economy, Palgrave Macmillan UK, London, 2010, pp. 269–287, https://doi.org/10.1057/9780230274907_5.
[7] A.K. Sah, Y.-M. Hong, e K.-C. Huang, «Enhancing brand value through circular economy service quality: the mediating roles of customer satisfaction, brand image, and customer loyalty», 2025.
[8] Z. Yu, S.A.R. Khan, e M. Umar, «Circular economy practices and industry 4.0 technologies: a strategic move of automobile industry», Bus. Strat. Env. 31 (3) (2022) 796–809, https://doi.org/10.1002/bse.2918, fascmar.
[9] J.N. Uhrenholt, J.H. Kristenses, S. Adamsen, S.F. Jensen, M. Colli, e B.V. Waehrens, «Twin transition: synergies between circular economy and internet of things – A study of Danish manufacturers», CE 1 (1) (2022) https://doi.org/10.55845/HRGW4040 fasc.
[10] N. Suchek, C.I. Fernandes, S. Kraus, M. Filser, e H. Sjögrén, «Innovation and the circular economy: a systematic literature review», Bus. Strat. Env. 30 (8) (2021) 3686–3702, https://doi.org/10.1002/bse.2834, fascdic.
[11] A.K. Gupta, e N. Gupta, «Environment practices mediating the environmental compliance and firm performance: an institutional theory perspective from emerging economies», Glob. J. Flex. Syst. Manag. 22 (3) (2021) https://doi.org/10.1007/s40171-021-00266-w fasc.Art. fasc. 3, set.
[12] J. Sá, L.P. Ferreira, T. Dieguez, J.C. Sá, e F.J.G. Silva, «Role of the industry 4.0 in the wine production and enotourism sectors», in *Advances in Tourism, Technology and Systems*, vol. 208, in: J.V. De Carvalho, Á. Rocha, P. Liberato, e A. Peña, A c. di (Eds.), Smart innovation, systems and technologies, Smart innovation, systems and technologies, 208, Springer Singapore, Singapore, 2021, pp. 171–180, https://doi.org/10.1007/978-981-33-4256-9_16.
[13] E. Pomarici, e R. Vecchio, «Will sustainability shape the future wine market?», Wine Econ. Policy 8 (1) (2019) 1–4, https://doi.org/10.1016/j.wep.2019.05.001, fascgiu.
[14] E. Pomarici, A. Corsi, S. Mazzarino, e R. Sardone, «The Italian wine sector: evolution, structure, competitiveness and future challenges of an enduring leader», Ital Econ J 7 (2) (2021) 259–295, https://doi.org/10.1007/s40797-021-00144-5, fasclug.
[15] P.P. Miglietta, D. Morrone, e L. Lamastra, «Water footprint and economic water productivity of Italian wines with appellation of origin: managing sustainability through an integrated approach», Sci. Total Environ. 633 (2018) 1280–1286, https://doi.org/10.1016/j.scitotenv.2018.03.270, ago.
[16] Unione Italiana Vini (UIV), «Osservatorio del Vino: report export 2022». 2023. Consultato: 22 settembre [Online]. Disponibile su, https://www.unioneitalianavini.it, 2025.
[17] M.B.S. Gonçalves, et al., «Wine industry by-products as a source of active ingredients for topical applications», Phytochem. Rev. 24 (5) (2025) 4065–4099, https://doi.org/10.1007/s11101-024-10030-4, fascott.
[18] E. Neethling, T. Petitjean, H. Quénol, e G. Barbeau, «Assessing local climate vulnerability and winegrowers' adaptive processes in the context of climate change», Mitig. Adapt. Strateg. Glob. Change 22 (5) (2017) 777–803, https://doi.org/10.1007/s11027-015-9698-0, fascgiu.
[19] S. Tabares, V. Parida, e K. Chirumalla, «Twin transition in industrial organizations: conceptualization, implementation framework, and research agenda», Technol. Forecast. Soc. Change 213 (2025) 123995 https://doi.org/10.1016/j.techfore.2025.123995 apr.
[20] M. Dressler, e I. Paunovic, «Sensing technologies, roles and technology adoption strategies for digital transformation of grape harvesting in SME wineries», J. Inno. Technol. Compl. 7 (2) (2021) 123, https://doi.org/10.3390/joitmc7020123, fascgiu.
[21] S. Sehnem, N.O. Ndubisi, D. Preschlak, R.J. Bernardy, e S. Santos Junior, «Circular economy in the wine chain production: maturity, challenges, and lessons from an emerging economy perspective», Pro. Plan. Cont. 31 (2020) 1014–1034, https://doi.org/10.1080/09537287.2019.1695914, fasc. 11–12set.
[22] B. Jesus, A. Cerveira, E. Santos, e J. Baptista, «The impact of optimizing hybrid renewable energy system on wine industry sustainability», in: 2024 IEEE 22nd Mediterranean Electrotechnical Conference (MELECON), Porto, Portugal, IEEE, 2024, pp. 278–283, https://doi.org/10.1109/MELECON56669.2024.10608594, giu.
[23] E. Kokkinomagoulos, e P. Kandylis, «Grape pomace, an undervalued by-product: industrial reutilization within a circular economy vision», Rev. Environ. Sci. Biotechnol. 22 (3) (2023) 739–773, https://doi.org/10.1007/s11157-023-09665-0, fascset.
[24] J. Caspers, P. Bade, e M. Finkbeiner, «Reusable beverages packaging: a life cycle assessment of glass bottles for wine packaging», Clean. Eng. Technol. 25 (2025) 100914 https://doi.org/10.1016/j.clet.2025.100914 mar.
[25] G. Ruggeri, C. Mazzocchi, S. Corsi, e B. Ranzenigo, «No more glass bottles? canned wine and Italian consumers», Foods. 11 (8) (2022) 1106, https://doi.org/10.3390/foods11081106, fascapr.
[26] J. Korhonen, A. Honkasalo, e J. Seppälä, «Circular economy: the concept and its limitations», Ecol. econ. 143 (2018) 37–46.
[27] A.B. Lopes de Sousa Jabbour, C.J.C. Jabbour, M. Godinho Filho, e D. Roubaud, «Industry 4.0 and the circular economy: a proposed research agenda and original roadmap for sustainable operations», Ann. Oper. Res. 270 (1–2) (2018) https://doi.org/10.1007/s10479-018-2772-8 fascArt. fasc. 1–2, nov.
[28] N. Adamashvili, N. Zhizhilashvili, e C. Tricase, «The integration of the Internet of things, artificial intelligence, and blockchain technology for advancing the wine supply chain», Computers 13 (3) (2024) 72, https://doi.org/10.3390/computers13030072, fascmar.
[29] G.P. Agnusdei, B. Coluccia, V. Elia, e P.P. Miglietta, «IoT technologies for wine supply chain traceability: potential application in the Southern Apulia Region (Italy)», Procedia Comput. Sci. 200 (2022) 1125–1134, https://doi.org/10.1016/j.procs.2022.01.312.
[30] J.N. Uhrenholt, J.H. Kristensen, M.C. Rincón, S.F. Jensen, e B.V. Waehrens, «Circular economy: factors affecting the financial performance of product take-back systems», J. Clean. Prod. 335 (2022) 130319 https://doi.org/10.1016/j.jclepro.2021.130319 feb.
[31] M. Geissdoerfer, P. Savaget, N.M.P. Bocken, e E.J. Hultink, «The circular economy – a new sustainability paradigm?», J. Clean. Prod. 143 (2017) 757–768, https://doi.org/10.1016/j.jclepro.2016.12.048.
[32] Y. Liu, M. Kang, T.-W. Kang, e J. Du, «Supply chain planning and innovation performance: the moderated mediation effect of IT usage», IMDS 122 (11) (2022) https://doi.org/10.1108/IMDS-01-2022-0053 fascArt. fasc. 11, nov.
[33] P. Rosa, C. Sassanelli, A. Urbinati, D. Chiaroni, e S. Terzi, «Assessing relations between Circular Economy and Industry 4.0: a systematic literature review», Int. J. Prod. Res. 58 (6) (2020) https://doi.org/10.1080/00207543.2019.1680896 fascArt. fasc. 6, mar.
[34] D.P.F. Möller, et al., «Impact of digital transformation for sustainable circular economic environments», Carb. Neut. Syst 1 (1) (2025) 7, https://doi.org/10.1007/s44438-025-00001-3, fascmag.
[35] S. Rajput, e S.P. Singh, «Industry 4.0 model for circular economy and cleaner production», J. Clean. Prod. 277 (2020) 123853 https://doi.org/10.1016/j.jclepro.2020.123853 dic.
[36] M. Ghobakhloo, «Industry 4.0, digitization, and opportunities for sustainability», J. Clean. Prod. 252 (2020) 119869 https://doi.org/10.1016/j.jclepro.2019.119869 apr.
[37] J. Martínez-Falcó, E. Sánchez-García, B. Marco-Lajara, e L.A. Millán-Tudela, «Analysis of the scientific knowledge structure on automation in the wine industry: a bibliometric and systematic review», Eur. Food Res. Technol. 250 (9) (2024) 2273–2289, https://doi.org/10.1007/s00217-024-04553-5, fascset.
[38] R.E. Stake, Multiple case study analysis, Guilford press, 2013.
[39] D.R. Hancock, e B. Algozzine, A practical guide for beginning researchers doing case study research, Teachers College Press, New York, 2006.
[40] R.K. Yin, «Case study research and applications: design and methods», 2018.
[41] C. Houghton, D. Casey, D. Shaw, e K. Murphy, «Rigour in qualitative case-study research», Nur. Res. 20 (4) (2013) fasc.
[42] P. Darke, G. Shanks, e M. Broadbent, «Successfully completing case study research: combining rigour, relevance and pragmatism», Inform. syst. J. 8 (4) (1998) 273–289, fasc.
[43] E.G. Guba, e Y.S. Lincoln, «Competing paradigms in qualitative research», in: Handbook of qualitative research, 2, SAGE Publications, 1994, p. 105, fasc.
[44] B. Rihoux, e B. Lobe, «The case for qualitative comparative analysis (QCA): adding leverage for thick cross-case comparison». The Sage handbook of case-based methods, SAGE Publications, 2009, pp. 222–242.
[45] M.W. Lipsey, Design sensitivity: statistical power for experimental research, Sage, Nachdr. Newbury Park, Calif, 1995.
[46] C. Santini, A. Cavicchi, e L. Casini, «Sustainability in the wine industry: key questions and research trendsa», Agric. Econ. 1 (1) (2013) 9, https://doi.org/10.1186/2193-7532-1-9, fascdic.
[47] D.S. Bindeeba, E.K. Tukamushaba, e R. Bakashaba, «Digital transformation and its multidimensional impact on sustainable business performance: evidence from a meta-analytic review», Futur Bus J 11 (1) (2025) 90, https://doi.org/10.1186/s43093-025-00511-z, fascapr.
[48] M.E. Latino, M. Menegoli, A. Corallo, e M.G. Gnoni, «Surfing twin transition in agri-food supply chains: the role of IoT and data analytics in sustainable decision-making», J. Ind. Inf. Integr. (2025) 100983 https://doi.org/10.1016/j.jii.2025.100983 ott.
[49] S. Bag, G. Yadav, P. Dhamija, e K.K. Kataria, «Key resources for industry 4.0 adoption and its effect on sustainable production and circular economy: an empirical study», J. Clean. Prod. 281 (2021) 125233 https://doi.org/10.1016/j.jclepro.2020.125233 gen.
[50] N. Tsolakis, T.S. Harrington, e J.S. Srai, «Digital supply network design: a circular economy 4.0 decision-making system for real-world challenges», Production Planning & Control 34 (10) (2023) 941–966, https://doi.org/10.1080/09537287.2021.1980907, fasclug.
[51] J. Kirchherr, et al., «Barriers to the circular economy: evidence from the European Union (EU)», Ecol. Eco. 150 (2018) 264–272, https://doi.org/10.1016/j.ecolecon.2018.04.028, ago.
[52] G. Bressanelli, F. Adrodegari, M. Perona, e N. Saccani, «Exploring how usage-focused business models enable circular economy through digital technologies», Sustainability. 10 (3) (2018) 639, https://doi.org/10.3390/su10030639, fascfeb.
[53] T. Stock, e G. Seliger, «Opportunities of sustainable manufacturing in industry 4.0», Procedia CIRP. 40 (2016) 536–541, https://doi.org/10.1016/j.procir.2016.01.129.