

Twin transition across Central and Eastern European innovation ecosystems in times of multi-crises: the quintuple-helix perspective

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Abstract: The issue of twin transition is gaining momentum and attracting increasing attention from policymakers, practitioners and researchers, particularly in Western economies. In contrast, Central and Eastern European (CEE) stakeholders have—paradoxically—just started to tackle this issue in very recent years, while comprehensive research on this phenomenon is rather scarce. As such, policy and practitioners’ information are lacking, threatening the attainment of strategic sustainability goals at international and local levels. In times of multi-crises, this situation can be amplified by unexpected events. In response, this study provides a topical contribution to the current knowledge by analyzing the state of the art on the issues of green and digital transformation within CEE innovation ecosystems. Grounded in the quintuple-helix theory perspective and using a qualitative literature review-based approach, we show that CEE countries currently face several structural barriers limiting their twin transitions. These include, for example, high dependency on external knowledge and

technologies, weak entrepreneurial initiative, limited absorptive capacity and low eco-awareness. Our findings offer several practical implications for businesses and policymakers, especially in the areas of supporting multi-helix cooperation, preparing more tailored policy initiatives and implementing circular economy practices for higher business resilience. In turn, we highlight the need for circular economy action plans, hubs and living labs based on the different maturity levels of CEE innovation ecosystems.

Keywords: *Central and Eastern Europe, circular economy, crises, digitalization, innovation ecosystems, quintuple helix, sustainability, twin transition*

1. Introduction

In the past decade, European countries and their innovation ecosystems have faced numerous challenges including ‘chronic crises’ linked to climate change, as well as sudden events such as the COVID-19 pandemic (Hartley *et al.*, 2023; Karman *et al.*, 2024a; 2024b), the energy crisis and geopolitical conflicts such as the Ukraine-Russia one (Mayberry *et al.*, 2024). These crises exert immense pressure on all actors of so-called innovation ecosystems—quadruple-helix actors like businesses, policymakers, universities and civil society—who must find ways to respond to these changes effectively while simultaneously building resilience in various regions (Su and Junge, 2023). Collaboration among these actors is often promoted as essential, but in practice, it is not always smooth, especially in Central and Eastern Europe (CEE), where relationships between industry and policymakers are more complex than in Western Europe, and the innovation climate is markedly different (Stojčić *et al.*, 2019; Stojčić, 2021; Prokop *et al.*, 2025).

Considering the global crises and what we already know about their effects, such crises significantly impact the strategic plans of organizations and entire industries. The uniqueness of the conflict in Ukraine lies in the fact that both sides control the supply of critical raw materials. Ukraine produces 10% of the world’s wheat, 16% of its corn and 40% of its sunflower oil (Green, 2022). Together with Russia, they account for over 25% of global wheat exports and nearly 80% of sunflower oil exports. Russia and Belarus collectively export 15% of the world’s fertilizers (*The Guardian*, 2022), with Russia producing approximately 10% of the world’s oil before the invasion

(Kilian and Plante, 2022) and being the largest exporter of natural gas. Pandemic crises, armed conflicts and the increased frequency of natural disasters highlight the vulnerabilities of existing systems, forcing society to rethink its approaches to innovation and long-term resilience (Sheth and Uslay, 2023). Current challenges show that preparedness for the crisis, rapid adaptation and robustness must become key elements in planning for the so-called twin transition, including both sustainability and digital transformations (Lüdeke-Freund *et al.*, 2024). Unanticipated crises that disrupt supply chains and change consumer behavior emphasize the need to incorporate resilience against these events into strategic plans (Uslay, 2019). This requires leaders to broaden their skillsets and diversify their management strategies to effectively address the complexities of modern business environments. Specifically, they must develop the capacity to respond swiftly and decisively to crisis situations, while also demonstrating resilience and adaptability in the face of uncertainty. Such capabilities are essential not only for navigating immediate challenges but also for securing future competitiveness in a rapidly evolving global landscape. Furthermore, these adaptive leadership qualities play a pivotal role in fostering long-term sustainability by enabling organizations to innovate, remain agile and align with emerging societal and environmental expectations (Sheth and Uslay, 2023).

From the perspective of the twin transition, sustainability and digital transformations represent fundamental challenges for current innovation ecosystems (Bocken, 2024; Prokop, 2025), viewed not only as an opportunity for improved preparedness for future crises but also as a pathway to increased resilience and adaptation to long-term environmental and economic changes (Corona *et al.*, 2019; Karman *et al.*, 2024a). In this regard, concepts such as circular economy (CE) and digital transformation offer concrete possibilities to strengthen system resilience and competitiveness (Hartley *et al.*, 2024). Moreover, in the context of building resilience to crises, implementing CE principles involves several key measures. The main steps include more efficient resource use, such as reducing material and energy waste, recycling raw materials in production processes, and extending product life through repair, reuse or recycling (Blomsma and Brennan, 2017). Another critical measure is reducing dependency on non-renewable resources, which has the potential to decrease companies' vulnerability during crises, such as limited access to raw materials during geopolitical conflicts like the war in Ukraine (Karman *et al.*, 2024a).

Regarding the status quo within the CEE region, implementing sustainability and digitalization principles poses a particular challenge due to high

dependence on foreign technologies and limited innovation capacity, which hinders the full implementation of these concepts (Stojčić, 2024). As Radošević (2017) previously noted, many companies in this region also continue to rely on traditional energy sources, further limiting their ability to transition to more sustainable production processes and reducing their resilience during crises. Although there is a broad consensus on the importance of these approaches, existing research has not yet sufficiently addressed how different regions can confront the challenges associated with the twin transition (Stojčić, 2021). Moreover, innovation ecosystems in European countries show significant differences in terms of absorptive capacity, quality and availability of human capital, business size and structure, infrastructure, business environment, and the scale of local economies. These factors make the implementation of CE and digital transformation unevenly achievable, affecting the competitiveness and resilience of various ecosystems across Europe (Disoska *et al.*, 2024).

Moreover, collaboration between ‘multi-helix/q-helix’ actors (Carayannis *et al.*, 2018) plays a crucial role within CEE innovation ecosystems. Governments are often identified as key players, providing financial support and creating policy frameworks necessary to foster innovation (Stojčić, 2021). Research institutions and universities contribute to research and development (R&D) in collaboration with businesses, thereby strengthening the innovative capabilities of companies (Kotkova Striteska *et al.*, 2024). Universities in the CEE region play a third key role in innovation ecosystems, going beyond their traditional functions in R&D. In addition to collaborating with businesses and supporting government strategies, universities are increasingly focusing on promoting sustainable development, including support for the CE. As highlighted by Serrano-Bedia and Perez-Perez (2022), universities are key actors in advancing circular economy principles and driving systemic changes at both regional and national levels. Their role in this transition encompasses education, research and industry collaboration to integrate sustainable and circular principles into business processes and models. However, Radošević (2017) emphasizes that the limited capacity of innovation ecosystems in CEE countries still relies on foreign knowledge, a point further supported by Švarc and Dabić (2019), who also note that knowledge commercialization generated in collaboration with universities is virtually non-existent in these countries. In CEE, universities have the potential to serve as a bridge between academia and industry, thus supporting the sustainable transformation of local economies. Serrano-Bedia and Perez-Perez (2022) suggest that universities in the region should

develop programs focused on environmental education, interdisciplinary research and support for innovation, which would enhance local innovation capacity. This connection could help overcome the current challenges facing CEE, including dependency on technological imports and the lack of internal innovation resources.

Based on the current state of the art, several notable gaps and promising avenues for future research have been identified and warrant further exploration. These gaps are associated with the limited ability of CEE states to effectively implement the principles of the CE and digital transformation, mainly due to dependence on foreign technologies and low innovation capacity. Further gaps relate to the insufficient understanding of how governments, businesses and research/academic institutions in the CEE region can coordinate their actions during crises to strengthen its resilience. Next, there is a need to address the weak commercialization of academic knowledge, as collaboration between universities and the industry still does not result in significant economic impact. Finally, we still know little about how crises affect these processes.

Following these lines of arguments, the aim of this study is to summarize the current state of the art and provide specific insights into the role of different multi-helix actors in supporting the twin transition within Central and Eastern European states, with a particular focus on their cooperation before, during and after multi-crises.

This catching-up CEE territory-oriented research introduces several contributions. The study integrates key theoretical frameworks, such as innovation ecosystems, the multi-helix model, the twin transition and the CE, exploring these approaches in the context of crises with an emphasis on business/ecosystem resilience. Applying these still emerging concepts within the CEE territory represents a theoretical contribution that research so far has called for (Karman et al., 2024a; Kotkova Striteska *et al.*, 2024; Prokop, 2025). Moreover, we propose practical implications—based on the current cross-country research and best practices—for practitioners, policymakers and researchers. These implications include more tailored policy initiatives that support digital and CE hubs and living labs, industrial and urban symbiosis, business transition towards the application of CE practices to increase resilience in multi-crises or promote education on the CE. We also suggest several lines for future research, such as analysis of the concept of sufficiency as a weapon against rebound effects and “circular economy paradoxes”.

The rest of this paper is structured as follows. Section 2 presents the main theoretical lenses and the CEE territory context, followed by Section 3 devoted to the description of the research process. The results of the CEE region analysis are presented in Section 4, whereas the key findings of the paper are discussed in Section 5, together with main implications. This paper concludes with Section 6, outlining suggestions for future research inquiries.

2. Background theory and research questions

2.1 Supporting theories and their nexus

This study builds on and combines several recognized theoretical approaches widely applied across Western and Northern European countries, whose impacts and validity within the CEE regions, however, may be debatable (Kotkova Striteska *et al.*, 2024). First, we find arguments for our next steps within the approach defining innovation ecosystems (IE) that represent complex networks of relationships among governments, companies, research institutions and civil society, aimed at fostering technological and innovation development (Jackson, 2011; Overholm, 2015). These ecosystems encompass both research-driven economies that are fueled by fundamental research and commercial economies that are focused on market applications of scientific knowledge. Effective connections between these components play a crucial role in transforming knowledge into innovation (Adner and Kapoor, 2010). Linking such an approach with our aim and with the current status quo (the multi-crises perspective), the importance of innovation ecosystems is accentuated by the opportunity for the twin transition among CEE states (Stojčić, 2021), which requires strong collaboration and adaptive capacities of actors to handle the crises and shifting global conditions (Bocken, 2024).

Second, in line with the transformation towards sustainability, as a response to a deteriorating environment, there has been a growing global interest in the concept of circular economy (CE) in recent years, which seeks to reduce the dependency of economic growth on finite natural resources (Harris *et al.*, 2021). CE is recognized as a restorative framework designed to extend the lifespan of products, materials and components, ensuring their prolonged use while optimizing their value and functionality (Ahmadov *et al.*, 2024). This approach offers a more sustainable alternative to the traditional linear economic model of ‘take-make-consume-dispose’ (Haas *et al.*, 2015) and has the potential to support sustainable development goals, such as

the Agenda 2030 (Dey *et al.*, 2022; Ahmadov *et al.*, 2024). It aligns with key European Union policies, including the European Green Deal, which emphasizes the transition to a climate-neutral economy by 2050 through resource efficiency and the promotion of circular practices. Additionally, it supports the Circular Economy Action Plan, which seeks to minimize waste, enhance resource efficiency and stimulate innovation in sustainable production and consumption. The approach is also consistent with the EU Taxonomy Regulation, which provides a classification system to identify environmentally sustainable economic activities, and the Biodiversity Strategy for 2030, aimed at restoring ecosystems and reducing environmental degradation. By integrating these policies, the approach contributes to a broader framework of environmental and economic transformation within the EU.

Implementing the CE concept requires the involvement and innovative approaches of various stakeholders, including businesses, policymakers and academic institutions (Bertassini *et al.*, 2021; Pieroni *et al.*, 2021). Linking stakeholders operating within innovation ecosystems, significant shifts in industrial structures, such as waste management and business operations, have highlighted the critical role of the private sector (Lieder and Rashid, 2016). For example, collaboration between small and medium-sized enterprises (SMEs) and their suppliers can foster the development of environmentally sustainable supply chains, decrease carbon emissions and cut down on waste across the production cycle (Akpan *et al.*, 2024). However, more specific and well-defined policy guidelines remain essential (Gerstlberger and Prause, 2024). CE has also become a priority in the political agendas of major global economies, such as the EU, China, Japan, the USA and Canada, which are working on macroeconomic strategies to support regional development (Geissdoerfer *et al.*, 2017; Kalmykova *et al.*, 2018). In other words, the concept of CE is based on the premise that economic growth and environmental protection can complement each other and coexist in harmony (Fonseca *et al.*, 2018).

Third, the above-mentioned twin transition to sustainability and digitalization has the potential to significantly impact industrial ecosystems and may, but does not necessarily, deepen economic and social inequalities. Digital technologies, including AI, ICT and Industry 4.0, are transforming growth and productivity, while green technologies are supporting the shift towards a low-emission economy (Dean and McMullen, 2007; Heyman *et al.*, 2021; Azizov, 2024). The development of digital and ecological technologies plays a crucial role in addressing multi-crisis, while also offering opportunities to

enhance economic competitiveness and autonomy (European Commission, 2022; Muench *et al.*, 2022). Furthermore, research continues to explore the new skills, job roles and funding needed to support these transitions and how they may affect gender equality and regional disparities (Amoroso and Moncada-Paternò-Castello, 2018; Gereben and Wruuck, 2021). However, these transitions may exacerbate inequalities and have varying impacts depending on regional and industrial specificities (Biggi *et al.*, 2022; Cicerone *et al.*, 2023). In addition, at the EU level, initiatives such as the New European Innovation Agenda and the European Skills Agenda play a crucial role in fostering innovation and equipping the workforce with the competencies required for emerging industries and digital transformation. The European Green Deal further emphasizes the need for green skills and innovation to achieve climate neutrality, creating opportunities for SMEs to lead sustainable transitions. Similarly, the EU SME Strategy highlights the importance of supporting SMEs by enhancing their access to funding, boosting innovation capacity and promoting digital transformation. These initiatives, alongside others such as Horizon Europe and Digital Europe, are designed to create a robust framework for innovation while addressing disparities and ensuring inclusivity across regions, thereby aligning with broader EU objectives for social and economic cohesion.

Moreover, digital technologies play a crucial role in this transformation by utilizing layered architectures that enable the modular design of digital innovations (Adomavicius *et al.*, 2008). This modular approach improves the effectiveness of labor specialization among various stakeholders in designing and manufacturing of complex systems (Sosa *et al.*, 2004; Staudenmayer *et al.*, 2005). As a result, digital technologies create new market dynamics and facilitate the exchange of specialized knowledge and skills among diverse participants within collaborative networks. The flexible structure of these advancements converts conventional value chains into interconnected value ecosystems and significantly reconfigures innovation processes (Sosa *et al.*, 2004). This transformation is also reflected in the Digital Economy and Society Index (DESI), developed by the European Commission, which monitors Europe's digital performance and tracks the progress of EU Member States in digital competitiveness. The DESI highlights the importance of key factors such as connectivity, digital skills, the integration of digital technologies and digital public services, which collectively drive the adoption of digital innovations (Paraschiv *et al.*, 2024). By fostering modular and interconnected digital architectures, Member States can enhance their DESI performance, thereby promoting stronger innovation ecosystems and

boosting economic and social resilience across the EU (Stavytskyy *et al.*, 2019).

Applying the q-helix approach, universities and civil society are the other two missing pieces to this puzzle. Universities have increasingly emerged as significant players in research, innovation and regional development, having transformed from traditional educational institutions into key actors over recent years. They have a crucial influence on realizing the Sustainable Development Goals (SDGs), outlined in the 2030 Agenda, and can facilitate systemic transformation through research, innovation, education and campus management (Paletta *et al.*, 2019; Longoria *et al.*, 2021). This shift, referred to as the third and fourth generation of universities, emphasizes their role not only in education but also in supporting regional economies and addressing societal challenges, including sustainable development (Wissema, 2009).

The triple-helix model (Leydesdorff and Etzkowitz, 1996), which highlights collaboration between universities, industry and governments, demonstrates how these dynamic interactions enhance the region's innovation capacity. In later extensions of this model, such as the quadruple-helix, civil society is included, and in the quintuple-helix model, the environmental dimension is also integrated, addressing current sustainability challenges (Carayannis *et al.*, 2012; Vas, 2012; Miskolczi and Erdős, 2020). Despite their recognized role in influencing local change and economic growth (Mendoza *et al.*, 2019), uncertainties remain regarding the steps and strategies needed for an effective transition to a CE (Nunes *et al.*, 2018; Paletta *et al.*, 2019). The academic sector collaborates with industry through technology transfer, research and education (Ma *et al.*, 2024). However, according to Serrano-Bedia and Perez-Perez (2022), in the context of the CE, universities not only support research and innovation but also promote the implementation of sustainable practices on their campuses and collaboration with industry and governments. Interactions with the civil society ensure that innovations align with societal needs and values. The use of tools such as community-based research, citizen science and participatory technology assessment promotes social inclusion (Bellandi *et al.*, 2021). Collaboration between civil society and government involves providing feedback on policies (Ma *et al.*, 2024).

2.2 Emerging research questions regarding Central and Eastern Europe

Central and Eastern Europe (CEE) represents an intriguing context for examining the impacts of the twin transition toward sustainability and digitalization. The region faces unique challenges associated with transforming its innovation ecosystems, which differ significantly from those in developed economies. Structural weaknesses include low investment in research and development, dependence on foreign technologies and insufficient collaboration between academia and industry (Radošević, 2017; Corona *et al.*, 2019; Stojčić, 2021; Karman *et al.*, 2024a). Instead of generating original radical innovations, CEE economies often focus on adapting imported technologies and investing in the modernization of machinery and software (Iammarino *et al.*, 2012; Radošević, 2015; 2017). However, this approach limits the region's capacity to develop autonomous innovation capabilities and create high-value technologies.

Another significant area of focus is the impact of regulatory and legislative frameworks on innovation activities (Ciriaci *et al.*, 2019). Within the context of the twin transition, regulations serve as a crucial instrument. While well-designed regulations can stimulate innovation, overly strict or ambiguous rules may have the opposite effect, potentially destabilizing innovation ecosystems (Porter and van der Linde, 1995; Blind *et al.*, 2017). Global multi-crises have further highlighted the vulnerabilities of innovation ecosystems in this region. These crises underscore the urgent need to develop more resilient innovation systems capable of swiftly responding to unforeseen global challenges (Karman *et al.*, 2024a; Mayberry *et al.*, 2024). Given these challenges, the twin transition represents not only an opportunity to enhance economic competitiveness but also serves as a pathway to building greater resilience in innovation ecosystems. These systems, which rely on collaboration between governments, businesses, academia and civil society, play a crucial role in enabling the region to adapt to changing global conditions. However, existing research reveals that innovation ecosystems in CEE countries often struggle with effective collaboration among actors and demonstrate low levels of knowledge commercialization and technology transfer (Radovšević, 2015; 2017; Iammarino *et al.*, 2012; Stojčić *et al.*, 2019; Švarc and Dabić, 2019; Stojčić, 2021; Disoska *et al.*, 2024; Kotkova Striteska *et al.*, 2024; Stojčić, 2024).

Based on these insights, it is evident that CEE countries need not only overcome historical deficits in R&D but also focus on enhancing collaboration

among multi-helix actors leading to the support of the twin transition within innovation ecosystems and, in general, to increased innovativeness. To overcome these obstacles and get the twin transition started, it is necessary to answer the following research questions (RQ):

RQ1: How can CEE countries overcome the structural barriers in their innovation ecosystems and develop the capacity to independently generate and commercialize innovations?

RQ2: How can regulatory and legislative frameworks in CEE countries support innovation activities and investments in technologies without limiting companies' flexibility and willingness to innovate?

RQ3: How have multi-crises impacted the progress of CEE countries in achieving the twin transition?

3. Steps in the research process

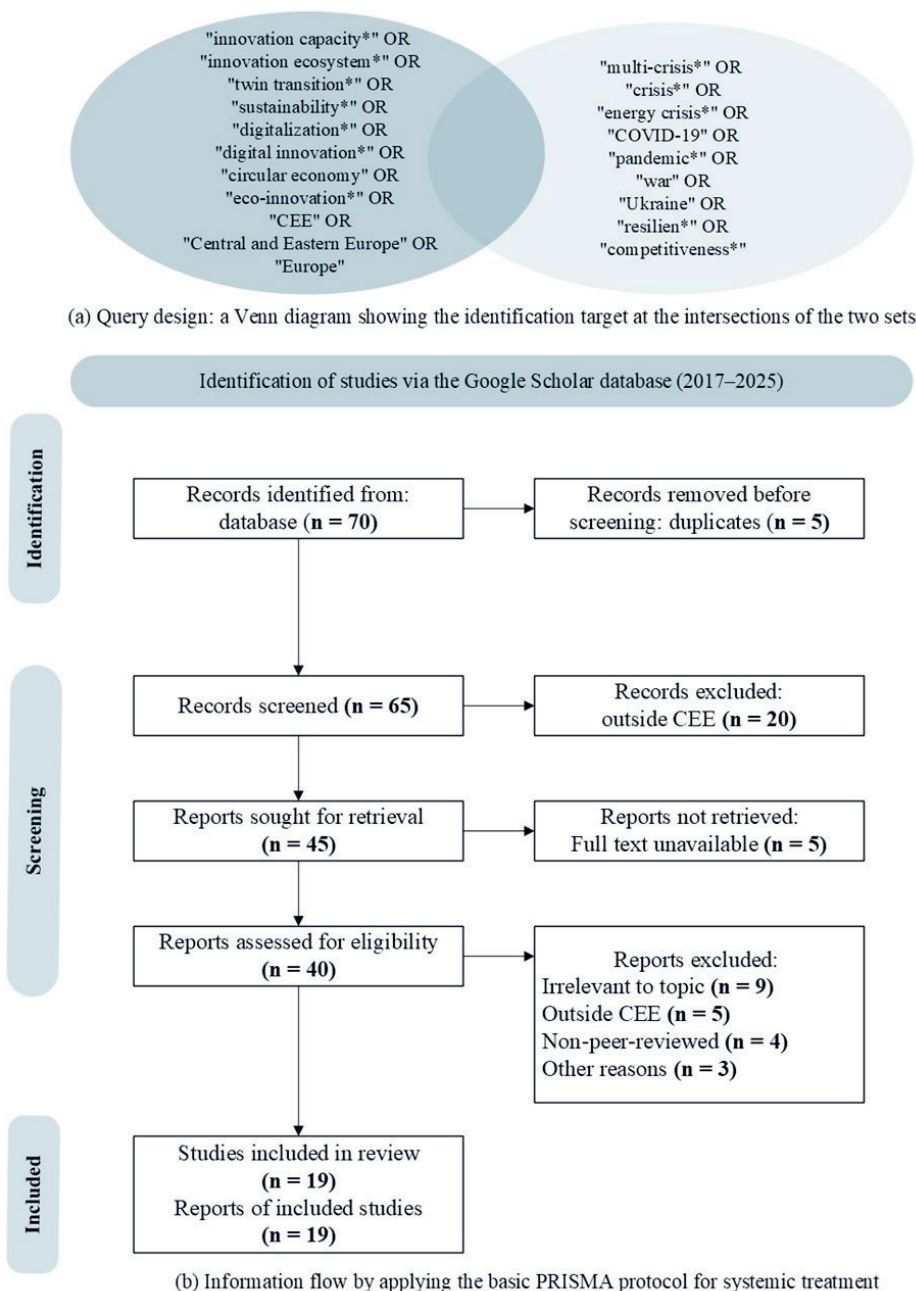
As the phenomenon of the twin transition is still emerging (Aagaard, 2024; Aagaard and Vanhaverbeke, 2024; Prokop, 2025), especially in the CEE countries, there is a lack of data for both policymakers (Karman *et al.*, 2024a) and researchers to conduct more comprehensive empirical analyses that will cover such topic and reflect the issue of multi-crises. For these reasons, this very first preliminary study employs the qualitative research approach. This method was chosen for its ability to explore multifaceted phenomena, such as the twin transition, and its impacts in CEE countries. Moreover, it enables an in-depth understanding of both theoretical and practical insights while identifying gaps that can inspire future research and policy development. Additionally, it is well-suited for synthesizing diverse data sources, including literature, indexes and frameworks, into a coherent analysis that offers practically applicable recommendations. For these reasons, our original five-step qualitative research approach includes following steps: (1) summarizing the current state of knowledge, (2) literature review conducted using the basic PRISMA-based protocol principles, (3) analysis of cross-country comparison using European Commission indexes, (4) summarizing knowledge in a conceptual framework and (5) designing a new framework. Table 1 summarizes the steps that were taken to answer the research questions of this study.

Table 1. Steps of the research process.
(Source: Authors’ elaboration.)

Research Question	Step 1	Step 2	Step 3	Step 4	Step 5
RQ1: <i>How can CEE countries overcome the structural barriers in their innovation ecosystems and develop the capacity to independently generate and commercialize innovations?</i>	Summarizing the current knowledge on structural barriers in CEE innovation ecosystems.	Systematic literature review of key factors for innovation capacity.	Cross-country analysis of innovation performance.	Developing a conceptual framework for CEE-specific conditions.	Proposing a new framework tailored to the specific needs of CEE countries.
RQ2: <i>How can regulatory and legislative frameworks in CEE countries support innovation activities and investments in technologies without limiting companies’ flexibility and willingness to innovate?</i>	Summarizing the current knowledge on regulatory and legislative frameworks affecting innovation in CEE.	Literature analysis and comparison of indexes of regulatory frameworks and innovation environment.	Comparing regulatory approaches across CEE countries	Developing a conceptual framework for CEE-specific conditions.	Proposing a new framework tailored to the specific needs of CEE countries.
RQ3: <i>How have multi-crises impacted the progress of CEE countries in achieving the twin transition?</i>	Summarizing knowledge on the impacts of crises on CEE innovation ecosystems	Systematic literature review of innovation vulnerabilities during crises.	Evaluating responses to crises and progress in the twin transition.	Developing a conceptual framework for CEE-specific conditions.	Proposing a new framework tailored to the specific needs of CEE countries.

A systematic literature review was conducted using the basic principles of the PRISMA-based protocol (Moher *et al.*, 2009). This review aimed to transparently identify and select studies addressing the intersection of innovation, the twin transition and the impacts of crises in the CEE region. The search was performed in the Google Scholar database for the period 2017–2025, using two sets of keywords (see Figure 1). The process involved several stages: initial identification of records, removal of duplicates, title and abstract screening, full-text assessment and the final selection of relevant studies based on predefined criteria (regional focus on CEE, thematic relevance and scientific quality). Given the exploratory nature of this study, a basic version of the PRISMA-based protocol principles was applied, which means that procedures such as double independent screening or detailed risk-of-bias assessment were not conducted. Nevertheless, the key principles of transparency and reproducibility were maintained throughout the process. An overview of the relevant studies and their key findings is provided in Table 2 in the section results.

Figure 1. Basic PRISMA-based information flow.
(Source: Authors' elaboration.)



4. Results

4.1 The CEE region: current state of the art and published literature so far

For this research, a comprehensive analysis of existing literature was conducted to examine the development and functioning of innovation ecosystems across various geographical and socioeconomic contexts. Numerous studies have already identified key factors influencing innovation performance, including the impact of the cultural context, external pressures such as regulatory and legislative frameworks and disruptive events such as economic or geopolitical crises. This research aims not only to synthesize the main insights from these studies presented in Table 2, but also to (a) present a conceptual framework summarizing the current status quo (Figure 2) and (b) propose a novel conceptual framework that integrates these factors and adapts them to the specific conditions of CEE countries, highlighting future directions towards higher sustainability and circularity, hand in hand with the twin transition principles (Figure 3; Section 5).

Table 2. Summary of related studies among CEE countries.
(Source: Authors’ elaboration.)

Author(s)	Key findings	Methods	Country
Faggian <i>et al.</i> (2025)	The study reveals that the twin transition is regionally uneven and complex, especially post-COVID-19. Calls for place-sensitive, multi-level policies, better alignment of scientific knowledge, sectoral applications (e.g., EVs, circular economy) and scrutiny of the environmental footprint of digitalization.	Conceptual / editorial synthesis	Primarily European regions (including those relevant to CEE)
Fazio <i>et al.</i> (2025)	The study highlights that ICT-oriented regions are far likelier to become twin-innovators than green-only regions; non-innovative regions persistently lag. Strong spatial clustering means positive spillovers are limited, so less innovative areas risk being “pulled down”. The COVID-19 pandemic accelerated transitions but did not erase disparities.	Markov chains, Moran’s I, LISA, ESTDA	259 European regions from 28 EU countries
Ferrazzi <i>et al.</i> (2025)	The study found that CESEE countries have improved innovation capacity, yet skills shortages, slowing productivity growth, low risk capital and uneven FDI benefits still hamper competitiveness. Raising public and private R&D investment, expanding lifelong learning and deepening university-business collaboration—especially around greenfield FDI—are critical to avoid stagnation.	Quantitative, descriptive benchmarking	Bulgaria, Croatia, Czechia, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, Slovenia

Author(s)	Key findings	Methods	Country
Darfo-Oduro <i>et al.</i> (2024)	The study confirms that R&D intensity is a significant factor for product innovation among SMEs in the CEE region. Capacity utilization exhibits an inverted U-shape, indicating that beyond a certain point, excessive capacity utilization may reduce innovation performance. Different ownership structures, particularly private ownership, positively influence the relationship between R&D intensity and innovation, while family ownership does not significantly moderate this relationship.	Regression analyses	Czech Republic, Bulgaria, Latvia, Poland, Lithuania, Slovakia
Demiankova (2024)	The study reveals that entrepreneurs in the Estonian entrepreneurial ecosystem draw inspiration from a diverse range of role models, including family members, competitors and well-known entrepreneurs. Those with access to direct role models within the ecosystem demonstrate a stronger and more specific orientation towards sustainability compared to those who rely on indirect role models, such as figures from literature or media. These findings underscore the importance of a supportive environment in fostering sustainable entrepreneurial practices.	Qualitative exploratory research, eight in-depth interviews with startup founders, Purposeful and snowball sampling, analysis based on social learning theory	Estonia
Karman <i>et al.</i> (2024a)	The study focuses on circular economy (CE) practices and their role in building the long-term resilience of organizations during crises such as the COVID-19 pandemic. The results show that companies that implement CE practices (e.g., industrial symbiosis) are more resilient to crises and better prepared for future economic and environmental challenges. Implementing CE allows organizations to improve their flexibility and resilience to external shocks.	Mixed methods (questionnaires, case studies, regression analyses)	Czech Republic, Slovakia, Poland
Karman <i>et al.</i> (2024b)	The study reveals that companies investing in environmental and social activities during the crisis achieve more positive economic outcomes and maintain their value better than those that do not engage in such initiatives.	Structured equation modeling (SEM), comparative analysis	Poland
Kotkova Striteska <i>et al.</i> (2024)	The study examines the determinants of the environmental behavior of SMEs in CEE countries. The results show that higher employee engagement and diversity can lead to better environmental outcomes. Conversely, family businesses tend to be less active in green practices, which may be due to traditional management structures.	Mixed methods (qualitative and quantitative analyses, case studies)	Czech Republic, Slovakia, Poland, Hungary

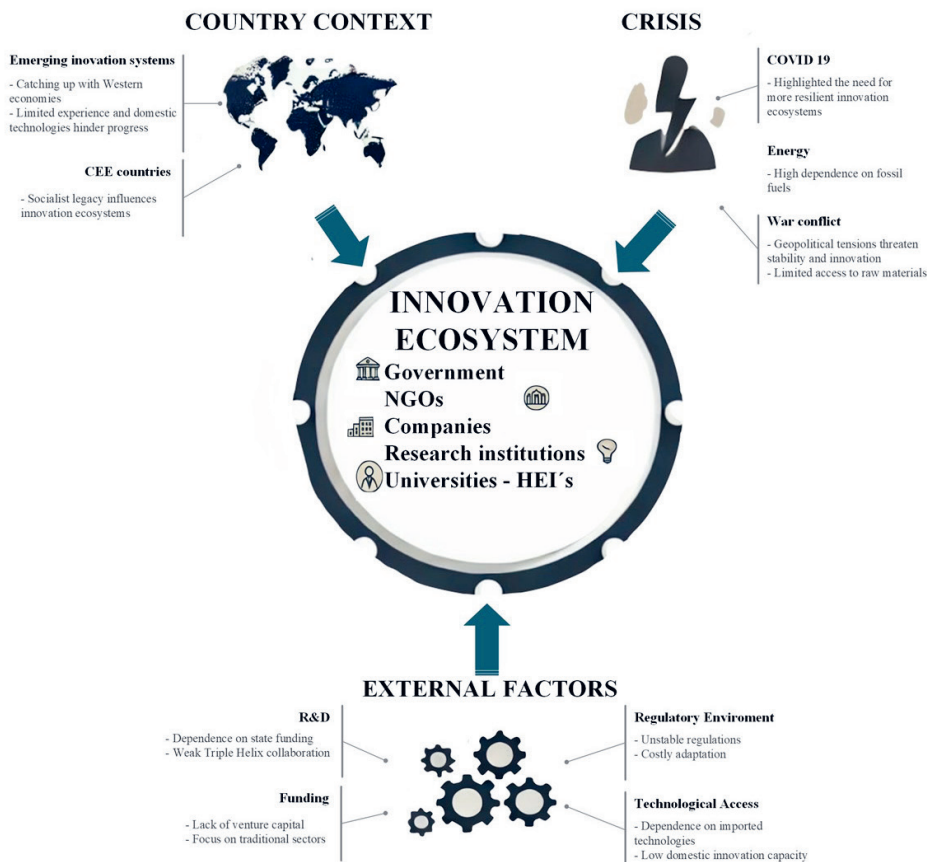
Author(s)	Key findings	Methods	Country
Majid (2024)	The study highlights the importance of digital innovations, particularly artificial intelligence and the Internet of Things, in enhancing the eco-efficiency of SMEs. It demonstrates that SMEs effectively implementing digitalization strategies are better at optimizing resources and reducing waste, thereby improving their sustainability. The COVID-19 pandemic accelerated digitalization in Polish enterprises, indicating that external shocks can drive digital transformation. Slovak SMEs perceive digitalization more optimistically than Hungarian ones, underscoring the need for tailored support strategies. The study concludes by emphasizing the crucial role of digitalization in driving innovation and transformation in SMEs and the importance of a supportive macro-environment for its successful implementation.	Systematic literature review, qualitative methods, CHAID decision tree	European SMEs, Hungary, Poland, Slovakia
Stojčić (2024)	The study focuses on the role of public support and training for innovative activities in reducing innovation failures. The results show that companies that receive public support and invest in innovation training show lower failure rates when introducing new products or processes. This is particularly important in CEE countries, where companies' innovation capacity tends to be limited and dependent on external resources.	Quantitative methods (panel data, econometric models)	Bulgaria, Czech Republic, Estonia, Croatia, Hungary, Lithuania, Slovakia
Stojčić, Dabić and Kraus (2024)	The authors focus on the role of user types and engagement strategies in the co-creation of product innovation. The study shows that different types of users (e.g., lead users, mass users) have different roles in the innovation process and their involvement is essential for the success of product innovations. Personalization and co-creation with users lead to higher market adoption of innovations.	Quantitative methods (questionnaire survey, regression analysis)	Estonia, Hungary, Croatia, Romania
Borcoși <i>et al.</i> (2023)	The use of electronic signatures among SMEs in Romania is a key step towards digitalization and sustainability, with 80.06% of Romanian SMEs utilizing electronic signature software. Although Romania is at the beginning of its journey towards digitalization and building a digital economy compared to the EU average, there is a strong interest and adoption of digital tools, indicating a positive trend for future development in this area.	Quantitative methods, statistical analysis using IBM SPSS, chi-square test.	Romania (main focus), Comparison with the EU-27 average in the area of SME digitalization.

Author(s)	Key findings	Methods	Country
Prokop <i>et al.</i> (2023)	This study does not focus only on Central and Eastern European (CEE) countries but demonstrates that women-owned businesses (OGD) increase the likelihood of achieving both radical and incremental innovations not only in this region but also in others. Companies with greater gender diversity in ownership exhibit a stronger tendency to innovate, enhancing their competitiveness. On the other hand, OGD does not influence the adoption of energy management practices, where other factors, such as market pressure and corporate values, play a key role. These findings highlight the need for targeted policies and initiatives that not only promote diversity but also raise awareness of the importance of energy efficiency and sustainability for businesses.	Logistic regression	Italy, Portugal, Slovenia, Czech Republic, Estonia, Latvia, Lithuania, Slovakia, Cyprus, Poland, and Bulgaria
Hojnik <i>et al.</i> (2022)	The study highlights that strong environmental orientation of companies and supportive regulations are crucial for fostering ecological innovations and improving outcomes like environmental protection and ecological efficiency. Regulations play a key role in motivating companies to adopt sustainable strategies and prioritize environmental goals. However, the findings reveal that R&D is not a primary mediator between regulations and environmental outcomes. Instead, the success of ecological innovations depends on the combination of a firm's commitment to sustainability and a regulatory framework that provides the necessary conditions for innovation to thrive.	PLS-SEM	Czech Republic, Slovenia
Stojčić (2021)	The study deals with cooperation in the field of innovation in emerging innovation systems. The author found that cooperation between companies and public institutions in the CEE region is often insufficient and innovation success is limited. Fragmented innovation systems and low levels of collaboration lead to less innovation capacity and companies lack the necessary resources to implement radical innovations.	Qualitative methods (case studies, interviews)	Bulgaria, Czech Republic, Croatia, Estonia, Latvia, Lithuania, Hungary, Romania, Slovakia
Miskolczi and Erdős (2020)	The study emphasizes that universities in Central and Eastern European countries face numerous challenges in contributing to the development of their regions. These challenges include the socialist legacy, low absorptive capacity of companies, mismatch between the research interests of universities and industry, and individual motivations. Successful policies and measures must take these factors into account.	Literature review	Bulgaria, Czech Republic, Estonia, Latvia, Lithuania, Poland, Hungary, Romania, Slovakia, Slovenia

Author(s)	Key findings	Methods	Country
Stojčić and Orlić (2019)	The study reveals that Foreign Direct Investment (FDI) generates positive productivity effects on domestic companies both within and across regions, while horizontal spillovers are negative. These effects increase with proximity to multinational corporations (MNCs) and with greater distance.	Spatial Durbin Model (SDM) and estimates were performed using the maximum likelihood method.	Czech Republic, Hungary, Poland, Slovakia, Slovenia, Romania, Croatia, Bulgaria
Švarc and Dabić (2019)	The study found that Croatia still experiences fundamental economic mechanisms from the Socialist era, such as state paternalism and weak entrepreneurial initiative, which slow down progress in technology transfer. Despite EU's support for modernizing technological capacities, the impact on market reforms has been either non-existent or negative. The slow technology transfer in less developed countries requires active government intervention to overcome stagnation and effectively utilize the benefits of EU integration.	Qualitative methods	Croatia, (comparisons to other former Socialist bloc countries and examples of successful nations such as South Korea, Ireland and Finland)
Radošević (2017)	The author emphasizes that the innovation capacity of CEE countries is significantly dependent on imported technologies and foreign investments. Local companies often focus more on incremental innovation and adaptation of foreign technologies than on their own research and development. This leads to dependence on external knowledge and to the inability of companies in CEE to carry out radical innovation. The study also highlights the need for improved collaboration between businesses, government and the academic sector.	Mixed methods, including quantitative analysis of innovation data and qualitative interviews with innovation experts	Estonia, Poland, Czech Republic, Hungary, Slovenia, Romania, Bulgaria

Based on the findings so far, presented in Table 2 and the literature review below, a conceptual framework has been designed and displayed in Figure 2 highlighting the key factors influencing the development and functioning of innovation ecosystems, particularly within the context of CEE countries. This framework builds upon three main areas—the CEE context, external factors, and crises—whose importance continues to grow and which are crucial for the long-term stability and resilience of innovation ecosystems. Addressing these areas is essential for understanding and managing innovation systems in a dynamic environment characterized by rapidly evolving technologies and socioeconomic changes.

Figure 2. Conceptual framework for CEE countries based on the multi-helix perspective. (Source: Authors' elaboration.)



4.2 Innovation performance and (eco)systems

Analyzing the current state of the art presented in Table 2 allows us to conclude that the innovation model in CEE differs from those in more developed economies. Radošević (2017) highlights that economic growth in this region is not primarily driven by research-based innovations but rather by the collaboration between local manufacturers and the inflow of imported equipment and inputs. In this context, R&D primarily serves to assimilate foreign knowledge and technologies rather than to stimulate domestic innovation efforts. Most innovation activities in these countries do not prioritize the development of innovation capabilities but rather

focus on investments beyond R&D, such as acquiring advanced machinery, software and equipment. Iammarino *et al.* (2012) point out that competency-building for introducing new products and services often takes place without adequately developing the skills necessary for breakthrough innovations. The economies of Central and Eastern Europe also exhibit limited innovation potential. These countries are characterized by structurally weak innovation ecosystems, with firms in the region often lacking internal capacities for independent innovation development (Radošević, 2015; 2017; Stojčić and Orlić, 2019; Stojčić, 2021). Despite these challenges, the region has produced several successful innovators that have gained global technological recognition, including companies such as Outfit 7, Rimac, Prezi, Sygic, Viber, Skype, TransferWise and Infobip. However, these achievements have largely been driven by individual initiatives and partnerships with foreign collaborators rather than by well-established domestic innovation systems (Spisak, 2017).

4.3 Regulatory and legislative frameworks

Effective regulatory and legislative frameworks are essential for fostering innovation, yet striking a balance between the needs of established businesses and emerging industries remains a challenge. Established firms often push back against changes that could undermine their market dominance. This conflict can slow down the process of “creative destruction”, as described by Schumpeter, where old technologies and processes are replaced by new ones (Ciriaci *et al.*, 2019). According to Stojčić, Vujanović and Baum (2024), another challenge for regulatory frameworks is the limited information on how technological progress impacts opportunities and risks. Policymakers often face dilemmas when choosing between public and private interests, highlighting the need for regulatory frameworks to function as effective mediators. Their function is to distribute resources efficiently, ensuring the greatest benefit for both private and public interests while safeguarding the rights of all stakeholders. Thoughtfully structured regulatory mechanisms can encourage businesses to invest in emerging technologies and innovative solutions with strong market prospects. On the other hand, overly strict or unclear regulations can limit companies’ flexibility, increase compliance costs and reduce their willingness to take risks, leading to a decrease in innovation. The literature on regulatory and legislative frameworks is not unified in its view of whether the positive or negative effects of regulation prevail. Some studies suggest that appropriately set regulations can stimulate innovation (Porter and van der Linde, 1995), while others warn of

the risks of stringent regulations that stifle innovation (Blind *et al.*, 2017; Cecere and Corrocher, 2016; Atanassov and Liu, 2020). These opposing views suggest that the impact of regulations depends on their specific design and context. Regulatory challenges become even more pressing during crises, which have significantly impacted innovation ecosystems in the CEE region.

4.4 Multi-crises effects

The multi-crisis has significantly impacted global economies, particularly affecting companies in emerging innovation ecosystems, including those in CEE (Hartley *et al.*, 2023). In 2020, the United Nations announced the beginning of the Decade of Action to achieve Sustainable Development Goals (SDGs) by 2030. However, the pandemic slowed this process and led to a global socioeconomic crisis that hindered progress in meeting these goals (Guan *et al.*, 2020). Economically, the pandemic affected all nations regardless of infection levels. It became evident that its socioeconomic consequences posed higher risks for developing countries and vulnerable social groups, including parts of the CEE region, creating further obstacles to achieving SDGs. This crisis underscored not only the vulnerability of various populations but also the urgency of meeting these goals (Sharma *et al.*, 2021).

As the pandemic receded, restarting the economy with a focus on sustainability and avoiding a return to unsustainable environmental practices became a priority. In response to the economic slowdown, countries worldwide introduced extensive fiscal packages worth trillions of dollars (Masterson, 2020). To achieve resilient and low-carbon economic growth, however, policymakers must prioritize fair and sustainable long-term strategies that go beyond economic protection during crises. These events not only cause social and economic shocks but also expose weaknesses in the innovation systems of these regions (Sharma *et al.*, 2021; Karman *et al.* (2024a).

Additionally, the war in Ukraine has highlighted geopolitical risks that can fundamentally affect the stability of innovation ecosystems and the availability of strategic resources. The conflict has severely disrupted supply chains for essential commodities such as wheat and energy, leading to significant changes in the global business environment. Companies are now forced to respond to new conditions and seek alternative ways of securing resources. Many manufacturers are diversifying their supply options, finding substitutions for materials and energy and adopting broader approaches to securing critical materials. In doing so, they are also incorporating principles of the CE to enhance sustainability and operational efficiency (Mayberry *et*

al., 2024).

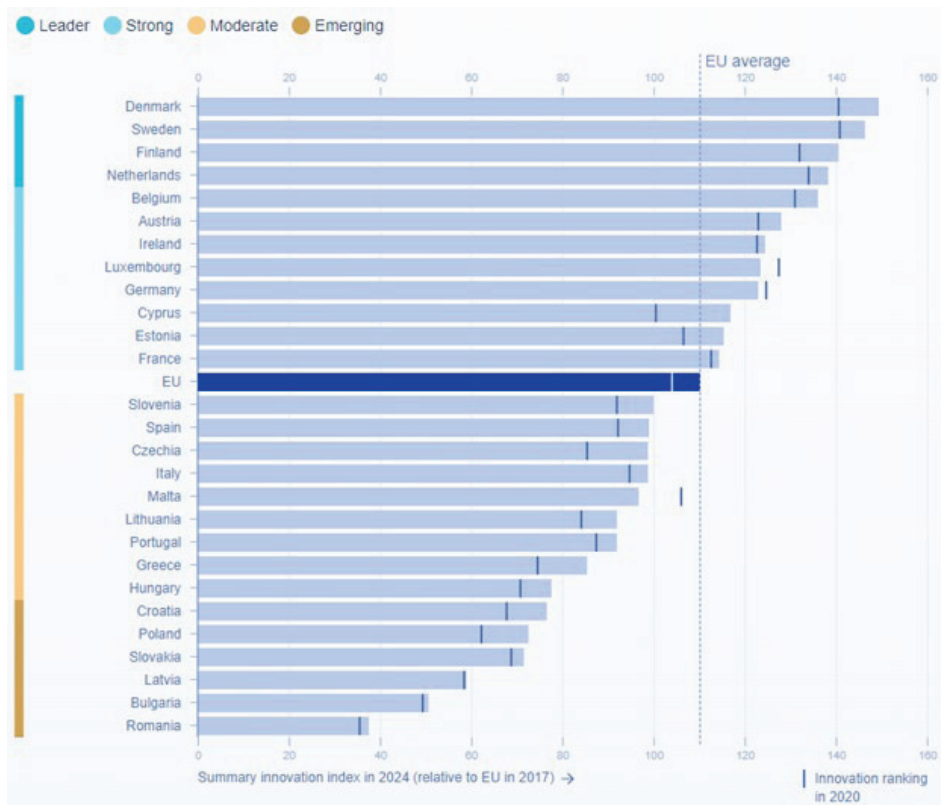
Given the potential long-term nature of the conflict and other unexpected events, companies and other stakeholders should reassess the possible impacts of such disruptions on their activities and adjust their strategies accordingly. In addition to preparing for cyclical economic phases (Cortez *et al.*, 2023), it is essential to identify potential risks and develop strategic plans focused on addressing the growing geopolitical instability (Sheth and Sisodia, 2006). The crises not only highlighted the vulnerability of innovation systems but also contributed to the deepening disparities in innovation performance among CEE countries.

4.5 Comparison of (eco)innovation performance

According to Stojčić (2021), CEE countries, apart from Estonia, exhibit low to moderate innovation performance and are classified as innovation underperformers. This finding supports earlier arguments by Radošević (2017), who highlights that innovation in CEE is typically not driven by R&D. Public and corporate investments in R&D, as well as venture capital, remain modest in the region. Only one CEE country ranked among the group of strong innovators (Figure 3), and this occurred in 2020. Comparative analyses also indicate that the level of cooperation among innovative SMEs is rated as moderate in some countries, such as Bulgaria, Hungary, Latvia, Poland and Romania, while similar results are observed in Croatia and Slovakia. Stronger collaboration is observed only in selected parts of the region.

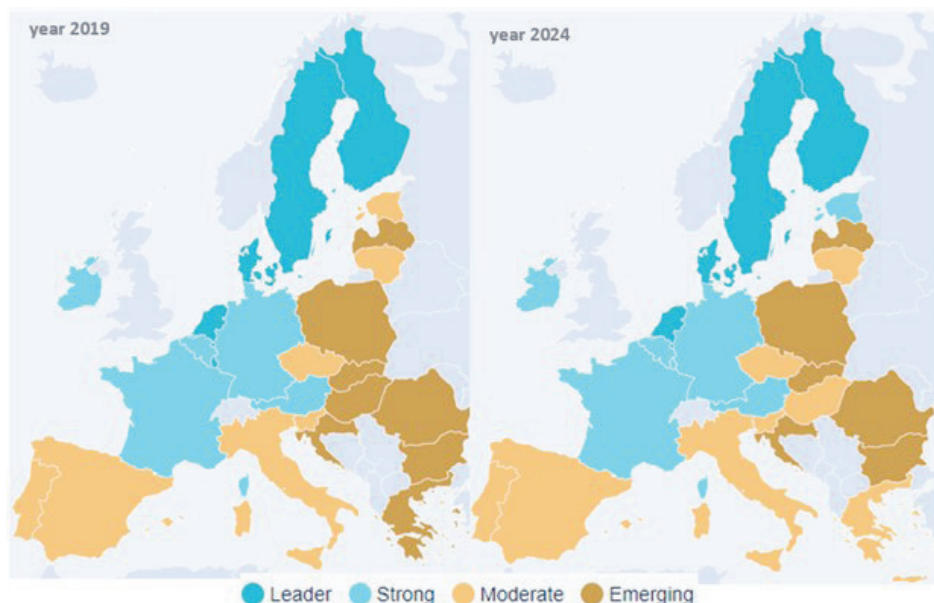
The EU's research and innovation policy represents a key instrument for achieving the goals of digitalization and sustainability, as highlighted by the 2024 European Innovation Scoreboard (EIS). The EIS shows that the EU's innovation performance has increased by 10% since 2017, primarily due to the European Innovation Agenda, launched in 2022. The European Innovation Council plays a fundamental role in enabling the development of innovative firms. However, the EIS also points to significant disparities in the pace of progress among Member States. These differences underscore the need for increased investment in R&D, particularly from the private sector, and the urgency of fostering innovation in regions such as CEE.

Figure 3. Innovation ranking change 2024 vs. 2020.
(Source: European Commission, 2024.)



Countries in CEE, except for Estonia, lag behind the European average in key innovation performance indicators. According to the 2024 EIS, EU countries are divided into four groups: Innovation Leaders, Strong Innovators, Moderate Innovators, and Emerging Innovators. No CEE country falls into the Innovation Leaders category, which includes Denmark, Sweden, Finland and the Netherlands. Estonia, due to consistent improvement since 2017, has advanced to the Strong Innovators group (Figure 4), alongside Belgium, Austria and others. In contrast, Slovenia, the Czech Republic and Hungary are classified as Moderate Innovators, with performance between 70% and 100% of the EU average. Croatia, Poland, Slovakia, Latvia, Bulgaria and Romania are categorized as Emerging Innovators, with performance below 70% of the EU average.

Figure 4. Innovation index change 2019 vs. 2024.
(Source: European Commission, 2024.)

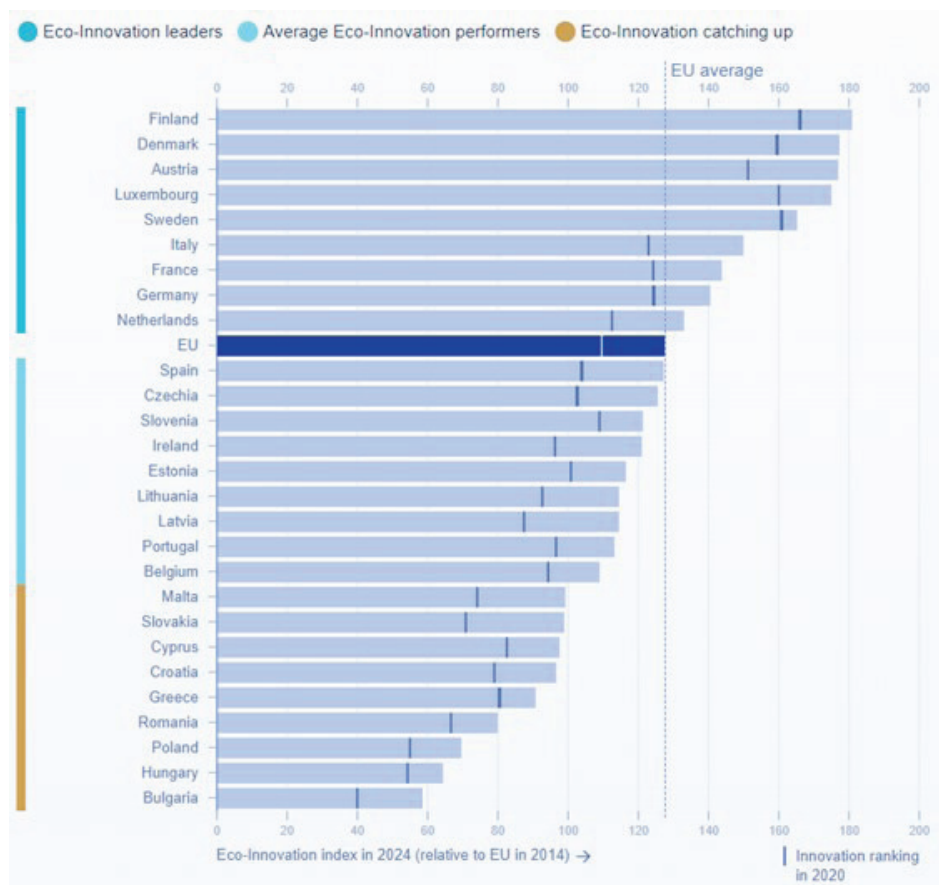


This uneven progress aligns with the low to medium innovation performance of most CEE countries, as noted by Stojčić (2021). The region continues to face challenges such as insufficient investment in R&D, weak linkages between academia and industry and low absorptive capacity among companies. Estonia remains an exception, as its advancement to the Strong Innovators category demonstrates that targeted policies, effective utilization of European funds and a focus on digital transformation can lead to significant improvements. By contrast, the majority of countries, such as Bulgaria, Romania, Hungary and Slovakia, remain categorized as ‘moderate’ or ‘emerging’ innovators, indicating slow progress in the field of innovation. This stagnation highlights the necessity of targeted measures aimed at fostering innovation and increasing the CEE region’s engagement in European innovation activities. A key prerequisite for achieving this goal is the creation of suitable conditions for more efficient use of European funds, improving collaboration among innovative companies and promoting private investment in R&D.

Although some CEE countries are experiencing slight improvements in performance and collaboration, innovation outputs, such as patents and the commercialization of new products, still lag significantly behind the EU average. This situation corresponds with the conclusions of Švarc and Dabić

(2019), who emphasize the minimal level of knowledge commercialization through university-industry collaboration in CEE. Furthermore, Pai *et al.* (2012) highlight that collaboration with partners from more advanced economies results in higher-quality innovation outcomes, whereas partnerships with local companies or from nations with a comparable stage of development typically yield weaker results, a pattern that remains evident in some CEE countries today.

Figure 5. Eco-innovation ranking 2024 vs. 2020.
(Source: European Commission, 2024.)



The development of the Eco-Innovation Index (EII) in CEE countries highlights significant disparities in the performance of individual states (Figure 5). As a region, CEE continues to lag behind the EU average, with key weaknesses including low government spending on R&D and a lack of patents related to eco-innovation. However, the Czech Republic, Slovenia

and Estonia stand out as the most successful countries in the region. The Czech Republic has achieved moderate growth due to an increase in the number of academic publications, although this progress has been partially offset by a decline in government investment in environmental research. Estonia, on the other hand, demonstrates consistent improvement, driven particularly by a significant increase in ISO 14001 certifications and academic publications, reflecting its emphasis on environmental standards and a robust knowledge base. Slovenia also maintains a relatively strong position, bolstered by above-average growth in academic publications, despite stagnation in some other indicators. Latvia and Lithuania exhibit positive trends, largely driven by growth in academic publications. However, the lack of detailed data makes it difficult to assess their exact position within the index.

Other countries in the region, such as Slovakia and Croatia, have shown significant progress. Slovakia improved its score through successful initiatives aimed at enhancing productivity and eco-innovation. Croatia experienced growth primarily driven by increases in productivity and ISO 14001 certifications. However, both countries continue to lag in critical areas such as patents and government investments in R&D, highlighting the need for stronger support in these key aspects. At the opposite end of the spectrum are Poland, Hungary, Romania and Bulgaria. Poland has shown slight improvement due to growth in academic publications but continues to underperform in essential indicators. Hungary, despite stagnant progress, remains affected by low government investments in R&D and weak performance in most other indicators. Romania has maintained its position at the lower end of the index, with its results pointing to the need for reforms across all dimensions of eco-innovation. Bulgaria, while demonstrating improvement driven by increases in ISO 14001 certifications, remains far below the EU average in most other indicators.

The development of eco-innovation in CEE countries demonstrates that the region has significant potential to improve its performance through targeted investments in R&D and more effective implementation of sustainability-focused policies. While countries such as Estonia, Slovenia and the Czech Republic have achieved relatively strong positions, others, such as Romania and Bulgaria, continue to lag behind. These disparities highlight uneven progress and the need for tailored strategies. The region faces persistent challenges, such as low investments in R&D and a lack of patents, which limit its ability to compete at the EU level. Addressing these issues requires well-designed policies to support eco-innovation, focusing on strengthening key indicators such as knowledge commercialization, international collaboration

and the application of green technologies. By tackling these challenges, the region could move closer to the EU average and make a more significant contribution to the goals of the green transition.

5. Discussion and implications

Discussing our findings, we start with the first research question: *How can CEE countries overcome the structural barriers in their innovation systems and develop the capacity to independently create and commercialize innovations?*

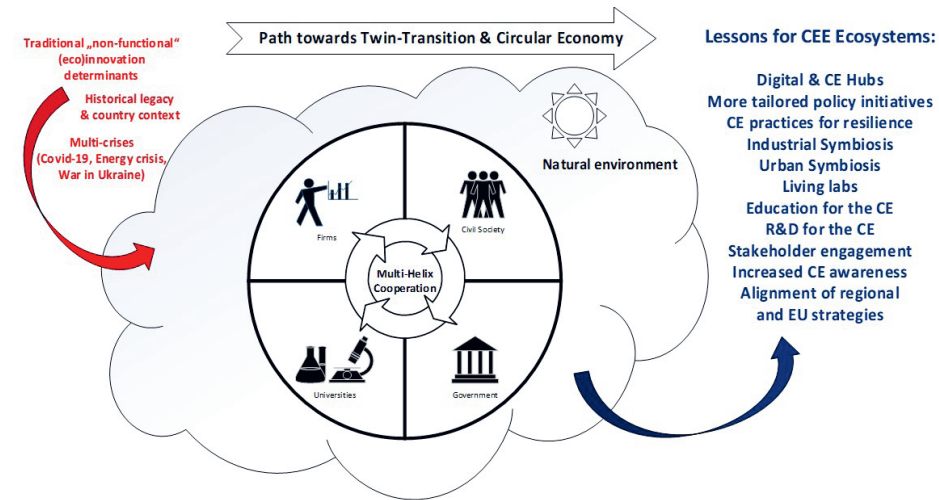
Before the crises, innovation strategies in CEE were primarily focused on technological improvements and traditional growth models. Companies concentrated more on adapting foreign technologies rather than conducting their own research and development, a situation that continues to limit the region's ability to generate radical innovations, as noted by Radošević (2017) and Stojčić (2021). The circular economy remained a marginal concern, with traditional production and consumption models dominating and a minimal emphasis on resource efficiency. The legacy of Socialism still had a significant impact on innovation systems in some countries, such as Croatia. Švarc and Dabić (2019) highlight state paternalism and weak entrepreneurial initiative as factors that hindered technological progress and modernization. Despite the EU support, technologies were not effectively transferred into market practices. These historical factors contributed to the persistent fragmentation of innovation systems and the weak absorptive capacity of companies in the region. Even after the crises, CEE countries continue to face structural barriers, including low innovation capacity, reliance on imported technologies and fragmented innovation ecosystems.

These persistent challenges are now compounded by new barriers associated with the rapid digital transformation of economies. In the context of the twin transition, digitalization itself has become a critical domain in which the structural deficits manifest most visibly. Beyond structural barriers, CEE countries face persistent digitalization challenges that continue to constrain their innovation performance. The shortage of employees with advanced digital skills remains a critical bottleneck for firms, inhibiting both innovation and the adoption of new technologies. Moreover, investment in digital infrastructure consistently lags behind Western European standards, limiting the scalability of digital solutions in the region (Ferrazzi *et al.*, 2025).

As digitalization advances, cybersecurity risks are becoming increasingly salient. Many firms lack the resources and expertise to address these threats effectively, further exposing the region to vulnerabilities (Vevera *et al.*, 2021). Addressing these digital challenges requires not only targeted policy measures but also coordinated action among key innovation ecosystem actors. In this context, universities and higher education institutions have a central role to play.

As noted by Mendoza *et al.* (2019) and Serrano-Bedia and Perez-Perez (2022), universities play a crucial role in bridging academic research and practice, as they serve not only as educational institutions but also as drivers of innovation and the application of scientific knowledge to the real world. This transition also involves supporting student-led innovations through incubators and accelerators, increasing research funding and strengthening collaboration between academic institutions, industry and governments (a triple-helix based collaboration). However, a successful transition requires not only technological and financial investments but also coordinated cooperation among all key actors within the so-called multi-helix model (Figure 6). This model emphasizes the importance of integrating diverse resources, knowledge and competencies to enable the effective implementation of the principles of digital transformation and sustainability. The key to long-term success lies in the adaptation of values, cultures and strategies that foster the sharing of innovations and ensure that the CE becomes a tangible reality rather than merely a conceptual framework.

Figure 6. Proposed CEE quintuple-helix-based innovation ecosystem. (Source: Authors' elaboration.)



The crises have also accelerated the adoption of CE principles. Organizations that integrated these principles demonstrated greater resilience to external shocks. However, progress in this area remains uneven. Overcoming these challenges requires targeted strategies such as increasing investments in R&D and fostering closer multi-helix-based collaboration between universities, industries, governments and civil society. Reducing dependence on imported technologies through initiatives that incentivize companies to invest in domestic innovation activities is essential. Strengthening companies' absorptive capacity and supporting local innovation ecosystems are also critical steps in this process. In addition, looking ahead, industrial symbiosis (IS), urban symbiosis (US) and the broader CE principles are expected to remain central to achieving higher sustainability. These go hand in hand with emerging trends including the use of digital technologies like blockchain and the Internet of Things (IoT) to track resource flows and ensure transparency in circular processes.

Policymakers can support the above efforts by establishing digital innovation hubs and providing targeted funding for IS projects through initiatives such as Horizon Europe. Moreover, tax incentives and grants for collaborative R&D between academia and industry could drive the development of innovative solutions tailored to regional needs. Another promising avenue involves integrating living labs into local innovation ecosystems. These labs serve as experimental environments where stakeholders can co-create and test sustainable and digital solutions in real-world settings. For example, the Circular Economy Living Lab in the Netherlands showcases how communities, businesses and universities can collaboratively address challenges such as resource scarcity and climate change. Encouraging similar initiatives in the CEE region could accelerate the adoption of sustainable practices while fostering collaboration among quadruple-helix actors. To fully realize the twin transition, it is imperative for CEE countries to adopt multi-stakeholder strategies that combine investments in infrastructure with regulatory frameworks that drive innovation. For instance, establishing the above-described living labs and regional innovation clusters focused on sustainability and digitalization can enable localized experimentation and adaptation of global best practices. These initiatives should be tailored to the specific needs of individual countries, ensuring that less-developed regions are not left behind.

In addition, supporting the creation of CE hubs seems to be the way to support CE transitions among CEE states. However, there is a need to analyze the maturity levels of such hubs (and ecosystems as a whole) among these

regions (seed hubs, intermediate hubs, advanced hubs) to better understand the preparedness and needs of stakeholders. For example, regarding seed hubs, there is a need for increased emphasis on stakeholder engagement and mapping, which goes hand in hand with more tailored mentorship programs and international collaboration with advanced economies.

Finally, aligning long-term regional strategies with European-level policies, such as the New European Innovation Agenda and the EU SME Strategy, will be essential. These strategies should prioritize resilience-building, leveraging crisis-induced opportunities to enhance energy independence, adopt renewable energy and reduce reliance on imported technologies. By addressing these practical implications and leveraging trends such as IS, living labs, CE hubs and policy alignment, CEE countries can unlock their innovation potential and lead the way in achieving the twin transition. Policymakers can also support the creation of 'CE mentor hubs', investments in pilot CE projects, R&D for the CE, grants for the CE to industry (including, for example, decarbonization of industries or the use of material waste for IS or urban symbiosis) and study visits.

Following above policy recommendations, the second research question raised was: *How can regulatory and legislative frameworks in CEE countries support innovation activities and investments in technology without restricting companies' flexibility and willingness to innovate?*

As noted by Stojčić, Vujanović and Baum (2024), the regulatory frameworks in the region often lack the flexibility needed for companies to respond quickly to changing conditions. According to Ciriaci *et al.* (2019), regulations aligned with innovation objectives can motivate companies to adopt new technologies and processes. Furthermore, Hojnik *et al.* (2022) confirm that appropriate regulations, combined with companies' environmental orientation, significantly support eco-innovations and improve environmental outcomes, such as environmental protection and ecological efficiency. However, their research emphasizes that the key driver of successful eco-innovations is not merely R&D investment but rather companies' focus on sustainability, complemented by a supportive regulatory environment that fosters innovation. Policymakers must act as mediators to ensure a balance between public and private interests (Stojčić *et al.*, 2024). For example, the introduction of performance-based regulations instead of prescriptive rules can enhance flexibility without compromising accountability. Regulatory frameworks should also encourage companies to take risks through tax incentives, grants and venture capital. Offering tax breaks or grants

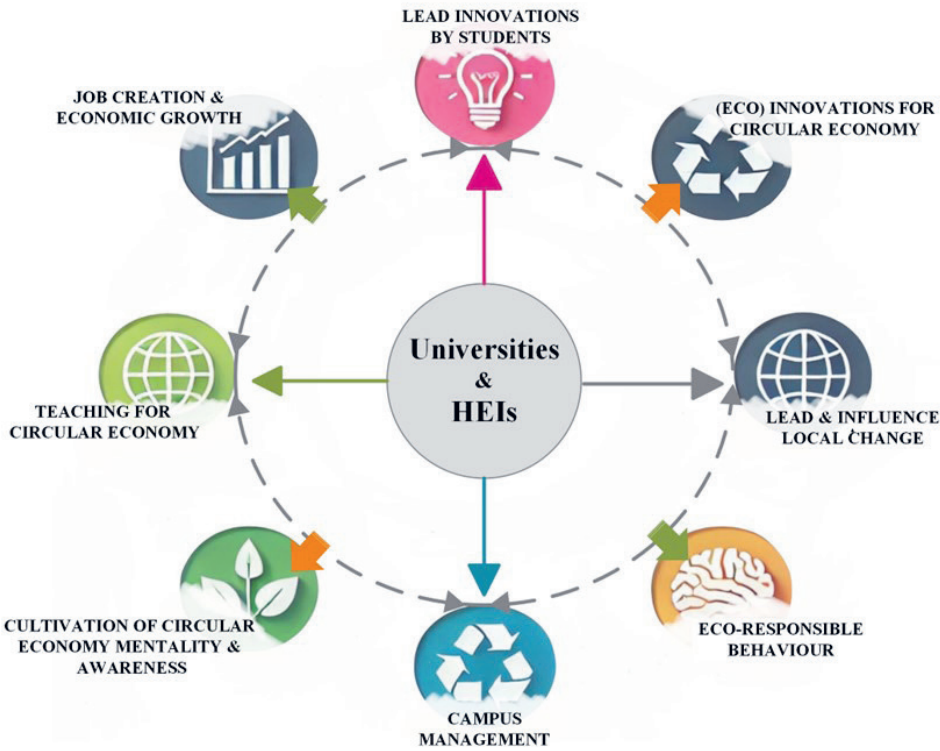
for research and development can motivate companies to invest in new technologies.

The final research question examined *how multi-crises have impacted the progress of CEE countries in achieving the twin transition*.

These crises highlighted the vulnerability of innovation systems in CEE countries and deepened the disparities between individual states in their ability to respond to emerging challenges. While some countries, such as Estonia, have accelerated their digital transformation and strengthened their position in the twin transition through targeted policies and investments, others, such as Romania and Bulgaria, continue to lag behind (Stojčić, 2021). These differences can be largely attributed to varying levels of digital infrastructure and workforce skills: countries with stronger digital foundations and higher digital skills responded more effectively and adopted new technologies at a faster pace during the crises (Ferrazzi *et al.*, 2025), whereas those with persistent gaps faced greater obstacles, further widening the divide. The COVID-19 pandemic further accelerated the uptake of digital technologies, especially in countries with pre-existing technological infrastructure, while less developed states struggled to implement modern solutions and keep pace with digital transformation. In addition, the war in Ukraine has underscored the importance of energy security and the transition to renewable energy sources, both of which have become critical pillars for sustainable growth across the region.

Companies that embraced CE principles, such as efficient resource utilization and waste minimization, demonstrated greater resilience and adaptability to changes. However, progress in this area remains uneven. These events illustrate that crises can serve as an opportunity to accelerate the twin transition, but they also demand strategic measures that align short-term economic goals with long-term ambitions for sustainability and digitalization. As highlighted by Serrano-Bedia and Perez-Perez (2022), collaboration among the key actors within innovation ecosystems is a crucial step in addressing the challenges associated with the twin transition. Universities and higher education institutions (HEIs) can play a pivotal role as a bridge between research and industry in various ways (see Figure 7), particularly in the field of the CE, where education and research can deliver tangible applications in practice. In this way, Kirchherr and Piscicelli (2019) suggest five educational tenets for a CE training and education, covering both theory and practice at micro, meso and macro levels.

Figure 7. Education for the CE: The role of universities and HEIs.
(Source: Authors’ processing based on Serrano-Bedia and Perez-Perez, 2022.)



In sum, despite the post-crisis improvements, numerous challenges persist in the region. The implementation of circular economy (CE) principles often remains theoretical, with many organizations lacking the necessary resources and expertise for full integration. As noted by Vence *et al.* (2022), this phenomenon is referred to as the ‘CE paradox’—a situation where the CE is widely present in political agendas and corporate strategies, but its actual application is limited. This paradox indicates that although there is a consensus on the importance of the CE, concrete steps toward its implementation often fall short. Many organizations struggle with a lack of motivation and support, which are essential for the adoption of CE practices. This results in these concepts often remaining on paper and failing to be translated into real-world practices. As Veyssi re *et al.* (2021) and Kasmi (2018) highlight, obstacles such as insufficient information, technical barriers and economic constraints hinder an effective transition to circular models. Organizations frequently lack the resources and necessary knowledge

to fully integrate the CE into their processes. Funding for R&D remains limited, and collaboration between universities, industry and governments lacks a systematic approach. However, universities can play a crucial role, as suggested by Figures 6 and 7, serving as examples of successful implementation of circular practices and inspiring future generations to develop innovative solutions within emerging innovation ecosystems aimed at creating the ‘circular society’ (Leipold *et al.*, 2021).

6. Conclusions and future trends

This article provides a synthesis of key insights from the existing scientific literature on the twin transition in Central and Eastern Europe in the context of crises. The findings highlight structural barriers such as limited funding for R&D, reliance on imported technologies and fragmented innovation ecosystems, continuing to hinder the region from fully leveraging the potential of the twin transition toward sustainability and digitalization. These factors weaken the ability of CEE countries to independently create and commercialize innovations, which is crucial for achieving long-term competitiveness. The analysis of the current state of the art revealed that crises not only exposed weaknesses in innovation systems but also created opportunities for their transformation. Some countries, such as Estonia, have strengthened their digital and sustainable infrastructure through targeted policies and investments, while others, such as Romania and Bulgaria, continue to lag behind. These disparities underscore the need to adapt strategies to the specific contexts of individual countries and to promote the sharing of best practices across the region. The role of universities, as illustrated in Figures 6 and 7, is critical in bridging academic research and practical application, particularly in the field of the circular economy. Universities can act as a bridge between research institutions and industry, support education focused on sustainability and serve as examples of successfully implementing circular practices. Despite these opportunities, the implementation of such principles in the region often remains theoretical, with adoption varying widely.

This study is not without limitations. As this article is based on a non-empirical analysis of the existing literature and the current state of the knowledge, it does not provide empirical data nor primary data but rather offers an integration and synthesis of the current findings. The authors also

acknowledge that the use of the PRISMA-based approach has its limitations. In this case, this is mainly due to the use of a single source in the form of Google Scholar. Also, the focus on a specific (less studied) territory results in a lower number of analyzed studies. Therefore, for future research, it is necessary to consider other sources of scientific studies. By contrast, our limitations, in general, allow us to propose several future directions, starting with those proposing an empirical verification of our findings, either in the form of an empirical multi-country analysis or in the form of mixed-method research based on an empirical analysis, which will be supplemented by insights from interviews with key stakeholders. For such purposes, primarily within the CEE territory, different data sources could be considered, including the World Bank Enterprise Survey, the Refinitiv Eikon database or Eurobarometer surveys (Prokop *et al.*, 2025). Future research should also explore how specific regulatory and legislative changes impact innovation performance in CEE countries and analyze the long-term effects of crises on innovation capacity and economic growth. Additionally, it is essential to focus on best practices in collaboration between universities and industry, which could help advance the twin transition. Further studies should also evaluate the potential for expanding CE practices in less developed regions of CEE. Comparative studies with other regions facing similar challenges could bring new perspectives and help identify effective solutions. These research areas can contribute to a deeper understanding of how to align short-term crisis response measures with long-term goals for sustainability and digitalization. In this way, future research could support efforts by CEE countries to overcome the current barriers and maximize their potential for the twin transition in an era of global changes. Moreover, we also consider examining the internal capacities of key stakeholders, such as companies, as important. In this case, it is necessary to focus on the technological capabilities that can—especially in times of crisis—increase the resilience of the entities concerned (Gemici *et al.*, 2024; Jiang *et al.*, 2024).

We also suggest evaluating the role of industrial symbiosis (IS) as a catalyst for both economic and environmental resilience (Karman *et al.*, 2024a) because it could reveal pathways to strengthen collaboration between industries and reduce resource dependency. Successful IS examples, such as Kalundborg Symbiosis in Denmark, demonstrate the potential of circular practices to create value while addressing sustainability goals. Next, exploring mechanisms to enhance university-industry partnerships is crucial (Secundo *et al.*, 2024; Damioli *et al.*, 2025). Developing interdisciplinary curricula, fostering co-creation initiatives and aligning academic research

with market needs can accelerate the practical application of sustainability and digitalization principles. These research areas can contribute to a deeper understanding of how to align short-term crisis response measures with long-term goals for sustainability and the digital transformation. Such efforts will support CEE countries in overcoming current barriers and maximizing their potential for the twin transition in an era of global changes.

Finally, despite the implementation of the CE as a crucial step toward achieving sustainability, it is not sufficient on its own. As highlighted by Bocken *et al.* (2022) or Jouzi *et al.* (2024), the concept of ‘sufficiency’ represents a missing link in the transition to the CE, emphasizing the need to avoid overconsumption and support conscious consumer decisions. Sufficiency calls for rethinking our needs and consumption patterns, including activities such as repairing, maintaining existing products or purchasing secondhand and refurbished goods. This approach addresses the challenges linked to crises, such as climate change and biodiversity loss, while aligning with long-term sustainability goals. For businesses, it entails re-evaluating business models, limiting the sale of unnecessary products and focusing on value-driven strategies that promote sustainable practices. The combination of CE principles and sufficiency thus forms a comprehensive approach that can ensure more efficient resource use, reduce the ecological footprint and improve the overall quality of life for current and future generations. A combination of these approaches therefore appears to be another important line for future research.

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