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Blockchain unlocking collaborative opportunities for environmental sustainability through innovation intermediaries

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Abstract
This paper delves into the growing need for collaborative technological solutions to address environmental challenges, with a focus on the underexplored potential of Industry 4.0 technologies, in particular as regards blockchain technology (BCT) in small and medium-sized enterprises (SMEs). Recognizing the obstacles faced by SMEs when embracing green and digital transformation, this research aims to investigate how innovation intermediaries are able to unlock the collaborative potential of BCT for SMEs so as to enhance their environmental sustainability. When assessing and analysing the role of innovation intermediaries, we have also considered their interconnections and interactions with other actors: universities, government institutions and firms (the so-called "stakeholders"). Our research is based on a multiple case study of a still largely unexplored intermediary in the European context, the digital innovation hub (DIH), which extends the applicability of the technological innovation system framework. This approach contributes to research both on innovation intermediaries and on the development of collaborative partnerships for digitalization. The findings reveal the challenges encountered by DIHs, particularly in legitimizing BCT-based solutions. To address these, identified, weaknesses, the paper proposes a conceptual roadmap aimed at improving collaboration among DIHs, SMEs, and their stakeholders. This roadmap outlines three essential functions: enabling, core, and facilitating effective partnerships and innovation processes.

Keywords Blockchain · Collaborative partnership · Digital innovation hub · Digitalization · Environmental sustainability · Innovation intermediary

Special issue: The impact of digitalization and virtualization on technology transfer in strategic collaborative partnerships

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1 Introduction

Industry 4.0 (I4.0) aims to strengthen industrial capabilities through the adoption of new digital technologies, specifically the Internet of Things (IoT), blockchain (BCT), artificial intelligence (AI), Big Data, robotics and cloud computing (Luthra et al., 2020). Along with creating new business opportunities (Bai et al., 2020; Esmaeilian et al., 2020), these technologies also enable firms to better address the increasing number of issues in the area of environmental sustainability,[1] such as climate change, deforestation, water pollution, and public health (de Sousa Jabbour et al., 2018a; Feng et al., 2022).

Technological solutions supporting environmental sustainability are particularly important for small and medium-sized enterprises (SMEs) which are the backbone of many economic ecosystems around the globe. On the one hand, SMEs represent the main drivers of global economic growth; in the European Union they constitute about 99% of all businesses (Journeault et al., 2021). On the other hand, the environmental impact of SMEs is around 60–70% at both the European and the global level (Madrid-Guijarro & Duréndez, 2024). Given the key economic role of SMEs and their environmental footprint, efforts to promote sustainability are likely to succeed only if their participation is facilitated (Journeault et al., 2021). At the macro level, the diffusion of new green technologies can contribute to preserving environmental quality (Song & Wang, 2016) when these are aligned with political targets (de Sousa Jabbour et al., 2018b), while at the micro level, advanced technologies enable firms to allocate resources more efficiently, thus creating sustainable industrial value (Stock & Seliger, 2016).

Among the most important I4.0 technologies that can drive environmental sustainability, blockchain technology (BCT) is attracting more and more attention (Parmentola et al., 2022; Saberi et al., 2019; Soriano-Pinar et al., 2023). BCT nurtures relations based on trust in strategic alliances among and between SMEs and socio-economic stakeholders of the ecosystem: university research centres, government institutions, large firms, regional economic development organizations, trade associations, consultants and technical experts (European Commission, 2021a; He et al., 2020; Journeault et al., 2021; Liu et al., 2022; Parmentola et al., 2022). BCT is a distributed database structured in a chain of blocks containing transactions. This type of database provides a decentralized and secure infrastructure for tracing and tracking products, services and transactions (Saberi et al., 2019). Recent studies have started looking into the contribution of BCT to both environmental (Giganti et al., 2024) and social sustainability, across diverse dimensions, including community welfare, regional development, employability, humanitarian supply chains, fraud migration, and animal health (Munir et al., 2022). Because BCT promotes data sharing, transparency, trust development and monitoring across the entire product lifecycle (Friedman & Ormiston, 2022; Parmentola et al., 2022; Saberi et al., 2019; Upadhyay et al., 2021), environmental sustainability is enhanced through the reduction of carbon emissions, improved waste management, and better environmental impact monitoring (Giganti et al., 2024). Moreover, social sustainability is fostered by ensuring food safety, consumer trust, and financial inclusion for small firms Giganti et al., 2024) and vulnerable populations,

[1] Environmental sustainability is defined as a state of equilibrium, resilience, and interconnectivity enabling human society to meet its needs without surpassing the regeneration capabilities of its ecosystems or reducing biological diversity (Morelli, 2011).

especially in developing countries (Rawhouser et al., 2024). Both environmental and social sustainability can also be augmented by providing behavioural incentives for producers, consumers and prosumers (Esmaeilian et al., 2020).

Although BCT application for environmental sustainability is still evolving (Esmaeilian et al., 2020; Giganti et al., 2024), its potential contribution looks promising especially in the field of energy production (Swiatek et al., 2017), waste management (Clohessy & Acton, 2019), green logistics and transportation (Esmaeilian et al., 2020), and the agri-food supply chain (Compagnucci et al., 2022), where it can also contribute to social cohesion and equitable access to resources by strengthening interactions between consumers and firms (Giganti et al., 2024). Nevertheless, most SMEs are not exploiting the "green" potential of BCT (Ghobakhloo & Ching, 2019; OECD, 2018, 2019) for several reasons, highlighted in the literature. First, SMEs have limited awareness of both the benefits associated with sustainability and how to integrate it into their business models; also, SMEs often have time, human and financial constraints (European Commission, 2020b; Journeault et al., 2021). Second, SMEs are often not ready to adopt BCT (Ølnes, 2016) since it requires a cultural and operational shift in terms of trust building, data sharing, knowledge transfer and privacy (He et al., 2020). Third, SMEs do not take advantage of the collaborative potential of BCT since few such firms actively integrate this technology into existing procedures (Compagnucci et al., 2022; Friedman & Ormiston, 2022). Fourth, there are several barriers to the cooperation required for the diffusion of BCT among SMEs and their key stakeholders. Not only are such barriers exacerbated by both the complexity and the global nature of sustainability challenges, but also they are often underexplored (Friedman & Ormiston, 2022). Fifth, although SMEs need tailored approaches, based on cooperation, in order to integrate advanced technologies such as BCT (Benitez et al., 2020; Hilkenmeier et al., 2021; Rajalo & Vada, 2021), there is little information as to how the specific roles performed by diverse stakeholders would be able to contribute to enhanced technology adoption in SMEs (Boiral et al., 2019; Johnson & Schaltegger, 2016; Journeault et al., 2021).

Starting from these information gaps, this paper investigates the role played in Europe by innovation intermediaries in realising the collaborative potential of BCT for SMEs in promoting environmental sustainability (e.g., Caloffi et al., 2023; Kivimaa et al., 2019; Rossi et al., 2022). When assessing and analysing the role of innovation intermediaries, we also took into account their interconnections and interactions with universities, government institutions and firms (the so-called "stakeholders") (Johnson & Schaltegger, 2016).

The literature on innovation intermediaries is increasing (e.g. Gliedt et al., 2018; Kant & Kanda, 2019; Rossi et al., 2022). Innovation intermediaries are defined as agents facilitating the process of technology/knowledge transfer between people, and organizations, by addressing the factors that enable, or restrain or them (Battistella et al., 2016; O'Kane et al., 2021). Innovation intermediaries have various functions (Battistella et al., 2016), such as connecting SMEs and stakeholders (Alexandre et al., 2022; Howells, 2006; Russo et al., 2018), managing collaborations (Hernández-Chea et al., 2021), mapping knowledge and technological needs (Russo et al., 2018), and mobilizing financial resources (Polzin et al., 2016). Indeed, the multiple functions of intermediaries reflect the high degree of complexity they have to deal with, often in contexts where there is a high degree of uncertainty, when managing diverse activities and stakeholders, (Agogué et al., 2017). Moreover, intermediaries usually face further challenges, including the lack of resources, legitimacy (Bush et al., 2017) and specialized expertise in the technological domain (Chandran et al., 2013; Gajzago, 2017). Innovation intermediaries also deal with the changes required by digitalization concerning resource mobilization, which include the search for, access to, and the governance of resources (Inceoglu et al., 2024). In

facing this challenge, their ability to mobilize resources depends on external networks which are able to provide them organizational legitimacy (Granovetter, 1985; Lee et al., 2001).

This paper addresses the following research questions within the context described above:

1. To what extent, and how, do innovation intermediaries involve SMEs in the design and adoption of BCT for environmental sustainability?
2. To what extent, and how, can the actors of the innovation ecosystem, universities, government institutions and firms, support innovation intermediaries in their role?

To answer these questions, we developed a multiple case study analysis (Baxter & Jack, 2008; Yin, 2018) of a sample of twelve digital innovation hubs (DIHs) in Europe. DIHs are an emerging type of innovation intermediaries which are seen as orchestrators of collaborative networks that support the development, and adoption, of technologies tailored for SMEs (Crupi et al., 2020), and contribute to achieving European Green Deal targets (European Commission, 2021c). The sample was investigated between 2020–2023, by adapting the functional and structural approach suggested by Kanda et al. (2019) within the technological innovation system (TIS) framework (Carlsson & Stankiewicz, 1991). This approach was designed to evaluate innovation intermediaries' roles in a socio-technical system of actors who are seeking to develop and apply specific technologies.

This paper advances both the academic and the policy-making debate in several ways. First, it carries forward the research on innovation intermediaries (e.g., Battistella et al., 2016; Caloffi et al., 2023; Kivimaa et al., 2019; Good et al., 2019; O'Kane et al., 2021; Palaco et al., 2022; Rossi et al., 2022) and on collaborative partnerships for digitalization (e.g., Antonioli et al., 2017; Harrigan et al., 2017; He et al., 2020; Liu et al., 2022) by focusing on the emerging role of DIHs (e.g., Crupi et al., 2020; Georgescu et al., 2021). Second, it contributes to the literature on digitalization and resource mobilization by considering digitalization as the research context within which management issues (Inceoglu et al., 2024) related to innovation intermediaries and their stakeholders are examined. Third, a roadmap has been drawn up, based on the results obtained from the qualitative analysis, to overcome the barriers to cooperation (Friedman & Ormiston, 2022) between DIHs, SMEs, and the actors of the ecosystem, and to check they align with environmental sustainability targets. Fourth, from the methodological perspective, this study demonstrates how widely the TIS framework could be applied. Indeed, the approach adopted offers a broader application of the TIS as it considers the role stakeholders can, or could play in supporting innovation intermediaries.

The paper is structured as follows. Section 2 reviews the literature on BCT for environmental sustainability, innovation intermediaries and DIHs. Section 3 illustrates the methodology and data collection. Section 4 outlines the results. Section 5 presents the discussion. Drawing on our results, a roadmap for policy makers and DIHs is proposed in Sect. 6. The final section summarizes the main findings, theoretical and practical implications, and suggests future directions for research.

2 Theoretical background

2.1 Blockchain and collaborative partnerships for sustainability

A blockchain is a decentralized, distributed database, structured as chains of blocks containing transactions. Specifically, a blockchain is extended by each additional block and

is a complete record of the history of a transaction based on timestamped and hashed data (Nofer et al., 2017). Transactions are shared among parties without the intervention of an intermediary. By ensuring the integrity and immutability of data, the BCT provides a trusted database for collecting, storing, and managing data (Zhao et al., 2016).

Based on its peer-to-peer mechanism, BCT can also offer an opportunity to increase financial inclusion for both entrepreneurs who typically face challenges in accessing financing (Butticè & Vismara, 2022; Vismara, 2022), and for more vulnerable populations, especially in developing countries (Chainalysis, 2021; Rawhouser et al., 2024). Indeed, BCT is expected to assist firms when developing new forms of collaboration regarding the application of this technology in domains outside mere cryptocurrencies (Liu et al., 2022). Unlike other information technology solutions, BCT offers an innovative way to enforce agreements and to achieve cooperation by overcoming traditional contractual and relational governance (Lumineau et al., 2021). BCT can impact collaboration by streamlining communication, sharing information and processes, and by supporting decision making among partners throughout the supply chain.

Moreover, BCT can help economic agents connect and re-combine internal resources and capabilities with those available externally (Audretsch et al., 2023). This means that BCT can enhance collaborative partnerships by facilitating both auditability and accountability, by improving data and information transparency, and by strengthening trust in B2B relationships (Rejeb et al., 2021). Thus, BCT can become a single source of information through automatization, leading to reduced information asymmetries and to the replacement of centralized databases (Schlecht et al., 2021). These characteristics make the technology ideal for supporting environmental sustainability actions and green transition. Indeed, through BCT, governments also expect to achieve, ambitious environmental sustainability targets (European Commission, 2019a, 2019b) which concern both the equilibrium of environmental systems and a responsible use of natural resources (Glavič & Luckman, 2007), all of which are crucial for communities and for all aspects of their development (Elder & Olsen, 2019; Morelli, 2011).

To contribute to achieving sustainable development goals (SGDs), BCT can be used to track and verify the environmental footprint of products along the supply chain (Soriano-Pinar et al., 2023), and to share such traceable data in order to raise awareness about environmental issues. Furthermore, BCT can strengthen the enactment of food safety regulations, by identifying contaminated batches along the supply chain, thus preventing the spread of foodborne illnesses and safeguarding public health (Niu et al., 2021). BCT can also be integrated with other I4.0 technologies, such as IoT, to automatically upload data on transactions occurring in the supply chain (Kamilaris et al., 2019). Customers can even use their mobile phones to scan the QR codes printed on products, thereby accessing the traceability data stored on the BCT (Bumblauskas et al., 2020). Furthermore, BCT can be applied to address waste management issues by rewarding citizens with a virtual wallet of coins each time they sell their solid waste to the municipality (França et al., 2020). It means that BCT enables consumers to make more ethical and sustainable decisions about their consumption (Rainero & Modarelli, 2021).

In the field of collaboration for energy management, Swiatek et al. (2017) have presented a BCT application for monitoring and optimizing energy systems. This digital solution affects the interaction between end-users and maintenance operators, encouraging them to follow-up on their improvement actions by using a BCT-based green certification. BCT can become a key driver to make energy distribution feasible, which is crucial when deploying the use of renewable energy sources at the global level. In particular, the introduction of BCT in the energy industry can contribute to improving the quality of life of

populations living in vulnerable regions or remote geographical areas, both of which are affected by severe shortcomings in either energy production, or in distribution (Jackson, 2022).

As regards collaboration for environmental sustainability, Kim and Huh (2020) introduced a BCT-based verification structure that integrates artificial intelligent (AI) algorithms for measuring carbon emission rights. More recently, Rolinck et al. (2021) implemented a BCT solution that promotes collaborative partnerships for environmental sustainability in the aircraft industry. The solution proposed aims to improve life cycle assessment (LCA) by focusing on maintenance and repair.

SMEs can also benefit from BCT by integrating sustainable environmental practices into their business strategies. While traditional supply chains lack transparency and traceability, SMEs using BCT are able to increase cross-organisational collaboration and knowledge transfer, thus becoming more integrated into national and international supply chains and overcoming barriers to market entry (Philipp et al., 2019). Indeed, BCT further strengthens the functionalities provided by other Industry 4.0 technologies, such as IoT and Big Data, by extending supply chains and logistics towards larger markets. There are several BCT applications that have been developed by international companies, including Circulor, Unilever, and Bext360, these offer traceability services and fair payment methods to customers and partners seeking to obtain natural resources from farmers in developing countries. This helps producers to achieve transparency, visibility and, in turn, legitimation when using labour force and natural resources in a responsible manner (Hyperledger, 2019).

The literature also stressed that BCT has the potential to improve social sustainability especially in underdeveloped countries (Kumar et al., 2022; Ronaghi & Mosakhani, 2022). For instance, as regards property-related transactions in these countries, commonly subject to bribery and corruption, BCT-based applications can contribute to avoiding this, at least partially, by replacing paper-based registries, which latter usually lack transparency, accessibility and security, thus improving the effective enactment of property rights (Thakur, et al., 2020). Furthermore, BCT permits specific types of financing which are important for vulnerable communities. One such example is the World Food Program's (WFP) 'Building Blocks' project started in 2017. This application was involved to supply food and cash assistance to needy families in Pakistan and Jordan (Wong, 2017). Moreover, as a new form of crowdfunding, BCT financing with initial coin offerings (ICOs) is becoming a widespread practice among small firms not only in developing countries (Belitski & Boreiko, 2022). Fisch et al. (2022) examined the extent to which ICOs provide a neutral framework for individuals to collect money and start their activities. The authors have empirically demonstrated that such solutions improved the financing conditions for young teams, ethnic minorities, and entrepreneurs in remote locations.

Although developments in BCT are making collaboration possible (He et al., 2020) and business is predicted to grow further in this domain (European Commission, 2023), BCT still faces several challenges, including scalability, energy consumption, integration with the legacy of infrastructures, interoperability, potential collusion between participants, management of public–private keys, and the protection of personal, sensitive or confidential data (Chiarini & Compagnucci, 2022; European Commission, 2020a).

It is worth noting that the global scale of environmental issues amplifies the need for shared and diffused technological solutions, especially among SMEs which play a crucial economic role and exert a growing impact on the environment. On the other hand, efforts to promote environmental sustainability are unlikely to succeed without the commitment of SMEs (Journeault et al., 2021). Indeed, there is still a lack of involvement between SMEs and stakeholders within the ecosystem, when designing and implementing BCT

(Compagnucci et al., 2022; Friedman & Ormiston, 2022). Innovation intermediaries could well prove crucial for overcoming this gap, as will be seen in the next section.

2.2 Innovation intermediaries

Innovation intermediaries have been portrayed as «innovation brokers» (Winch & Courtney, 2007, p. 747), «boundary spanners» (Keszey, 2018, p. 1061), «bounded knowledge commons» (Miller et al., 2017, p. 14) or «gatekeepers» (Sovacool et al., 2020, p. 1). In other words, an innovation intermediary is «an organisation or body that acts as an agent or broker in any aspect of the innovation process between two or more parties» (Howells, 2006, p. 720).

Intermediaries can support firms by helping them to become aware of both the tools and the resources required to achieve their goals by means of knowledge and technology mapping (Russo et al., 2018). They can also generate non-financial value including network-based benefits (De Silvia et al., 2018). These entities can also serve as brokers within entrepreneurship and innovation ecosystems, by offering services that accelerate the development of entrepreneurial activities (O'Kane et al., 2021). Depending on the type of intermediary, i.e., public, semi-private or private, a specific form of collaboration can be established, which will influence influencing the links between SMEs and stakeholders (Klewitz et al., 2012). Such collaboration also supports firms to acquire financial, managerial and knowledge resources, thus reducing costs and sharing risks (Nambisan et al., 2019). Thus, the ability of innovation intermediaries to mobilize resources and define entrepreneurial opportunities is linked to external networks (Granovetter, 1985; Lee et al., 2001). In this collaborative scenario, the connecting role of these intermediaries is crucial, especially with respect to SMEs with fewer knowledge capacities (Alexandre et al., 2022).

Although the literature on innovation intermediaries is increasing (e.g., Gliedt et al., 2018; Kant & Kanda, 2019; Rossi et al., 2022), Palaco et al. (2022) have recently argued that extant research has mainly focused on descriptions of the typologies of intermediaries (e.g., Good et al., 2019) and their functions (e.g., Battistella et al., 2016) in relation to innovation performance (Zhang & Liu, 2023). Nevertheless, innovation intermediaries have become increasingly diversified (Caloffi et al., 2023) so as to coordinate multi-party systems for implementing new digital technologies (Rossi et al., 2022) and in order to address environmental sustainability (Kanda et al., 2018; Kivimaa et al., 2019; Klewitz et al., 2012). Indeed, intermediaries can show, and share, the extent of the environmental benefits of novel environment-based technologies to key stakeholders (Kanda et al., 2018; Klewitz et al., 2012), by organizing testbeds and demonstration projects. Overall, intermediaries can complement the functions of green actors within a local ecosystem (Gliedt et al., 2018).

However, the literature has also argued that stakeholders within the ecosystem, especially SMEs, have limited awareness of the benefits associated with sustainability (Journeault et al., 2021) and most of such firms are not yet ready to adopt BCT (Ølnes, 2016). This is a major issue since the effectiveness of BCT for environmental sustainability relies on fully exploiting the collaborative potential of BCT for ensuring the diffusion of such technology on a wider scale. Although the introduction of new technologies enables greater social and digital engagement with SME's stakeholders, as well as reducing their transaction and operational costs (Audretsch et al., 2023), SMEs are usually reluctant to start a process of digitalization for environmental sustainability (European Commission, 2020a; 2021c). This is often due to their limited financial and organizational resources

(Clohessy & Acton, 2019; European Commission, 2020b; OECD, 2019) as well as to a lack of awareness about how to integrate sustainability into their business models (European Commission, 2020b).

Furthermore, investors still have little knowledge about BCT, which stops them being able to assess the technical and financial viability of BCT-based solutions (European Commission, 2020a). This means that SMEs need support when financing, designing and integrating BCT applications; support which should consider the characteristics of both the company and of the industry concerned (Chege & Wang, 2020). There are also cooperative barriers which may hinder the diffusion of BCT among SMEs (Friedman & Ormiston, 2022). The likelihood of there being cooperation is negatively influenced any knowledge and financial obstacles that may be present. The benefits of cooperation rely both on a certain level of absorptive capacity and on the transaction costs linked to gathering information, sharing knowledge, communicating, selecting partners and establishing such cooperation (Antonioli et al., 2017; Kivimaa et al., 2019).

On the one hand, SMEs require tailored approaches based on collaboration with different stakeholders, such as companies, public authorities, and universities (Benitez et al., 2020; Rajalo et al., 2021; Hilkenmeier et al., 2021). These interactions are expected to increase the innovative capacity of SMEs for sustainable-oriented innovation (Klewitz & Hansen, 2014). On the other hand, SMEs typically show a preference for local and informal contacts within the networks and the need to refer to guide-figures when interacting with external knowledge sources (Giaretta, 2014). To contribute to understanding and overcoming these issues, this paper examines how innovation intermediaries act in order to involve SMEs in both the design and the adoption of BCT for environmental sustainability.

2.3 Digital innovation hubs

The level of digitalisation of SMEs varies widely in the Member States of the European Union (EU). Indeed, there are only four countries, Finland, Denmark, Malta and Sweden, where the share of firms with a very high digital intensity index (DII)[2] is above 9%. On the contrary, in countries such as Romania, Bulgaria and Hungary, more than 60% of firms have made only small investments in digital technologies. Regardless of the economic sector, digitalization challenges SMEs mainly because of the lack of awareness of the potential of such technologies. Furthermore, few SME employees have sufficient skills and expertise to be able to integrate these new technologies into their firm's operations (European Commission, 2023). However, several EU countries have invested substantial resources in projects, such as the creation of Digital Innovation Hubs (DIHs), in order to support digitalization and technology transfer in SMEs (Kalpaka et al., 2020).

DIHs are innovation intermediaries that were recognized by the European Commission, in the Digitizing European Industry initiative of 2016,[3] as orchestrators of collaborative networks that contribute to the development and the adoption of technologies tailored for SMEs (Crupi et al., 2020). With different technological focus and structures, DIHs create a multi-layered innovation system that can be exploited at the regional, national, and European level (Butter et al., 2019). According to the European Commission (2017), DIHs

[2] Basic DII level requires usage of at least four technologies such as blockchain, big data, cloud computing, artificial intelligence, e-commerce (European Commission, 2023).

[3] https://digital-strategy.ec.europa.eu/en/library/digitising-european-industry-initiative-nutshell.

should act in line with the needs identified in regional innovation strategies, namely smart specialisation strategies (S3).

As shown in Table 1, the first peer-reviewed articles about DIHs related to the fields of business, management, economics and social sciences, were published in 2020. Extant studies focused on the intermediary role of exemplary DIHs and on the transfer of knowledge between stakeholders (Crupi et al., 2020; Hervas-Oliver et al., 2021; Lepore et al., 2023), on giving access to I.40 technologies (Dyba et al., 2022; Gladysz et al., 2023), on addressing regional needs for innovation (Aragonés et al., 2020; Hervas-Oliver et al., 2021) and on proposing models and solutions for DIHs (Charvát et al., 2022; Sassanelli & Terzi, 2022a, 2022b; Feltus et al., 2023). To analyse the value generated by DIHs, Sassanelli and Terzi (2022a) proposed the Value Proposition Canvas to a network surrounding the hub, including providers, users, academic and technology organizations. Sassanelli and Terzi (2022b) also introduced a model to study the main functionalities of DIHs, namely networking, skills and training, test before investing, and access to funding. Similarly, Feltus et al. (2023) suggested an ontology to establish the boundaries and components of the DIHs that support technological networks. In addition, Charvát et al. (2022) presented a web mapping solution to facilitate publication of data by DIHs as a way of creating a new social space for geographic information sharing.

As regards environmental sustainability, DIHs are expected to contribute to achieving the targets set by the European Green Deal (EGD) by promoting the development, and the adoption, of digital technologies, including BCT, which might be able to help the EU to become a resource efficient economy and a climate-neutral society (European Commission, 2021c).

Nevertheless, there are few studies on the relationship between DIHs and environmental sustainability. Stojanova et al. (2022) argued that rural DIHs represent an efficient way of improving local environments in a more sustainable way. Drawing on a case study, their findings revealed that the DIH had several positive impacts on local winegrowers. First, firms benefitted from increased economic sustainability through business process optimization, cost reduction, employment opportunities and targeted marketing strategies. Second, the DIH helped firms to strengthen their environmental sustainability by assessing the conditions in the vineyards to determine both the optimal time and the location for actions taken to reduce their environmental footprint. Moreover, social sustainability was also enhanced through fairer distribution of social opportunities, digital inclusion, and better-informed consumers.

As regards the development of a bio-based economy, Aragonés et al. (2020) investigated the collaboration between DIHs and their stakeholders. To contribute to achieving this goal, DIHs have organized various initiatives, such as knowledge transfer events and demonstration days, to promote information and communication technology (ICT) tools and, also, both remote and in-person showcase events to match stakeholders and to create business opportunities. Furthermore, Charvát et al. (2022) investigated a DIH that promotes innovation based on data and technologies in order to facilitate the development of a more ecological and efficient agricultural sector, thus also strengthening the social benefits.

More recently, a growing stream of research on DIHs has highlighted the need for policy makers, SMEs, DIHs and research institutions to collaborate, in order to identify and assess both the opportunities and the challenges deriving from the implementation of BCT-based solutions (Ilbiz & Durst, 2019; Pólvora et al., 2020). However, there is a marked lack of both empirical evidence and of models to assist, improve, better understand the role of DIHs both role as orchestrators of collaborative networks (Crupi et al., 2020; Georgescu

Table 1 Selection of studies on Digital Innovation Hubs

Studies	Methodology	DIHs role
Gladysz et al. (2023)	Survey	•Intermediary between AI providers and users (SMEs)
Feltus et al. (2023)	CP	•Support cooperation in areas of innovative technologies
Lepore et al. (2023)	CP	•Facilitate collaborative innovation in the context of smart cities
Stojanova et al. (2022)	CS	•Improve economic, social and environmental sustainability at the local level •Support local businesses to implement innovative technology solutions
Sassanelli and Terzi (2022a)	CP	•Overcome innovation barriers •Contribute to supporting SMEs in Europe in the I4.0 revolution
Sassanelli and Terzi (2022b)	CP and Survey	•Perform the following main functions: networking, skills and training, test before investing, and advise re-accessing funding •Provide technical knowhow, experimental skills and specialist knowledge
Dyba et al. (2022)	MCS	•Disseminate I4.0 technologies •Overcome barriers to I4.0 implementation at the level of firms**
Charvát al. (2022)	CP	•Create links between people, companies and other stakeholders •Connect end-users with developers or researchers •Support innovation
Hervas-Oliver et al. (2021)	MCS	•Establish place-based alliances in the regional innovation system •Trigger the transfer of knowledge from large companies to SMEs
Aragonés et al. (2020)	MCS	•Understand stakeholders' needs •Involve industries to discuss the technologies integrated at the regional level
Crupi et al. (2020)	MCS	•Manage the selection, the exchange and the integration of knowledge for supporting SMEs during digitalization
Riva & Riva (2020)	CP	•Promote and support innovation and the implementation of robotics in the healthcare sector

CS case study; *MCS* multiple case study; *CP* conceptual paper

[a]Other sectors include education, governance and finance which are excluded from the analysis as they are not directly linked to environmental sustainability

Review conducted on Scopus searching for the keyword "Digital Innovation Hub*" in articles published in English in the areas of business, management and accounting and economics, econometrics, and finance, and social sciences

et al., 2021) and of their interactions with other stakeholders which seek to contribute to the adoption of digital technologies tailored for SMEs.

3 Methodology

We adopt a case study methodology (Yin, 2018). To provide a comparative analysis, we used a multiple case study based on a sample of twelve DIHs. Multiple case studies offer a broader evaluation of research questions proposed (Baxter & Jack, 2008). The methodology is based on the step-by-step approach proposed by Kanda et al. (2019). This approach consists of a sequence of steps that enable assessment of the functions of innovation intermediaries through the lens of the Technological Innovation System (TIS) approach which is a socio-technical system of actors whose interactions seek to develop and apply selected technologies (Carlsson & Stankiewicz, 1991).

The TIS system includes elements linked to a given technology, BCT in our case, and integrates all the mechanisms which concern the innovation activities behind that technology (Bergek et al., 2008). The literature on TIS has started to acknowledge that intermediary actors can boost TIS functions (Lukkarinen et al., 2018). Indeed, since several innovation intermediaries are connected to local, regional, and national governments, they can better promote the conditions that support the achievement of environmental sustainability targets better (Gliedt et al., 2018). The approach suggested by Kanda et al. (2019) was adapted to fit the case of DIHs so as to contribute to the overlapping boundaries of the literature on innovation intermediaries and that of the research on collaborative partnerships for digitalization.

The adapted Kanda's five steps-approach is illustrated below, along with details about data collection and analysis.

Step 1—Define the study focus. We checked the appropriateness of DIHs as intermediary structures allowing BCT adoption among SMEs for fostering environmental sustainability, in compliance with the functions of the TIS (Carlsson & Stankiewicz, 1991). Table 2 links the seven functions of the TIS to those attributed to innovation intermediaries and then matches them with DIH activities. To map the activities of DIHs, we considered both the general list of activities included in the European catalogue of DIHs and the emerging literature on DIHs.

Step 2—Identify intermediaries in their context. We adopted a keyword search strategy for "blockchain" in the European catalogue of DIHs,[4] and included both fully operational DIHs and those in preparation in 2020 and 2023. In 2020, out of a total sample 512 DIHs, we selected a group of 18 DIHs considering the BCT-based solutions for SMEs. Eight of the DIHs agreed to take part in the study. In 2023, out of a total sample of 717 DIHs, we identified 43 DIHs that were considering BCT-based solutions for SMEs, which included 18 of the DIHs that had already been contacted in the first round of interviews. Eight DIHs, including four of the previous round of interviews, decided to take part in the study.

[4] The EU DIH catalogue was set up to provide a comprehensive picture of DIHs in the EU across varying competences, structures and service offerings, https://s3platform.jrc.ec.europa.eu/dih-catalogue (consulted on January 2023). In the updated version of the DIH catalogue (namely EDIH catalogue) DIHs are presented as having similar activities to EDIHs but are not connected to the network, https://european-digital-innovation-hubs.ec.europa.eu/edih-catalogue.

Table 2 From TIS functions to the intermediary role of DIHs. *Source*: Authors' elaboration based on Bergek et al. (2008); Crupi et al. (2020); Hekkert et al. (2009); del Río and Bleda, (2012); Kanda et al. (2019); Lukkarinen et al. (2018); European Catalogue of DIH (https://s3platform.jrc.ec.europa.eu/en-US/dih-catalogue)

TIS functions		Intermediary role		DIH role
Resource mobilization *Definition:* financial and human resources to be exploited in innovation processes	→	•Creating collaborative partnerships •Managing financial resources	→	•Ecosystem building •Collaborative research •Funding *Definition* •Networking activities connecting regional and extra-regional stakeholders •Seeking funding opportunities to support the digitalization of SMEs and innovative SMEs
Knowledge development and diffusion *Definition:* creation and exchange of knowledge serving as inputs for innovation	→	•Training, mentoring, supporting knowledge selection, creation, combination, and dissemination	→	•Awareness creation •Education *Definition* •Selection and diffusion of knowledge supporting the digitalization of SMEs through awareness events
Guidance on search *Definition*: selection of how to distribute resources and define incentives to develop selected technologies	→	•Identifying needs •Developing strategies	→	•Vision strategy •Digital maturity assessment *Definition* •Planning activities for supporting the introduction of technologies in SMEs •Digital maturity assessment
• **Entrepreneurial experimentation** *Definition:* testing of new technologies and markets	→	•Creating conditions for testing, validating, and training	→	•Valid prototype •Pre-competitive serious production •Testing *Definition* •Provision of spaces and resources to create, test and validate prototypes and new technologies
• **Market formation** *Definition:* market creation for new technological solutions	→	•Accelerating the application and commercialization of technologies •Defining business opportunities	→	•Commercial infrastructure •Marketing intelligence *Definition* •Support and mentoring in seeking business opportunities

Table 2 (continued)

TIS functions		Intermediary role		DIH role
•**Development of externalities** *Definition*: opening to new actors in the TIS	→	•Supporting the entrance of new actors so as to strengthen the other functions •Creating jobs	→	•Incubator /Accelerator *Definition* •Incubator and accelerator services for start-ups and innovative SMEs
•**Legitimization** *Definition:* facing resistance to change and compliance with relevant organizations	→	•Evaluating regulatory, social and environmental impacts	→	•Customer voice •Digital maturity assessment *Definition* •Identifying SMEs' needs based on digital maturity assessment •Dialogue with ecosystems and users

Table 3 Summary of sources collected *Source*: Authors' elaboration

Primary data	*1st phase of data collection (2020)* •n. 18 e-mails sent to the reference contacts of the DIHs, as reported in the EU catalogue of DIHs (May 2020) •n. 8 semi-structured interviews of 40/60 min each with the reference contact (May–September 2020) •n. 8 follow-up interviews (September – December 2020) •n. 8 follow-up e-mails for sharing the summary of results collected to cross-checking findings and collect further integrations (December 2020) *2nd phase of data collection (2023)* •n. 43 e-mails sent to the reference contacts of the DIHs, as reported in the EU catalogue of DIHs (January 2023) •n. 8 semi-structured interviews of 40/60 min each with the reference contact (January-March 2023) •n. 8 follow-up e-mails for sharing the summary of results collected to cross-check findings and collect further integrations (April 2023)
Secondary data	•Description in the EU catalogue of DIHs •Website of DIHs •Additional documents provided by the DIHs

Step 3—Map of intermediary functions for environmental sustainability. Data was gathered through both semi-structured interviews and secondary sources, in order to assess the intermediary functions of DIHs and the role of their stakeholders. See Table 3.

Primary data was collected by carrying out twenty-four interviews, including follow-up interviews, with the reference contacts listed in the European DIH catalogue. The interviewees were directors and representatives of the DIHs, scientific coordinators of specific projects developed by the DIHs, and academics and experts working for the DIHs. To add greater depth and rigor to data collection, the interviews took place in two time periods which were about three years apart: 2020 and the beginning of 2023. The aim was to understand whether there had been any changes since the first interviews and to integrate new DIHs cases. We considered the twenty-four interviews (including the follow-up interviews,) enough as a point of saturation appeared to have been reached when (on both occasions) the transcripts of interviews began to show several consistencies. Interviews were held in either English or Italian and, on average, lasted between 40 and 60 min.

As for the questions, we structured the interviews into three parts: (i) understanding the mission and structure of the DIH and their level of expertise in BCT; (ii) investigating to what extent and how the DIH had been promoting BCT-based applications among SMEs through collaborative partnerships which focused on solutions for environmental sustainability; and, (iii) exploring the contribution of stakeholders within the functions of the innovation intermediaries.

To organize data obtained from both primary and secondary sources, we emulated previous studies that had used the TIS (e.g., Planko et al., 2017). Thus, data were coded according to the TIS processes as defined in the literature. We took Table 2 as reference, as it links the seven functions of the TIS to those attributed to innovation intermediaries and then matches them with DIH activities. The conceptualization reported in Table 2 helped us to interpret the results of the interviews and, specifically, the role of DIHs and stakeholders within a certain function.

Step 4—Assessment intermediation for environmental sustainability. Assessment was carried out by a panel of experts on environmental sustainability, DIHs, and BCT, on the basis of the functional and structural approach of the TIS. The assessment was based on

Table 4 Scale for assessing intermediation for environmental sustainability

Qualitative scale for assessing functions	Description
Strong	•Contribution to addressing most aspects of a particular system function
Medium	•Contribution to addressing many aspects of a particular system function
Low	•Contribution to addressing a few aspects of a particular system function
Not detected	•No detectable roles connected to aspects of a particular system function

Source: Authors' elaboration based on Kanda et al. (2019)

identifying the strength of each function using the scale suggested by Kanda et al. (2019) and reported in Table 4.

Step 5—Formulation of recommendations. Based on triangulation of the primary and secondary data collected, we propose a selection of recommendations which have been translated into a roadmap for policy makers, DIHs and their stakeholders, which could contribute to improving intermediaries' functions and partnerships, and their alignment with environmental sustainability targets.

4 Results

In 2020, eight DIHs agreed to take part in the first phase of the study. In 2023, eight DIHs, including the first four of the previous phase, decided to participate in the second phase of the research project. Overall, we found the number of DIHs considering BCT-based solutions in Europe had risen: from 18 in 2020 to 43 in 2023.[5]

The twelve DIHs revealed a wide range of structures involved as innovation intermediaries: universities, science and technology parks, consortiums, and research centres, which could also be coordinators of a DIH. As stated by Hervas-Oliver et al. (2021), preliminary findings confirm the heterogeneity and overlapping of some DIH structures and coordinators (Table 5). The only exceptions were two DIHs from Spain and one from Romania (DIH12), which had been founded directly in as DIHs. Seven DIHs had a university as coordinator, which was usually focused on achieving Third Mission goals: knowledge production and its transfer to the market either by means of patents or by creating start-ups. As regards DIH2, DIH5 and DIH10, BCT was already an area of interest for the universities cooperating in their activities. Thus, in these three cases, the university determined the inclusion of BCT among the core technologies considered by the intermediary. Three DIHs in the sample considered BCT as the main technology in their mission (DIH4, DIH5, DIH10). The other DIHs recognize BCT as one of the many enabling technologies within the wider range of I4.0 technologies. However, DIH7 which had been considering BCT projects in 2020, stopped focusing on this technology in 2023.

The staff of DIHs includes technical experts and business-oriented specialists who support SMEs in implementing digital technologies and in accessing funds for financing and marketing new technologies. Although experts on BCT-based solutions are usually a small group within the total staff of the DIHs, there has been an increase in the number of collaborators with this expertise over the last two years of the period studied. For example, as

[5] However, among the DIHs contacted in 2023, one is closing its activity while another is no longer considering BCT-based solutions.

Table 5 The characteristics of the sample

DIH cases	Interviews*	Country	Innovation performance of the country (2022)**	Region (NUTS2)†	DIH nature	DIH coordinator	BCT focus††	BCT key sector†††[a]
DIH1	2020–2023	Slovenia	Moderate	Western Slovenia SI04	Public–private-people partnership	University	NE	ENERGY
DIH2	2020–2023	Romania	Emerging	South-Muntenia RO31	Consortium	University entrepreneurial centre	NE	AGRI
DIH3	2020	Spain	Moderate	Valencia Community ES52	DIH within H2020 project	Business accelerator and incubator	NE	AGRI
DIH4	2020–2023	The Netherlands	Leader	South Holland NL33	Port subsidiary	Business accelerator, incubator	MT	LOGISTIC
DIH5	2020	Germany	Strong	Darmstadt DE71	Think-tank and research centre	University	MT	ENERGY
DIH6	2020	Croatia	Emerging	Continental Croatia HR04	Innovation/research and education hub	University	NE	AGRI
DIH7	2020–2023	Italy	Moderate	Lombardy ITC4	Science and technological park	University	NE (2020)	AGRI
DIH8	2020	Spain	Moderate	Castile-Leon ES41	DIH	Research organization	NE	AGRI
DIH9	2023	Italy	Moderate	Lazio ITI4	DIH	Industrial association	NE	AGRI
DIH10	2023	Slovenia	Moderate	Western Slovenia SI04	Public–private-people partnership	University	MT	DATA
DIH11	2023	Romania	Emerging	South-Muntenia RO31	Foundation	DIH	NE	AGRI
DIH12	2023	Romania	Emerging	South-Muntenia RO31	Network organization	University	NE	AGRI

* Interviews were carried in the first phase (2020) and/or in the second phase (2023) of the study. The total number of interviews (n = 24) includes follow-up interviews that were carried out in 2020

**European innovation scoreboard 2022

†NE = not exclusive; MT = main technology

††Regions are classified according to the Nomenclature of Territorial Units for Statistics https://ec.europa.eu/eurostat/web/nuts/background. See also European Commission (2017)

†††AGRI = agriculture; DATA = data management

Source: Authors' elaboration

regards DIH4, BCT experts had risen from 8 in 2020 to 40 in 2023. Above all, the presence of coordinators for each DIH highlights the role that selected stakeholders play in shaping the functions of the DIH and, also, the nature of collaborative partnerships for SMEs. Overall, DIHs agreed that BCT is, by definition, a technology that requires collaboration:

> «Without collaboration blockchain does not make sense» (DIH4).

Collaboration between different stakeholders can be observed both in the adoption and in the development stages. In this collaborative context, blockchain is defined as a:

> «Horizontal service that can be used to enhance the potential of current services by improving transparency» (DIH6).

Section 4.1 presents the findings related to the role of DIHs, Sect. 4.2 focuses on the contribution of the other actors of the innovation ecosystem. The role of digital intermediaries and the contribution of their relevant stakeholders are assessed on the basis of the TIS model. A 3 level-scale, strong, medium and weak is used.

4.1 The role of DIHs

4.1.1 Strong level

Interviews and secondary sources have revealed that DIHs are mainly active in entrepreneurial experimentation through support offered to SMEs when they are constructing BCT prototypes and use cases. According to DIH6, since BCT is a complex technology, prototypes must be developed in order to illustrate, to prove, the advantages of BCTs to stakeholders:

«If the technology is complex, you cannot see the real benefits. You need to create a prototype to show them» (DIH6).

DIHs role is to develop and manage collaborative partnerships between local innovative SMEs, start-ups and large corporations. These DIHs appoint internal or external experts to support firms at each stage of project development. Large companies often refer to the DIHs, as explained by DIH3:

> «We define a series of challenges with large corporations and then start a scouting process looking for the best start-ups and SMEs» (DIH3).

Focusing on specific projects, eight DIHs have been, and are, building collaborative pilot actions in the agricultural sector where BCT is used to increase transparency and to facilitate informed decision-making. These initiatives aim to encourage collaboration throughout the supply chain and to automatically ensure both the transparency and responsibility of data. BCT solutions have also focused on tracing the supply chain of forest sensor-based products (DIH8) and on registering vehicle and machinery events in agroforestry applications (DIH3). These applications permit both more sustainable management of forest resources and optimization of machinery use, thus reducing environmental footprints through more efficient operations. Other I4.0 technologies have also been adopted to amplify environmental sustainability efforts: AI and Machine Learning make advanced data analysis possible while IoT is utilized to enhance real-time data collection from and between devices and systems.

As regards the energy sector, BCT solutions have been being developed to optimize and control energy sources. These applications focus on tracing the energy produced by

renewable sources while checking CO_2 emissions (DIH3, DIH5). Furthermore, BCT allows firms to certify CO_2 emissions at the global level, thereby contributing to ensuring clean and affordable energy (SDG7).[6] BCT is also being used for trading energy to strengthen sustainability in global transactions (DIH4). There have also been experimental projects that try to charge electric vehicles and lights based on the Ethereum blockchain (DIH1).

DIHs concurred that logistics offer a highly promising sector, with BCT anticipated to enhance supply chain transparency in the applications mentioned which have already been tested in agriculture and energy sectors. Projects that focus more on logistics can be found in DIH4 which uses BCT to improve port logistics, and has had a positive impact on global trade. Other BCT solutions that promote mobility are related to environmental sustainability: e.g. introducing electric scooters, motorbikes, and other vehicles (DIH5). In these cases, data uploaded on the BCT helps to increase the opportunities for shared mobility, which reduces both the need for costly intermediaries and for payment processing fees.

Unlike other DIHs in the sample, DIH10 uses its BCT expertise in a wider variety of sectors as it adds construction and, more generally, data management. This hub acknowledges is aware of the environmental potential of BCT and has a wider perspective than do most others, as it includes the idea of using BCT for raising funds for environmental causes in many settings or contexts.

It is worth noting that the entrepreneurial experimentation function is supported by a strong role in resource mobilization. Indeed, the twelve DIHs are regularly involved in seeking funding opportunities and knowledge resources to support innovative SMEs when developing BCT solutions. As DIH1 says, the intermediary revises BCT projects submitted by SMEs and research institutions, to support them and to make them eligible for funding.

4.1.2 Medium level

The implementation of BCT in SMEs is still at an experimental stage. Consequently, DIHs find it challenging to market these solutions and set strict standards in order to ensure widespread adoption. Indeed, when BCT solutions, DIH1 points out that:

> «It is still a prototype. It didn't go into the commercialization stage […] we need standards for the industry» (DIH1).

The development of positive effects includes networking activities, which can be a key tool for creating collaborative partnerships between BCT developers, through specific, open, innovation programs. As for guidance on research, DIHs provide preliminary information on BCT in order to help potential SME adopters to select the most suitable BCT applications. To discover the needs of companies, DIHs assess SMEs' digital maturity and then offer tailored services and partnerships. The assessment considers both BCT and a wider range of I4.0 technologies that can, or could, be combined with BCT as means of enhancing transparency and efficiency. This is, for example, the case in DIH8 which evaluates the possibility of integrating IoT and BCT.

While in 2020 these models still had no reference for measuring, validating and communicating the environmental implications of BCT, by 2023 a group of DIHs had started developing models for environmental assessment. DIH2 has been creating a quality framework to be validated by farmers and to be registered by accreditation bodies. This

[6] For further details about the 7th SDG of the UN, "Ensuring access to affordable, reliable, sustainable and modern energy for all", see https://sdgs.un.org/goals/goal7.

framework includes indicators to mitigate climate change and to support more sustainable agriculture. DIH1 has developed solutions for making wine production more sustainable at the local level. Environmental data was collected through sensors and presented on a monitoring dashboard while BCT was used to enable consumers to examine the data collected. On the other hand, DIH11 has developed a project in a DIH consortium for ensuring innovation in agriculture. This latter hub has considered the possibility of creating dimensions for measuring BCT impact in terms of environmental sustainability while paying attention to customers. As regards logistics, DIH4 is building a BCT solution that makes it possible to track all types of environmental footprints generated by a product, including measurements for CO_2 and green hydrogen. However, DIH10 assesses BCT impact on environmental sustainability and SDGs, by taking into consideration the trade-off between security and usability. Similarly, DIH9 uses a model for assessing a firm's environmental targets that is applicable in any sector and for any technology.

4.1.3 Weak level

When fulfilling their legitimization function, DIHs have to struggle to prove that BCT does offer a promising solution and by doing so obtain support from national and regional governments. A key source of legitimization is successfully measuring and communicating the economic and environmental value of BCT. As highlighted by DIH6, this could be achieved through increased involvement of consumers. Indeed, solutions must be legitimized by consumers because:

> « [..] if you want people to pay a premium price and use blockchain, then you have to certify that you are selling ecologically grown food» (DIH6).

Also, the reputation of DIHs and of their coordinators at the local level, is expected to become a key driver of the legitimization required both to attract local SMEs and to encourage them to adopt BCT:

> «We have a good reputation and I think most companies, also SMEs, know us at this point, but this is of course not true for all of Europe» (DIH5).

Finally, to legitimize BCT-based solutions, DIH3 assesses not only the needs of SMEs but also those of investors and key stakeholders.

When seeking to create and disseminate knowledge of BCT, DIHs offer workshops to potential SME adopters. Unlike large companies, SMEs are often limited by both available expertise and funds. Indeed, DIHs agree that the SMEs which adopt novel technologies, such as BCT, are those that already have a high level of awareness of I4.0 technologies. However, even in the case of awareness events, DIHs do not, as yet, emphasize the environmental implications of BCT applications.

4.2 The contribution of the stakeholders

To advance the development and the adoption of BCT, DIHs also rely on the contribution of other stakeholders, universities, government institutions, SMEs, start-ups, and large companies, at both the local and the international level. The contribution of these actors to the role played by the DIHs analysed was as follows.

4.2.1 Strong level

Within the function of entrepreneurial experimentation, DIHs acknowledge, recognise, the mutual support and influence offered by local universities in developing BCT prototypes and use cases. Universities often provide experts for designing the new technological solutions that SMEs apply. The presence of academics characterizes DIHs coordinated by local universities. Innovative solutions are also developed by involving students, for instance, by organizing hackathons as reported by DIH2. Cooperation involves firms, mostly innovative start-ups and large firms, which provide expertise for developing BCT solutions. More generally, as specified by DIH2:

> « The most important stakeholders in blockchain technology are companies with a vision. We are targeting people with entrepreneurial experience and discoveries» (DIH2).

Given their function of mobilizing resources, DIHs rely heavily on the support provided by European institutions, such as the European Commission, to overcome both any lack of knowledge and the chronic lack of financial support for BCT. Indeed, thanks to European funded projects, launched within both the Horizon 2020 programme and the most recent Horizon Europe programme, DIHs have acquired both the funding and the knowledge needed to assist innovative SMEs when building BCT prototypes. For instance, the Blockpool project[7] involved two DIHs, targeting energy, utilities, and raw materials sectors. Another European project, Blockchers,[8] involved one DIH and financed the development of use cases with equity-free funds. The originality of this project is that it aimed to incentivise SME adopters to become engaged in use case development, by partnering SMEs and BCT specialists. There is a mutual exchange of knowledge with local universities and jointly defined training programs to target students in both the technical and the business fields. Moreover, international actors have emerged as crucial partners for enabling knowledge exchange about BCT, especially thanks to the participation of DIHs in European funded projects:

> «The BCT world is very international. It is composed of many stakeholders around the world with different skills. BCT is an emerging technology and participating in European projects enables us to discuss and share best practices on BCT developments» (DIH7).

When considering international stakeholders, three DIHs said they were collaborating with the University of Nicosia because of its high degree of specialisation in BCT. In 2020, DIHs usually knew little about what other DIHs were doing in the area of BCT. More recently, following the European DIH funding programmes,[9] DIHs have started increasing their networking activities. Indeed, as reported by the Slovenian and Romanian hubs, a sample of DIHs got to know other national and European DIHs working on BCT. Furthermore, DIH2, recognized as an EUDIH, has recently developed a sister hub (DIH12) with the aim of providing services for the South-Muntenia region and of extending relationships with Italian, French and Greek DIHs.

[7] https://cordis.europa.eu/project/id/828888.

[8] https://cordis.europa.eu/project/id/828840.

[9] https://digital-strategy.ec.europa.eu/en/activities/edihs.

4.2.2 Medium level

Stakeholders can play a crucial role when identifying and facing the challenges related to implementing BCT in the market formation function. In this regard, DIH6 highlights the importance of the Triple Helix Model (THM), as introduced by Etzkowitz (1998), for revealing certain challenges. Specifically, when the university-led DIH6 undertook collaborative BCT projects, it became crucial for ensuring profitable solutions for industry:

> «[…] from the perspective of the companies that are approaching us, they need something that is profitable» (DIH6).

Within the market formation function, the European program, Blockpool, includes training initiatives that help managers market BCT solutions and design sustainability-oriented business models. Similarly, the program, 4DLTALL[10] included training sessions supporting BCT market training for students and investors. However, as reported, in 2023, once the project had finished, the DIH involved did not continue to explore the opportunities of BCT.

As regards guidance on research, technical advice and mentoring were mainly provided by external experts, targeting both national and international markets. These human resources identified the SMEs' needs that would then shape entrepreneurial experimentation. Nevertheless, involving experts, especially when working for large companies, might be challenging:

> «There is a scarcity of experts in blockchain technology in the area. [..] Experts are working for big companies. There is no way to divert them from that job» (DIH2).

4.2.3 Weak level

The legitimization function appears to pose the greatest challenges. Greater involvement of stakeholders is often sought from national and regional governments where the dialogue is mainly focused on other digital technologies. However, some progress has been made. For instance, unlike in the 2020 interviews, in 2023, Romanian DIHs reported that the Ministry of Agriculture and Economy had started supporting ecology frameworks where BCT could be included.

As for collaboration with national and local government, DIH4 emerged as a good practice because there was close cooperation with the local municipality. This collaboration sought to create a smart port using BCT and promoting its environmental implications for the city. Projects launched by the European Commission have also permitted both dialogue between DIHs and European regulators, and sharing of good practices and of challenges.

As regards the activities aimed at creating and disseminating knowledge about BCT, DIHs usually collaborated with local universities to organize workshops for SMEs. As reported in 2023, DIH2 organized knowledge sessions to match scholars and BCT developers with farmers and operators to raise awareness about BCT-solutions and to implement them in companies. These sessions are still taking place, and some tangible results are expected over the coming three years since currently there is still:

> «a lack of knowledge transfer culture among entrepreneurs regarding, the applications of blockchain» (DIH2).

[10] https://dlt4all.eu/.

This challenge highlights the critical need for enhancing knowledge dissemination regarding BCT within the entrepreneurial community. Once again, funding from European projects has supported DIHs in knowledge transfer initiatives. As already stated, the program DLT4ALL addresses students and SMEs while promoting a general understanding of BCT. However, the program does not focus on advances in BCT in terms of environmental sustainability.

5 Discussion

I4.0 has enabled new forms of business in several industrial sectors and markets, by leveraging on advanced technologies, including BCT, and their potential applications (Luo & Zahra, 2023).

Although there is still limited knowledge about the application of I4.0 technologies for tackling environmental issues (Esmaelian et al., 2020), «trust "builders"» (Giaretta, 2014, p. 675) seem to be the key ingredient for fully exploiting the potential of BCT for environmental sustainability. Indeed, our findings confirm that SMEs increasingly need guide-figures (Giaretta, 2014) to tackle relational and cooperative barriers by creating trust with their stakeholders (Friedman & Ormiston, 2022). Given the global scale of environmental challenges, it is important to rescale BCT and, thus, exploit its collaborative potential in an effective manner. Efforts to promote environmental sustainability are unlikely to succeed without the participation and commitment of a large pool of SMEs and stakeholders along supply chains. Nevertheless, there is little evidence regarding the mechanisms which drive BCT scalability (Tatarinov et al., 2023).

In the context of this analysis, DIHs are innovation intermediaries within the local ecosystem, which build and manage collaborative partnerships among and between SMEs and other socio-economic stakeholders, cooperation gaps when developing and rescaling BCT in the area of environmental sustainability. Although collaboration with innovation intermediaries, including DIHs, has become increasingly common among SMEs, there is little knowledge about their operational mechanisms and values for innovation (Hossain, 2018). Our findings have revealed that the main functions undertaken by DIHs concern resource mobilization, offering proof that digitalization does have an impact on the search for, access to and management of resources (Inceoglu et al., 2024), and that the ability to mobilize resources is dependent on external networks (Granovetter, 1985; Lee et al., 2001). Mobilizing resources is one means of providing financial and knowledge resources for entrepreneurial experimentation which mainly targets BCT-based solutions in agriculture, energy and logistics. Key activities linked to mobilizing resources include organizing networking events, and advanced and tailored training. On the other hand, activities related to entrepreneurial experimentation involve finding and recruiting experts, SMEs, start-ups and large firms. By drawing on previous works (e.g. Tsolakis et al., 2021), we found that

these applications have a close connection to sustainable development goals (SDGs) and to the European green deal (EGD) which includes affordable and clean energy (SDG7)[11] and sustainable production and consumption models (SDG12).[12]

Findings also confirmed that BCT facilitates the promotion of sustainability by encouraging collaboration between diverse socio-economic stakeholders in the ecosystem (Tsolakis et al., 2021; Upadhyay et al., 2021). Drawing on the TIS framework, we also found evidence of the growing complexity of intermediation as discussed by Agogué et al. (2017). On the one hand, DIHs generate networks by leveraging on personal relationships and knowledge, thus increasing their role within the innovation system of countries, regions and sectors (De Silva et al., 2018). On the other hand, this complexity justifies the importance attributed to stakeholders as innovation intermediaries when tackling environmental challenges (Boiral et al., 2019; Johnson & Schaltegger, 2016; Journeault et al., 2021).

As regards the contribution to meeting the challenges of DIHs made by stakeholders, universities emerge as one of the principal actors. They usually manage, or influence, DIHs with scientific expertise. These findings confirm previous research on the role of the university as a facilitator of collaboration among and between key socio-economic stakeholders at the local level. This type of cooperation aims to develop a knowledge-based society for innovation and sustainability (Compagnucci & Spigarelli, 2020). Nevertheless, challenges may arise when universities do not ensure that applied research is conducted correctly as regards commercialisation to bridge the so-called Valley of Death, i.e. start-ups failing in their initial phase. As for national and regional governments, they usually provide financial resources to DIHs for the digitalization of SMEs (without specifically targeting BCT).

We have found that European institutions are key stakeholders in supporting and financing the development and adoption of BCT. Our analysis confirms that DIHs are increasingly engaging in shaping policy interventions, which results in convergence around the interests of key stakeholders within the regional, national and European ecosystem (De Silva et al., 2018).

Even though DIHs, as intermediaries, can become the «architects of the unknown» by coordinating entrepreneurs (Agogué et al., 2017, p. 35; Hernández-Chea et al., 2021), as stated by Bush et al., (2017), these intermediaries still face challenges, especially when seeking legitimacy. This can hamper the adoption of BCT among SMEs. It is often very complicated to offer proof of the advantages of BCT from an economic point of view and, also, to convince local and national governments to invest in this technology. Furthermore, there is a marked lack of BCT experts willing to collaborate with DIHs to construct solutions, which need to be tailored for individual SMEs, while also considering both the appropriateness and the effectiveness of BCT solutions for local development needs. Indeed, extant research has recognized the lack of specialized expertise which limits the effectiveness of the DIH role (Chandran et al., 2013; Gajzago, 2017).

There is a considerable difference between 2020 and 2023 as regards guidance on research; ever since DIHs started considering BCT for directly addressing environmental

[11] For further details about the 7th SDG of the UN "Ensuring access to affordable, reliable, sustainable and modern energy for all", see https://sdgs.un.org/goals/goal7.

[12] For further details about the 12th SDG of the UN, "Ensure sustainable consumption and production patterns", see https://sdgs.un.org/goals/goal12.

footprints. On the other hand, some recent interviews have also revealed that knowledge dissemination activities do not always target a specific sector of reference, one which is necessary in order to understand the practical implications of the solutions proposed. As argued in previous studies (e.g., Journeault et al., 2021) awareness events may fail to focus adequately on explaining what the environmental benefits deriving from BCT really are. Initiatives specifically targeting the environmental impact of BCTs should play a crucial role in bringing about a cultural shift in perception among both BCT developers and adopters (He et al., 2020).

When investigating relationships between functions, we found limited interaction. While resource mobilization is strongly related to entrepreneurial experimentation, relationships with other functions are often still not being either sought or identified. Furthermore, there are many challenges posed when legitimizing BCT and a variety of improvements could, and should, be made to both knowledge creation and to dissemination for SME adopters. Moreover, market opportunities are not always fully exploited and there are limited positive externalities. To overcome their limitations, DIHs should engage in collaborative partnerships with other DIHs that are working on BCT for SMEs, and should rely more on the knowledge and financial resources of their supporting stakeholders. While the interviewees do recognize the importance of international partnerships there is still little awareness of DIHs that are targeting BCT solutions. Furthermore, extant collaborations are mainly occasional and informal. Table 6 synthetises the key findings as discussed above, based on the TIS framework.

6 Roadmap

To overcome the functional weaknesses identified in the approach of DIHs and the involvement of key actors of the innovation ecosystem, we propose a roadmap of activities (Friedman & Ormiston, 2022; He et al., 2020; Madrid-Guijarro & Duréndez, 2024; Polzin et al., 2016). The roadmap (see Fig. 1) highlights key areas for interventions to guide DIHs and their stakeholders in order to maximize their supporting role in moving SMEs towards environmental sustainability. Extending the TIS framework, the roadmap proposes three key actions: enabling, core, and resulting.

6.1 Enabling functions

Enabling functions include all those intermediary activities that are required for the successful development of the other functions of the roadmap. Starting from knowledge creation and dissemination, which has been revealed to be weak, DIHs in the new European network should exchange information on good practices and organize awareness events on BCT that involve both SME developers and adopters. DIHs could, or should, also organize networking events and advanced training programmes, also involving SME adopters (who can provide practical insights into BCT adoption within their processes and business models). Such initiatives could also serve to boost resource mobilization between BCT experts and SMEs. As argued by Crupi et al. (2020), the involvement of SMEs in technological development is considered a crucial starting point for establishing trust in the new technologies. This approach might well be able to overcome any current innovation barriers between and among SMEs, enabling them to change their mind-set in terms of trust building, data sharing, knowledge

Table 6 Key findings *Source*: Authors' elaboration

Qualitative scale for assessing functions	TIS function	DIHs role	Key stakeholders	Stakeholder role
Strong	*Entrepreneurial experimentation*	•Recruiting experts •Recruiting SMEs, start-ups, large firms	•Universities •Innovative SMEs •Start-ups •Large firms	•Collaboration in developing prototypes and use cases •Organizing hackathons with university students
Strong	*Resource mobilization*	•Organizing networking events •Facilitating access to funding •Organizing advanced and tailored training	•Universities •European Commission •Innovative SMEs, start-ups, large companies •International stakeholders	•Organizing, and participating in, knowledge exchange activities •Organizing advanced training activities for students/experts •Facilitating access to funding sources
Medium	*Market formation*	•Spreading knowledge of BCT among investors	•Incubators •Investors •European Commission	•Organizing and financing training activities for constructing sustainable business models •Raising awareness among investors
Medium	*Development of positive effects*	•Organizing open innovation programs	•Innovative SMEs, start-ups, large companies •International stakeholders	•Development of partnerships involving innovative SMEs
Medium	*Guidance on research*	•Providing technical advice for innovative SMEs •Mapping the needs of SMEs	•Universities •National and international experts	•Support in defining whether, why, and how, SMEs need BCT and other I4.0 technologies
Weak	*Legitimization*	•Trying to define value propositions for stakeholders •Facing resistance to change •Mapping the needs of investors and stakeholders	•European Commission	•Visibility for BCT solutions and use cases •Promoting discussion with EU regulators
Weak	*Knowledge creation and diffusion*	•Training events for innovative SMEs •Awareness events on BCT	•International stakeholders •European Commission •Universities	•Participation and organization of networking events •Financing awareness events

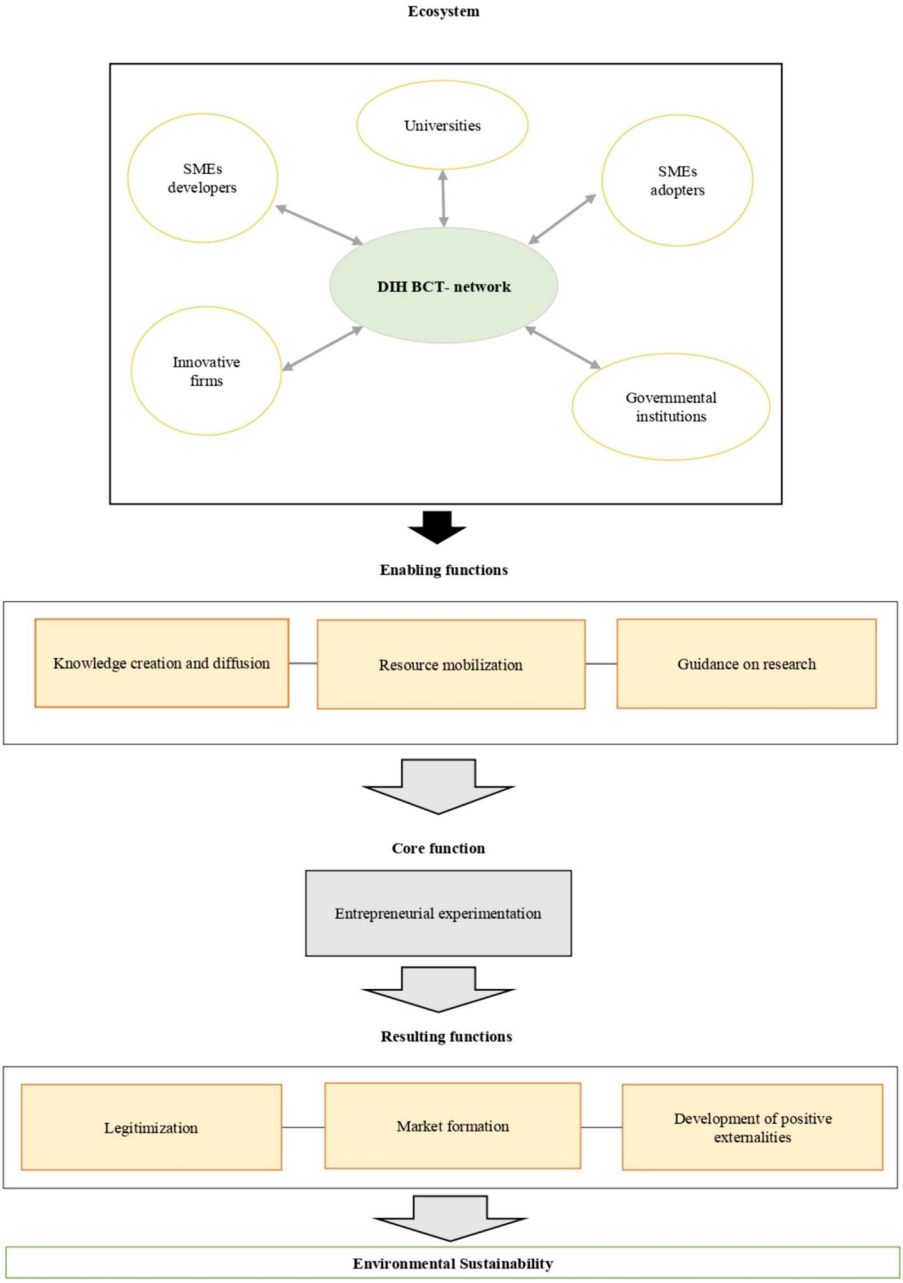

Fig. 1 Roadmap for connecting intermediary roles. *Source*: Authors' elaboration

transfer and privacy (He et al., 2020). Knowledge creation and dissemination (including showcase BCT prototypes and use case), as well as resource mobilization, should be designed according to sustainability-oriented models. For this purpose, guidance on research should be strengthened. By collaborating with universities, research centres

and government institutions, DIHs should introduce and promote a common framework of reference both for evaluating the appropriateness of BCT in SMEs and for assessing the environmental impact of this technology.

6.2 Core functions

The first level functions should become the foundation on which entrepreneurial experimentation is based. The sharing of knowledge and financial resources should encourage co-creation of solutions among and between DIHs based on the insights gained from BCT experts and SME adopters. In its turn, entrepreneurial experimentation, which was, and is, recognised as a strong function, should make it possible to manage the major challenges posed by the legitimization and marketing of BCT solutions even while it is promoting positive externalities, which will then become part of the resulting functions that are managed by DIHs.

6.3 Resulting functions

The revision of enabling and core functions should, periodically, be addressed in order to overcome the challenges identified in the functions of DIHs. To start with, DIHs should monitor, measure and communicate the impact of BCT on SDGs and EGD so as to gain greater legitimization and support. These functions are expected to boost market opportunities for SME developers by acting on market formation itself which, in its turn, might amply the generation of positive externalities in the area of environmental sustainability.

7 Conclusions

This paper has sought to understand how to unlock the collaborative potential of BCT for environmental sustainability in SMEs, leveraging on the role of innovation intermediaries (namely DIH and relevant stakeholders of the innovation ecosystem). To do this, the analysis has been based on a multiple case study of a sample of twelve European DIHs which were investigated in the period between 2020–2023 by applying the TIS framework and by adjusting the step-by-step approach suggested by Kanda et al. (2019).

On the one hand, the findings reveal that BCT can offer collaborative opportunities for SMEs in the area of environmental sustainability by tracing and tracking products and services, especially in the areas of agriculture, energy, and logistics. Leveraging on the collaborative potential of BCTs, SMEs also benefit from data sharing and transparency for decision making which, in turn, increases the efficiency of firm, reduces transaction costs, and contributes to reducing carbon footprints. On the other hand, SMEs are not always ready, or willing, to exploit the "green" opportunities offered by this emerging technology and they may come up against various financial and organizational constraints, which could create further obstacles to cooperation. Based on our results, innovation intermediaries, such as DIHs, do seem to be able to assist SMEs with BCT adoption. This type of support was found especially in activities related to resource mobilization and entrepreneurial experimentation.

Nevertheless, DIHs frequently operate in contexts of technological collaboration characterized by multiple stakeholders whose interventions, interests and targets are often undeclared or unknown. Moreover, the lack of competences, financial resources and the legitimization issues related to BCT, can, or do, hamper the effectiveness of the DIH role. Thus, stakeholders' contributions are necessary, if not crucial, since DIHs play a complex role, especially in relation to the legitimization function. Universities are one of the main stakeholders because they usually manage, or influence DIHs, driving both their scientific and business initiatives. However, collaborative partnerships are difficult when universities do not ensure that applied research is correctly conducted for commercialisation. While national and regional governments should play a more active role in monitoring and supporting the digitalization of SMEs, the contribution of European institutions is also crucial in assisting and financing both the development and the adoption of BCT among SMEs.

7.1 Theoretical implications

This study contributes to the field of innovation intermediaries (Battistella et al., 2016; Caloffi et al., 2023; Kivimaa et al., 2019; Good et al., 2019; O'Kane et al., 2021; Palaco et al., 2022; Rossi et al., 2022) and collaborative partnerships for digitalization (Antonioli et al., 2017; Harrigan et al., 2017; He et al., 2020; Liu et al., 2022).

First, we provide insights, suggestions, for overcoming cooperation gaps (Friedman & Ormiston, 2022; He et al., 2020; Johnson & Schaltegger, 2016; Madrid-Guijarro & Duréndez, 2024; Polzin et al., 2016) by assessing the role of innovation intermediaries in encouraging SME involvement when designing and developing BCT solutions in the domain of environmental sustainability. We have done so by selecting an as yet underexplored intermediary, namely the DIH (Crupi et al., 2020; Georgescu et al., 2021).

Second, exploring the functions intermediaries in relation to mobilizing resources, we contribute to those research areas that have focused on resource mobilization and digitalization (Inceoglu et al., 2024). Specifically, within this research direction, digitalization is the research context within which to explore the management issues addressed by both innovation intermediaries and stakeholders within the ecosystem.

Third, this paper improves understanding of how stakeholders within the ecosystem can support the complex role of innovation intermediaries which operate in uncertain contexts (Agogué et al., 2017). Our findings go beyond the definition of functions and intermediary typologies, as noted by Palaco et al. (2022), by outlining, delineating, the variety of roles played by stakeholders in supporting the mission of innovation intermediaries. In addition, our paper extends previous studies (Boiral et al., 2019; Johnson & Schaltegger, 2016; Journeault et al., 2021), by investigating how the stakeholders in DIH could contribute to the advancement of SMEs, in terms of environmental sustainability, by providing customized financial and knowledge resources.

Fourth, from the methodological perspective, the novelty of this study lies in extending the applicability of the TIS framework suggested by Kanda et al., (2018, 2019). We have proposed an approach which is, effectively, a new application of the TIS, that broadens its scope to include stakeholder engagement in supporting innovation intermediaries.

7.2 Practical implications

This paper can also contribute to developing practical strategies for enhancing the role of innovation intermediaries as well as of their stakeholders. In particular, the study offers a roadmap which is based on dividing the TIS functions into three main categories: enabling, core, and resulting. The roadmap could prove to be a useful tool for policy makers, DIHs, and for their stakeholders, in assessing their functions and overcoming weaknesses within the innovation ecosystem. It could also be used to develop interactions between intermediary functions in a manner that is coherent with both SDGs and the European Green Deal objectives. Indeed, such objectives were drawn up to create a connected European DIH ecosystem, designed to assist SMEs in the green transition.

7.3 Limitations and future research perspectives

This paper has focused on twelve DIHs all of which are European pioneers as regards the promotion of BCT among SMEs. Given the fact that most of these DIHs do not focus solely on BCT, future research should test the generalisability and effectiveness of the roadmap. To this end, the sample should be broadened while clustering DIHs according to specific I4.0 technologies addressing distinctive sectors and their environmental sustainability. To further validate the approach, it would be beneficial to draw up a set of indicators for each of the functions included. This would make it possible to evaluate the contribution of the roadmap towards achieving specific SDGs and EGD objectives. Future research could, and should, encourage the use of the TIS approach to evaluate the role of intermediaries and stakeholders, thereby offering information to policy makers at various levels.

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Author contribution FS supervised the research team, administered the research project and reviewed the paper. LC and DL equally conceptualized the research idea and the methodology. LC and DL equally contributed to the investigation and data curation, and to the writing of both the original draft and the reviewed version of the manuscript.

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