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Urban living labs as catalysts for innovation: Advancing urban ecosystems within the quintuple helix model

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A B S T R A C T

Innovation plays a key role in responding to increasingly interconnected and complex urban challenges, which require integrative approaches supported by technology, citizen participation, and collaborative governance. This study explores the transformative role of Urban Living Labs in shaping urban innovation ecosystems through the Quintuple Helix Model. By examining the interaction between academia, industry, government, civil society, and the natural environment, this research explores how Urban Living Labs can act as catalysts for collaborative knowledge production, co-creation, and policy integration. It employs a qualitative analysis based on action research considering three Urban Living Labs carried out in Portugal between May 2023 and November 2024. The findings emphasize that Urban Living Labs reduce uncertainties before large-scale implementation of urban solutions, but diverse stakeholder interests require mediation mechanisms for effective co-creation. Additionally, Urban Living Labs accelerate digital transformation, fostering more participatory urban development. Although the natural environment appears less frequently in discussions, its role in sustainability and resilience is crucial. The study reinforces that aligning technological and economic progress with knowledge, public policies, and ecological solutions is essential for long-term urban innovation.

1. Introduction

Rapid urbanization has imposed significant challenges on societies and governments, requiring innovative solutions in several areas. Sustainable development has become a central concern, as the disorderly expansion of cities puts pressure on natural resources and makes it difficult to implement adequate infrastructure. Unemployment and informality are on the rise as job opportunities fail to keep pace with migration to urban centers, generating social inequalities (Chen et al., 2023). Education faces the challenge of providing access and quality for a growing population, while demand for energy increases, intensifying environmental impacts and the need for sustainable sources (Cartwright et al., 2023). Security has become a crucial issue, with rising crime and social vulnerability in some urban regions (Roy et al., 2024). In addition, public services need to adapt to serve an ever-growing population, demanding efficiency and innovation in the management of health, transportation, and sanitation (Akgün et al., 2024). Given this scenario, smart urban planning and integrated policies are key to making cities more sustainable, resilient and inclusive.

Although cities occupy around 2 % of the earth's surface, urban residents consume more than three-quarters of the world's natural resources, produce equivalent amounts of waste, use the oceans and soil as dumping grounds and are the main contributors to the greenhouse effect and gas emissions, which threaten to be the planet's greatest danger (Hoornweg et al., 2020; Kumar 2021; Yu et al., 2024). Sustainable urbanization is therefore the key to successful development. The aim of sustainable development is to find a way to promote the city economically, while defending social justice and always paying attention to the environment (Sorooshian, 2024). In this sense, technological progress must be highly subject to the interests of sustainable development, otherwise there will have to be drastic changes in consumption patterns and consequent production patterns. Growing urbanization has thus turned cities into complex social ecosystems, where ensuring sustainable development and quality of life must be paramount concerns. Furthermore, Kaftan et al. (2023) point out that the current economic crisis has forced many cities to cut budgets and set priorities. As a result, new strategies need to be developed to enable cities to achieve better performance and sustainability. To this end, there are already a number of projects being developed in cities with the aim of transforming them into smart cities, i.e. transforming the socio-economic environment into one in which citizens, companies and governments can access resources and services more efficiently. Smart city initiatives have emerged as a model for mitigating and remedying current urban problems and making cities better places to live.

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Urban Living Labs (ULLs) have emerged as innovative platforms for tackling the complex challenges associated with rapid urbanization and the transition toward smart cities. These labs function as experimental environments where different actors (e.g., citizens, businesses, academia, and governments) collaborate to co-create, test, and scale innovative solutions in real-life urban settings (Laborgne et al., 2021). Therefore, ULLs address the challenges of sustainable urban development by serving as real-world testing grounds where innovative solutions emerge. As indicated by Bulkeley et al. (2016), a key feature of ULLs is their participatory approach to urban governance. ULLs develop and deploy civic engagement applications that allow residents to interact directly with local governments, report urban issues, and participate in decision-making processes. Some common functionalities of these applications are reported in the literature such as crowd-sourced model, participatory budgeting, and community engagement forums (Voorwinden et al., 2023; Willems et al., 2023). Furthermore, Scholl et al. (2022) note that ULLs promote social sustainability by ensuring that urban transformation is inclusive, equitable, and beneficial for all residents, particularly marginalized communities. Accordingly, special attention is given to marginalized communities, ensuring that their voices are heard in decision-making

The Quintuple Helix Model was proposed by Carayannis and Campbell (2010), and it builds upon previous models of innovation, particularly the Triple Helix Model (Etzkowitz & Leydesdorff, 1996) and the Quadruple Helix Model (Carayannis & Campbell, 2009), by adding the natural environment as a key driver of knowledge production and innovation. Quintuple Helix Model integrates five key subsystems (i.e., academia, industry, government, civil society, and natural environment) that contribute to sustainable development, emphasizing the role of society and the environment in shaping innovation. Unlike earlier models (Triple Helix and Quadruple Helix), it explicitly incorporates the natural environment as a key element, emphasizing that sustainable innovation must consider ecological and social responsibility. Quintuple Helix Model is particularly important in the context of ULLs due to the relevance of exploring the collaboration between multiple stakeholders. Therefore, it can be assumed that Quintuple Helix Model is an ideal framework for understanding how ULLs function.

Current studies such as Bhatta et al. (2024) and Ebbesson et al. (2024) indicate that ULLs rely on co-design as a core methodology to engage multiple stakeholders in shaping sustainable urban solutions. They also highlight that achieving co-design requires continuous collaboration than a one-off approach. Furthermore, Florez Ayala et al. (2022) denote these interactions evolve over time, forming adaptive, iterative, and participatory processes. Moreover, Borda et al. (2024) note that open innovation can be used in the context of living labs to accelerate the adoption of sustainable innovations and refine solutions that enhance human well-being. Despite this, the exploration of the Quintuple Helix Model in the context of ULLs has been little explored. The work performed by Esashika et al. (2023) is relevant but lies in its context-specific nature and limited generalizability. Additionally, the study focuses on the Quadruple Helix Model, which lacks the explicit inclusion of the natural environment, a crucial factor for sustainability in smart cities, later addressed in the Quintuple Helix Model. Another relevant study was performed by Merino-Barbancho et al. (2023), which effectively demonstrates how the Quintuple Helix Model supports innovation. However, it focuses only on LifeSpace initiative which limits the generalizability of findings across different urban settings. Furthermore, it struggles to provide clear frameworks for transitioning from localized labs to large-scale ecosystems. This study addresses this research gap on exploring the transformative role of ULLs in shaping urban innovation ecosystems considering three projects in smart cities held in Portugal that involve national and international partners. It employs the Quintuple Helix Model to examine the interplay between academia, industry, government, civil society, and the natural environment in fostering sustainable urban transformations. Furthermore, it aims to highlight how ULLs act as catalysts for collaborative knowledge production, co-creation processes, and policy integration, facilitating the transition from short-term pilot projects to long-term, institutionalized urban innovation ecosystems. In this context, two research questions emerge:

RQ1. How is the collaboration between the various players involved in the innovation process promoted by ULLs characterized?

RQ2. How does the integration of the natural environment within the Quintuple Helix Model shape the Urban Innovation Ecosystems?

Although ULLs have been the subject of prior research as innovation drivers, this study is unique in that it incorporates the natural environment, which is frequently disregarded in conventional helix models, as a significant factor in shaping urban transformation. Moreover, the study offers empirical insights into how ULLs evolve from short-term initiatives to long-term, institutionalized urban innovation ecosystems by analyzing three smart city projects in Portugal with national and international collaboration. This study emphasizes the role of digital transformation, particularly digital twins and participatory governance, in forming sustainable cities and advances our understanding of collaborative knowledge production and co-creation in urban innovation ecosystems. Additionally, it provides empirical contributions through a comparative analysis of three case studies, which gives useful insights into how ULLs have changed in Portugal. Moreover, it identifies critical success factors, such as multi-sectoral engagement, participatory decision-making, and hybrid financing, in scaling urban innovation projects.

The rest of this manuscript is organized as follows: First, a theoretical review is given of smart cities and the quintuple helix model. This is followed by a presentation of the study methodology and a description of the methods applied. Next, the results are systematized and discussed according to the research questions previously formulated. Finally, the conclusions of the study are listed, its main contributions are explored and indications for future work are given.

2. Literature review

2.1. Smart cities

In recent years, a series of new challenges have arisen for cities, which has reinforced the popularization of the smart city idea. Smart cities represent a multidisciplinary field, constantly shaped by technological advances and urban development (Bibri & Krogstie, 2017; Gracias et al., 2023). Ensuring the necessary living conditions in the context of rapid global urban growth requires an in-depth understanding of the smart city concept. The challenge is essentially to find new forms of management to achieve cities that are sustainable and satisfactorily livable. As Manjushree et al. (2024) point out, cities are becoming smart not only in terms of the way in which technology can automate day-to-day functions that serve people, buildings and traffic systems, but also in the way in which they can monitor, understand, analyze and plan the city as a whole, to improve its efficiency, equity and quality of life for citizens. In summary, cities can thus become smarter in the long term through continuous reflection in the short term.

The evolving study of smart urban environments has revealed different conceptions of what is often called a “smart city”. The concept is increasingly used around the world in different contexts and meanings, and there is no unanimous and consistent understanding among academics of this new urban phenomenon, since the concept is highly context-dependent. Consequently, a plurality of projects prevails with highly varied objectives, motivations, actions, partners and funding models. Giffinger et al. (2007) believe that a city is smart when it is implemented in a forward-looking way, in terms of the economy, people, governance, mobility, the environment and quality of life, and this is achieved through a combination of donations and citizen activity. Dirks and Keeling (2009) consider a smart city to be an organic integration of systems. The interrelationship between the core systems of a city is considered to make the system of systems smarter, i.e.

no system operates in isolation. From this perspective, the smart city is seen as an organic whole with a network and connected systems. Washburn et al. (2010) envision a smart city as a collection of intelligent computing technologies applied to critical infrastructure components and services. Smart computing refers to a new generation of integrated hardware, software and network technologies that provide IT systems with real-time, real-world awareness and advanced analytics and actions that optimize city services.

A key pillar of a smart city is, inevitably, people or, in other words, social capital. As Mohiuddin and Yasin (2023)) argue, social capital means not only people's education and skills, but also people's ability to build trust in each other, to cooperate, to participate in social networks and dialogues, to share common goals, to be proactive. However, this component has often been neglected, to the detriment of understanding political and technological aspects. Even so, Munoth et al. (2022) and Sancino and Hudson (2020) report on various smart city projects that aim to make citizens more informed, educated and participatory so that they can take part in the management and governance of cities. According to Johnes et al. (2017), the higher a population's level of education, the more local productivity will grow. Thus, areas with better educated populations will be conducive to a better quality of life, because better educated individuals stimulate economic growth. Citizens and communities are the human engines of cities, an element that has a behavioral influence on the city's historical and cultural heritage (Yang & Zhen, 2024). Social capital emerges as a fundamental element for the development of entrepreneurial activity, as well as an engine for innovation and a decisive factor in a city's attractiveness.

As cities faced growing climate, social, and economic challenges, the sustainable city concept emerged as a broader framework that integrates smart technologies with socio-economic equity, ecological resilience, and participatory governance (Almeida et al., 2024; Karal & Soyer, 2024). This shift was accelerated by global frameworks like the UN Sustainable Development Goals (SDGs), particularly SDG 11 (Sustainable Cities and Communities), which emphasized resilience, inclusivity, and environmental stewardship. As recognized by Almulhim et al. (2024), this goal emphasizes resilience, inclusivity, and environmental stewardship, guiding cities toward a more holistic and sustainable approach to urban development. The integration of these principles is important to recognize the transition from a purely technology-driven smart city model to a people-centered, climate-adaptive, and resource-efficient urban ecosystem that balances innovation with long-term sustainability.

2.2. Quintuple helix model

The evolution of Helix Models is represented in Table 1 and can be seen as a conceptual progression in understanding innovation ecosystems. These models show the increasing complexity of knowledge production and societal transformation. They have evolved from linear innovation processes to multi-stakeholder collaborative frameworks, addressing economic, social, and environmental challenges.

The Quintuple Helix Model emerged in response to global challenges by recognizing that scientific and technological progress must be aligned with ecological sustainability. It also advocates that innovation must be holistic and inclusive as proposed by Chen et al. (2018). Unlike earlier models that prioritized economic development, the Quintuple Helix aligns sustainability goals (e.g., SDGs) by incorporating ecological and social considerations into innovation systems.

The Quintuple Helix Model is particularly relevant in regions that face high environmental concerns. In areas struggling with environmental degradation and resource depletion, this model ensures that technological advancements and economic growth are aligned with ecological preservation. Furthermore, Carayannis et al. (2021) indicate that regions with significant social challenges, such as economic inequality, unemployment, and limited access to education, also benefit from this model. Therefore, the inclusion of civil society as an essential stakeholder ensures that innovation is inclusive and participatory. It is also noted by Kholiavko et al. (2021) that universities and research institutions play a crucial role in fostering knowledge transfer and capacity building, helping societies adapt to technological advancements while ensuring that marginalized groups are not left behind.

In areas with complex governance structures, where decision-making involves multiple stakeholders across different levels of government, the Quintuple Helix Model fosters collaborative governance (Kitsios et al., 2021). This requires that academia, industry, government, civil society, and the natural environment are elements that participate into the innovation process. This model also promotes interdisciplinary dialogue and shared decision-making through co-creation and stakeholder engagement. The consequence is the reduction of conflicts and fostering policy alignment between national, regional, and local authorities (Yazıcı, 2023). Therefore, this model incentivizes governments to work closely with research institutions to develop evidence-based policies, while businesses and civil society contribute practical insights and innovative solutions that enhance implementation effectiveness.

3. Methodology

3.1. Research design

This study follows the theoretical lens of quintuple helix and applies action research to explore the role of ULLs in the urban innovation ecosystems. This approach has previously been used by Baccarne et al. (2016) in their work to explore how ULLs can be used to govern collaborative innovation processes in the context of the quintuple helix model, aimed at tackling socio-ecological challenges in urban areas. However, Baccarne et al. (2016) conducted their action research on two projects focused on eco-entrepreneurship. In this study, the approach seeks to understand the phenomenon not only from the perspective of entrepreneurial startups, but also including projects that arise motivated by incumbent companies and other organizations, which can be entities from the scientific and social environment.

As recognized in the literature by Coghlan (2019) and Stringer and Aragón (2020), action research is a participatory and iterative research

Table 1
Evolution of helix models.

Model	Authors	Goal	Impact
Linear	Bush (1945)	Describe the process of technological advancement and economic growth as a sequential flow from basic research to market applications.	Establish a structured and predictable approach to innovation. Emphasize the role of scientific research as the primary driver of technological progress.
Triple helix	Etzkowitz and Leydesdorff (1996)	Collaboration between universities, industries, and governments.	Recognizes universities as entrepreneurial entities. Encouraged public-private partnerships.
Quadruple helix	Carayannis and Campbell (2009)	Civil society and media/culture as active participants in innovation.	Shift from a technology-driven to a user-driven innovation approach. Recognizes the role of social dynamics and public engagement.
Quintuple helix	Carayannis and Campbell (2010)	The natural environment as a driver of innovation and sustainability.	Linked innovation to SDGs. Address sustainability as a global challenge.

Table 2
Phases of the applied action research methodology.

Phase	Goal	Methods
Diagnosing	Identification of key challenges and research problems within the urban innovation ecosystem.	Stakeholder analysis to identify key actors. Mapping the urban challenges that require innovative interventions.
Action planning	Develop a participatory plan of action to address the identified challenges using Living Labs.	Participation in stakeholder engagement workshops. Involvement in co-creation sessions to define project priorities.
Action taking	Execute the planned actions and test the proposed solutions in real-world settings.	Prototyping and experimentation. Engagement of local communities through participatory methods (e.g., workshops and presentations).
Evaluating	Assess the impact of interventions and extract insights for theory and practice.	Gathering qualitative data from participants using focus groups. Identify barriers and enablers in the innovation process.
Learning & iteration	Improve the intervention strategies based on lessons learned and scale successful initiatives.	Knowledge dissemination. Integration into urban policy frameworks.

Table 3
Overview of the projects.

Project	Focus area	Description
#PJT-SMC-01	Smart mobility, energy transition, digital city, and circular economy.	A collaborative innovation platform that brings together businesses, government organizations, and citizens to co-create sustainable urban solutions. Projects include smart grids, energy-efficient buildings, and IoT-based urban management.
#PJT-SMC-02	IoT-based smart city solutions, environmental monitoring, and mobility	An urban lab that deploys thousands of IoT sensors across the city to monitor air quality, noise levels, traffic, and waste collection. It serves as a testbed for large-scale smart city applications.
#PJT-SMC-03	Digital innovation, public services, and smart mobility	An initiative that fosters collaboration between startups, academia, and government to develop technology-driven urban solutions. It includes projects on real-time public transport data, digital governance, and citizen engagement platforms.

methodology that integrates theory and practice to solve real-world problems while generating academic knowledge. Action research is particularly relevant in the context of sustainable innovation to engage the multiple stakeholders' perspectives of the co-creation processes and to encourage a systemic thinking approach. Table 2 provides an overview of the adopted phases with a brief description of their goals and applied methods. The Diagnosing phase identifies key challenges through stakeholder analysis and urban challenge mapping. Action Planning involves co-creation and stakeholder engagement to develop strategies. Action Taking focuses on implementing and testing solutions through prototyping and community participation. Scrum was adopted as a prototyping approach. Scrum is an agile project management framework that enables teams to develop and test solutions incrementally through short, time-boxed iterations called Sprints (Hidalgo, 2019). We have applied sprints of three weeks for all living labs. A cross-functional team was built, which included a Product Owner, a Scrum Master, and the Development Team. Product Owner was responsible for representing the stakeholders' vision and define priorities; Scrum Master facilitated the implementation process and removed impediments; and the Development Team was responsible for the technical implementation and included urban planners, sustainability experts, and software engineers. Evaluating phases assesses the impact of interventions by gathering qualitative data and identifying success factors. For that, we have conducted a focus group analysis at the end of the project (after the completion of all sprints). Furthermore, we have collected qualitative data from all retrospective sessions, which had the objective of reflecting on the team's performance and identifying areas for improvement. Finally, Learning & Iteration refines strategies based on lessons learned, ensuring knowledge dissemination and integration into urban policy frameworks for broader scalability.

3.2. Data

The data was obtained from three projects in smart cities, involving national and international partners in both the technical and scientific fields. Each project focuses on different dimensions of smart cities, such as urban mobility, energy efficiency, digital governance or IoT infrastructure. All the projects involve the creation and development of a smart city in Portugal. These projects were carried out between May 2023 and November 2024. Among the institutions involved are universities, research centers, private companies, startups and governments. All the projects seek to carry out explicit technology transfer actions, as indicated by Soe et al. (2021), when they highlighted the role of these institutional cooperation initiatives in the adoption of new technological solutions. The following areas are covered in the technical domain: digital infrastructure, urban sensors, big data, artificial intelligence applied to urban services. Table 3 gives a brief presentation of these initiatives considering their scope and objectives. #PJT-SMC-01 is broader in scope, integrating multiple urban sustainability aspects. #PJT-SMC-02 is more focused on IoT-based monitoring and data collection. #PJT-SMC-03 prioritizes digital governance, public service innovation, and citizen engagement.

Table 4 provides a more detailed vision of the sample by analyzing the main key differences between the projects. All three projects emphasize smart mobility, aiming to improve urban transportation systems using digital and IoT-based technologies. Each project leverages advanced technologies such as IoT, digital platforms, and real-time data analysis to enhance city functions. Furthermore, all initiatives involve multi-stakeholder participation, and contribute to sustainability through different means, whether by improving mobility, reducing environmental impact, or optimizing urban services.

3.3. Focus group

The adopted focus group approach aimed to explore the role of ULLs in the urban innovation ecosystems through the quintuple helix framework and action research methodology. The organization structure of the focus group is presented in Table 5. We have followed the approach suggested by Krueger and Casey (2014), who argues that the focus group approach is important for capturing qualitative data by allowing participants to interact and argue. It also gives the moderator a great deal of flexibility within the meeting to introduce and deepen the elements

Table 4
Differences between the projects.

Feature	#PJT-SMC-01	#PJT-SMC-02	#PJT-SMC-03
Primary approach	Collaborative innovation platform	Large-scale IoT deployment	Digital governance & public services
Key technologies	Smart grids, IoT, circular economy solutions	IoT sensors for real-time monitoring	Digital platforms, real-time data for governance
Urban focus	Holistic sustainability, covering mobility, energy, and circular economy	Environmental monitoring, mobility, and infrastructure efficiency	Digital transformation of public services and citizen engagement
Main beneficiaries	Businesses, government, citizens	City infrastructure and environmental monitoring agencies	Citizens, policymakers, and urban planners
Use cases	Energy-efficient buildings, digital services, mobility solutions	Air quality monitoring, noise level tracking, traffic optimization	Real-time public transport data, digital governance, citizen engagement

Table 5
Focus group organization.

Aspect	Details
Objective	To discuss how urban living labs contribute to urban innovation ecosystems, leveraging the quintuple helix model.
Participants	Representatives from local government, businesses, universities, and civil society. #PJT-SMC-01 has 3 participants from local government, 4 from businesses, 3 from universities, and 2 from civil society. Average age of participants is 31.8 years and 67 % (8 in 12) of the participants are male. #PJT-SMC-02 has 2 participants from local government, 3 from businesses, 2 from universities, and 2 from civil society. Average age of participants is 38.1 years and 67 % (6 in 9) of the participants are male. #PJT-SMC-03 has 2 participants from local government, 2 from businesses, 3 from universities, and 2 from civil society. Average age of participants is 29.8 years and 56 % (5 in 9) of the participants are male. At least two representants by role were assigned or each focus group.
Format	Structured discussion of around 90 min, moderated by the facilitator.
Methodology	An action research approach was adopted.
Location	Hybrid (physical meeting with virtual participation option).
Tools	It was adopted Miro as a collaborative digital whiteboard. Additionally, a shared document in google drive was provided.

Table 6
Focus group questions.

Section	Duration (min)	Questions
Welcome & introduction	10	Briefing on the study objectives and structure.
Understanding urban living labs	15	Q1. How would you define an urban living lab (ULL) based on your experience? Q2. What are the main objectives of ULLs in your project?
ULLs and the quintuple helix model	15	Q3. How do ULLs facilitate collaboration between government, industry, academia, civil society, and environmental organizations? Q4. What are the main challenges in aligning these five stakeholder groups in ULL initiatives?
Role of ULLs in urban innovation ecosystems	20	Q5. What role do ULLs play in shaping smart city policies and projects? Q6. How do ULLs contribute to sustainable urban development? Q7. Can you share examples of successful urban innovations that emerged from ULLs?
Action research & practical implications	20	Q8. What strategies have worked best for ensuring active stakeholder engagement in ULLs? Q9. How can ULLs become more inclusive and representative of diverse urban communities? Q10. What policy recommendations would you suggest enhancing the impact of ULLs?
Future perspectives	10	Q11. How do you see the future of ULLs evolving in the next 5–10 years? Q12. What new technologies or approaches should be integrated into ULLs to improve urban innovation?

of the discussion. We started the session by informing the participants about the objectives of this study. All participants gave their consent, were voluntary and not remunerated. Furthermore, we have prepared a structured agenda with open-ended questions (see Table 6) to encourage dialogue. The Welcome & Introduction (10 min) serves as an opening phase where participants receive a briefing on the study objectives and structure, ensuring clarity and engagement. The Understanding ULLs section (15 min) focuses on defining ULLs and their main objectives from participants' perspectives, providing foundational insights. The ULLs and the Quintuple Helix Model (15 min) explores how ULLs facilitate collaboration among key stakeholder groups—government, industry, academia, civil society, and environmental organizations—while addressing challenges in multi-stakeholder alignment. The Role of ULLs in Urban Innovation Ecosystems (20 min) examines how ULLs influence smart city policies, sustainability efforts, and real-world innovation cases. The Action Research & Practical Implications (20 min) discusses effective stakeholder engagement strategies, inclusivity, and policy recommendations to enhance ULL impact. Finally, after the session, the data was revised and uploaded to MAXQDA v.24 software to perform a thematic analysis. As Braun and Clarke (2021) argue, the versatility of thematic analysis makes it possible to describe data in a rich, detailed and refined way.

4. Results and discussion

Fig. 1 shows the results of the thematic analysis considering the 1st order concepts, 2nd order themes, and aggregate dimensions. The codes were categorized and extracted from MAXQDA v.24 and then the corresponding aggregate dimension was added using SmartDraw v. 2017. In the aggregate dimensions the following acronyms are used: (G) government; (I) Industry; (A) Academia; (CS) Civil Society; and (NE) Natural Environment. The 1st order codes represent the views of the participants, while the 2nd order codes connect these perceptions to theoretical concepts. This approach allows for the construction of a solid conceptual model, adding meaning to the raw data. Furthermore, the use of aggregated dimensions facilitate comparison with other studies and makes it easier to derive practical and theoretical implications. The governmental, industrial and academic dimensions are those most strongly associated with the themes identified. Civil society also plays a major role in these initiatives as a participant and recipient of the solutions developed in the ULLs. Finally, the role of the natural environment only appears in specific actions, such as the focus on the sustainability and environmental components of the solutions. Nevertheless, this role is a central and transversal element of the solutions that are presented to be solved in the urban environment.

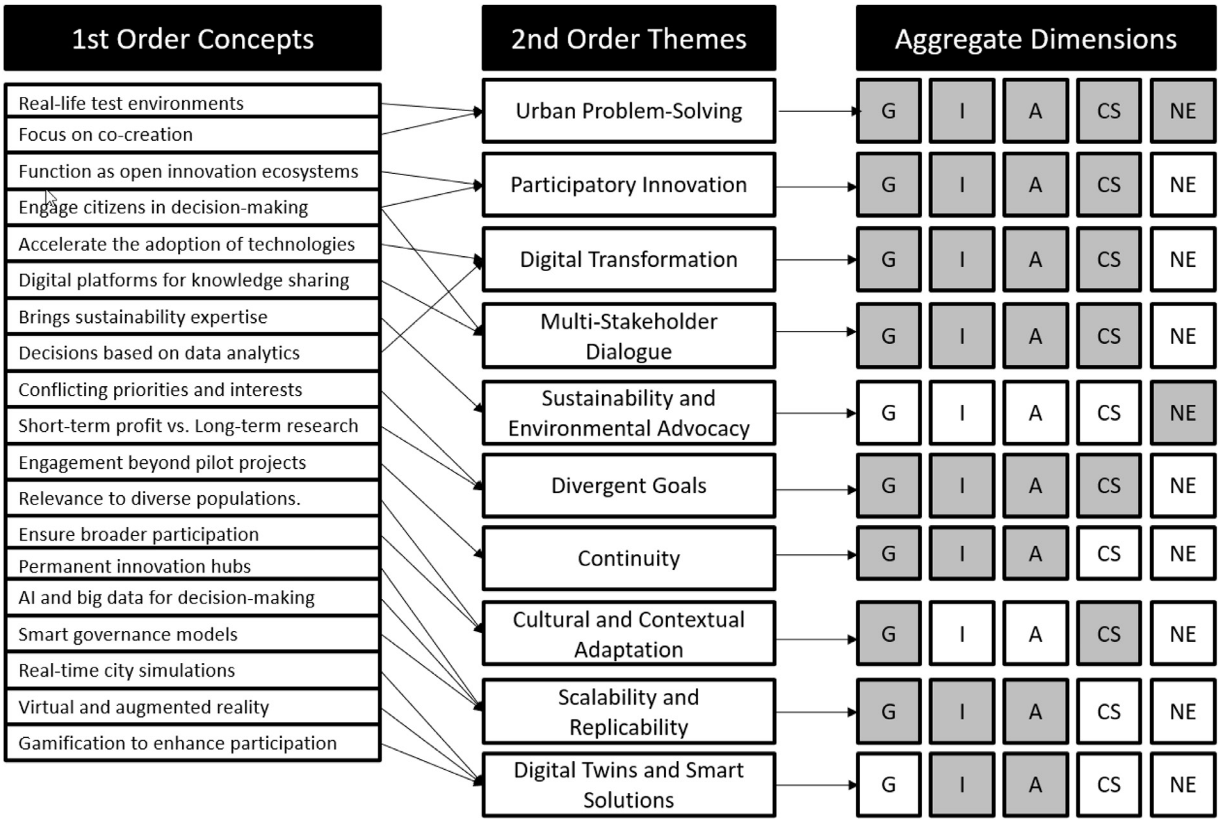

Fig. 1. Thematic analysis.

4.1. RQ1. How is the collaboration between the various players involved in the innovation process promoted by urban living labs characterized?

The findings indicate that the collaboration between these actors is fundamental to addressing the objectives of ULLs. They allow new ideas to be tested in real urban environments, reducing uncertainties before they are adopted on a large scale. However, the results also point out that the diversity of opinions and interests can create obstacles to the process of co-creating and implementing solutions. In this sense, it is important to adopt mediation and facilitation mechanisms. This can be achieved by creating discussion forums in which diverse interests are balanced. Another complementary approach is highlighted by Alexandrakis (2021) and Rizzo et al. (2021), who apply methodologies such as design thinking, through which they seek to ensure greater representation in decisions. Another impediment identified through thematic analysis is ensuring the continuity of solutions. Many of these initiatives are funded and only show results during their lifetime. One way to mitigate this difficulty is to adopt hybrid financing, which seeks to combine public, private and third sector resources to diversify funding sources. In CS3, the local municipality allocates part of its budget to pilot sustainable mobility solutions such as electric bike-sharing. This financial support is complemented by national grants to reduce the upfront costs of these initiatives. There are also complementary measures such as incorporating these projects into public policies (e.g. urban strategic plans) and/or integrating these initiatives into broader models of digital and sustainable transformation (von Wirth et al., 2018).

Co-creation and experimentation are two key characteristics that stand out in the three ULLs. CS1 highlights “we use rapid prototyping models to anticipate the testing of new solutions and to involve the various stakeholders in the creation of solutions”. CS2 notes the use of hackathons and innovation sprints. They organize short-term collaborative events where interdisciplinary teams co-develop and prototype solutions for urban challenges. This observation is also supported in literature where it is noted that hackathons democratize innovation by allowing citizens and local businesses to contribute ideas (Perng et al., 2018; Pihlajamaa & Merisalo, 2021). Furthermore, engagement in these initiatives tends to be multi-sectoral and inclusive. Bussey et al. (2023) characterize the role of diverse actors such as academia, the public sector, companies, citizens, and environmental and social organizations. For example, the role of academia in producing knowledge and developing evidence-based methodologies is highlighted; or that of companies in providing technology, funding and scalability for solutions. Although the role that each of these entities can play is clear, the results obtained from the three living labs indicate that this role should not be static and that local synergies should be sought. The geographic proximity between the various entities is important, but so is previous experience of participating in collaborative networks. Equally important for the development of these solutions is the existence of an open and inclusive dialog between the actors involved. CS3 reports on the importance of adopting participatory decision-making methods, highlighting the role of participatory budgeting. As highlighted by Schugurensky and Mook (2024), participatory budgeting is a democratic tool that allows citizens to decide how part of the public budget should be invested, which has gradually been adopted in Portuguese municipalities.

The findings also point to the role that ULLs can play in the digital transformation of cities by promoting collaborative development and experimentation. This digital transformation also seeks to be aligned with the needs of society through the integration of various stakeholders in the innovation process. The Quintuple Helix Model works as a conceptual model that allows the interaction between the five spheres to be articulated: academia, industry, government, civil society and the environment. The digital transformation of cities unfolds through the integration of emerging technologies into urban systems. It begins with the extensive collection of urban data via sensors, cameras, and connected devices, enabling real-time monitoring of key aspects such as traffic, energy consumption, air quality, and resource distribution

(Dahmane et al., 2024; Sarker, 2022). Algorithms based on machine learning and deep learning models then process this data to provide valuable insights to support informed decision-making (Heidari et al., 2022. These AI-driven innovations are made possible through partnerships between various players, ensuring that technological advancements align with real-world needs. This ecosystem of collaboration ensures that AI is not just a tool for automation but a means to build smarter, more sustainable, and more inclusive cities. As urban challenges continue to evolve, the success of AI-powered decision-making will increasingly depend on the ability of diverse stakeholders to work together. However, as Bayat and Kawale (2023) argue, digitalization also impacts governance by introducing citizen participation platforms and open data, enabling greater transparency and engagement of society in the construction of public policies. Two examples of the implementation of projects in this area can be found in CS1 and CS2. CS1 highlights the implementation of digital payment systems and digital identity to simplify the relationship between governments and citizens, while CS2 reports the implementation of urban sensors and digital platforms to monitor energy consumption and air quality.

4.2. RQ2. How does the integration of the natural environment within the quintuple helix model shape the urban innovation ecosystems?

Although the natural environment only appears explicitly in 2 of the 10 themes identified, its importance should not be underestimated. The natural environmental component emerges in the context of developing urban solutions. This component is applied with the objectives of promoting urban sustainability and resilience. As Dunlop et al. (2024) state, Nature-Based Solutions are innovative approaches that use natural processes and ecosystems to tackle environmental, social and economic challenges. Two examples can be found of this approach. In CS1 the creation of parks and green corridors was implemented to increase biodiversity and improve the city's natural drainage, while in CS2 a project was developed that allows citizens to install air sensors and share data on air pollution. In CS3, a new approach emerges based on digital twins. In the context of green infrastructure and reducing the carbon footprint, these digital models play an essential role in making sustainable decisions. One example found in CS3 is the adoption of digital twins for route planning for electric public transportation to reduce emissions. Preliminary data from this project indicates a 35 % reduction in CO_2 emissions when optimizing electric bus routes.

The Quintuple Helix Model underscores that sustainability is not solely a product of technological progress or economic growth but emerges from the complex and dynamic interactions among knowledge systems, innovation ecosystems, governance structures, and environmental imperatives. As contemporary research in sustainability transitions and socio-technical systems suggests, environmental considerations are no longer peripheral but serve as a structuring foundation for strategic decision-making and innovation processes (Geels, 2019). In the environmental dimension, the role of the natural environment is particularly evident in the shift toward regenerative practices and the adoption of nature-based solutions. The natural environment, in this context, is not merely a passive recipient of human interventions but an active agent shaping innovation trajectories. From a political and governance perspective, integrating environmental concerns into decision-making processes fosters transformative policy frameworks that align technological advancements with ecological resilience. Research on mission-oriented innovation policies (Kirchherr et al., 2023) and sustainability transitions (Mintrom & Rogers, 2022) suggests that governments are increasingly shifting from a market-driven approach to a collaborative innovation paradigm. The findings of this study align with current research avenues in socio-ecological innovation and circular economy transitions, reinforcing the idea that sustainability must be embedded across all dimensions of the innovation process (Pichlak & Szromek, 2022). The Quintuple Helix Model thus serves as a theoretical and practical framework for fostering systemic change, emphasizing that environmental sustainability is not a constraint but a catalyst for new forms of value creation.

5. Conclusions

This study makes it possible to understand that collaboration between actors is essential for the success of ULLs, allowing urban solutions to be experimented with in real environments and reducing uncertainties before large-scale adoption. However, the diversity of interests can hinder co-creation, requiring mediation mechanisms. Experimentation and co-creation are key features of ULLs, which also drive the digital transformation of cities through collaborative development. Although the natural environment is a component not often found in the themes identified in this study, its relevance should not be underestimated, as it plays a major role in urban sustainability and resilience. Finally, the Quintuple Helix Model reinforces this approach by integrating the environment as one of the five pillars of sustainable innovation, recognizing that technological and economic progress must be aligned with knowledge, public policies, and ecological solutions to ensure more resilient cities.

This study adds to our understanding of ULLs' function as places for co-creation and experimentation that lower uncertainty before large-scale urban solutions are implemented. It emphasizes how cooperation between government, business, academia, civil society, and the environment promotes experimentation, co-creation, and digital transformation. To guarantee the sustainability of urban innovations, the study emphasizes the significance of hybrid financing and participatory techniques, such as participatory budgeting. Moreover, it promotes conversations about Nature-Based Solutions and how digital twins can help maximize plans for environmental sustainability. It served as an example of how local governments can fund pilot projects and use federal grants to scale up sustainable solutions, like electric vehicles, in the local context. The role of academia in knowledge generation and businesses in scaling innovations is also emphasized. In terms of policymaking, the study offers practical recommendations for embedding ULL-driven innovations into urban strategic plans and broader digital transformation agendas. It suggests integrating citizen participation platforms and open data policies to enhance governance transparency and social engagement. Policymakers are encouraged to adopt regenerative urban planning approaches, incorporating Nature-Based Solutions (e.g., urban green corridors) and leveraging digital twins for data-driven decision-making. The case of optimized electric bus routes in CS3, which led to a 35 % reduction in CO_2 emissions, serves as an example of how digital technologies can support sustainable urban transitions.

It is important to consider the limitations of this study. The absence of a systematic framework for a new Sixth Helix Model, which may expand on the Quintuple Helix by adding cutting-edge digital technologies as vital innovation facilitators, is one of the study's main weaknesses. Although the natural environment is effectively incorporated into the innovation ecosystem by the Quintuple Helix Model, it does not specifically take into consideration how technologies like blockchain, big data, artificial intelligence (AI), and the Internet of Things (IoT) are influencing the development of next-generation sustainability strategies. Future studies should therefore examine how sustainability-focused urban innovation might incorporate digital transformation, ethics, and societal well-being. In particular, it is necessary to investigate how AI-driven governance may improve adaptive urban planning, regulatory compliance, and policy formation by analyzing enormous volumes of real-time data in order to maximize resource allocation and reduce environmental concerns. Furthermore, it is yet unclear how digital platforms for public involvement may promote social inclusion and participatory governance. This research stream would benefit from examining how AI-powered tools, such as human-centric AI design, decentralized governance models utilizing blockchain, and predictive analytics for public service delivery, could support more efficient and equitable urban innovation. The lack of reliable Key Performance Indicators (KPIs) to methodically evaluate the impact of ULLs is another important drawback. Although qualitative evaluations offer insightful information, it is challenging to measure the long-term sustainability and scalability of these labs due to the absence of defined, quantitative metrics. Future studies should concentrate on creating a thorough KPI framework that takes sustainability's social, economic, and environmental facets into account. These KPIs should not only measure the immediate outcomes of ULL initiatives but also capture their broader systemic impacts over time.

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