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# Integration of IoT and Technological Innovation in Urban Gardens: Case of ULL Fenicia

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***Abstract–. Urban Living Labs (ULLs) serve as dynamic frameworks for fostering socio-technical innovation within smart cities. This study examines the application of a technological innovation management model in the Fenicia ULL, aimed at enhancing the efficiency and sustainability of urban garden management. The project integrates IoT-enabled humidity and temperature sensors, powered by solar energy, to monitor real-time environmental conditions and energy production. These data streams feed into a digital twin platform, enabling predictive analytics and informed decision-making for both community members and urban planners. This research underscores the alignment between technological advancements and community-driven initiatives, demonstrating how digital twins and renewable energy solutions contribute to participatory governance and urban sustainability. By implementing this innovation management model, the study addresses critical urban challenges, including resource optimization and citizen engagement, particularly in developing regions. The findings provide valuable insights into scalable and replicable models for smart urban agriculture, reinforcing the role of ULLs in shaping resilient and adaptive urban ecosystemss.***

***Keywords—Urban Living Labs (ULLs), Smart Urban Agriculture, Digital Twin Technology, Internet of Things (IoT) in Urban Gardens, Sustainable Urban Development.***

## I. INTRODUCTION

Urban gardens have emerged as critical elements in the pursuit of sustainable urban living, offering not only ecological benefits but also serving as hubs for community engagement and education. These green spaces contribute to environmental sustainability by mitigating urban heat, enhancing biodiversity, and fostering local food production, as highlighted in studies from both developed and developing contexts [1,2]. Additionally, urban gardens encourage social cohesion, improve public health, and provide opportunities for learning sustainable practices [3,4].

Urban Living Labs (ULLs) have gained prominence as frameworks for fostering innovation and addressing urban challenges through participatory experimentation [5]. By integrating diverse stakeholders, including academia, local governments, and communities, ULLs offer a platform to co-create solutions tailored to local needs. Their importance lies in their ability to combine technological and social innovations to tackle complex urban issues, such as climate change, resource scarcity, and socio-economic disparities [5,6].

Despite their promise, urban gardens often face challenges in efficiency and sustainability, particularly in rapidly urbanizing areas. The integration of technology into these spaces remains limited, with issues such as inadequate monitoring of environmental conditions and inefficient resource use hindering their full potential [2,7]. Addressing these gaps requires innovative approaches that merge technological tools with participatory urban planning frameworks.

The Technological Innovation Management Model for Urban Living Labs provides a structured framework for addressing urban challenges through socio-technical innovation. This model emphasizes participatory governance, adaptive technologies, and iterative experimentation to align urban solutions with local socio-economic and environmental contexts. For example, the urban garden within the Fenicia ULL in Bogotá, Colombia applied this model by integrating digital twin platforms to address key urban issues such as waste, energy, and information management. These strategies foster inclusivity, scalability, and sustainability by engaging diverse stakeholders and leveraging advanced technologies for urban problem-solving.

Data-driven approaches in urban gardens significantly impact community engagement and decision making. Real time data provided by Internet of Things (IoT) systems empowers citizens to actively participate in garden management by making informed decisions about water irrigation schedules, plant selection, and maintenance. Such transparency fosters a sense of ownership and collaboration within the community [8]. Furthermore, digital twin platforms enhance participatory engagement by offering virtual tools for planning and simulation, bridging the gap between technology and societal needs. This alignment is critical for urban gardens to function as both green infrastructure and community hubs, as highlighted by [5]. These tools demonstrate how ULLs can drive sustainable urban transformation by integrating innovative technologies with community-driven initiatives.

Furthermore, considering the efforts of the United Nations (FAO, IFAD, WHO, WFP, UNICEF) through the Sustainable Development Goals, particularly those aimed at eradicating hunger, ULLs provide an opportunity to enhance food security in urban settings by leveraging technology for sustainable urban agriculture [9].

### A. *Technologies Applied in Urban Gardens*

Technological advancements have revolutionized urban gardening, integrating solutions like IoT sensors, solar energy, and digital twins to enhance sustainability. IoT devices, such as humidity and temperature sensors, provide real time environmental monitoring, ensuring optimized resource use and plant growth [7]. Solar energy systems not only power these devices but also promote cost-efficiency and environmental sustainability. Additionally, digital twin platforms allow simulations and predictive analytics, enabling gardeners to optimize practices and address challenges effectively. For instance, the U-Garden project demonstrates how these technologies enable better decision making and resource allocation in urban gardens, contributing to greener and more resilient urban landscapes.

Once the crops have been selected in the urban garden using a simulation program, various environmental factors are taken into account, such as climate, temperature, humidity, and especially frost forecasts that may impact the growth cycle. These predictive insights allow for the application of appropriate technologies to optimize cultivation conditions, ensuring improved resilience and productivity of urban gardens.

Urban gardens are increasingly embracing advanced technologies to enhance their efficiency, sustainability, and community impact. These technologies, which include IoT systems, renewable energy sources like solar panels, and digital tools such as Geographic Information Systems (GIS), are proving essential for addressing the challenges of urban gardening.

The application of IoT in urban gardening has transformed the way gardens are monitored and managed. IoT systems enable real-time data collection on key environmental variables such as soil moisture, temperature, and humidity. For example, in the U-GARDEN project, IoT devices were integrated into urban gardens to provide continuous monitoring, optimize environmental conditions, and ensure efficient resource use [7,10]. This approach allows gardeners to make informed decisions based on live data, enhancing plant health and productivity.

Renewable energy, particularly solar energy, is playing a pivotal role in making urban gardens more sustainable. Solar panels are utilized to power IoT devices and other operational systems within gardens. In a study of photovoltaic systems in urban environments, multi-criteria decision-making tools were applied to optimize their integration, ensuring efficiency and minimal environmental impact [11].

GIS and big data technologies have revolutionized urban garden management by enabling precise mapping and analysis of green spaces. These tools are used to monitor plant nutrients and control of pests, supply of nutrients, manage water resources, and analyze environmental impacts. For instance, GIS sensor technologies were employed in a digital management system for urban gardens, allowing for efficient data collection and analysis to support adaptive strategies [12].

Digital twin platforms, which create virtual replicas of urban gardens, facilitate simulations and predictive analytics. These platforms support informed decision making by providing insights into the potential impacts of various environmental and management scenarios. In the Fenicia ULL, a digital twin was implemented to integrate data from sensors and solar panels, enabling real time monitoring and adaptive management strategies.

### B. *Impact of Data-Driven Information Communities*

The implementation of data-driven technologies in urban gardens significantly influences community engagement and decision making. By providing accessible and transparent information, these systems empower citizens to participate actively in the sustainability and productivity of green spaces.

Data collected from IoT sensors and digital tools fosters a participatory approach, allowing communities to engage in the management of urban gardens. For example, in Pune, India, urban gardening initiatives utilized real time data to educate gardeners on efficient resource use and sustainable practices [4,13]. This engagement not only improves garden outcomes but also strengthens community bonds.

The availability of precise and actionable data enables community members and stakeholders to make informed decisions about resource allocation, crop selection, and garden maintenance. In California, citizen science initiatives encouraged gardeners to adopt sustainable water management practices, which improved the resilience of urban gardens to environmental changes [8].

Urban gardens equipped with advanced technologies provide broader socio-ecological benefits, including improved air quality, climate regulation, and biodiversity conservation. These outcomes contribute to the well-being of urban communities and enhance their capacity to adapt to climate challenges [13,14]. Through the integration of these technologies, urban gardens are becoming hubs for innovation, community involvement, and sustainability, demonstrating their potential as key components of resilient urban ecosystems.

This study aims to develop and implement a monitoring system for an urban garden within the Fenicia ULL in Bogotá, Colombia. The system will integrate solar-powered sensors to monitor soil moisture and temperature, with data transmitted to a digital twin for real-time simulations and informed decision-making. By doing so, this research aligns with the Technological Innovation Management Model for ULLs, emphasizing socio-technical solutions that enhance community involvement and sustainability.

Through this initiative, the study seeks to demonstrate the practical application of socio-technical innovation strategies in urban gardens. By fostering a collaborative environment where technology and community insights converge, the project aims to deliver actionable solutions that contribute to the broader discourse on sustainable urban development. Ultimately, this work highlights the potential of ULLs to serve as catalysts for transformative urban innovation [5].

## II. Methodology

The methodology chapter outlines the structured approach employed to address the objectives of the research through an iterative socio-technical framework. This chapter is divided into four key sections: Study Design, which introduces the socio-technical innovation model and its focus on co-creation and transformative solutions; Technological Development, detailing the implementation of IoT systems, renewable energy configurations, and digital twin integration; Use of Platforms for Simulations, describing how FIWARE LAB and the Smart Data Model AgriApp are employed to validate and simulate system performance; and Community Participation (Future Phase), outlining the planned engagement and capacity building initiatives for stakeholders, which will be implemented in a subsequent stage. Together, these components provide a comprehensive roadmap for the deployment and refinement of innovative solutions to urban challenges.

### A. *Study Design*

This study employs a socio-technical innovation model that integrates co-creation, experimentation, and the implementation of transformative solutions to address urban challenges. The proposed model that is shown in Figure 1 emphasizes the iterative evaluation of outcomes against key performance indicators (KPIs) of the ULL, namely:

1. *Quality of Life:* Improving community well-being through sustainable solutions.
2. *Productivity:* Enhancing the efficiency of urban systems and resources.
3. *ICT-Based Sustainability:* Leveraging Information and Communication Technologies for sustainable development.

While the methodology covers both technological development and community participation, this paper focuses on the technological development phase, with community engagement planned for a subsequent stage. Simulations of the system will be conducted using FIWARE LAB and the Smart Data Model AgriApp provided by FIWARE, ensuring alignment with state-of-the-art smart city frameworks.

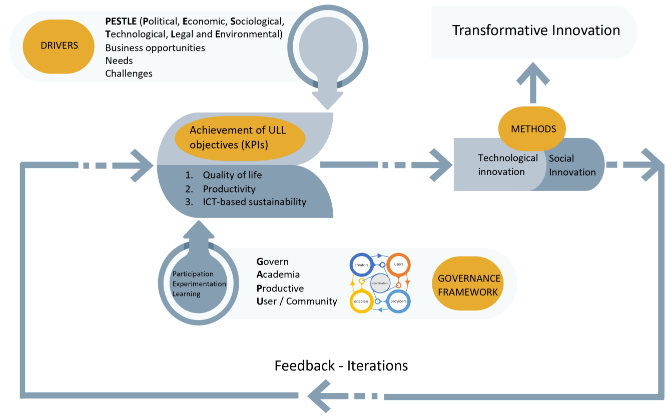


Fig. 1 Methodology framework to socio-technical innovation management.

### B. *Technological Development*

The primary focus of this phase is the development, testing, and validation of the technological infrastructure necessary to support the objectives of the Fenicia ULL. The technological implementation is structured around innovative smart urban farming solutions that align with sustainable urban development goals [15]. To enhance agricultural productivity and sustainability, the Fenicia ULL has incorporated a range of IoT technologies as shown in Figure 2, including a projected rain water irrigation systems that optimize water usage through real-time soil moisture monitoring, smart sensor networks that track key environmental parameters such as temperature, relative humidity, soil moisture and solar radiation, and a data-driven decision-making system that provides real-time analytics via a centralized dashboard for monitoring and predictive analysis as shown in Figure 3.

These sensors were seamlessly integrated with FIWARE's Smart Data Model AgriApp, which enables standardized data exchange tailored for agricultural applications, ensuring compatibility and scalability within broader smart city frameworks.


Fig. 2 IoT Sensor .

Source: Implementación de un sistema integrado para la telemetría agrícola y gestión sostenible en la Huerta Fenicia [15].

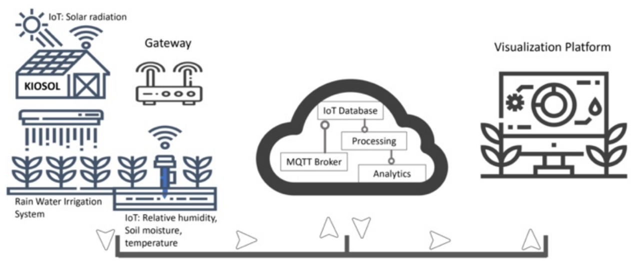


Fig. 3 Fenicia ULL Urban Garden System Architecture.

To power the IoT sensors and associated systems sustainably, a solar photovoltaic system developed by KIOSOL project was installed [16] as shown in Figure 4. KIOSOL provides an advanced modular photovoltaic solution tailored for urban environments, integrating high efficiency solar panels with smart energy management systems. The system includes an energy storage component that allows for uninterrupted operation during periods of low sunlight, ensuring energy availability for critical systems such as irrigation pumps, sensors, and lighting. The platform also enables remote monitoring and optimization of energy consumption, further enhancing efficiency and sustainability.


Fig. 4 KIOSOL project with solar panels, hybrid inverter and batteries.
Source: An Intelligent Distributed Energy Resources Living Laboratory [16].

A system has been developed for the MATE3 monitoring module of the KIOSOL components, as shown in Figure 5. This module successfully communicates using the Modbus TCP/IP protocol. Currently, the system reads essential battery bank parameters, including voltage (approximately 42V), current, and power. The implemented system features logging capabilities, structured storage in CSV files, and is designed for continuous operation on the server, taking measurements at regular intervals of 5 seconds. Its architecture allows for expansion to include additional parameters, such as inverter data, battery state of charge (SOC), accumulated energy, and system status. The code is structured in a modular and robust manner, incorporating error handling and the ability to detect reading or communication issues. The captured data is processed and appropriately scaled, making it ready for direct analysis or visualization.


Fig. 5 MATE 3 is a system and display controller to monitor and program each outback component.
Source: An Intelligent Distributed Energy Resources Living Laboratory [16].

The performance of the energy system was rigorously evaluated over one-month trial period, during which it was subjected to various environmental conditions to assess its reliability and efficiency.

In addition to the physical components, a digital twin platform was implemented to enhance data utilization, with 3D visualization shown in Figure 6. To develop this digital twin for the urban garden, aerial surveys were conducted using drones to create a high-resolution 3D model of the site. These models were then uploaded to the GIS platform Supermap, which allows for advanced spatial analysis and real-time monitoring. The Supermap platform also enables the integration of artificial intelligence to simulate various events affecting the garden, providing valuable insights for optimizing resource use, predicting environmental impacts, and improving overall management strategies. Simulations of operational scenarios, such as climate variations or changes in planting schedules, were conducted using FIWARE LAB.

Other factors are also taken into account, although they are not in real time, such as pH and concentration of minerals necessary for the supply of nutrients, in turn, not in real time but for decision making about the crops in the urban garden are necessary to determine crops to be carried out due to the climate, the altitude, and other factors, with which it is necessary to make simulations according to said parameters.

Building upon the Fenicia pilot, planned expansions include integration with broader smart city initiatives to establish a replicable urban farming model, advanced AI and automation to further improve efficiency and sustainability, and educational and capacity building programs to ensure long term community engagement and knowledge transfer. Through the deployment of these technological solutions, the Fenicia ULL demonstrates a replicable and scalable approach to sustainable urban agriculture, fostering innovation in smart city development.


Fig. 6 Digital Twin: 3D Visualization of urban garden and KIOSOL

*C. Use of FIWARE for Simulations*

The use of FIWARE for simulations plays a critical role in validating the proposed system within a controlled environment. FIWARE LAB, a cloud based platform specifically designed for experimenting with smart solutions, is employed to test the functionality and scalability of the technological infrastructure. This platform enables researchers to replicate real world scenarios, ensuring that the system can adapt to varying conditions and demands. Through FIWARE LAB, simulations such as changes in environmental conditions, system load stress tests, and adjustments to operational parameters can be conducted, offering valuable insights for optimization and refinement.

A key component of the simulation process is the integration of the Smart Data Model AgriApp, which provides a standardized framework for managing agricultural data. This model facilitates seamless data exchange between different system components, ensuring compatibility with global standards for smart agriculture and urban gardening. By adopting the AgriApp model, the system supports consistent data formats, enabling interoperability with other smart city technologies and enhancing its potential for integration into broader urban sustainability initiatives.

By leveraging both FIWARE LAB and the AgriApp model, the research ensures that the system adheres to best practices in smart city development. These tools enable the project to achieve high levels of interoperability and scalability, essential for expanding the system beyond the initial implementation phase. Additionally, this approach aligns with global efforts to standardize and enhance the adoption of ICT-driven sustainability solutions, ensuring that the system remains adaptable and future-proof in dynamic urban environments.

Figure 7a shows general FIWARE architecture and Figure 7b shows IoT FIWARE Architecture for Fenicia ULL Urban Garden System.

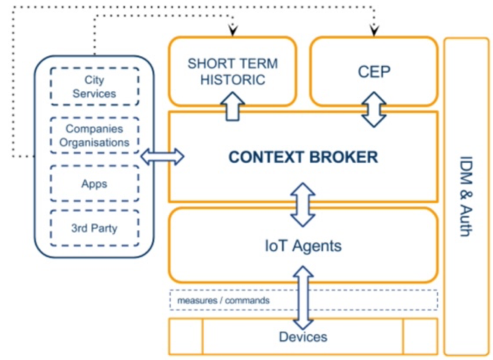


Fig. 7a General FIWARE Architecture

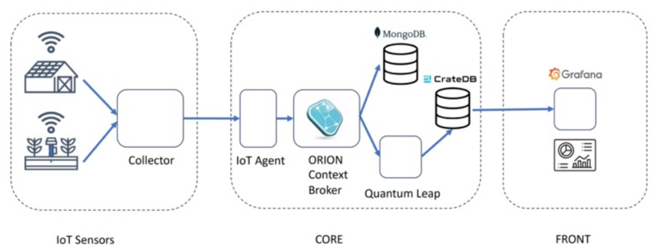


Fig. 7b IoT FIWARE Architecture for Fenicia ULL Urban Garden

IoT platforms play a pivotal role within the IoT ecosystem by serving as the interface between sensor devices and data networks. They enable the integration of data from diverse sensors and support applications that process and interpret this information. Ensuring interoperability across different IoT systems is essential to achieve seamless connectivity, and effective management is required due to the complexity of components involved.

The architecture proposed for a smart city prototype leverages FIWARE components to develop intelligent applications that interact with data collection layers. FIWARE was chosen following an evaluation that prioritized access to heterogeneous devices (e.g., sensors, actuators), open-source availability, independence from public cloud infrastructure, scalability via containers, semantic interoperability, developer usability, and suitability for both urban and industrial contexts.

The developed prototype is based on a FIWARE architecture designed to simulate an environmental monitoring point that captures solar radiation, temperature, relative humidity, and soil moisture. A sensor data acquisition layer is implemented to collect these values in real time.

The connection between physical or simulated sensors and the platform is established through the IoT Agent, a FIWARE component that acts as a bridge between IoT devices and the context management system. This agent receives data from sensors using lightweight communication protocols such as MQTT, with measurements structured in JSON format to ensure interoperability and easy parsing. The IoT Agent translates this data and forwards it to the Orion Context Broker, which maintains a structured and updated representation of the observed environment.

In FIWARE, an entity is a digital representation of a real-world object (e.g., a sensor, waste bin, or weather station). Each entity has a unique id, a type, and a set of attributes. Entity attributes are measurable or observable properties of the object. For example, an entity of type "WeatherObserved" may include attributes like "temperature", "relativeHumidity", and "solarRadiation", along with metadata such as "location" and "dateObserved".

Once entities are created and updated, their historical data must be stored for further analysis. This is managed by the persistence layer, responsible for storing sensor measurements over time. In FIWARE, this functionality is provided by the QuantumLeap service, which subscribes to the Context Broker and writes any entity updates as time series entries in CrateDB, a distributed database optimized for temporal and spatial data.

This architecture enables time series queries, trend analysis, and data-driven insights. Visualization can be achieved using business intelligence tools like Power BI, web-based mashup platforms like WireCloud, or real-time monitoring dashboards such as Grafana, which integrates seamlessly with CrateDB or QuantumLeap APIs to display environmental metrics using dynamic graphs and interactive panels.

To illustrate how sensor data is structured and transmitted in the prototype, the following example shows a JSON payload conforming to the NGSI-LD specification, which is the current standard for context information representation in FIWARE.

The example simulates a sensor entity that reports solar radiation, including geolocation and timestamp metadata:


```
{
 "id": "Sensor:SolarRadiation:001",
 "type": "WeatherObserved",
 "solarRadiation": {
  "type": "Number",
  "value": 680,
  "metadata": {
   "unit": { "type": "Text", "value": "W/m2" }
  }
 },
 "location": {
  "type": "geo:json",
  "value": {
   "type": "Point",
   "coordinates": [-74.0628, 4.6010]
  }
 },
 "dateObserved": {
  "type": "DateTime",
  "value": "2025-05-11T10:00:00Z"
 },
 "source": {
  "type": "Text",
  "value": "SimulatedSensor"
 }
}
```


In this structure, the entity of type "WeatherObserved" represents a sensor reporting a single environmental attribute—"solarRadiation"—with its value expressed in watts per square meter (W/m2). The observation is geolocated and timestamped, and the metadata includes the data source type, which in this case is identified as a simulated device.

This format enables real-time integration into the FIWARE context management system and supports downstream operations such as data persistence in QuantumLeap and visualization in platforms like Grafana or Power BI. By maintaining consistency in entity structures, the system ensures that heterogeneous environmental data can be queried, correlated, and analyzed uniformly across the smart city architecture.

In the prototype, the simulation of solar radiation (UV radiation), soil moisture, and temperature is carried out for a sensor located in the Fenicia ULL Urban Garden. This configuration enables the contextual monitoring of microclimatic conditions that influence soil and plant dynamics in densely built environments. Solar radiation plays a fundamental role in driving evapotranspiration, which directly affects soil water retention. When combined with real-time temperature data, these variables allow for the analysis of hydration cycles, heat stress, and potential irrigation needs. Modelled as interoperable entities within the FIWARE architecture, these simulated measurements provide a basis for environmental diagnostics and adaptive management strategies in urban agriculture settings.

To support analysis and decision making, each variable is visualized in Figure 8 through individual simulated time-series graphs, generated from the stored data. These visualizations allow users to observe temporal trends, identify anomalies, and compare environmental conditions across time, enhancing the garden's management through data-driven insights.

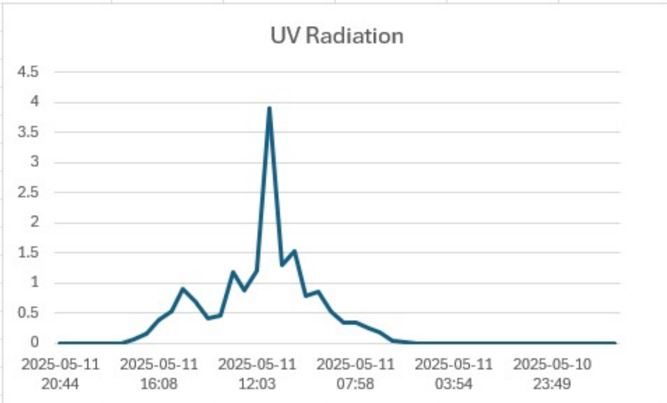


Fig. 8a Simulated UV Radiation for Fenicia ULL Urban Garden

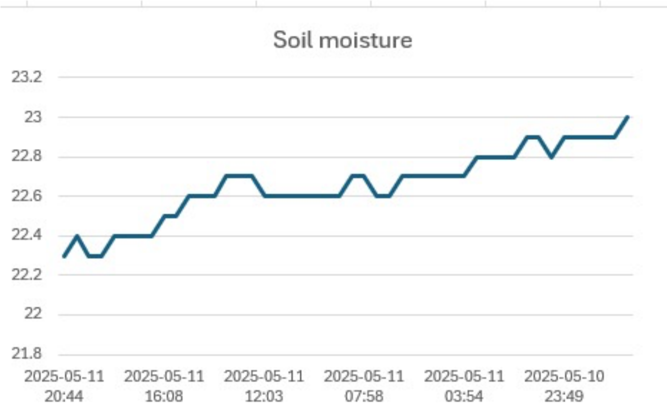


Fig. 8b Simulated soil moisture for Fenicia ULL Urban Garden

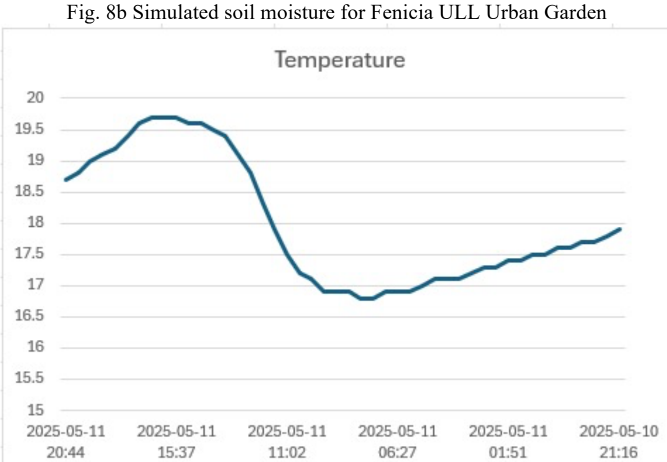


Fig. 8c Simulated Temperature for Fenicia ULL Urban Garden

### D. *Community Participation (Future Phase)*

Community participation will be a central focus of the next phase of the project, building upon the successful deployment and validation of the technological systems outlined in this paper. This phase will prioritize active engagement with stakeholders to ensure the integration of social dimensions into the socio-technical innovation framework. Through structured activities, the project aims to foster a sense of ownership and collaboration among community members, ensuring that the solutions developed align with their needs and expectations.

One of the key activities planned for this phase is the organization of community workshops and training sessions. These workshops will be designed to equip stakeholders with the knowledge and skills needed to effectively use the IoT systems, the digital twin platform, and sustainable gardening practices. By providing hands-on training, these sessions will enhance the community's ability to actively participate in the management and maintenance of the systems, promoting long term sustainability.

Another critical component of this phase is the implementation of feedback and co-creation mechanisms. Structured methods such as surveys, focus groups, and participatory discussions will be used to gather valuable insights from community members. This feedback will play a pivotal role in identifying areas for improvement, enabling iterative refinements to both the technological and social aspects of the ULL. Co-creation processes will further ensure that community voices are integrated into decision-making, fostering inclusivity and enhancing the relevance of the solutions.

While this paper primarily focuses on the technological development phase—including the deployment of IoT sensors, renewable energy systems, and simulation environments—the integration of community participation will follow as a vital next step. This future phase will complete the socio-technical innovation framework, bridging technological advancements with social empowerment to create transformative, sustainable solutions for urban challenges.

## III. Results and Discussion

The simulations conducted using FIWARE LAB provided valuable insights into the performance of the proposed system. Simulated data for soil temperature and humidity revealed stable trends under controlled conditions, confirming the system's reliability in monitoring environmental parameters essential for optimizing irrigation schedules and ensuring effective soil management [7]. Additionally, simulated results from environmental sensors and water flow meters demonstrated the successful integration of these components within the IoT system. This integration enabled accurate modeling of environmental impacts and efficient water resource management, both of which are critical for the sustainability of urban gardens [10,12]. The monitoring system's ability to deliver real-time alerts for significant environmental changes was also validated, underscoring its potential for enhancing the operational efficiency of urban garden management [7].

The simulations further evaluated the energy efficiency of the solar panel system, which indicates that performance was sufficient to power the IoT sensors and irrigation systems required for maintaining optimal conditions in the urban garden [11]. The use of renewable energy aligns with global sustainability goals, demonstrating the potential of integrating clean energy solutions into urban garden systems to enhance their environmental impact.

In evaluating the applied model, the results indicated the scalability and adaptability of multi-criteria decision-making tools, such as GIS and IoT, when tailored to specific local conditions. Simulations emphasized the importance of addressing socioeconomic variables to maximize system performance and relevance [10,13]. Additionally, the findings highlighted the potential of climate adaptation strategies, such as the use of drought resistant plants, adjustments in planting schedules, and the application of soil cover, which collectively improved the resilience of the urban garden to climate variability and extreme weather events [14].

When compared with documented cases from Europe and Asia, the simulated scenarios aligned with global best practices, particularly regarding the integration of digital twin platforms and real time monitoring systems [5,7]. These tools demonstrated their effectiveness in addressing complex urban challenges and enhancing the scalability of the proposed system. However, the simulations also reaffirmed common challenges identified in the literature, such as overcoming institutional fragmentation and addressing disparities in access to advanced technologies. These barriers highlight the need for strategic planning and coordination to fully realize the potential of innovative urban garden systems [13].

## IV. Conclusions

The integration of IoT sensors in the urban garden of the ULL Fenicia highlights the transformative potential of technology to optimize resource use, such as water and energy, and improve environmental sustainability. By leveraging real-time data, the project demonstrates how technological advancements can drive informed decision-making and enhance operational efficiency in urban green spaces. These innovations not only contribute to environmental benefits but also pave the way for replicable models in other smart city initiatives.

The implementation of a digital twin platform has proven to be a valuable tool for simulation and strategic planning, offering a robust framework for addressing urban challenges. This underscores the importance of integrating advanced technological solutions that align with the specific needs of urban ecosystems, enabling stakeholders to navigate complex socio-environmental dynamics effectively.

While the current focus has been on technological and operational enhancements, future stages of the project aim to incorporate community engagement as a central element. This planned phase will prioritize active feedback mechanisms and participatory governance to foster a deeper sense of ownership and collaboration among local stakeholders. Addressing this aspect will be critical to ensuring the long-term sustainability and inclusivity of the initiative.

Despite its achievements, the project has identified certain challenges, such as the need for more robust digital infrastructure and better alignment among stakeholders. Overcoming these barriers will be essential to scaling this model to other urban contexts and fully realizing its potential to contribute to sustainable and intelligent city development.

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