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Urban Harvesting: Building Resilience Through Circular Agriculture

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Abstract

Contemporary food systems have reached a turning point, as they are required to simultaneously ensure food security and minimize the pressure they exert on the environment, aiming to balance human needs and the rhythm of nature. The low efficiency of current models of food production and distribution systems have revealed the need for a major transition toward circular solutions based on resource circulation, local adaptation, and the responsible use of urban spaces. This study explored the integration of circular economy principles with urban agriculture as a new framework for developing resilient, low-emission, and human-centered cities. In addition, a multiscale (micro, midi, and maxi) approach, combined with SWOT, Weighted SWOT, and TOWS analyses, was applied to identify key factors, barriers, and possible directions for implementation and development strategies. The results showed that the greatest potential of these systems lies in the synergy between water and energy recovery and resource efficiency, while energy intensity and regulatory frameworks have remained major challenges. The proposed strategic approach highlights the need to link food production to renewable energy sources, implement simplified evaluation standards (TEA/LCA-lite), and strengthen social acceptance through education and transparency. Circular urban agriculture emerged as a new type of infrastructure, both technological and social, that may become a pillar of sustainable and resilient cities in the future, supporting the achievement of SDGs 11, 12, and 13.

Keywords: circular urban agriculture; green–blue infrastructure; food systems; resource efficiency; urban resilience

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Academic Editor: Giouli Mihalakakou

Received: 18 September 2025
Revised: 7 November 2025
Accepted: 13 November 2025
Published: 25 November 2025

Citation: Zaręba, A.; Krzemińska, A.; Adynkiewicz-Piragas, M.; Jia, H. Urban Harvesting: Building Resilience Through Circular Agriculture. *Sustainability* **2025**, *17*, 10560. https://doi.org/10.3390/su172310560

1. Introduction

Contemporary food systems face complex challenges related to ensuring food security while simultaneously reducing the negative environmental impacts of food production. One of the key issues—both environmental and socio-economic—is the inefficient management of food, leading to significant losses and waste of resources [1]. Food production, processing, and distribution involve significant amounts of natural resources, such as water, energy, and soil, and also require extensive transportation and logistics infrastructure [2–4]. These processes generate high levels of greenhouse gas emissions, contribute to ecosystem degradation, and lead to the irrational use of urban spaces [5–7]. Food loss and waste occur at all stages of the supply chain, from primary production to final consumption, and represent a global issue. According to the United Nations, approximately 13.2% of global food production is lost between harvest and retail, while 19% is wasted in the retail, hospitality, and household sectors [8]. This means that nearly one-third of the food produced using limited environmental resources is irrevocably lost. Eurostat data from 2021 show that the average EU resident generated 131 kg of food waste annually, totaling over 58 million tons. The largest share of this amount came from households (54%, i.e., over 31 million tons), clearly indicating the need to implement instruments supporting rational purchasing decisions and educate urban residents on responsible consumption. Other sectors of the economy also generate significant losses, including food processing (21%), hospitality and restaurant services (9%), primary production (9%), and retail (7%) [9]. These challenges highlight the urgency for the systemic transformation of food production and distribution models toward circular, resource-efficient, and locally adaptive systems that can operate under the constraints of urban environments. This study determined how the incorporation of circular economic principles into urban agriculture can contribute to building more sustainable, resource-efficient, and resilient urban food systems. The paper investigates Circular Urban Agriculture (CUA), which creates a sustainable urban food production system by integrating the principles of the circular economy within urban and peri-urban contexts It aims to optimize the use of local resources by closing nutrient, water, and energy loops, reducing waste generation, and reusing organic by-products as inputs for food production. Circular Urban Agriculture (CUA is based on the transformation of urban metabolism through the integration of agricultural practices with urban resource flows, thereby enhancing resource efficiency, environmental performance, and urban resilience. CUA contributes to sustainable urban development by minimizing linear resource consumption and promoting circular resource use across the food–energy–water nexus. This paper examines how the integration of circular economy principles with urban agriculture can contribute to building more sustainable, resource-efficient, and resilient urban food systems.

2. Materials and Methods

In recent years, cities have faced numerous challenges associated with intensive urbanization, climate change, and the need to reduce environmental impacts. The most urban problems related to the food economy that must be addressed in coming years include the limited space available for food production, the wastage of natural resources, the pollution of the urban environment, and increasing demands from urban residents for access to healthy and ecological food [5,6,9,10]. Urban agriculture, especially when combined with food management consistent with circular economic principles, can be an important component of sustainable city strategies [11]. The implementation of urban agricultural systems in closed-loop systems integrating food production with recycling and resource management processes, including energy and water, contributes to improving residents' quality of life and to the protection of the natural urban environment. These issues are the subject of research being conducted as part of the project "Food Production and Supply through Circular Urban Systems in European Cities," conducted by the University of Wrocław from 2024 to 2027 under the international Driving Urban Transitions (DUT Call 2022) program, financed by the National Centre for Research and Development. The main goals of the project include promoting the concept of circular urban agriculture and shaping public awareness regarding integrated food production and distribution systems in urbanized areas.

As shown below, a model of the synergy between urban agriculture and the urban environment within a circular economy, combined with sustainable urban planning, aimed to develop a comprehensive approach to assessing food production in cities—one that is not only efficient, environmentally friendly, and healthy but also reflects the multidimensional nature of urban agriculture. In the proposed model, a multiscale, partially self-sufficient urban system was developed by integrating food production systems into recycling processes and sustainable resource management, including energy and water, while considering the logistical distribution of food products. Its primary objectives were to minimize waste generation, optimize resource utilization, and enhance the overall quality of life in urban areas.

2.1. Conceptual and Methodological Framework

The research process (Figure 1) was designed to capture the complexity of circular urban agriculture, including its spatial, environmental, and social interrelations. The study combined analytical and interpretative methods, making it possible to describe the phenomena and understand their mutual connections within the structure of a city.

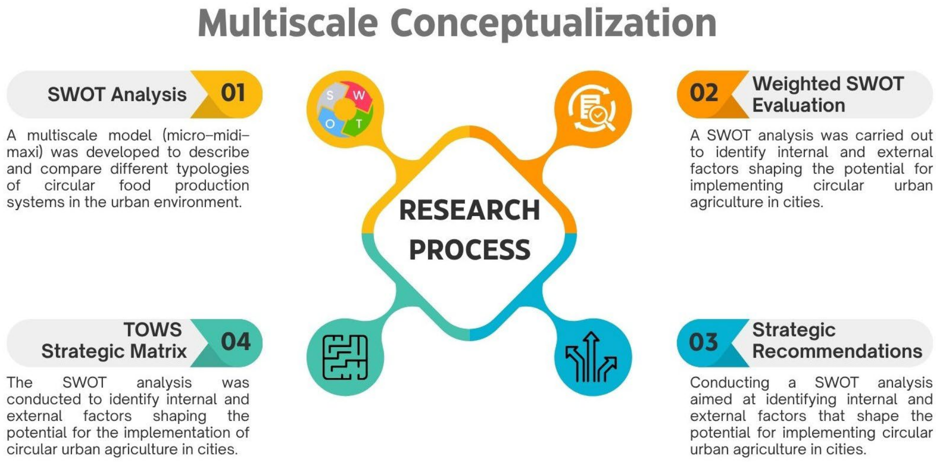

Figure 1. Research framework for circular urban agriculture analysis.

First, a multiscale approach, ranging from the microscale of individual crops and rooftop installations, through district-level systems, to citywide networks in which food production is intertwined with water and energy cycles, was developed. Each level revealed different dependencies and degrees of technological integration with the urban fabric, capturing an image of cities as living and interdependent organisms. Thereafter, a SWOT analysis was performed to identify the factors that support or hinder the development of circular urban agriculture. The analysis was based on literature data and expert knowledge, thus facilitating the identification of a wide range of conditions, from climatic and spatial to institutional. To enhance the understanding of the strength of individual factors, a weighted SWOT analysis was applied, in which each element was assigned a specific weight and score, enabling the determination of the hierarchy of importance as well as the identification of key factors. The obtained results were verified by testing their sensitivity to the assumed changes and by comparing those that most strongly influenced the implementation potential of the system. The final stage involved using a TOWS matrix to translate the results into a strategic language, which made it possible to connect the strengths and opportunities in development models and to identify areas requiring protective or adaptive actions. Thus, the analysis gained a practical dimension, becoming a tool for planning and reflecting on how circular food systems can be realistically and sustainably integrated into a city's structure. The proposed methodology combines spatial analysis with strategic reflection, treating urban agriculture not only as a technology of food production but also as a cultural element and a pillar of future urban resilience.

All figures, tables, and diagrams presented in this article were developed by the authors as part of the research process.

2.2. The Context of Urban Agriculture and the Circular Economy

Circular Urban Agriculture (CUA) represents a new emerging approach that integrates circular economy model into urban food production, aiming to create a closed-loop system where resources, such as water, energy, and waste are reused. The concept of Circular Urban Agriculture is grounded in the principles of regenerative food production within the framework of the circular economy, a paradigm that is extensively elaborated in the academic literature [12–18]. Circular Urban Agriculture (CUA) offers a direct, manageable, and scalable solution for addressing urban food production challenges by focusing on local agricultural systems, resource circularity, and community involvement. The principles upon which CUA is based are precise and include sustainable management of: organic waste, water, energy, and also assume the development of new forms of urban agriculture, transportation, as well as education and community engagement CUA provides a pathway for cities to increase food security, reduce waste, and enhance ecological sustainability without the complexities of overhauling an entire food system.

The application of the circular economy model, such as CUA in the context of urban agriculture constitutes a strategic response to key challenges of contemporary urbanization, climate change, and the ongoing degradation of the natural environment. This concept assumes full reintegration and optimization of resource flows within urbanized systems, encompassing closed-loop water management, organic waste utilization, local food production, and the implementation of renewable energy sources [12–14]. These practices enable the effective integration of biological and technological processes into urban structures, promoting ecosystem regeneration, and minimizing the exploitation of primary resources [12–15]. At the operational level, this strategy includes the implementation of advanced plant production systems, such as hydroponics, aeroponics, and aquaponics, which are characterized by significantly lower water consumption and increased energy efficiency compared to traditional cultivation methods [16–18]. An integral component of this model is the transformation of organic fractions of municipal waste into high-value resources, including compost and bioenergy, using community composting sites and anaerobic digestion units [14,19,20].

Numerous studies have confirmed that the implementation of circular solutions in urban agricultural systems significantly reduces greenhouse gas emissions, improves soil and water quality parameters, and strengthens the local resilience of food systems [21–23]. Furthermore, the deployment of circular economy technologies fosters the activation of local communities, development of a green job market, and creation of innovative models for the cooperation and management of urban resources [24–26]. These processes are gaining increasing institutional and political support as part of sustainable urban development strategies and framework documents such as the New Urban Agenda and UN Sustainable Development Goals (SDG 11, 12, and 13) [27].

2.3. Closed Loops in Urban Agriculture and Sustainable Urban Development: Goals and Strategies

2.3.1. Increasing Access to Local, Fresh, and Organic Food

Cities are increasingly implementing urban agriculture as a means to enhance food security and provide residents with access to healthy, organic food [28]. Initiatives such as community gardens, rooftop farms, and other forms of urban cultivation enable local production of fresh fruits and vegetables, significantly improving access to nutritious food [29]. Local production reduces the reliance on long supply chains and long-distance transportation, which translates into a reduced carbon footprint [30,31]. The reductionin food distribution costs—so-called "food miles"—not only curbs greenhouse gas emissions but also improves air quality [30]. Moreover, participation in urban agriculture supports healthy dietary habits and lowers food costs [32].

2.3.2. Promoting Bio-Architectural Projects for Urban Agriculture

The integration of agricultural production with urban architecture represents a significant direction of development. Bio-architectural projects including green roofs, green facades, vertical gardens, and greenhouse systems on buildings—transform unused roof and wall surfaces into cultivation areas [33] (Figure 1). Green roofs can serve as urban vegetable gardens, enhancing the food self-sufficiency of residents [33]. Moreover, these solutions contribute to improved building energy efficiency, mitigation of the urban heat island effect, air purification, and increased biodiversity [33].

2.3.3. Reducing Food Waste in the Spirit of the Circular Economy

The reduction in food loss is a key element in closing urban resource loops. Cities are implementing "zero waste" strategies that promote the redistribution of surplus food to social organizations and people in need [21,33,34]. One example is Milan, where food waste from households and the hospitality sector is effectively directed towards composting or distributed as food aid. Organic waste is processed into compost, a valuable fertilizer for urban cultivation. Composting reduces the volume of waste sent to landfills, lowers methane emissions, improves soil quality, and reduces the need for synthetic fertilizers. Local composting sites, selective collection of biowaste, and municipal biogas plants are important components of the circular economy strategy.

2.3.4. Reducing Environmental Impact Through Efficient Resource Use (Own Elaboration)

The goal of urban agriculture within the circular economy model is to minimize environmental impacts through the rational management of water, energy, and materials. Modern urban farms use hydroponic and aeroponic systems, which can reduce water consumption by up to 90% compared with traditional growing methods [13,14,31]. Renewable energy sources such as photovoltaic panels, wind turbines, and biogas plants are also being used. Research shows that vertical farms powered by green energy are among the most environmentally friendly forms of food production. Closing resource loops also includes recycling: plant and food waste can be composted, and used water can be treated and reused. Technologically advanced greenhouses are increasingly integrating systems for heat and carbon dioxide recovery from the surrounding environment, supporting plant growth, and reducing dependence on external resources.

2.3.5. Building Climate Resilience Through Blue-Green Infrastructure

Cities are implementing components of blue-green infrastructure as part of climate adaptation strategies (Figure 1). These include natural and semi-natural systems such as parks, green roofs, rain gardens, retention basins, and wetlands. Urban agriculture can be integrated with these systems, for example, by designing rain gardens or using green roofs for stormwater retention [33]. Studies indicate that green roofs can retain between 40% and 100% of precipitation, and rain gardens can effectively reduce surface runoff and improve the quality of urban waters [15,33]. These practices are applied in the UK (SuDS), USA (LID), and China (sponge cities) as part of sustainable stormwater management systems. Diverse farming systems exhibited location-dependent performance, underscoring their critical roles in food security, flood protection, employment, income generation, and environmental quality, with increasing significance under climate change [34].

2.3.6. Sustainable Food Distribution Systems

Transforming supply chains towards local, short, and low-emission solutions is one of the foundations of urban food policy [35]. The development of local markets, community-supported agriculture (CSA), and "farm-to-table" initiatives helps reduce the distance between producer and consumer and lower fossil fuel use. Simultaneously, cities are promoting environmentally friendly modes of transport for food distribution. Electric delivery vehicles and cargo bikes, which are more efficient in urban conditions and generate no exhaust emissions, are gaining popularity [36].

2.3.7. Environmental Education and Resident Engagement

Effective implementation of sustainable urban agriculture strategies requires the active involvement and awareness of residents. Therefore, many cities invest in environmental education through gardening workshops, composting courses, school activities, and events promoting circular economic principles. Community gardens often function as local educational centers where children and adults can acquire practical skills. Environmental education and community engagement form the foundation of sustainable urban culture and support lasting changes in resident behaviour.

3. Research

Urban agriculture (UA) represents a crucial component of the circular economy (CE) by integrating food production systems with closed-loop resource management. The proposed model of synergy between urban agriculture and the city within a circular framework considers the optimization of material, energy, and water flows in the urban environment (Figure 2). Organic waste generated by households, marketplaces, and restaurants is recovered through composting, anaerobic digestion, and nutrient recycling, providing biofertilizers and renewable energy to support UA. Water circularity is enhanced through rainwater harvesting, greywater reuse, and the implementation of advanced technologies such as hydroponics and aquaponics, which significantly reduce freshwater demand. Energy efficiency is achieved by integrating renewable energy sources, waste-to-energy conversion systems, and intelligent climate control technologies used to power vertical farms, rooftop gardens, and aquaponic facilities. Furthermore, UA models maximize the use of limited urban space, shorten supply chains, and reduce greenhouse gas emissions by localizing food production and distribution. At the same time, UA fosters community engagement and environmental education, enhancing public awareness and supporting green entrepreneurship. Collectively, these interrelated strategies—structured around spatial planning and technological innovations—enable cities to close resource loops, minimize environmental impacts, and develop resilient, climate-neutral, and inclusive food systems. The multi-dimensional model of UA–city synergy within the CE framework proposed by the authors may serve as a catalyst for implementing circular economy principles, linking sustainable food production, resource efficiency, and social innovation into a coherent and adaptive urban ecosystem.

The synergy of urban agriculture within the circular economy is based on several key actions: Organic Waste, Sustainable Water Management, Sustainable Energy Management, Development of New Forms of Urban Agriculture, Transport and Environmental, Education and Community Engagement (Figure 3).

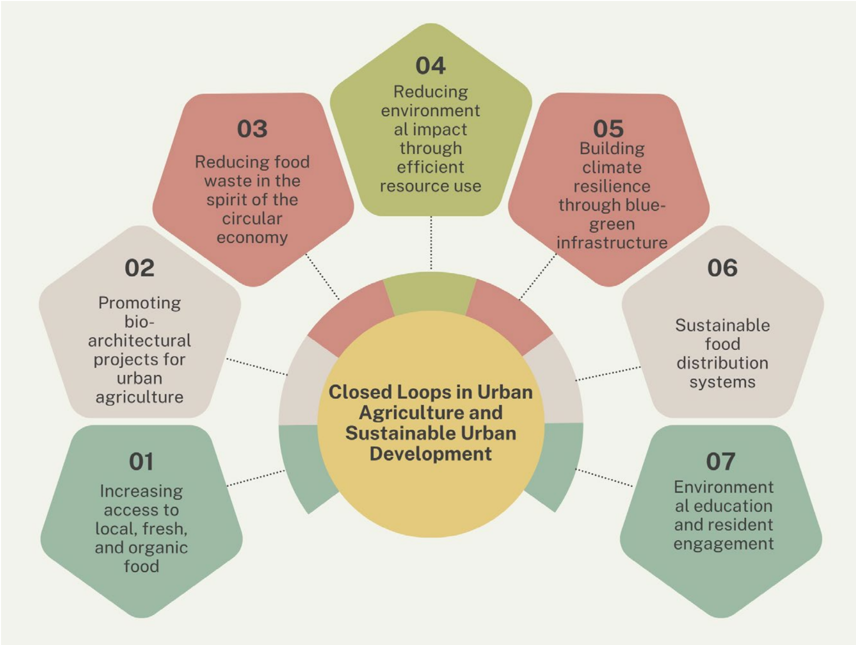

Figure 2. Conditions Related to the Implementation of Circular Urban Agriculture (own elaboration).

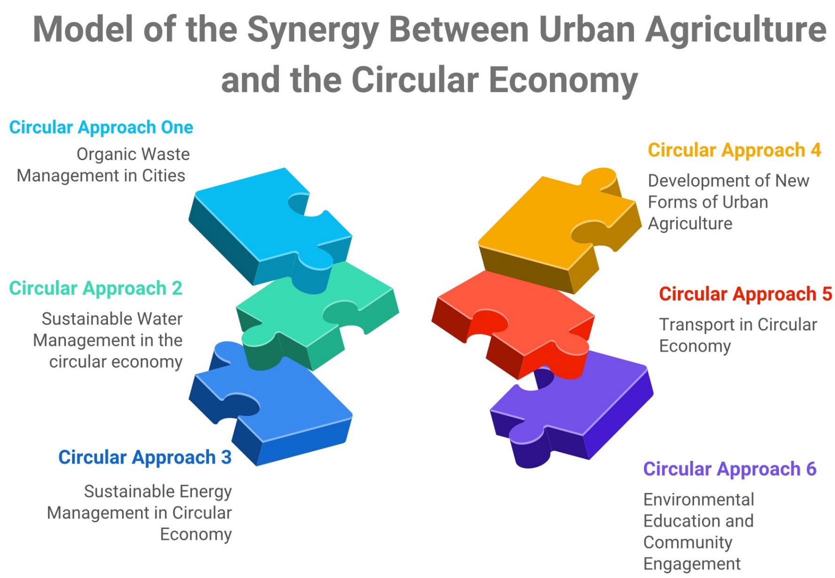

Figure 3. Synergy of urban agriculture within the circular economy (own elaboration).

3.1. Organic Waste Management in Cities—A Circular Approach

Effective management of organic waste in cities requires a multilevel, circular approach in which kitchen and green waste are treated as valuable resources to be locally utilized for the production of biofertilizers and biogas [1,37] (Figure 3). The creation of an integrated micro-midi-maxi network—from household composters to neighbourhood-scale micro-composting units to city-level high-efficiency anaerobic digestion facilities can reduce the carbon footprint of organic waste systems. Such solutions support local food production models and strengthen the self-sufficiency of residential districts [10]. A key aspect is the simultaneous expansion of selective organic waste collection points in marketplaces, educational institutions, and hospitals along with the implementation of two-stream sorting (green and kitchen waste).

The use of digital technologies, such as IoT sensors, to monitor container fill levels for route optimization allows for a reduction in logistics costs while significantly improving organic waste collection efficiency in cities [38]. Implementing diverse circular practices reduces food waste, fosters sustainable customer behaviors, and can significantly impact various sectors of the economy, such as the hospitality industry [39].

Enriching compost with biochar derived from woody-green fractions enhances the soil's carbon sequestration capacity and water retention, which is particularly important for degraded and reclaimed areas [34].

Implementing comprehensive educational programs and information campaigns on selective bio-waste collection, combined with incentive systems such as "bio-premiums" and the operation of municipal circular partnership platforms, provides an effective tool for increasing public participation. These efforts have led to greater public acceptance, improved quality of waste separation, and enhanced urban resilience to environmental and food crises [40]. Consequently, biowaste management is transforming from a cost-based system to one of the key pillars of urban climate, resources, and food policy (Figure 4).

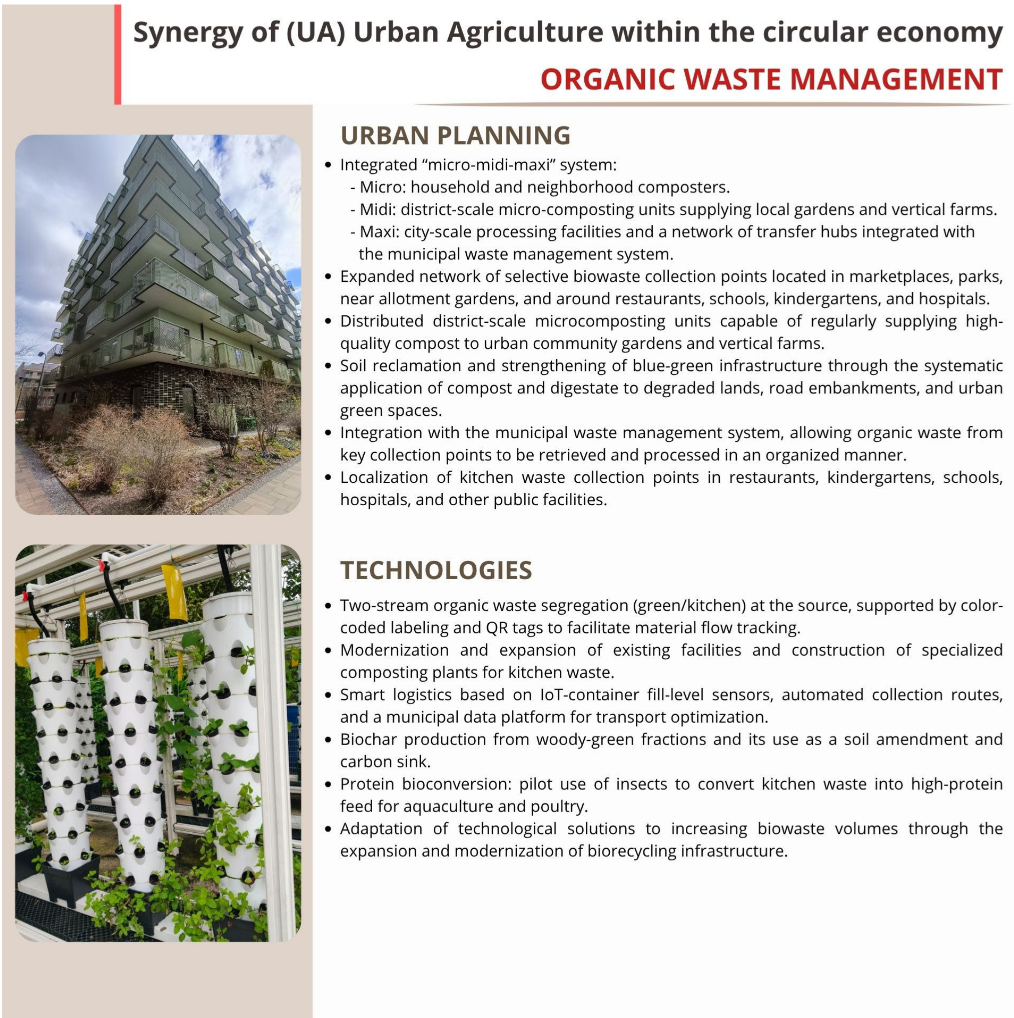

Figure 4. Organic Waste Management in Cities—A Circular Approach (own elaboration).

3.2. *Sustainable Water Management in the Circular Economy*

Sustainable water management in urban agriculture plays a key role in building resilient, functional, and environmentally conscious urban areas (Figure 5). In the context of urbanization and increasing water demand, cities face the challenge of efficiently managing water resources, particularly for local food production. This concept involves integrating modern water-saving and reuse technologies with urban infrastructure in order to minimize water loss and reduce pressure on water supply and sewage systems [13,41].

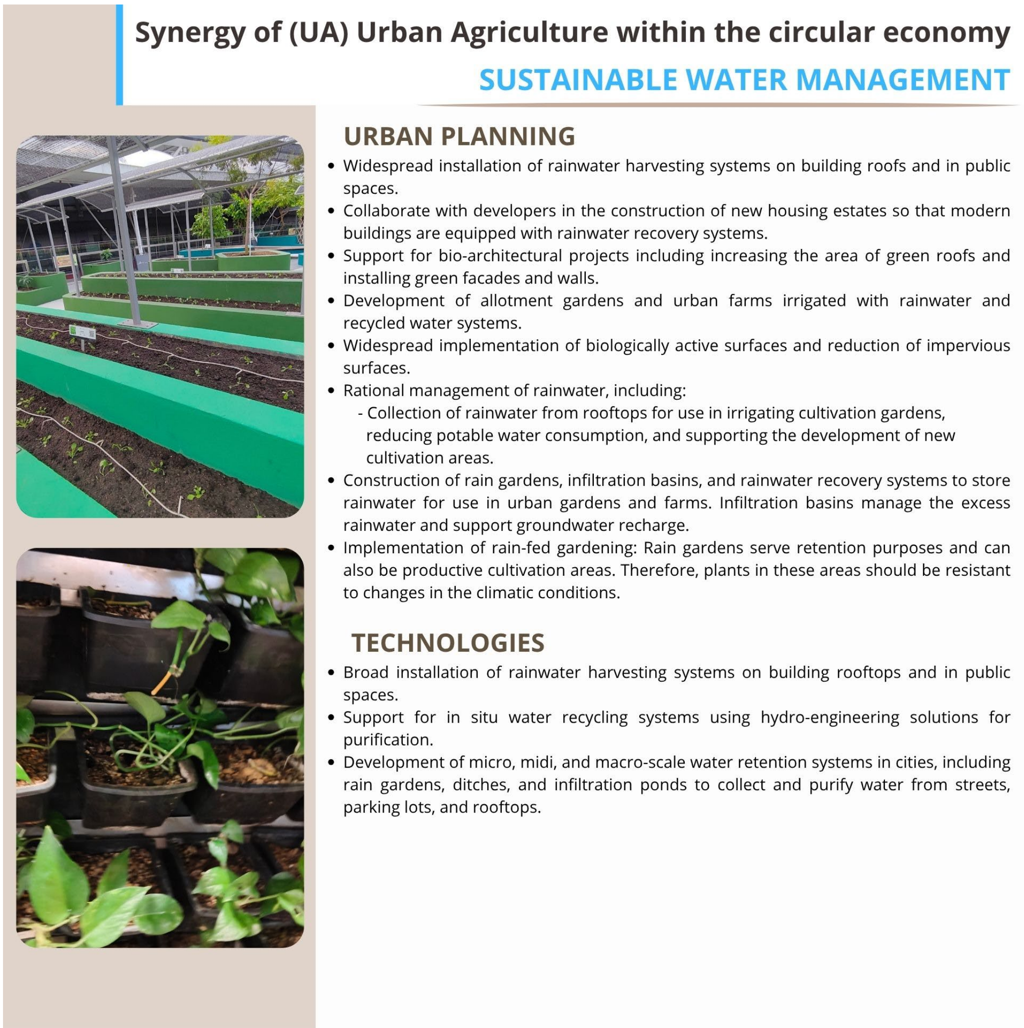

Figure 5. Sustainable Water Management in the Circular Economy (own elaboration).

Various practices supporting sustainable water use are implemented in urban agriculture, including rainwater harvesting, use of greywater from households, and water recirculation in hydroponic and aquaponic systems [10]. These technologies not only save resources but also enhance control over water quality and availability, which is crucial in densely built-up areas often subject to water scarcity.

Additionally, sustainable water management includes educational and social dimensions such as promoting responsible water-use habits, strengthening ecological awareness, and engaging residents in decision-making processes related to water management in urban spaces [10]. Implementing such practices not only reduces water consumption but also strengthens local social bonds and increases urban resilience to climate change [26,27,42]. Water infrastructure embedded in the urban environment allows for dynamic management of water flows while maintaining water quality and energy efficiency [43].

3.3. Sustainable Energy Management in Circular Economy

Sustainable energy management is a fundamental element of adaptive and pro-ecological strategies in urban agriculture that enables the optimal use of energy resources in the context of increasing energy demand in urbanized areas (Figure 6). In light of intensifying urbanization and the growing effects of climate change, managing energy efficiently, in a circular manner, and adapting to local conditions has become a priority challenge for urban policies and agroecological practices [13,18].

Within urban food production systems, integrated technological solutions are being implemented to minimize energy loss. These practices include technologies such as powering urban farms with renewable energy, locating municipal biogas plants, but also use of active and passive energy systems [44,45].

Sustainable energy management goes beyond the technological aspects and encompasses both social and institutional components. Supporting environmental education, promoting conscious energy use, and engaging local communities in decision-making processes are essential for implementing long-term energy resource management strategies [25,26].

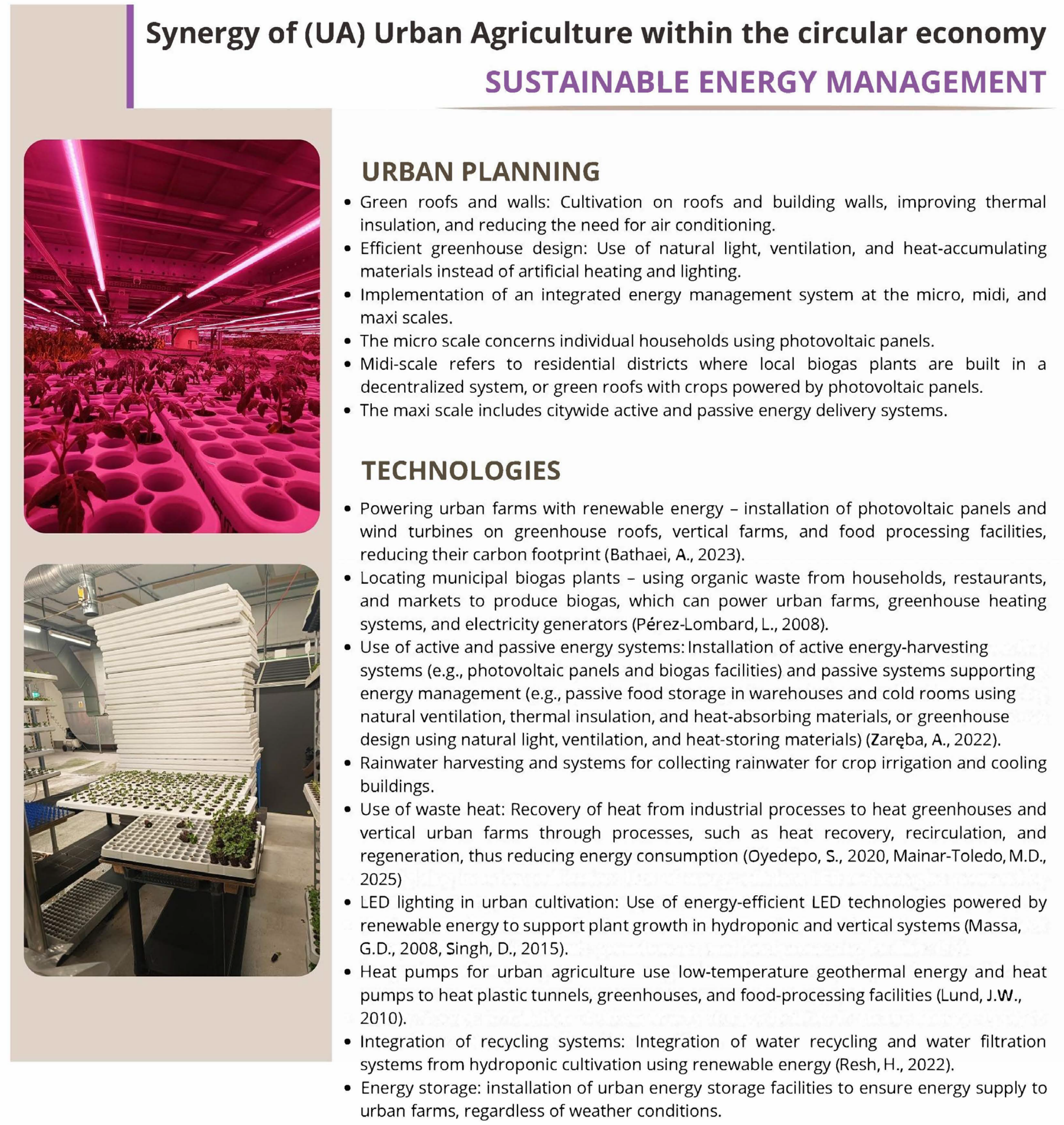

Figure 6. Sustainable Energy Management (own elaboration) [46–54].

3.4. Development of New Forms of Urban Agriculture

Cities consist of areas where urban agriculture can develop without conflicting with other urban needs, such as the expansion of services or new residential zones (Figure 7). Urban agriculture can develop on rooftops, urban wastelands, or within inner courtyards, where community gardens, among other things, can be created.

Figure 7. Development of New Forms of Urban Agriculture (own elaboration) [21,55–64].

3.5. Transport in Circular Economy

Food within cities has a significant impact on greenhouse gas emissions. Solutions that reduce the negative environmental impact of transport while simultaneously promoting local agricultural markets are crucial to the potential synergies between urban agriculture and the circular economy in the urban environment (Figure 8).

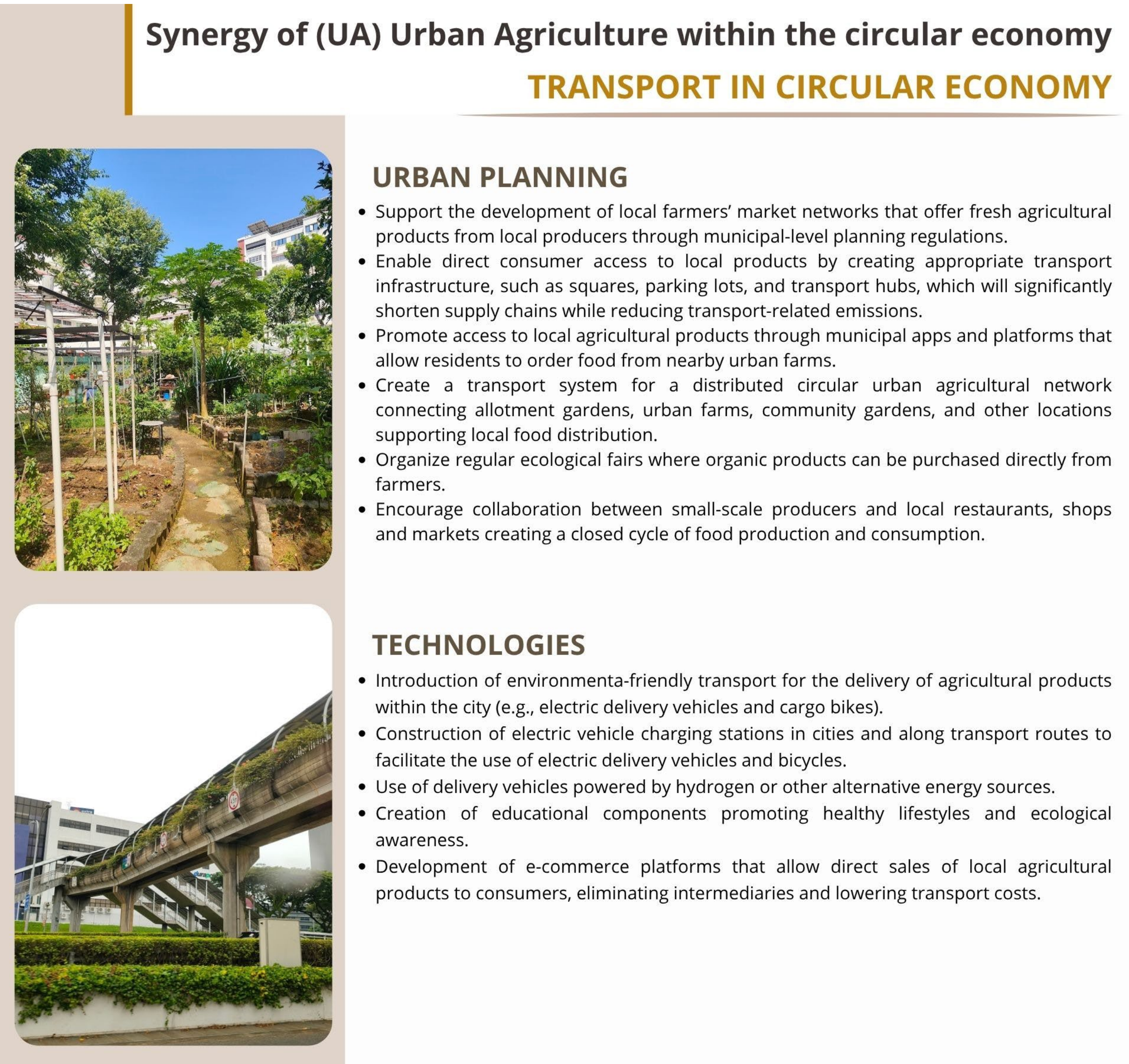

Figure 8. Transport in Circular Economy (own elaboration).

3.6. Environmental Education and Community Engagement

Educating residents about urban agriculture and the circular economy is crucial for supporting sustainable and resilient food systems in cities. Ongoing urbanization and increasing pressure on environmental resources require raising public awareness of sustainable food production methods and responsible consumption. Educational initiatives contribute not only to knowledge transfer but also to shaping pro-environmental attitudes and strengthening the engagement of local communities. Activities in this area—such as workshops and training programs—enable participants to acquire practical skills in techniques like hydroponics, aquaponics, composting, and vertical farming (Figure 9). These initiatives demonstrate how efficient resource utilization can be implemented in densely populated urban areas, which can directly translate into grassroots urban agriculture initiatives. Additionally, information campaigns promote environmentally responsible behaviors, such as reducing food waste and fostering sustainable dietary habits, while also strengthening the sense of collective responsibility. Increasingly, community gardens and urban farming centers emerging in cities play a significant role in shaping pro-environmental attitudes. By combining educational activities with local food management efforts, they foster collaboration between residents, policymakers, and entrepreneurs. Ultimately, educational activities act as a catalyst for systemic transformation, enabling cities to transition toward circular, inclusive, and resource-efficient food system.

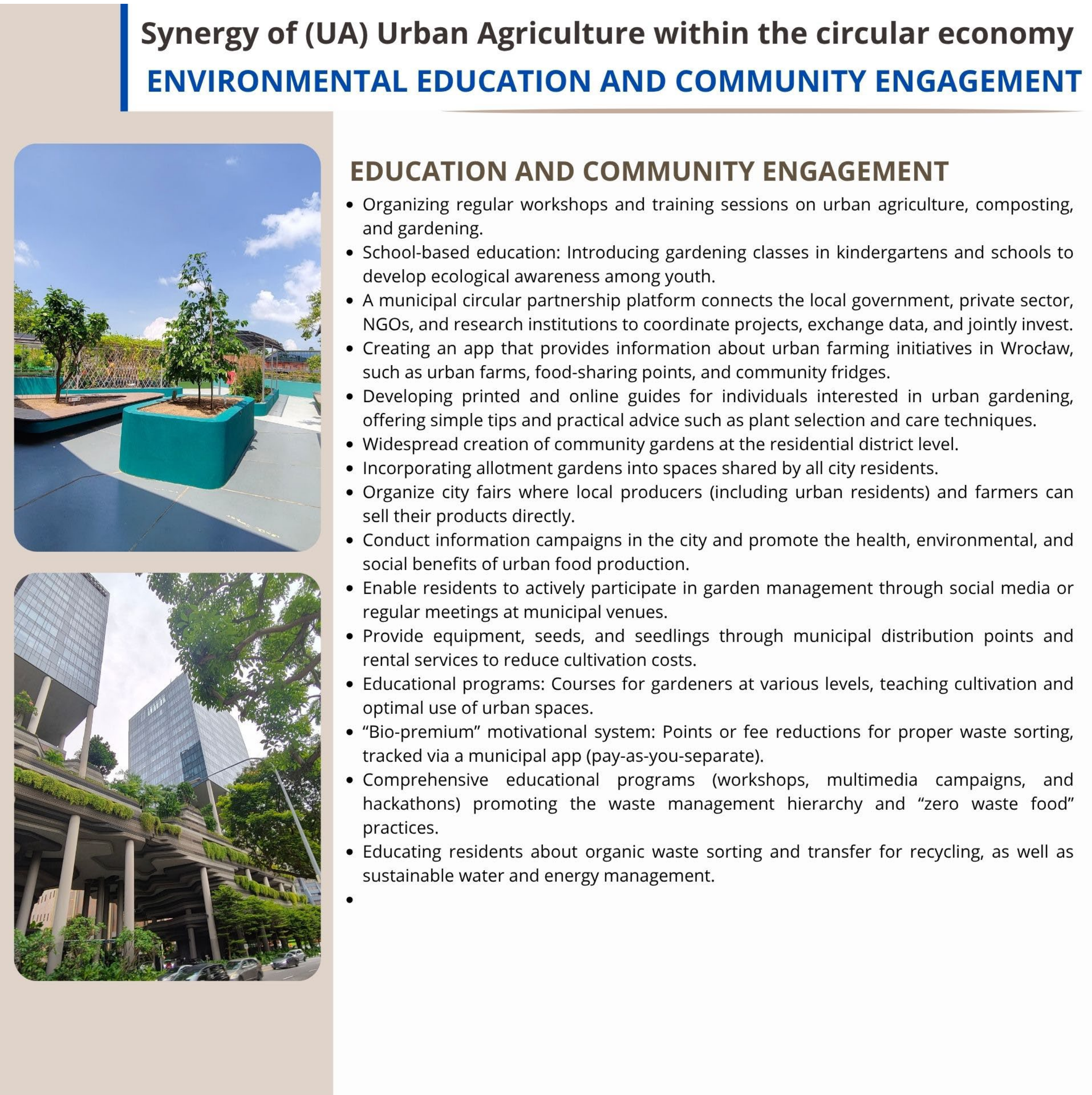

Figure 9. Environmental Education and Community Engagement in Urban Agriculture (own elaboration).

4. Multiscale Model of Synergy Between Urban Agriculture and the Urban Environment Within a Circular Economy

The multiscale model of the synergy between urban agriculture and the urban environment within a circular economy was based on the analyses presented above, and it examined the closed-loop circulation of urban agriculture with respect to key environmental conditions and resource systems, including energy, water, and waste management, as well as transportation and education. Innovative forms of urban farming, which are integrated into resource management systems to enhance efficiency and sustainability, play an important role in shaping this circular model of urban agriculture. Embedded within a broader circular resource management framework, these new forms of agriculture represent a transformative vision of a city, one that strives for self-sufficiency, shortened supply chains, and alignment with the widely adopted concept of a 15 min city, where access to essential services and food resources is optimized within a compact urban structure. A key aspect of this model is the creation of diverse and interconnected loops that support the functioning of a new circular city, based on three spatial planning scales: mini, midi, and maxi. These scales enable a multilevel integration of urban systems, combining local, district, and citywide strategies to foster resilience, resource efficiency, and sustainable urban development.

The model refers to three scales of urban design, as defined, among others, by Günay (1999) [65], which distinguished between the macro, mezo, and micro scales in shaping urban forms. In this framework, the mezo scale (referred to here as the midi scale) is conceptualized as a bridge between architectural projects and spatial planning decisions. It serves as a critical link between the macro and micro scales, mediating between comprehensive master plans and detailed design elements, making it among the most frequently applied scales in contemporary urban design. Within the context of the proposed model of the synergy between circular urban agriculture and the urban environment, the midi scale corresponds to the residential district level. Practically, this scale typically operates within design ratios of 1:1000 and 1:500, which makes it one of the most common planning frameworks and justifies its characterization as a district-level scale (Figure 10). Furthermore, it supports the principles of a 15 min city, emphasizing the spatial organization that enables residents to meet most of their daily needs within a short walking or cycling distance. At this level, the focus is placed on integrated, sustainable systems encompassing waste management, water recovery, energy generation, transportation, food production, and education. A key component of organic waste management at the district scale is the deployment of micro-composting units distributed across neighborhoods. These facilities process organic waste locally and supply high-quality compost to community gardens and vertical farms, contributing to circular material flows. Through integration with municipal waste management systems, these units allow for the efficient collection and processing of bio-waste from designated points within residential areas. The model also assumes that new housing developments will be equipped with rainwater harvesting systems, thus promoting rain-fed gardening and the creation of rain gardens combining stormwater retention and productive cultivation. These spaces are designed using climate-resilient plant species, which enhances the adaptive capacity of urban ecosystems in response to environmental change. In terms of energy management, the midi scale relies on decentralized solutions, such as district-level biogas plants that convert bio-waste into renewable energy, as well as green roofs with integrated crop cultivation powered by photovoltaic panels. These strategies reduce dependency on external energy sources, supporting localized energy efficiency and the development of self-sufficient urban systems. The model also highlights the development of urban agriculture within residential districts, facilitated through collaboration between property owners and developers to create rooftop cultivation spaces. This approach enhances local food self-sufficiency and contributes to food networks that are more resilient. An important complementary element is the integration of transportation systems to establish efficient food distribution networks connecting allotment gardens, community gardens, urban farms, and local marketplaces. At this scale, urban planning policies further support the development of local farmers' markets and encourage collaboration among small-scale producers, restaurants, retail outlets, and marketplaces, thereby establishing a closed-loop food system. This framework minimizes food waste while also strengthening short supply chains and promoting a sustainable urban food economy.

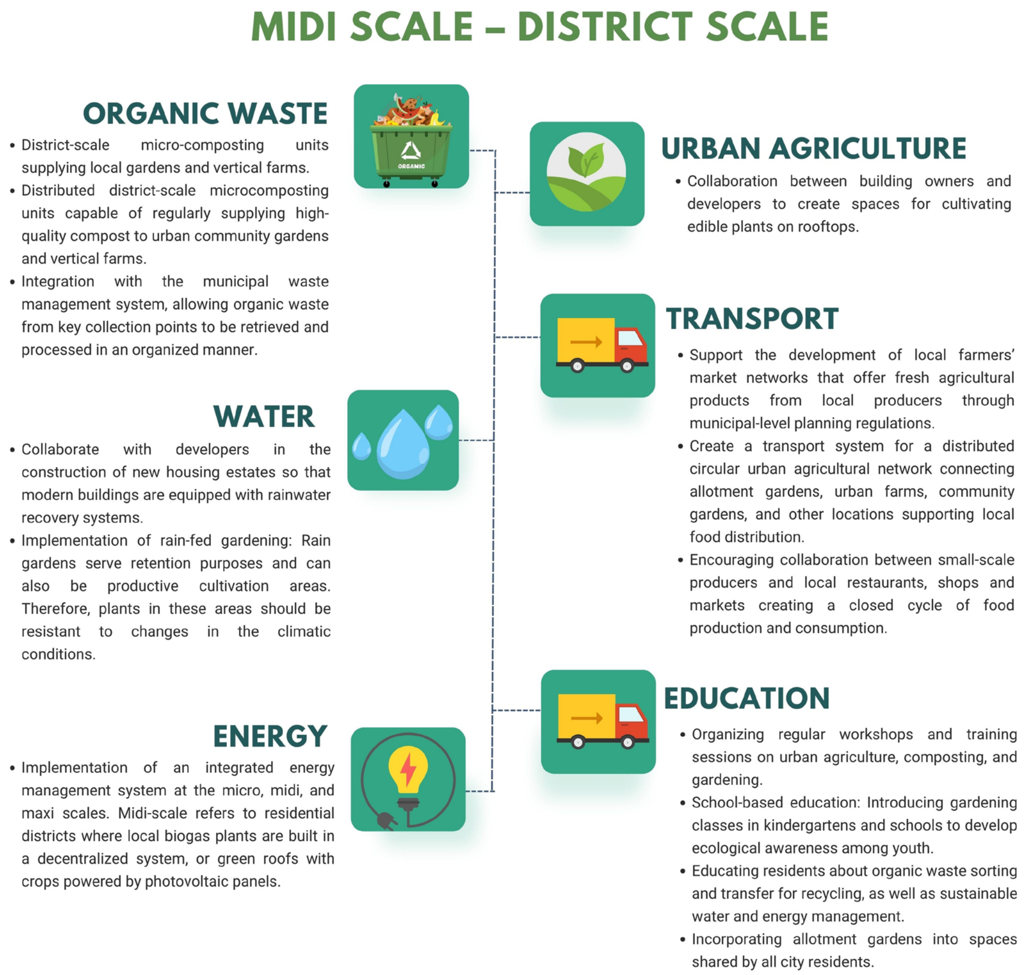

Figure 10. Synergy of Urban Agriculture within the circular economy—midi scale.

At the micro scale, spatial design is focused on elements that are directly perceived and experienced daily, thereby significantly influencing human spatial cognition and environmental interactions (Figure 11). In this context, the micro scale refers to the level of an individual dwelling or residential block, where the configuration of space contributes to the formation of localized microenvironments. Within such microenvironments, diverse components—such as urban agricultural systems, renewable energy infrastructures, and water management processes—can be functionally integrated, creating synergistic relationships. Collectively, these interactions form a fundamental structural unit of a city's ecological biome, thereby supporting environmental resilience, resource efficiency, and an overall enhancement of urban well-being. At the micro scale, sustainable practices focus on individual households, small communities, and local facilities. Mini organic waste management involves the use of household and neighborhood composters, as well as establishing kitchen waste collection points in restaurants, kindergartens, schools, hospitals, and other public facilities to enable efficient recycling. Sustainable water management is supported through rainwater collection from rooftops, which can be used to irrigate cultivation gardens, reduce potable water consumption, and facilitate the development of new urban growing areas. Energy efficiency is enhanced by integrating green roofs and walls, which improve thermal insulation, reduce the need for air conditioning, and provide opportunities for small-scale cultivation. Individual households also contribute by adopting photovoltaic panels as part of an integrated energy management system. New forms of urban agriculture are promoted by encouraging the use of small spaces such as balconies, courtyards, and terraces for growing plants and herbs, which supports local food production. Integrated transport solutions are supported by municipal apps and digital platforms connecting residents to nearby urban farms, allowing them to order fresh, locally grown products. Meanwhile, education and community engagement play a key role in shaping sustainable behavior, with mobile apps providing information regarding urban farming initiatives in Wrocław, including food-sharing points and community fridges. Additionally, printed and online guides offer practical tips on plant selection, care techniques, and sustainable gardening practices, empowering residents to actively participate in urban agriculture.

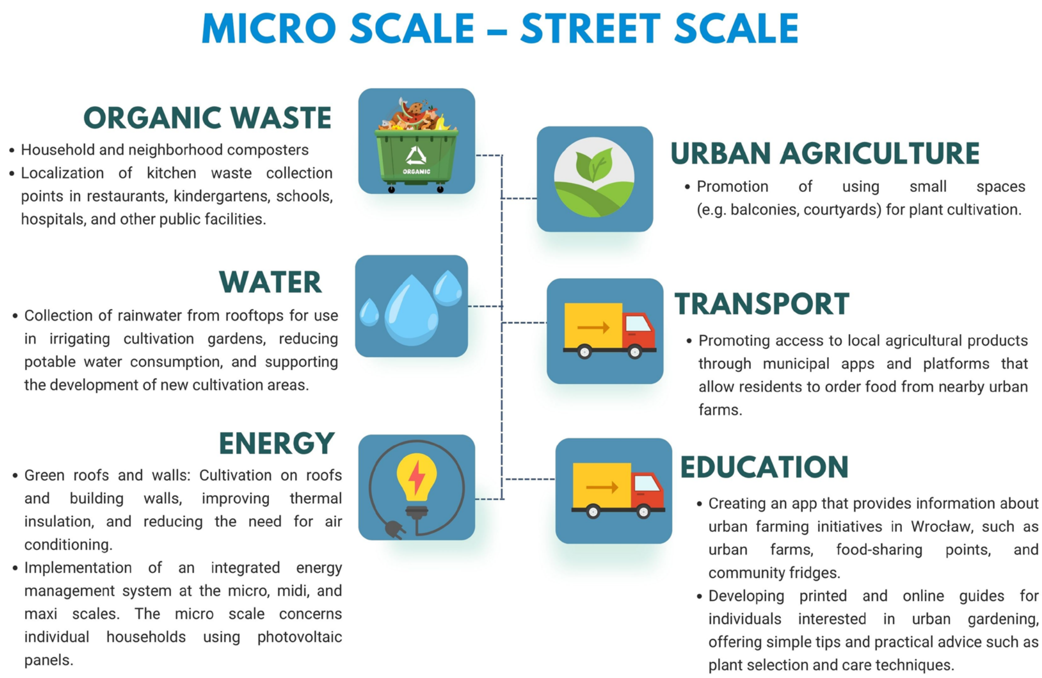

Figure 11. Synergy o Urban Agriculture within the circular economy—micro scale (own elaboration).

At the maxi scale, urban agriculture integrates waste, water, energy, transport, and educational systems to create a sustainable and resilient city ecosystem (Figure 12). City-scale processing facilities and transfer hubs manage organic waste within municipal systems, supported by an expanded network of biowaste collection points in public spaces and institutions. In the synergy model, urban agricultural compost and digestate from these facilities are used for soil restoration, thus strengthening blue–green infrastructure and enhancing biodiversity. Rainwater harvesting systems are widely installed on roofs and in public areas, while green roofs, façades, and walls improve stormwater retention and urban microclimates. Urban farms and allotment gardens rely on recycled water systems, infiltration basins, and biologically active surfaces to optimize water use and support groundwater recharge. In energy management, integrated citywide systems combine active and passive solutions, including efficient greenhouse designs using natural light, ventilation, and heat-storing materials. In the synergy model of urban agriculture within the urban fabric, community gardens and urban farms are developed on unused urban plots, supporting local food production and transforming neglected spaces into productive green zones. Edible plantings and insect habitats are promoted to enhance biodiversity and ecosystem health across the city. Transport infrastructure connects urban farms, community gardens, and local markets, enabling efficient distribution and reducing emissions through shorter supply chains. Ecological fairs and local marketplaces provide direct access to fresh products, thereby supporting local economies. Education plays a central role, with municipal platforms linking the government, NGOs, businesses, and research institutions to allow them to coordinate projects and share knowledge. Public campaigns and municipal programs provide residents with seeds, tools, and training to encourage participation in urban farming activities. Educational initiatives include workshops, courses, and hackathons that promote sustainable cultivation, zero-waste practices, and efficient resource management. A "bio-premium" incentive system rewards adequate waste sorting and sustainable behavior via a municipality.

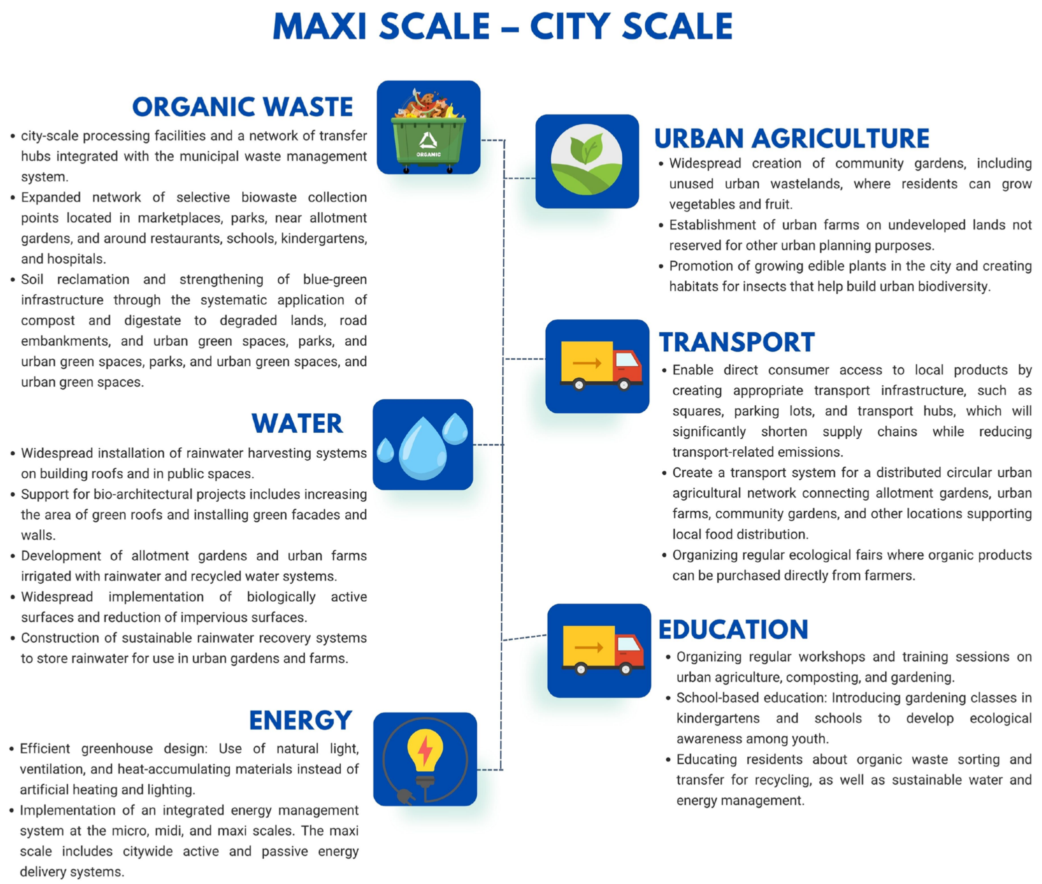

Figure 12. Synergy of Urban Agriculture (UA) within the circular economy—maxi scale—city scale (own elaboration).

To close the modeling section and smoothly transition to the Results and Discussion sections, the findings were organized into two complementary frameworks. The first was based on a multiscale (micro, midi, and maxi) approach that helped capture what works, what limits development, and what is required for further advancement. The second arranged the analytical material within the structure of a SWOT analysis, its weighted version, and a TOWS matrix, which together provided a broader strategic perspective on potential and risks. This dual approach made it possible not only to calibrate the strengths and weaknesses of the system but also to identify elements requiring standardization, energy contracting, and a simplification of implementation procedures. Table 1 presents the key characteristics of circular urban agricultural systems across three spatial scales (micro, midi, and maxi).

Table 1. Comparative overview of circular urban agricultural systems across different spatial scales (micro, midi, and maxi).

Categories	Micro	Midi	Maxi
Spatial scale	Single location/building; small indoor/outdoor units	District/cluster; selected infrastructure facilities	City/metropolitan scale; system-level planning
Technology	Simple CEA; low-power hydro/aeroponics; modular systems	Integrated CEA; heat and CO_2 recovery; monitoring/IoT	Connection standards and requirements; PPA/ESCO models
Resources	Water saving; low energy use; basic reuse where possible	Energy–water balance; heat/CO_2 loops; retention systems	Network mix; tariffs; integration with urban circulation systems
Logistics	On foot/bicycle; ultra-short supply chain	District hubs; cold chain; cargo Logistics	Integration with urban mobility/logistics plans (SUMP)
Economy	Low CAPEX; low OPEX; high educational value	Medium CAPEX; testing of business models	Financial instruments; incentives; PPP frameworks
Social/Education	Learning by doing; community engagement; quick outcomes	District programs; workshops; partnerships	Food policy; citywide programs; social acceptance
Risks/Limitations	Maintenance continuity; volunteer fatigue; local approvals	Energy costs; sanitary procedures; coordination of multiple actors	Interdepartmental coordination; regulatory clarity; public acceptance

At the micro scale, the proximity to people and spaces is the greatest strength. It represents a realm of quick action, small experiments, and learning through experience. It brings about a sense of agency and strong educational value, although its potential is limited by low production volumes and sensitivity to maintenance continuity. The midi scale introduces collaboration and integration, in which the cycles of water, energy, and matter begin to intertwine, and results become measurable. It is a space for testing business models and balancing energy costs, sanitation requirements, and the coordination of multiple actors. At the maxi scale, a system perspective, that is, the integration of policies, financial instruments, and shared standards for data and connections, emerges. At this level, the need for institutional coherence and regulatory transparency becomes evident, ensuring that visions evolve into practices. The overall structure shows that an effective transformation depends on the harmony of all three scales (micro, which builds social awareness and acceptance; midi, which delivers tangible outcomes; and maxi, which provides durability, stability, and a framework for further development).

The following summary (Table 2) organizes the three scales in a practical dimension, showing not only what currently works effectively but also the barriers that most often slow down progress, as well as the conditions necessary for stable implementation. This arrangement reveals the continuity of the process—the path that urban food systems follow, from local and grassroots initiatives to integrated programs encompassing an entire city.

A clear shift in emphasis can be observed across the different scales. At the micro level, education, awareness, and simple implementation tools are essential, allowing people to learn through action. The midi scale acts as a laboratory, a type of space for testing economic models, integrating resource cycles, and obtaining a balance between performance and availability. At the maxi level, the process enters the institutional dimension, where success depends on coordination, standardization, and appropriate financial instruments. This gradation shows that sustainable urban agriculture requires the co-operation of grassroots and systemic forces. It is their parallel action, from micro-grants to PPA contracts and one-stop-shop regulations, that allows ideas to move from visions to practices.

Table 2. Synthesis of key conditions and implementation needs across three functional scales of circular urban agricultural systems.

Categories	Micro	Midi	Maxi
What works	User proximity; quick activation; visible benefits; education and awareness	Integration of resource cycles; measurable outcomes; verification of business models	Policy integration; economies of scale in procurement and data; long-term stability
What limits	Dependence on volunteer time; limited volume; varied maintenance quality	Energy costs; sanitation compliance; coordination among multiple stakeholders.	Bureaucratic silos; inconsistent regulations; challenges of social acceptance
What is needed for implementation	Simple service contracts; light procedures; micro-grants; training kits	Energy contracts (PV, heat recovery, PPA); SOPs; district support office	One-stop permits; unified guidelines; incentives and PPPs; public communication

A complementary element to the previous analyses is a table of operational indicators, which organizes the key parameters for each scale, from energy and water consumption to investment and operating costs, as well as logistical and social aspects (Table 3). This perspective makes it possible to see how, with increasing scale, not only does technological complexity grows but also the nature of relationships among people, infrastructure, and institutions. As the system expands, the level of coordination and responsibility also increases from individual actions to complex urban networks, where technical decisions become social ones.

Table 3. Efficiency indicators and operating conditions of circular urban agricultural systems across three spatial scales (micro, midi, and maxi).

Categories	Micro	Midi	Maxi
Energy	Low to medium power; dependent on lighting; no or minimal HVAC systems	Moderate demand; possible heat and CO_2 recovery; IoT monitoring	Dependence on energy mix; PPA/ESCO possible; tariff optimization
Water	Significant savings through CEA; precise dosing	Water and energy balance; retention and circulation; stable consumption	Urban policies on retention and reuse; standardization of indicators
CAPEX/OPEX *	Low CAPEX; low to medium OPEX; high educational value	Medium CAPEX; medium OPEX; revenue models under verification	High CAPEX (system level); OPEX optimized by scale
Supply Chain	Ultra-short (on-site, walking/bicycle); no or small cooling facilities	District level (hubs, cold storage, cargo); short routes	City level (integration with SUMP/urban logistics); data integration
Social Acceptance	Usually high at the local level; strengthened through educational programs	Variable; increases with the visibility of results and partnerships	Requires food policy and public communication

* CAPEX: capital expenditure (investment costs); OPEX: operational expenditure (operating costs).

The summary clearly shows that, as the scale increases, the importance of systemic connections grows. From simple, lightweight installations at the micro level, through increasingly complex energy and logistics arrangements at the midi scale, to fully integrated urban systems at the maxi level, each stage requires a different way of thinking and a distinct logic of action. Furthermore, with the expansion of scale, operational flexibility tends to decrease, whereas the need for standardization, supervision, and long-term agreements ensuring process stability becomes more pronounced. In the social dimension, a subtle gradient can be observed, from spontaneous engagement and high acceptance within small initiatives to the need for formalization and public communication in large-scale urban programs. The collected indicators create a bridge to strategic analyses (SWOT and TOWS), which help explain how potentials and risks should be balanced so that the implementation of circular urban agriculture is not only effective but also durable and socially embedded.

To better understand the interrelations between the internal and external factors shaping the development of circular urban agriculture, a SWOT analysis was conducted (Table 4). This made it possible not only to identify the strengths and weaknesses of the system but also to capture the opportunities and threats arising from the institutional, economic, and technological contexts. Unlike traditional planning models, this analysis was firmly rooted in the realities of a city in its energetic, spatial, and social rhythms, revealing how these three dimensions intertwine in practice to form a single, interdependent organism.

Table 4. SWOT analysis for circular urban agricultural systems.

Strengths (S)	Weaknesses (W)	Opportunities (O)	Threats (T)
S1 High water-use efficiency in CEA systems and precise dosing	**W1** Energy intensity of certain solutions (lighting, HVAC) and sensitivity to the energy mix	**O1** Policy and funding frameworks (climate, CE, food security, BGI/SuDS/LID)	**T1** Energy price volatility and uncertainty of operating costs
S2 Year-round controlled production and stable supply	**W2** High initial costs (CAPEX) and longer payback period	**O2** Access to degraded and underground spaces with revitalization potential	**T2** Regulatory uncertainty and complex sanitation requirements
S3 Proximity to consumers and shortening of supply chains (food miles)	**W3** Lack of standardized evaluation indicators (TEA/LCA; energy, water, emissions)	**O3** Decarbonization of grids, development of renewable energy and energy storage, PPA/ESCO agreements	**T3** Limited social acceptance/NIMBY attitudes
S4 Resource synergies: heat and CO_2 recovery, water retention and reuse	**W4** Limited range of crops economically viable at large scale	**O4** Digitalization and automation (IoT, monitoring, last-mile logistics)	**T4** Competition for space and institutional silos within the city
S5 Social and educational functions, building social capital	**W5** Varied organizational maturity and operational risk at the start	**O5** Cooperation with education, tourism, and public health	**T5** Disruptions in supply chains of components and materials
S6 Use of underutilized spaces (rooftops, façades, underground areas)	-	-	-

The results clearly show that the greatest potential of circular urban agriculture lies in resource efficiency and the synergy between water and energy cycles, as well as in the proximity to consumers, which shortens the distance between production and consumption and stabilizes local supply. Meanwhile, these systems reveal their main weaknesses: high initial costs, high energy intensity, and the lack of standardized evaluation indicators, which make comparison and planning more difficult. Regarding opportunities, there is growing support from climate policies, the development of renewable energy sources, digitalization, and municipal programs that can accelerate the implementation of innovations. Conversely, the main threats stem from energy instability, unclear regulations, and a low level of social acceptance. This arrangement confirms that the future of these systems depends not only on technology but also on stable institutional frameworks and trust among sectors and between cities and their residents. These findings formed the basis for the Weighted SWOT analysis, which allowed for the structuring of factors according to their strengths and significance for system development.

To capture the relationships between the factors and their actual impacts on the implementation of circular food systems, the results of the SWOT analysis (Table 5) were expanded to include the quantitative dimension. The use of weights and scores made it possible to identify the elements that truly drive the transformation process, as well as those that slow it down. This approach allowed the factors to be organized according to their significance, from key potentials to barriers requiring intervention, and to assess how stable they remained under changing energy and regulatory conditions.

Table 5. Weighted SWOT analysis.

Code	Factor	Weight	Score (−5… +5)	Weighted Result	Comments
			Strengths (S)		
S1	Resource synergies: heat and CO_2 recovery, water loops	0.35	4	**1.40**	Integration with urban infrastructure
S2	High water-use efficiency in CEA systems	0.30	5	**1.50**	Precise dosing and closed cycles
S3	Proximity to consumers and shortening of food miles	0.20	3	**0.60**	Freshness, lower losses, reduced transport
S4	Year-round, controlled production	0.15	3	**0.45**	Stable supply regardless of weather
	Suma (S)	**1.00**		**3.95**	
			Weaknesses (W)		
W1	High energy consumption (lighting, HVAC) and sensitivity to energy mix	0.40	−5	**−2.00**	Impact on OPEX and carbon footprint
W2	High initial investment costs (CAPEX)	0.30	−4	**−1.20**	Longer payback period
W3	Lack of standardized evaluation indicators (TEA/LCA)	0.20	−3	**−0.60**	Difficulty in comparison and reporting
W4	Limited range of crops profitable at large scale	0.10	−2	**−0.20**	Dominance of leafy greens, herbs, mushrooms
	Suma (W)	**1.00**		**−4.00**	
			Opportunities (O)		
O1	Policy frameworks (climate, CE, food security, BGI/SuDS/LID)	0.35	4	**1.40**	Support programs and funding mechanisms
O2	Access to degraded and underground spaces	0.25	3	**0.75**	Lower alternative land cost
O3	Network decarbonization and renewable energy/storage (PPA/ESCO)	0.20	4	**0.80**	Reduction in energy costs and footprint
O4	Digitalization and automation (IoT, monitoring, logistics)	0.20	3	**0.60**	Higher control and efficiency
	Suma (O)	**1.00**		**3.55**	
			Threats (T)		
T1	Energy price volatility and uncertainty of OPEX	0.40	−4	**−1.60**	Strong impact on profitability
T2	Regulatory uncertainty and sanitation requirements	0.25	−3	**−0.75**	Complex implementation procedures
T3	Limited social acceptance/NIMBY attitudes	0.20	−2	**−0.40**	Need for communication and transparency
T4	Disruptions in supply chains of components and materials	0.15	−3	**−0.45**	Risk of delays and additional costs
	Suma (T)	**1.00**		**−3.20**	

The analysis revealed a clear balance between potential and limitations. The highest positive values were recorded for factors S2 and S1, which refer to high water efficiency and resource synergies, confirming the advantages of systems capable of precisely managing water, energy, and material flows within the urban metabolism. Among the opportunities, O1 and O3, which are related to policy frameworks and decarbonization, stood out, emphasizing the importance of stable instruments of support and financing. Regarding weaknesses and threats, W1 and T1 were the most significant, representing energy intensity and energy price volatility, which pose real risks to the long-term economic and climatic stability of these systems. The overall picture reveals a kind of duality: on one hand, strong innovative potential and alignment with climate policies, and on the other, energy and financial vulnerability. Therefore, it becomes essential to act simultaneously in two directions: increasing the share of renewable and recovered energy in urban systems and introducing simplified yet consistent standards for efficiency assessment (TEA/LCA-lite).

A sensitivity analysis (Table 6) was conducted to assess the robustness of the obtained results, assuming variations of approximately 15 percent in the weights of the key factors. This approach made it possible to verify whether even slight shifts in the importance of individual elements could influence the order of the weighted results and the suggested strategic directions. The analysis was complemented by a ranking of the ten most influential factors (TOP10) that had the greatest impact on implementation potential and investment decisions within circular urban systems.

Table 6. Most influential factors (TOP10) shaping the development and implementation of circular urban agricultural systems.

Rank	Code	Quadrant	Short Description	Weight	Score (−5... +5)	Weighted Result
1	W1	W	High energy consumption (lighting, HVAC) and sensitivity to the energy mix	0.40	−5	−2.00
2	T1	T	Energy price volatility and uncertainty of OPEX	0.40	−4	−1.60
3	S2	S	High water-use efficiency in CEA systems	0.30	5	1.50
4	S1	S	Resource synergies: heat and CO_2 recovery, water loops	0.35	4	1.40
5	O1	O	Policy frameworks (climate, CE, food security, BGI/SuDS/LID)	0.35	4	1.40
6	W2	W	High initial investment costs (CAPEX)	0.30	−4	−1.20
7	O3	O	Network decarbonization and renewable energy/storage (PPA/ESCO)	0.20	4	0.80
8	O2	O	Access to degraded and underground spaces	0.25	3	0.75
9	T2	T	Regulatory uncertainty and sanitation requirements	0.25	−3	−0.75
10	S3	S	Proximity to consumers and shortening of food miles	0.20	3	0.60

The sensitivity analysis confirmed the stability of the obtained results; even with a weight variation of approximately 15 percent, the arrangement of key factors remained unchanged. Regarding strengths, S2, representing water efficiency, and S1, referring to resource synergies, were dominant, while among weaknesses and threats, W1, which is related to the energy intensity of HVAC systems, and T1, reflecting energy price volatility, were the most prominent. This indicates that the main challenge lies in achieving energy and cost resilience, while the most prominent strength was the ability to manage water efficiently and integrate resource cycles within urban infrastructure. The structure of the TOP10 ranking confirms this balance, as the most influential factors included positive elements, such as S2, S1, O1, and O3, and limiting elements, such as W1, W2, T1, and T2. This shows that an effective transformation requires the simultaneous strengthening of resource efficiency pillars and the development of safeguards against energy market instability. The stable results of the sensitivity analysis confirm the reliability of the factor hierarchy and provide a solid foundation for developing the TOWS strategy, which organizes the directions of action and formulates recommendations for urban policies.

Based on the results presented in Table 7, which include the SWOT and Weighted SWOT analyses, a TOWS matrix was developed to organize the strategic directions for further action. This stage aimed to determine how to leverage the strengths and opportunities revealed in the analysis while minimizing the impact of weaknesses and threats that may slow down the implementation process. The matrix comprises four interrelated groups of strategies: offensive (SO), focused on exploiting internal potentials and favorable external conditions; adaptive (WO), aimed at strengthening capacities in response to emerging opportunities; defensive (ST), oriented toward reducing risks while maintaining existing advantages; and protective (WT), designed to enhance system stability under uncertain conditions. Together, these strategies form a coherent implementation framework for the sustainable development of circular urban agricultural systems, integrating strategic thinking with spatial, environmental, and energy planning.

Table 7. TOWS matrix—strategies for the development of circular urban agricultural systems.

Opportunities (O) **Strategies for Leveraging Opportunities**	**Threats (T)** **Strategies for Reducing Risks**
Strengths (S)	
SO—Use strengths to seize opportunities	**ST—Use strengths to mitigate threats**
SO-1: Couple heat and CO_2 recovery with the decarbonizing grid and renewable energy sources (RES), launching pilot projects in public facilities and transport hubs (S4 × O3/O1).	**ST-1:** Secure energy costs through PPA contracts and heat recovery, using resource synergies to reduce vulnerability to price fluctuations (S4 × T1).
SO-2: Use water efficiency and proximity to consumers to supply resilience hubs and public catering, ensuring stable year-round provision (S1/S2/S3 × O1/O2).	**ST-2:** Use proximity and steady supply to build stable distribution channels, reducing the effects of supply chain disruptions (S2/S3 × T5).
SO-3: Develop educational and tourism programs around midi-scale installations to strengthen social license and increase demands for local products (S5 × O5/O4).	**ST-3:** Standard hygiene procedures and quality monitoring, combined with public visibility of projects, strengthen trust and reduce NIMBY risks (S5 × T2/T3).
Weaknesses (W)	
WO—Overcome weaknesses by taking advantage of opportunities	**WT—Minimize weaknesses and avoid threats**
WO-1: Introduce a simplified set of indicators (TEA/LCA-lite) into procurement and grant documentation to standardize reporting and improve comparability (W3 × O1/O4).	**WT-1:** Establish regulatory sandboxes and one-stop permitting with clear sanitation guidelines to lower implementation barriers (W3/W5 × T2/T4).
WO-2: Gradually reduce CAPEX through PPP/ESCO models and long-term leases of unused underground spaces, accelerating the learning curve (W2 × O2/O3).	**WT-2:** Implement modular scalability and phased investments to reduce CAPEX risk and adapt the energy profile to market conditions (W1/W2 × T1).
WO-3: Broaden crop portfolios and technological modules by integrating systems with varying intensity and energy demand (W4 × O4/O3).	**WT-3:** Develop service contracts and short supply chains for components to reduce vulnerability to disruptions (W5 × T5).

The TOWS matrix (Table 7) outlines four complementary strategic directions forming the framework for developing circular urban agricultural systems. Offensive strategies (SO) are focused on harnessing existing potential, particularly resource synergies and climate policies, as a driving force for pilot projects in public and semi-public spaces. Their essence lies in coupling heat and CO_2 recovery with renewable energy networks and integrating food production with transport infrastructure and resilience hubs across a city. Adaptive strategies (WO) aim to overcome organizational and economic barriers by introducing simplified evaluation standards (TEA/LCAlite), reducing initial investment costs through PPP and ESCO models, and diversifying technological portfolios according to the energy demand and local context. Defensive strategies (ST) strengthen the resilience of systems to external risks. They rely on stabilizing energy costs through PPA contracts and heat recovery, as well as ensuring transparency and quality control throughout production processes, factors that help build public trust and reduce the risk of community resistance. Protective strategies (WT) emphasize the need for clear and flexible institutional frameworks, including streamlined procedures, one-stop permitting pathways, and regulatory sandboxes. These mechanisms reduce administrative barriers and mitigate regulatory uncertainty that often slows innovation.

Together, the TOWS strategies form a coherent structure of recommendations that weave the technological, social, and institutional dimensions together. Their implementation requires coordinated political, financial, and educational support as well as collaboration between municipal departments. The sequence of analyses, from the micro, midi, and maxi framework, through the SWOT and Weighted SWOT analyses, to the TOWS strategies, reveals the logic of circular urban agriculture as a multi-layered system in which technologies, institutions, and communities interact and evolve together. This perspective opens space for a broader reflection on how resource efficiency and systemic resilience can coexist and reinforce one another to shape the future of sustainable urban policies.

5. Discussion

The integration of the circular economy (CE) with urban agriculture represents an innovative and systemic response to the contemporary challenges of urbanization, climate change, and environmental degradation. The presented analyses confirm that circular food production models implemented in urban environments generate multifaceted ecological, social, and economic benefits.

From the perspective of resource efficiency, urban agriculture operating within the CE model enables the reintegration of the closed cycles of water, organic matter, and energy. Technologies such as hydroponics, water recirculation systems, photovoltaics, and anaerobic digestion support the optimization of resource flows, contributing to the reduction in primary resource consumption and greenhouse gas emissions. Importantly, the localization of food production in urban spaces leads to shortened supply chains and a reduction in food miles, which translates into improved logistical and environmental efficiencies of the entire system.

Moreover, urban agriculture serves as a social and educational infrastructure, activating residents and strengthening local social capital. Community gardens, environmental education programs, participatory platforms, and “zero waste” initiatives contribute to increasing environmental awareness, shared responsibility, and local engagement. It is worth emphasizing that the effectiveness of implementing circular solutions is strongly correlated with the existence of integrated urban policies, institutional support, and legislative frameworks that promote innovation and cross-sector collaboration.

Building on the conducted analyses, it becomes clear that integrating circular urban agriculture into the fabric of a city requires maturity not only in technology but also in institutions. The effectiveness of implementation depends on the level of advancement of the cultivation systems themselves, such as CEA, hydroponics, or aquaponics, and, most importantly, on their ability to interact with existing energy, water, and waste infrastructures. These interlinkages create synergies that strengthen the urban metabolism and enhance the climate resilience of a city. The Weighted SWOT analysis revealed a dual dynamic within these processes. On one hand, the greatest strengths lie in resource efficiency, in the synergy between water and energy recovery, and in the shortening of supply chains. On the other, their development remains constrained by the high energy intensity, high investment costs, and regulatory uncertainty. In this context, the TOWS matrix (Table 7) indicates specific strategic directions: integrating food production with renewable energy and heat recovery systems, introducing simplified efficiency assessment standards (TEA/LCA lite), developing public–private partnership (PPP/ESCO) models, and strengthening social legitimacy through education and transparent communication.

From a broader perspective, the results confirm that circular urban agriculture can become a pillar of green–blue infrastructure and urban resilience policy. This system produces food and restores the balance between human activity and the rhythm of nature, directly contributing to the achievement of SDGs 11, 12, and 13. Embedding circular food production into planning instruments—such as urban food strategies, climate adaptation plans, or integrated mobility plans (SUMP)—creates a foundation for the holistic management of resources, emissions, and ecosystem services. Ultimately, the transformation toward circular urban food systems requires a new, cross-sectoral governance model built on cooperation among technology, institutions, and communities. Only the integration of these three dimensions (technical, social, and planning) can ensure the durability, scalability, and social legitimacy of circular urban agriculture as a key component of the sustainable metabolism of a city.

6. Conclusions

The multiscale model of synergy between urban agriculture and the urban environment within a circular economy framework offers a comprehensive approach to sustainable urban transformation. By embedding food production within integrated systems of water, energy, organic waste, and transportation management, cities can move toward becoming resilient, low-emission, and self-sufficient ecosystems. The research demonstrates that innovative forms of urban farming—from vertical farms and rooftop gardens to community-based agricultural hubs—play a crucial role in shaping circular resource flows. Their integration into broader environmental and infrastructural systems enhances the efficiency of energy and water use, reduces food miles, and contributes to the regeneration of urban ecosystems. A central feature of this model is its multiscale spatial organization. By applying the mini–midi–maxi framework, the model connects local, district, and city-wide strategies into an adaptive and interdependent structure. This ensures that resource cycles are optimized across different levels of the urban fabric, enabling effective circulation of materials, energy, and information. Furthermore, the transition toward circular urban agriculture cannot succeed without public policy support. Key priorities include the design of multilevel production and recycling systems, the implementation of intelligent resource management technologies, investments in blue-green and bio-architectural infrastructure, and the development of educational programs to engage residents. Ultimately, this integrated approach contributes to the vision of the 15 min city, where access to food, services, and green spaces is equitable, efficient, and sustainable. By closing resource loops and fostering synergies between natural and human-made systems, the proposed model redefines the relationship between cities, their inhabitants, and their environment. The implementation of integrated Circular Urban Agriculture (CUA) solutions contributes directly to the achievement of international sustainable development goals (SDGs 2, 11, 12, and 13) and to building future cities as ecologically resilient, socially inclusive, and resource-optimized systems. The conducted analyses, encompassing both the multi-scale model (micro midi maxi) and the SWOT TOWS framework, revealed that the transition toward circular urban agriculture requires parallel actions across the technological, institutional, and social dimensions. The greatest potential lies in integrating food production systems with urban energy and water networks, supported by clear efficiency assessment standards (TEA/LCA lite) and innovative financing models based on public–private cooperation (PPP, ESCO). Practically, cities should prioritize pilot projects implemented in underused public spaces, the deployment of energy and water recovery systems, and the development of participatory programs that foster trust and local engagement. From the perspective of urban policy, circular agriculture should be recognized as an integral part of green–blue infrastructure and incorporated into climate adaptation strategies and urban food policies.

Future studies should focus on refining the economic assessment of such systems, quantifying the ecosystem services they provide, and defining governance models that enhance their durability, scalability, and integration within the broader urban metabolism.

CUA integrates circular economy principles into urban food production and helps to minimize external inputs and reduce the environmental impact of agriculture on the environment. Despite its potential, the distinctions between CUA, conventional urban agriculture, and urban farming remain vague. Existing studies often refer broadly to the idea of "resource circulation," focusing on recycling or waste recovery, while they seldom define the levels of closed loop system circulation. Essential aspects such as the definition of system boundaries (spatial, temporal, and functional), measurable thresholds for resource recovery or reuse, and consistent technical indicators—like energy efficiency, nutrient cycling rates, or material circularity—are rarely detailed. This lack of precision limits the ability to evaluate, compare, and scale CUA practices effectively. To strengthen the framework, future research should move past general discussions of circularity and develop clear, quantifiable parameters to assess how circular processes operate within urban agricultural systems.

Author Contributions: Conceptualization, A.Z., A.K. and M.A.-P.; methodology, A.Z., A.K. and M.A.-P.; software, A.Z. and A.K.; validation, A.Z., A.K., M.A.-P. and H.J.; formal analysis, A.Z., A.K. and M.A.-P.; investigation, A.Z., A.K. and M.A.-P.; resources, A.Z., A.K. and M.A.-P.; data curation, A.Z., A.K. and M.A.-P.; writing—original draft preparation, A.Z., A.K., M.A.-P. and H.J.; writing—review and editing, A.Z., A.K., M.A.-P. and H.J.; visualization, A.Z. and A.K. supervision, A.Z. and A.K.; project administration, A.Z. and A.K. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the National Centre for Research and Development (NCBR) under the DUT 2022 program, with a total budget of PLN 1,125,906.50. The project duration is from 1 February 2024 to 31 January 2027. A project titled as 'Food production and provisioning through Circular Urban Systems in European Cities' (FOCUSE) is being carried out at the University of Wrocław.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Data are contained within the article.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

AHP	Analytic Hierarchy Process	OPEX	Operational Expenditures
BGI	Blue–Green Infrastructure	PPA	Power Purchase Agreement
CAPEX	Capital Expenditures	PPP	Public–Private Partnership
CEA	Controlled Environment Agriculture	SDG	Sustainable Development Goals
CE	Circular Economy	SOP	Standard Operating Procedure
CUA	Circular Urban Agriculture	SuDS	Sustainable Drainage Systems
ESCO	Energy Service Company	SUMP	Sustainable Urban Mobility Plan
HVAC	Heating, Ventilation, and Air Conditioning	TEA	Techno-Economic Assessment
IoT	Internet of Things	UA	Urban Agriculture
LCA	Life Cycle Assessment	LID	Low-Impact Development

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