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Review

Technological Innovations in Urban and Peri-Urban Agriculture: Pathways to Sustainable Food Systems in Metropolises

Shulang Fei [1,2,*], Ruiqin Wu [2], He Liu [2], Feifei Yang [2] and Nan Wang [1,2,*]

[1] Institute of Urban Agriculture, Chinese Academy of Agricultural Sciences, Chengdu 610213, China
[2] National Agricultural Science & Technology Center, Chengdu 610213, China
* Correspondence: feishulang@caas.cn (S.F.); wangnan02@caas.cn (N.W.)

Abstract: Metropolitan areas increasingly confront complex challenges related to food security, social inequality, environmental degradation, and resource scarcity, exacerbated by rapid urbanization, climate change, and the reliance on extended, fragile supply chains. Urban and peri-urban agriculture (UPA) is recognized as a promising approach to mitigate these issues. For example, it enhances food security and nutrition by strengthening local food supply systems, improves livelihoods by providing employment and income for local residents, and promotes environmental sustainability through the creation of greening spaces and reduction of food miles. However, the full potential of UPA remains constrained by various technological, economic, and social barriers, such as limited growing spaces, lack of land tenure security, low economic efficiency, and insufficient public awareness and acceptance. Given that the technological innovations are critical in overcoming these barriers and maximizing the positive impacts of UPA, this review provides a state-of-the-art overview of advanced technologies and tools applicable to UPA, aiming to inform how these innovations can be better enabled to enhance UPA's contributions to sustainable urban food systems. The review begins by defining UPA, categorizing its various forms, and exploring its multifunctional roles within urban contexts. It then presents a thorough analysis of a range of UPA technologies that serve specific purposes, including productivity and product quality improvement, space utilization optimization, resource recycling, and land use management. Furthermore, the review evaluates the current challenges faced by these technologies throughout the stages of research and development (R&D), dissemination and extension, and application and commercialization, employing an analytical framework adapted from Technology Life Cycle theories. In conclusion, the review emphasizes the crucial roles that UPA and relevant technological innovations play in transforming food systems and urban environments. It proposes four key recommendations: (1) enhancing funding mechanisms and fostering interdisciplinary collaboration for UPA R&D, (2) strengthening UPA technology dissemination systems, (3) promoting economic feasibility and market integration within UPA business models, and (4) establishing supportive environments among all stakeholders in the innovation process. These targeted strategies are essential for scaling UPA technologies, thereby strengthening food security, environmental sustainability, and socio-economic resilience in metropolitan areas.

Keywords: urban and peri-urban agriculture; technology; innovation; metropolis; city; food system

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1. Introduction

1.1. Metropolis and the Vulnerable Food Systems

While there is no globally agreed-upon definition, metropolises (or metropolitan areas) generally refer to large cities and their surrounding regions, which serve as key centers of national and regional socioeconomic activities. They are sometimes broadly defined as territories beyond administrative boundaries where strong economic and social integration occurs [1–3]. Metropolises play a crucial role in driving economic growth, material flows, social transformation, and the utilization of natural resources at a territorial scale. For instance, OECD data show that metropolitan areas contribute more than 60% of the GDP while housing 55% of the population in its member countries [4].

Despite these advantages, metropolises face complex and interrelated challenges. Rapid urbanization has significantly increased demand for land, resources, and services, often resulting in the conversion of agricultural land into built-up areas, especially in peri-urban regions [5]. Data from Stockholm, Sweden, indicate that urban areas expanded by approximately 4%, while green spaces decreased by 2% between 2003 and 2018 [6]. This expansion has intensified environmental risks such as air pollution, flooding, and rising sea levels, with larger cities becoming more vulnerable in certain cases [7,8]. For instance, Typhoon Ketsana [9] in 2009 submerged over 80% of metropolitan Manila, Philippines, under floodwaters, leading to significant economic losses, displacement of residents, and severe agricultural impacts. Urbanization can also deepen social inequality, both spatially and interpersonally. Migration from rural to urban areas strengthens metropolitan economies but leaves rural areas underdeveloped, thus widening inter-regional income gaps [10]. Moreover, within cities, migrant workers and other vulnerable groups often reside in poor settlements with limited physical and economic access to essential services, including healthy food [11].

Food security is a particularly pressing concern for metropolises, as they increasingly depend on external resources. By 2050, it is projected that 70% of the global population will live in cities, leading to a sharp rise in food demand, especially as farmlands and rural farmers continue to diminish [12,13]. In most cases, cities cannot sustain themselves with local resources and must rely on broader national and global food systems. This dependence on long, industrialized supply chains introduces significant risks to food supply, particularly in times of crisis. For example, during the COVID-19 pandemic, cities experienced greater disruptions to food supply chains compared to smaller towns, revealing their heightened vulnerability [14]. Poor food environments also constrain citizens' food security. For example, several food deserts have been identified within the metropolitan area of Monterrey, Mexico, where access to fresh food outlets is limited, making it difficult for residents to reach a grocery store on foot [15]. Moreover, ongoing agricultural land conversion due to urban sprawl further reduces local food production capacities, exacerbating cities' dependence on longer supply chains, which are more susceptible to environmental and logistical disruptions [5,16]. This loss of peri-urban farmland not only reduces local food availability but also contributes to biodiversity loss and the degradation of ecosystem services critical for sustainable food production, thereby increasing long-term food system vulnerabilities. These impacts are particularly pronounced in rapidly urbanizing regions of Asia and Africa, where unregulated urban sprawl worsens the fragility of local food systems [17]. Furthermore, climate change further compounds these vulnerabilities by intensifying environmental stressors like droughts and floods, disproportionately affecting metropolitan areas that rely on distant food sources [18].

Interestingly, while food insecurity is typically more severe in rural areas globally, recent findings suggest that urban populations in high-income countries may experience higher levels of food insecurity than rural populations. This paradox may be driven by the higher cost of living in cities, income inequality, and the marginalization of low-income groups, particularly in high-density metropolitan areas [11]. The complexity of food insecurity in urban settings highlights that higher urbanization and income levels do not necessarily translate into better food security outcomes and, in some cases, may even exacerbate these issues.

In conclusion, while metropolises drive significant economic growth and provide advanced services, they are becoming increasingly vulnerable in terms of food security due to rapid urbanization, environmental pressures, and their dependence on fragile, extended supply chains. Addressing these vulnerabilities requires a comprehensive approach to urban planning, sustainable land use, and resilient food sourcing strategies to ensure long-term food security in metropolitan areas.

1.2. Urban and Peri-Urban Agriculture (UPA) and Its Roles in Cities

Urban and peri-urban agriculture (UPA), defined as the production of agri-food and related activities within urban and peri-urban areas, has garnered significant attention in both academic research and policy discussions. Initially focused on food subsistence for residents, UPA has gradually expanded into a multifaceted industry that serves various purposes and engages diverse communities worldwide. It is playing an increasingly crucial role in urban development, not only by enhancing food availability and accessibility but also through its multidimensional contributions to sustainable urban growth, such as its socioeconomic, environmental, and educational benefits [19–23]. Further details will be discussed in Section 2.

UPA is intrinsically linked to the broader urban system, benefiting from, but also challenged by, the dynamics of urbanization. On the one hand, UPA's proximity to large urban consumer markets offers distinct advantages, allowing producers to cater directly to diverse and shifting demands. This proximity facilitates the marketing of agri-food products, access to urban services, and opportunities for farm diversification, further integrating UPA into urban economies [24]. On the other hand, UPA faces significant challenges, particularly in metropolitan areas. The pressure on land due to urban sprawl and encroachment is one of the most critical constraints, as agricultural land use is often perceived as less economically valuable compared to other uses such as industrial, residential, or infrastructural development [16]. This has led to continuous land loss, unstable land tenure, and difficulties in maintaining long-term agricultural activities in urban and peri-urban areas [25,26]. Additionally, UPA practitioners frequently encounter other obstacles, including soil contamination, insufficient water resources for irrigation, limited access to financial capital, and restricted market opportunities. These challenges are particularly exacerbated in areas with incomplete policy frameworks and inadequate governance mechanisms, which are essential for supporting UPA. Key issues include insufficient integration of UPA into urban planning, lack of clear policies supporting agricultural activities in cities, neglect of marginalized practitioner groups, and, in some cases, political suppression of UPA practices [26–31]. Addressing these challenges requires both technological innovations and policy interventions to support the sector's development [32].

1.3. Gap and Needs in Technological Innovations of UPA

Innovations are essential to tackling the above challenges and unlocking UPA's potential to enhance urban food security and promote more resilient and sustainable urban development across economic, social, and environmental dimensions [33,34]. In the context of food systems, innovation refers to the development and application of new technologies, practices, and institutional arrangements tailored to local contexts and driving transitions towards more sustainable and resilient food systems [35]. Food system innovations can be categorized into technology-driven approaches aimed at improving food productivity and supply chains, and those focusing on business models, social structures, and institutional environments to tackle socio-economic and environmental challenges. In the sector of UPA in particular, innovations encompassing technological advancements, market adaptations, and institutional reforms have emerged as essential strategies to tackle the unique challenges posed by urban settings. The proximity of UPA to urban centers facilitates innovation by offering access to a skilled workforce, cutting-edge technologies, and supportive infrastructure—key elements for driving transformative changes in urban food systems.

Technological innovations, including the rapid advancement of digital tools, serve as a critical foundation for supporting efficient, sustainable, and resilient production and supply chain management in UPA practices. These innovations enhance urban food security, promote sustainable food systems, and contribute to global development goals. A comprehensive understanding of these technologies and their multifaceted benefits for food systems and livelihoods is essential for informing more effective policy and practice decisions. Several studies have explored innovations in UPA across various dimensions [27,36–38]. However, there remains a lack of comprehensive evaluation of technology-based innovations specifically within the context of large metropolitan areas, where food system vulnerabilities and innovation capacities are uniquely intertwined. This paper seeks to contribute to the growing body of research on transforming urban food systems through technological innovation, particularly within metropolitan contexts, by offering a holistic review that facilitates the development and adoption of these innovations as effective solutions to the mounting challenges.

2. Urban and Peri-Urban Agriculture (UPA)

2.1. Evolution of the Concept

Urban and peri-urban agriculture (UPA), sometimes referred to as urban agriculture (UA), is a long-standing practice that traces its origins back to the emergence of cities. Historical examples of UPA can be found as early as B.C.E., with notable instances such as the "Hanging Gardens of Babylon" and the "sacred lands" in ancient Greek cities, which were designated for food production [20]. Over time, the role of UPA has evolved, taking on various forms to address urban food supply, contribute to landscape architecture, alleviate poverty, and even support war efforts [39]. In recent decades, advancements in technology have further expanded the scope of UPA, leading to the development of innovative models such as indoor farming, vertical farming, and aeroponics [40,41].

A widely accepted definition of UPA nowadays was proposed by Mougeot [42], who described it as "an industry located within (intra-urban) or on the fringe (peri-urban) of a town, city, or metropolis, which grows, raises, processes, and distributes a variety of food and non-food products, largely using human and material resources found in and around that urban area, and in turn, supplying resources back to the urban system". This definition emphasized the unique integration of UPA into urban economic and ecological systems, distinguishing it from traditional rural agriculture. Mougeot [43] identified several key dimensions of UPA, including its economic activities, food and non-food categories, intra-urban and peri-urban characteristics, production systems, and the scale and destination of products (Figure 1).

Building on this framework, the FAO et al. [14] offered an updated definition, recognizing UPA as "practices that yield food and other outputs from agricultural production and related processes (transformation, distribution, marketing, recycling, etc.), taking place within cities and surrounding regions, involving diverse urban and peri-urban actors, systems, and economies, and largely using local resources to meet the needs of local populations". The FAO's definition expands on Mougeot's foundation, emphasizing UPA's multifunctionality and its role in addressing broader urban challenges beyond food provision, such as sustainability, social inclusion, and economic development [44–46].

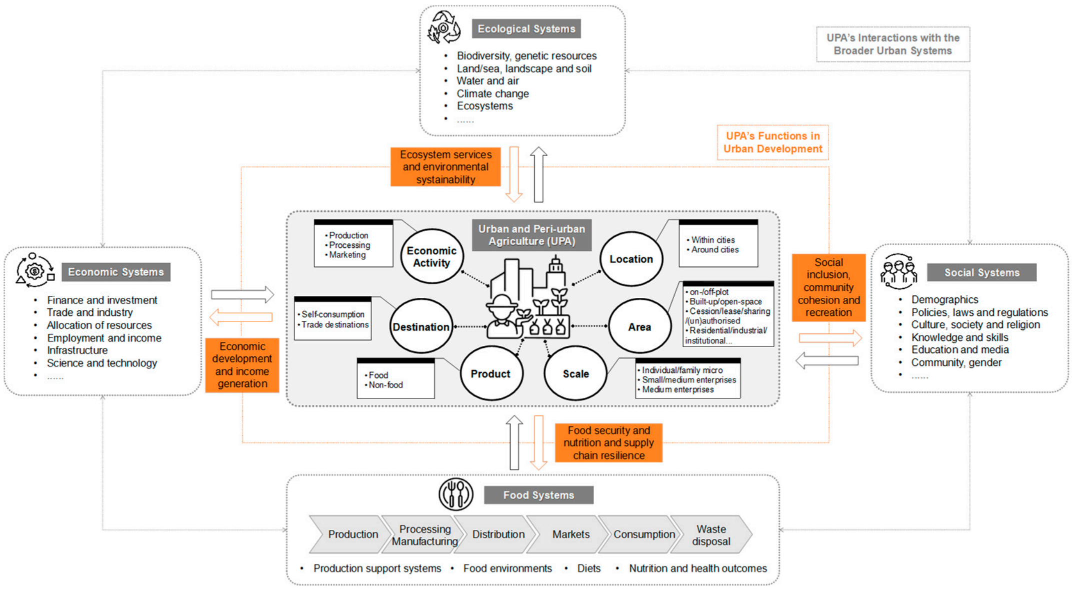

Figure 1. A conceptual diagram illustrating the definition and multiple functions of urban and peri-urban agriculture and its multidimensional interactions with the broader urban systems.

The evolution of UPA from a food production practice to a multi-functional urban system component reflects growing recognition of its potential to enhance urban resilience, food security, and sustainability (Figure 1). As cities face increasing pressures from population growth, climate change, and resource limitations, UPA represents a promising solution for creating more sustainable and resilient urban food systems [32,47].

Meanwhile, discussions surrounding the relatively new concept of UPA have been growing among city residents, with considerable debate on its advantages and disadvantages. Many citizens view UPA positively, recognizing it as a key driver of urban food security and social justice [48–50]. This positive perception is particularly prevalent among socially vulnerable communities, given UPA's contribution to greater food sovereignty. Families with higher nutritional needs and financial security—such as those with children, retirees, and white-collar workers—also tend to value the health benefits associated with UPA. However, concerns persist regarding food safety and land use trade-offs [50,51]. For example, in Warsaw, Poland, UPA products have been associated with potential health risks due to heavy metal contamination in urban soils. Similarly, in Romania, urban residents often prefer land allocation for non-agricultural purposes to maximize economic returns [52].

2.2. Diverse Ways of Categorization

Typologies are a valuable tool for planning urban and peri-urban agriculture (UPA) and managing related resources, particularly from a policy-making perspective. UPA can be categorized based on various criteria, often used in combination to create multidimensional frameworks. Common categorization criteria include location, scale, objectives, ownership, product varieties, land tenure, and production intensity.

Urban and peri-urban agriculture (UPA) are commonly categorized based on their location, with intra-urban agriculture often involving small-scale, subsistence-oriented practices, whereas peri-urban agriculture tends to be more market-oriented and operates on a larger, commercial scale [53]. This distinction underscores the spatial and economic variances between agricultural activities within urban centers and those on the urban fringe. A categorization approach based on scale, proposed by Pearson et al. [54], identifies micro-scale practices—such as green roofs, walls, backyards, and street verges; meso-scale activities like community gardens and urban parks; and macro-scale operations, including commercial farms and greenhouses. This scale-based model captures the range of UPA practices, from individual household projects to extensive commercial enterprises. For instance, Freightliners City Farm in London, spanning just 2.5 acres, serves as a community hub where locals engage in gardening activities [55]. In contrast, Fanpu Farm in Chengdu, with an initial 3 million yuan investment, now covers 21 acres as a large commercial operation providing a variety of farm-based activities and services [56]. In another model, Santo et al. [57] introduced a typology that classifies UPA by site types such as school gardens, urban farms, community gardens, backyard gardens, edible landscapes, and building-integrated agriculture, emphasizing the diversity of UPA forms and their purposes within urban spaces. In Australia, the Stephanie Alexander Kitchen Garden Foundation runs the Kitchen Garden program in 225 schools, benefiting over 100,000 children annually by fostering learning, well-being, and sustainability [58]. Similarly, in the United States, NYC Parks GreenThumb, the nation's largest urban gardening program, explores more than 550 community gardens, offering local residents green spaces for relaxation, social interaction, and food cultivation [59]. The FAO et al. [32] UPA sourcebook further refines these categories, proposing four core types: home-based gardening, community-based and other shared gardening, commercial crop production, livestock and fisheries, and institutional food growing. This framework, structured by practitioner type and operational mode, provides a robust basis for analyzing UPA across diverse urban settings. Most recently, the European Forum on Urban Agriculture (EFUA) introduced a multidimensional approach for classifying UPA in Europe, using ten indicators across four dimensions—spatial, production, operational, and community—to comprehensively characterize UPA initiatives [60]. This multidimensional framework reflects the diversity and complex interconnections of UPA practices, offering one of the most holistic classification systems to date.

As these examples illustrate, UPA typologies vary significantly depending on the criteria applied. The diversity of typological frameworks underscores the complexity and multifunctionality of UPA, making it essential to consider the specific objectives and contexts when developing policies or conducting research. The available studies provide useful insights for adapting UPA typologies to the unique needs of different urban settings [40,45].

2.3. Multiple Functions Inter-Wined with Urban Development

Urban and peri-urban agriculture (UPA) is increasingly recognized for its multifaceted contributions to urban food security, nutrition, and resilience, particularly as an adaptable response to growing urban challenges. One of UPA's primary functions is to enhance food accessibility and nutritional intake for urban populations. In low-income urban households, UPA often serves as a critical subsistence source, bolstering daily nutritional intake [61,62]. For wealthier regions and households, UPA helps improve access to fresh, nutritious food by shortening supply chains and ensuring higher food quality and diversity, thus reducing reliance on distant imports. However, the extent to which UPA enhances food self-sufficiency varies across regions. Recent studies by Weidner et al. [63] show that UPA's contributions can range from minimal (1%) to over 100%, depending on local factors. For example, peri-urban farms in cities such as Melbourne and Sydney in Australia supply over 97% of the states' fresh vegetables [64]. In contrast, UPA's role in food security in low-income countries, particularly in parts of Africa, remains constrained by land use and resource limitations [65].

With an evolving understanding of UPA's interactions with socio-economic and ecological urban systems, there is growing acknowledgment of its broader roles in urban development [20,21]. As an intersectional industry, UPA merges the agri-food sector with urban environments, facilitating transformations within primary industries and food supply chains through innovations in production systems and business models. This adaptation has the potential to stimulate economic development and income generation at both the urban and household levels [24,66]. For low-income households, UPA can directly supplement incomes while also reducing food expenditures, thereby offering economic advantages to marginalized urban populations [67]. In the social domain, diverse UPA models foster social inclusion and community cohesion, particularly for vulnerable populations. Typologies such as community gardens, intercultural spaces, accessible gardens, and care farming initiatives provide environments where individuals from various socio-economic backgrounds—including those who are marginalized, unemployed, disabled, or recently migrated—can engage in shared activities, fostering cross-cultural and intergenerational exchanges [68–70]. Additionally, UPA offers recreational and leisure benefits to the broader public, with activities such as sightseeing, farm-to-table experiences, and agro-tourism [45,71], thereby enhancing quality of life in urban areas. Environmentally, UPA generates green spaces within and around cities, delivering valuable ecosystem services, including nitrogen sequestration, water management, pollination support, and biodiversity enhancement [46,72,73]. Moreover, by shortening supply chains and facilitating resource recycling along the urban-rural interface, UPA contributes to reducing greenhouse gas emissions and can alleviate urban heat island effects under optimized practice conditions [74]. In terms of resilience, UPA's significance for urban sustainability and crisis management has gained renewed emphasis, particularly in response to recent disruptions such as the COVID-19 pandemic. Evidence during the pandemic highlights UPA's role in supporting local food systems when traditional supply chains encountered substantial breakdowns, underlining UPA as a vital element of urban resilience [22,75]. Beyond food security, UPA initiatives offer psychological, social, and health benefits, promoting community well-being and providing citizens with spaces for mental and social recovery during crises [76].

As UPA continues to evolve, cutting-edge scientific and technological innovations are increasingly integrated into its practices, enhancing its contributions to urban sustainability, resilience, and food security. For example, emerging digital tools and precision agriculture technologies are being applied to optimize resource efficiency, monitor plant situations, and improve production. Innovations such as vertical farming and biotechnological advancements contribute to higher yields and better nutritional quality in compact urban spaces. Resource recycling technologies and land management tools amplify UPA's environmental benefits by promoting waste reduction, energy efficiency, and sustainable land use, aligning UPA practices with broader sustainable goals and smart city initiatives [77]. Together, these technologies advance UPA's capacity as a transformative force within urban systems, supporting local food security, economic opportunities, environmental services, and community well-being. The following sections will examine these advancements in detail, analyzing their application in UPA and their potential to reshape the urban agri-food landscape.

3. Review of Advanced Technological Innovations in Urban and Peri-Urban Agriculture

In this section, we categorize technological innovations in UPA into four types based on their purpose, with specific technologies related to each type are discussed in detail. Firstly, improving productivity and product quality is a key goal of UPA, in which digital technologies and biotechnology play significant roles in achieving high-quality food production and supply. Since both digital technologies and biotechnology encompass a wide range of tools, they are introduced separately in Sections 3.1 and 3.2, respectively. Secondly, space and resource limitations are common challenges for UPA compared to traditional rural agriculture; therefore, space-saving production systems and related technologies are considered key solutions in urban food systems and are discussed in Section 3.3. Thirdly, as the development of a circular economy becomes increasingly important for achieving the Sustainable Development Goals, the role of UPA in facilitating resource recycling and environmental sustainability in cities need to be emphasized. Therefore, UPA technologies supporting ecological functions are introduced in Section 3.4. Lastly, from a management perspective, technologies and tools that assist policy makers in evaluating and managing UPA land use, a critical and challenging part, are elaborated in Section 3.5.

3.1. Digital Technology

Digital technologies are increasingly applied in the agri-food industry, playing a key role in improving food system resilience and driving transformation [78,79]. Particularly in metropolitan areas, where innovation is at the forefront and labor is a high-cost resource, digital transformation is an inevitable trend that enables data-driven decisions and labor-saving activities throughout the food supply chains [80].

Defined as technology that generates, stores, and processes data, the digital technology covers a variety of data-based tools and devices, such as the Internet of Things (IoT), big data (BD), artificial intelligence (AI), robots, and blockchain technology (BCT). In UPA, these technologies and tools are increasingly observed under R&D and application, in most cases in combination in practice [81]. Specifically, the Internet of Things (IoT) sets the foundation enabling other digital tools in data acquisition, processing, and analytics to support informed decisions about crop management, environmental control, and resource utilization [82–84]. Based on real-time data collected through physical devices such as the different types of sensors, the use of IoTs facilitates the primary automation of various urban farming tasks using integrated systems such as automated irrigation systems, environment control systems, and nutrient delivery systems [85]. These settings are widely applied in vertical farming, urban greenhouses, rooftop gardens, and community gardens. Combined with remote sensing, cloud computing, and others, IoT-based tools like mobile applications could offer urban producers real-time notifications from the field, as well as prediction and guidance in production activities [78,86]. For example, saffron cultivation, which has great potential for wide application in UPA, is highly sensitive to various environmental factors that are difficult to regulate in traditional farming systems. To address this challenge, an IoT-based saffron cultivation system was developed recently, enabling precise control of numerous agronomical variables within greenhouse environments. By leveraging real-time data collection, analysis, and storage, this system optimizes environmental conditions and supports efficient farm management through advanced digital technologies [87]. In Singapore, IoT-based urban farming is emerging as a key strategy to achieve the nation's "30 by 30" food security target. Wireless sensors are utilized to monitor environmental parameters and optimize growth conditions. A notable innovation involves the use of nanoparticles as nanosensors injected into plants to detect subtle changes at the molecular level, which helps urban farmers to identify diseases and pests before they are visible. Private sector companies, such as CrowdFarmX, are playing active roles in this transformation, offering IoT monitoring systems and data analysis on climates and soil conditions. These companies also provide shared platforms that connect farmers with agronomists and technologists, enabling them to develop advanced farming protocols and automate their farming practices [88].

Further, the addition of advanced technologies like big data and artificial intelligence (AI) considerably improves data analysis capacities and decision-making precision by managing vast amounts of data and using predictive analytics and optimization algorithms [81,89]. This combination is often observed in smart farming systems, such as to define various parameters in smart irrigation, lighting, weed detection, yield prediction or disease identification, fruit or crop classification, and fruit counting, achieving a dramatic increase in the level of automation in UPA activities [90–93]. For example, in Multiponics Vertical Farming systems, AI is employed to perform essential functions such as minimizing energy, chemical, and water consumption, as well as optimizing soil usage. Advanced AI algorithms, including deep learning models, have been developed to enable precise data analysis and decision-making. While promising, the application of these advanced models in vertical farming is still in its nascent stages, leaving substantial room for further research and development [94].

Similarly, the development of agricultural robots tailored for UPA has been on the rise, driven by the growing need to reduce labor requirements, although this technology also remains in its early stages and is not fully market-ready. Agricultural robots can be either fully autonomous with complex algorithms embedded or semi-autonomous targeted for specific phases of production activities, implemented in repetitive tasks to reduce human workload and to optimize time and cost regarding soil preparation, irrigation, plant protection, pruning, harvesting, surveillance and control, and mapping [95]. For example, an agricultural R&D company in Belgium has developed a fully autonomous strawberry picking robot capable of completing the entire process of detecting ripe fruits, harvesting them without causing damage, and placing them in containers [96]. More UPA-focused innovations, such as CityVeg from Greece, which offers automatic monitoring and management of urban gardens, and Multi-Agro from Indonesia, which uses a mobile app to facilitate home-scale self-plantation, have shown promising results during the R&D phase. However, they still require further testing and validation in real-world applications [97,98].

More recently, the rapid development of blockchain technology has also driven the digital transformation in UPA and the entire agri-food supply chain. Briefly, the blockchain is a data structure designed to support safe and efficient data storage in chained blocks. It provides a decentralized, immutable, transparent, reliable, and automated system for real-time monitoring and decision-making [99,100]. In the agri-food sector, the blockchain technology is often applied to establish traceability systems, which could contribute to a range of objectives such as the automation and improvement of agri-food supply chain management, reductions in food recall incidents and the automation of the recall process, reductions in food loss and waste, as well as nutrition, economic, and resource losses related to food loss [99].

In summary, while the digital technologies discussed offer unprecedented opportunities for UPA in addressing urban food security and environmental sustainability, their applicability varies by context. For example, IoT-based systems are highly effective in controlled environments, such as vertical farming and urban greenhouses, where environmental factors can be precisely monitored with automated responses implemented. Building on IoT capabilities, artificial intelligence (AI) and big data play a transformative role in smart farming systems by enabling predictive analytics for crop management. However, these technologies require substantial data and computational resources, making them more suitable for regions with robust IT infrastructure and research institutions, such as advanced metropolitan areas in Asia and the U.S. Agricultural robots, though still in the early stages, show potential in regions with high labor costs and strong demand for labor-saving technologies.

Nevertheless, several barriers need to be addressed to fully realize the potential of these technologies [101]. A major drawback is the high costs of both initial implementation and long-term maintenance, especially in metropolitan areas. The adoption may fail if limited economic returns are realized within a short period [102]. Other challenges, such as privacy concerns and lack of regulation, also require further attention and efforts from policy makers, practitioners, and researchers [103,104].

3.2. Biotechnology

Biotechnology involves developing or modifying products utilizing living organisms or their substances, and has become widely used in UPA [105]. It can improve the efficiency and sustainability of UPA, offering promising prospects for meeting urban food demands and ensuring environmental sustainability [106,107]. Biotechnology is generally applied in UPA to improve production through molecular breeding, biofertilizers, and biocontrol agents.

Typical molecular breeding technologies include genetic modification, genome editing, and genomic selection, improve crop performance and adaptability through genetic improvement, thereby increasing productivity, quality, and resistance. In the UPA context, it is particularly important to develop crop traits that are well-suited to the confined cultivation environment, such as compact shape, short production cycles, the ability to thrive under low light conditions, and high nutrient availability [108–110]. For example, Kwon et al. [111] developed a trait-stacking strategy and used one-step CRISPR-Cas9 genome editing to restructure vine-like tomato plants into compact and early yielding plants tailored for use in UPA. Safaei et al. [112] performed genetic analyses using an intraspecific mapping population that segregated for fruit color, fruit shape, and plant height, successfully breeding ornamental tomatoes that are better suited for UPA. In Africa, *Solanum aethiopicum* is an important indigenous vegetable with high nutritional value and medicinal properties, commonly cultivated in urban and peri-urban areas. Molecular breeding techniques have been employed to identify elite genetic resources for the development of improved varieties of *S. aethiopicum*, offering potential economic and nutritional benefits to numerous smallholder farmers across the region [113].

Bio-based agricultural inputs, such as biofertilizers and biocontrol agents, are often used in UPA to facilitate eco-friendly production activities and long-term productivity of soil. Biofertilizers refer to fertilizers containing living microorganisms like nitrogen fixers, phosphate solubilizers, sulfur oxidizers, or organic matter decomposers, which improve soil quality and nutrient absorption in a cost-effective, efficient, and renewable way [114,115]. According to the case of shallot cultivation in Tual City of Indonesia, the addition of chicken manure combined with biofertilizer could increase the dry weight of shoots and bulbs, resulting in a higher yield of shallot bulbs up to 14 tonnes per hectare [116]. In hydroponic systems that are widely applied in UPA, the treatment of eco-friendly biofertilizers was proven to be able to optimize the lettuce growth and nutrient content, indicating their effectiveness in enhancing nutrient availability and reducing the dependence on chemical fertilizers [117]. Notably, composting is a common way to generate biofertilizers in urban areas, details of which will be discussed in Section 3.4. Similarly, biocontrol agents provide a non-chemical method in plant disease management through using natural enemies of agricultural pests, pathogens, and weeds to control their infection. An example from the city of Abha in the Kingdom of Saudi Arabia used the plant-growth-promoting rhizobacteria (PGPR) as a biocontrol measure, which was effective in suppressing nematode-related diseases of bean plants and promoting plant growth [118]. It was reported that bioagents are increasingly used in agri-horticultural ecosystems, which have a profound impact on UPA [119]. Upon using bio-based agricultural inputs, urban soils are less disturbed due to reduced application of extensive chemical fertilizer and pesticides; not only could healthy produce be provided to city dwellers, but also the urban ecosystem is better protected and maintained [120].

While offering transformative potential for UPA, biotechnology also presents new risks and challenges such as fragmented market regulation and consumer skepticism toward biotech crops, particularly in urban settings [27,115,121]. In the field of biological breeding, inadequate intellectual property protection has emerged as a critical issue, potentially obstructing equitable and efficient technology transfer. At the same time, high licensing and technology transfer fees further restrict the adoption of these innovations in underdeveloped regions, thereby limiting their potential to deliver socioeconomic benefits. Bioethics has become another indispensable topic in discussions surrounding biotechnology. Concerns are growing over the genetic modification of plants and animals [122], which raises pivotal questions such as, How should the potential risks and unintended consequences of these technologies be assessed? Are there ethical boundaries or "red lines" that scientists and stakeholders should be cautious not to cross? Addressing these issues is essential to ensure that biotechnology advances in ways that are not only scientifically robust but also socially responsible and ethically accepted.

3.3. Building-Integrated Agriculture System

Building-integrated agriculture (BIA) represents a typical urban agricultural typology, referring to agricultural production integrated within or atop buildings. Compared to traditional ground-based systems, BIA offers the distinct advantage of space efficiency, making it an ideal solution for densely populated cities. This form of agriculture is often termed "Zero-acreage Farming" or "ZFarming", emphasizing its minimal land requirements [47].

BIA is generally categorized into two main approaches: rooftop farming and indoor vertical farming. Rooftop farming includes soil-based gardens and rooftop greenhouses. Soil-based rooftop gardens often employ traditional cultivation techniques with engineering adaptations to manage soil weight and optimize irrigation and drainage for roof structures [38]. These gardens, compared to protected soilless systems, are characterized by their capacity to cultivate a broader range of crops, though with lower productivity [123]. A notable example is the Thammasat Urban Farming Rooftop in Bangkok, which integrates traditional terraced landscaping with modern green roof technologies and utilizes the building's natural topography to establish tiered artificial soil layers [124]. This innovative design maximizes rooftop space, enabling the cultivation of over 40 varieties of edible crops. Rooftop greenhouses, on the other hand, combine the benefits of traditional greenhouse practices with the maximization of building spaces and the proximity to urban consumers. Rooftop greenhouses apply more advanced technologies than soil-based rooftop gardens, making them well-suited for commercial applications [123]. While they can be adapted to various sizes, achieving economic viability may require sufficient space to offset costs. These factors have led to their greater prevalence in regions with established urban rooftop agriculture practices, such as North America and Europe. For example, Gotham Greens established the first commercial rooftop greenhouse in New York, covering over 15,000 square feet. The facility incorporates climate-controlled hydroponics, transparent greenhouses for natural light, and renewable energy sources such as solar and wind power, enabling the production of over 100,000 pounds of fresh, sustainable leafy greens annually [125].

The second BIA type is controlled-environment vertical farming, conducted in fully enclosed indoor settings. Unlike rooftop systems, vertical farming is entirely independent of outdoor climate, allowing for full control over growth conditions and achieving year-round production, consistency in crop quality, and efficient resource use [126,127]. This type of farming requires advanced technology for regulating light, temperature, humidity, and nutrients, making it a high-tech agricultural model often referred to as the "Plant Factory with Artificial Lighting" (PFAL) in Asia and "indoor vertical farming" in Western contexts [40,128]. The indoor vertical farming systems rely on several advanced technologies, including artificial lighting, soilless cultivation methods, and modern greenhouse technologies such as sensor-based monitoring, automation, and artificial intelligence. Each component contributes to the high resource efficiency and productivity of vertical farms. Specifically, various light sources, such as incandescent, fluorescent, and high-intensity discharge lamps, are used in vertical farming. However, light-emitting diodes (LEDs) are increasingly preferred due to their high photosynthetic efficiency, energy savings, and customizable spectral output for crop growth [129,130]. LED technology is continually optimized through industry–academic collaborations—such as those by Panasonic, Toshiba, GE, and Fluence—aiming to reduce energy consumption and optimize light spectra for specific crop needs. The soilless cultivation techniques, including hydroponics and aeroponics, are fundamental to vertical farming, as they enable efficient nutrient delivery and minimize soil-related pathogens. In hydroponics, plants are grown in nutrient-enriched water, while aeroponics involves spraying roots with nutrient mist, reducing water and fertilizer requirements [77,131,132]. Recent advancements, such as ultrasonic atomization, improve nutrient absorption and reduce energy usage by producing fine mist particles less than 100 nm in diameter [133]. These techniques are vital in maximizing resource efficiency in dense urban spaces. The controlled-environment vertical farming also leverages digital tools such as sensor networks, automation, data analytics, and artificial intelligence to optimize growing conditions, reduce operating costs, and ensure consistent crop quality. For example, sensors continuously monitor light, humidity, and nutrient levels, while AI-driven algorithms adjust these parameters for optimal plant health [38]. Such digital innovations support sustainable productivity, especially in urban metropolitan contexts where reliable, high-quality local produce is increasingly in demand.

Recent applications in highly mechanized cities, including Singapore, London, and Dubai, demonstrate the potential of indoor vertical farming to supply fresh produce close to urban populations, reduce dependency on imported food, and increase urban resilience to supply chain disruptions [40,134]. Sky Greens, the world's first commercial vertical farm from Singapore, employs its proprietary "a-go-gro" rotating vertical cultivation system, which utilizes automated rainwater collection for irrigation and power generation, to drive its hydroponic operations [135]. Compared to conventional farming methods, Sky Greens delivers 5–10 times higher yields per hectare. Singapore's efforts to meet 30% of its nutritional needs locally by 2030 are largely supported by these high-tech vertical farms, reflecting a growing trend in metropolitan areas to invest in vertical farming as a part of sustainable food security strategies [36]. Additionally, countries with limited resources, such as those in the Middle East, have recently demonstrated increased interest in and begun actively adopting indoor vertical farming [36]. For instance, the Crop One Holdings farm in Dubai, developed in collaboration with the U.S. vertical farm company Crop One Holdings and the local catering provider Emirates Flight Catering, is currently the largest vertical hydroponic farm in the world [136]. By employing cutting-edge technologies such as hydroponics and artificial intelligence, the farm produces over one million kilograms of high-quality leafy greens annually.

In summary, building-integrated agriculture represents a promising model of urban and peri-urban agriculture that meets the demand for local food production, environmental benefits, and urban resilience. In particular, the mobility feature of vertical farms enables their establishment in most urban settings, facilitating continuous and highly efficient production. This significantly enhances production quality while supporting the development of localized food supply chains. Studies have shown that vertical farming can achieve yields over 1000 times greater than those of traditional open-field farming [137]. In cities like New York, Tokyo, and Paris, vertical farms are increasingly used not only to provide fresh, local food but also to improve urban air quality and mitigate heat through green infrastructure [45,72]. Additionally, the environmental and community benefits of rooftop farming make it a popular sustainable urban and peri-urban agriculture solution that aligns with climate resilience goals. Through technological advances and integrated systems, BIA aligns with broader urban sustainability goals, offering a scalable solution for cities aiming to improve food security and environmental health in the face of urbanization.

Despite its benefits, controlled-environment vertical farming faces significant challenges, primarily the uncertainty of the building itself and high energy costs associated with maintaining artificial lighting and climate control, which can impact economic feasibility and environmental sustainability [138]. For example, the Via Gandusio rooftop garden in Bologna was discontinued due to building renovations, while commercial farms such as UF002 De Schilde, AeroFarms, and AppHarvest faced bankruptcy due to high costs. In such vertical farming systems, energy expenses alone account for approximately 28% of total costs, significantly driving up operational costs while also contributing to higher greenhouse gas emissions [139]. Efforts to develop more energy-efficient lighting and climate control technologies are ongoing, aiming to enhance vertical farming's economic and ecological viability in urban contexts. For instance, innovations in renewable energy integration, such as solar panels and energy recapture systems, are being explored to offset electricity demands and reduce the environmental footprint of vertical farms [140].

3.4. Resource Recycling Technology

One of the major co-benefits of UPA lies in its contribution to the urban environment, green infrastructure, and the related ecosystem services [141]. With the continuous technological innovation to achieve environmentally friendly production, UPA can be a solution to improve the environmental performance of agricultural systems and promote circular economy and sustainable development in sustainable cities [142–145].

A range of technologies applied in UPA practices, such as those involved in urban organic waste conversion, water recycling, and nutrient cycling, help maximize the utilization of all resources in the city and optimize the food-energy-water-waste nexus [146]. The technologies for urban organic waste conversion in UPA primarily include biological processing such as composting, anaerobic digestion, fermentation, and the use of microorganisms. These methods have proven to be promising in managing the abundant urban waste generated from food, livestock, cropping, and plant residues [147]. Composting converts organic components of urban waste into biofertilizers through an aerobic decomposition process, producing new resources for energy fuel after combustion. This process satisfies the fertilizing needs of urban farming and facilitates energy recovery [148–152]. Anaerobic digestion, fermentation, and the use of microorganisms operate through processes such as hydrolysis, acidogenesis, and acetogenesis, which consume less energy and can generate biofuels like biogas and biomass and high-value byproducts like animal feed. These methods are typically used in urban food waste treatment plants and on-farm facilities [153–156]. Polo et al.'s [157] study on organic municipal solid waste (OMSW) in the Metropolitan Area of Barcelona revealed that the existing waste management system has the potential to substitute up to 8% of the total demand for nitrogen (N), phosphorus (P), and potassium (K) (NPK) required by UPA through composting. The system could also reduce environmental impacts by up to 39% and achieve a 130% reduction in global warming.

Water recycling technologies are specifically reflected in rainwater harvesting (RWH) and wastewater treatment. Generally, UPA is considered to be a form of green infrastructure, converting impervious areas into urban gardens or green roofs (GR) to reduce urban surface runoff and collect rainwater, which is used to supplement urban irrigation water demand [158–162]. Specialized RWH equipment, such as hoop houses, may be used in the process [147,163]. In building-integrated agriculture, the integrated rooftop greenhouse has successfully managed to use collected rainwater for crop irrigation [164]. A study on the efficiency of green roofs has shown that in Johannesburg, South Africa, direct water savings from green roofs could account for 5.3–7.1% of the city's water conservation targets. Similarly, in São José dos Campos, Brazil, rainwater harvested by green roofs was estimated to be 1.2–2.4 times the city's annual water demand [165]. For wastewater treatment, urban agricultural landscapes, such as wall-based green facades and wetland systems, represent viable solutions for on-site greywater treatment and crop production [47,166]. Additionally, many mature technologies like membrane filtration, advanced oxidation processes (AOPs), and biological treatment systems are applied to filter urban wastewater, making it suitable for agricultural irrigation [167]. It was estimated that the water cycling performance of vertical greening systems (VGS) in certain cities could enable the recycling of between 44% (Lisbon) and 100% (Berlin, Istanbul) of accumulated rainwater roof runoff, provided that water shortages during dry months are supplemented with greywater [168].

Technologies around renewable energy are increasingly developed and applied in UPA, particularly in the energy-consuming production systems such as indoor vertical farming. For example, photovoltaic energy was found sufficient to provide electricity for vertical farming operations for most crops, indicating that the use of renewable energy could be efficient to support energy-intensive operation of UPA systems [138,169]. However, there remain challenges in circular economy-related technologies, such as high cost, high technical requirements of equipment, and lack of professionals in this field, requiring further research and development of sustainable models in the context of urban production systems [19,170]. On a more specific level, there still remain technical gaps in the practical application of the existing technologies. For instance, adding organic or inorganic nutrients to soils with low-quality organic matter can accelerate the mineralization of organic material, depleting essential carbon and nutrient reserves needed for soil health. This highlights the need for tailored technological advancements to support sustainable soil management practices [157]. Additionally, implementing integrated recycling systems for urban rainwater, commercial waste, and industrial waste remains highly complex. Current research often focuses on isolated technical aspects, limiting progress toward comprehensive frameworks for effective multi-dimensional recycling solutions [168].

3.5. Land Management Technology

Land is the most important resource in agricultural production. However, in the urban ecosystem settings, the urbanization of land is found even faster than the urbanization of population, which not only leads to the overload of land resources but also accelerates the non-agricultural transformation of a large number of high-quality cultivated land resources [171]. It becomes unprecedentedly crucial to use the limited land resources wisely to ensure food security and maintain ecosystem sustainability.

A main category of technologies to assist with land resource management are geospatial tools such as remote sensing, satellite positioning systems, and geographic information systems (GISs) to support land planning and monitoring in UPA [172,173]. Specifically, remote sensing uses electromagnetic radiations reflected or emitted from the Earth's surface to monitor and assess the conditions of urban farmland and crops [174,175]. Based on the different sensor platforms, remote sensing technology can be categorized into ground-based, aerial, and satellite remote sensing. Ground-based remote sensing deploys sensors such as spectrometers, soil sensors, and LiDAR on fixed measurement points, unmanned ground vehicles, or portable devices, enabling the remote identification and collection of data by emitting or detecting signals that interact with surface soil, crops, and other elements [176]. It is particularly suitable for high-resolution monitoring in small-scale areas, such as urban farms. Aerial remote sensing usually installs thermal infrared or microwave radar sensors on aircraft and drones, which emit microwave signals that penetrate through clouds and vegetation and receive the reflected signals from the surface to collect data from the target area [177]. It offers significant advantages in observing land use patterns in densely built urban areas. Satellite remote sensing primarily collects surface information from Earth's orbit by sensors mounted on satellite platforms, enabling long-term observation and data acquisition of large-scale areas to support urban agricultural land use decision-making, which is more frequently utilized in countries with advanced satellite infrastructure, such as the United States, Germany, and Canada [178].

The satellite positioning system is used to generate complex satellite imageries of urban landscapes based on more reliable and precise positioning information from constellation signals [179–181]. For instance, an agricultural cooperative in Shanghai, China, has utilized the BeiDou Navigation Satellite System, an advanced satellite positioning system, to enable autonomous navigation and operation of agricultural machinery. This innovation fosters the practical application of smart agriculture and supports efficient resource management in UPA.

GIS promotes urban farmland mapping by managing, editing, and analyzing the volume of subject-specific urban spatial data [182–184]. In practice, GIS is often integrated with remote sensing and satellite positioning systems, which provide authoritative geospatial datasets, offering crucial support for urban decision-makers in UPA land use planning. For example, in Los Angeles, USA, UC Cooperative Extension Los Angeles has used GIS to create an interactive map that categorizes UPA land into four types: school gardens, community gardens, urban farms, and nurseries, providing a data-driven tool for informed UPA management [185].

Overall, land management technologies provide decision-makers with valuable tools to optimize land use in UPA. However, these technologies still face several limitations in the long term. On the one hand, the complexity of urban areas, combined with dynamic land cover types, may affect the accuracy of remote sensing and satellite positioning data, limiting their effectiveness in urban agricultural planning [186]. On the other hand, high costs, lack of specialized skills, and regulatory constraints related to procurement and operational expenses have prevented these technologies from fully realizing their potential in some regions of the Global South, widening the gap in urban agricultural development worldwide [187].

4. Challenges in Technological Innovations

Urban and peri-urban agriculture (UPA) technologies hold significant potential for addressing food security, environmental sustainability, and economic development in urban areas. However, in the process of developing and implementing UPA technologies, each stage presents unique challenges. Understanding these issues and barriers in each phase is essential for scaling the technologies and advancing UPA as a sustainable practice [188].

The research and development (R&D) stage is pivotal for UPA innovation as it establishes the foundation for sustainable and productive urban agricultural solutions. However, several challenges hinder the progress of R&D in UPA, with one of the main obstacles being the high costs and resource demands, particularly for infrastructure-intensive technologies such as controlled-environment vertical farming systems and digital innovations. These technologies require substantial investments in both hardware and software, as well as high energy costs throughout the development process [88,189–192]. Since UPA is a relatively new field with inadequate recognition from both policy and public, there is always a lack of funding mechanisms and stable financial support in UPA, which are available to more traditional agricultural sectors [20,77,193]. This has made it difficult for many small- and medium-sized enterprises to invest in R&D for innovative technologies, particularly given the high risks associated with R&D, where failure is a common outcome at the early stages [194]. For research institutions, inadequate long-term funding would also result in talent shortage and a lack of research capability, further limiting their support for UPA development [195]. Another key issue is that many of the currently developed technologies fail to address real-world challenges effectively. A primary reason could be that most technological innovations remain at the experimental phase and have not undergone the necessary maturation and refinement needed for long-term practical application in diverse urban contexts, which may be attributed to insufficient funding, strict regulations, and the inherent complexity of the technologies themselves [41,196]. The lack of dialogue or collaboration mechanisms between research entities and UPA practitioners also exaggerates this gap. On the one hand, researchers often design and develop technologies based on theoretical models, which are often idealized while overlooking the complex, on-the-ground realities and needs of UPA [197]. On the other hand, UPA practitioners, especially those from marginalized or small-scale operations, often lack access to the latest research findings and technological innovations [198]. This gap in communication limits continuous feedback and adaptation of technologies with great potential, hindering the development of practical and effective solutions. Additionally, the interdisciplinary nature of UPA necessitates collaboration across fields such as agricultural science, engineering, environmental science, and urban planning. However, coordinating efforts across these diverse disciplines is often challenging, which impedes holistic technological development and innovation in the sector [54,199]. To address this, there is an urgent need for more cross-disciplinary research initiatives and stronger public-private partnerships to foster innovation [200].

The dissemination and extension stage focuses on the effective spread and implementation of UPA technologies, crucial for bridging the gap between innovation and its adoption among practitioners, policymakers, and other stakeholders. However, a lack of institutional frameworks and structured technology extension systems has been observed in some regions, where UPA practitioners do not receive adequate training and technical support in production and managing practices, particularly in terms of innovative solutions [47,201,202]. Incubators and extension institutions in these areas frequently lack resources or the technical expertise necessary to effectively scale UPA technologies, which restricts technology transfer to those who will benefit most [127]. Further, the concentration of intellectual property (IP) rights for many advanced UPA technologies in more developed regions has exacerbated the global inequalities, leaving underdeveloped regions in the Global South with limited access to many technological innovations that could improve their food security and local economies [203]. This problem highlights the need for targeted strategies and capacity-building programs to enhance technology availability in underserved regions [204]. Additionally, ethical concerns surrounding the use of UPA technologies are becoming increasingly important, which hinders the effective dissemination and scalability of certain technologies. Ethical issues can arise in various forms, such as concerns over data privacy, especially with the widespread use of IoT-based systems and AI in UPA. There is also the potential for exploitation of marginalized communities, who may lack the knowledge or resources to fully benefit from new technologies, or whose land rights could be undermined by the introduction of new agricultural practices or technologies. Furthermore, the genetic modification of crops for urban farming or the use of biotechnology to boost production may also raise public concerns about food safety and the environmental impacts of such innovations. Improved communication and outreach programs and demonstration projects are also needed to raise awareness of a broader public on the benefits of UPA innovations in real-world urban settings [205].

For the application and commercialization stage, a main concern is economic feasibility, as many UPA technologies are resource-intensive, with high energy, labor, and maintenance costs [206]. These high costs make it difficult for UPA enterprises to achieve consistent profitability, limiting the scalability of some innovative production systems [106,207]. Additionally, UPA-produced goods are often marketed as premium products due to their high production costs, targeting a niche, affluent market. This market segmentation not only limits the broader social acceptance and uptake of UPA products but also makes these business models more vulnerable to market fluctuations and economic uncertainties [134]. Beyond business strategies of the practitioners, the availability and quality of public infrastructure and equipment play a crucial role in the effective application and scaling of innovative UPA technologies [208]. For example, the lack of affordable public energy infrastructure would increase the operational costs for energy-intensive technologies like controlled-environment agriculture systems and vertical farms [209,210]. In underdeveloped regions, such as parts of Africa, the absence of digital infrastructure and data networks limits the application of IoT-based systems, which are essential for UPA and food system transformation [211]. Furthermore, the lack of well-structured urban zoning and land use policies also hinders the transition from experimental to commercial phases [27,212].

To summarize, technological innovation in UPA is a multi-stage process, with each phase presenting distinct challenges that affect the development, dissemination, and commercialization of these innovations. Addressing these barriers requires a collaborative approach among all actors, including researchers, policymakers, industry stakeholders, NGOs, international agencies, and farmers. Figure 2 illustrates the roles of different actors throughout the technology innovation cycle. Through collective actions, including awareness-raising, increased funding, technology development adapted to practical needs, targeted dissemination strategies, innovative business models, and structured public policies and programs, UPA can be transformed into an integral component of sustainable urban development.

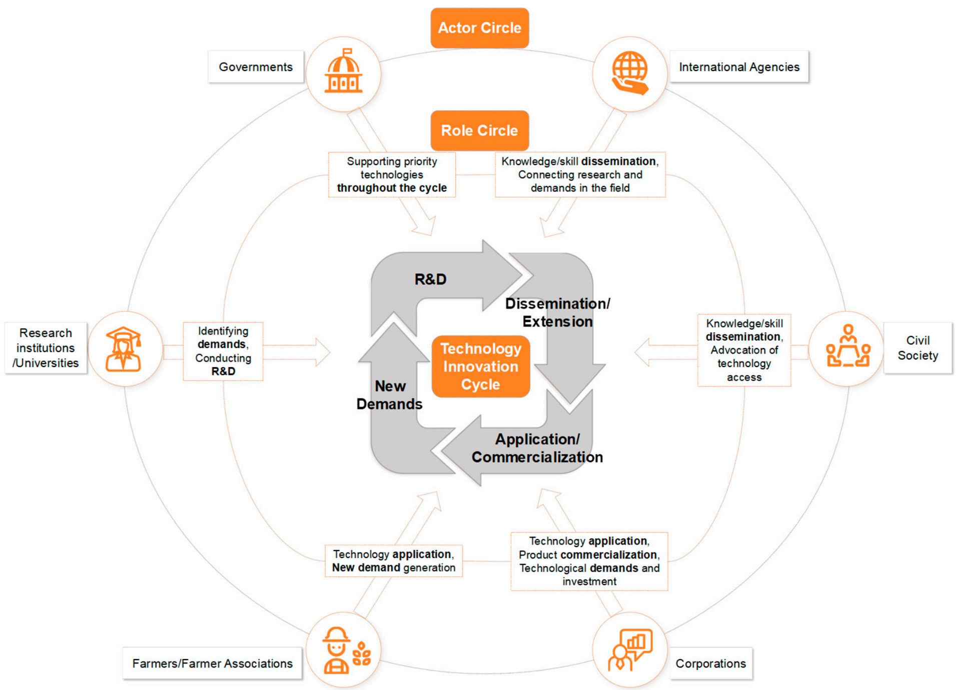

Figure 2. Actors involved in UPA technological innovations and their distinct roles throughout the innovation process.

5. Conclusions and the Way Forward

Maintaining consistent innovation is essential for unlocking UPA's full potential, contributing to improved food security, and addressing urban socio-environmental challenges. As cities transition toward resilient and sustainable futures, comprehensive studies are needed to explore how technological advancements can strengthen UPA's role in urban development while identifying the challenges it faces.

This review highlights the growing relevance of UPA within sustainable urbanization. We provided an overview of UPA's history, definition, and typologies, offering insights into technological innovations in this emerging field. Key advancements essential for UPA development were examined, including digital technologies and biotechnology, which are transforming food production and supply systems; building-integrated agriculture, which optimizes space utilization in urban environments; resource recycling technologies, which promote circular economy principles and strengthen urban-rural linkages; and land management technologies, which enable data-driven decision-making for land use. When effectively integrated, these innovations can support delivering reliable and sustainable food production and enhance UPA's contribution to urban food systems.

However, the path to fully integrating UPA technologies faces various obstacles. Challenges such as high initial costs, limited political recognition, and market uncertainties must be addressed to ensure broader acceptance and profitability. To further explore these barriers, we developed an analytical framework examining challenges across the stages of R&D, dissemination and extension, and application and commercialization of UPA technologies. A total of nine challenges, such as inadequate R&D investment, weak technology extension systems, and limited economic feasibility at each stage, among a total of nine challenges, were identified as key obstacles in advancing UPA technological innovations.

Looking forward, the successful development and scaling of UPA will require a holistic, multi-disciplinary, and multi-stakeholder approach, supported by strategic policy and governance. Firstly, policymakers and funding agencies should establish dedicated funding streams for UPA research and development (R&D). In particular, financial support should be ensured at the initial stage for capital-intensive technology areas to facilitate their development and implementation. Special emphasis should be placed on fostering interdisciplinary collaboration to address the complex and context-specific needs of UPA [213]. Public-private partnerships (PPPs) can play a crucial role in bridging resource gaps and facilitating the transfer of academic research into actionable, scalable solutions. Secondly, developing structured technology dissemination frameworks that include targeted extension programs and localized capacity-building initiatives is vital to ensure equitable access to UPA technologies. Special attention should be paid to underserved regions, particularly in the Global South, such as Africa and Latin America, through tailored training, technical support, and equitable intellectual property (IP) sharing agreements. Communication strategies such as demonstration projects and community outreach programs should also be scaled up to enhance public awareness and acceptance of UPA innovations. Thirdly, UPA business models must evolve to reduce production costs and enhance resource efficiency. This could include adopting renewable energy systems, optimizing labor and resource use, and exploring circular economy practices. Moreover, policymakers and industry stakeholders should develop subsidies, tax incentives, and financial tools to support UPA enterprises, particularly for the small and medium-sized enterprises during early-stage commercialization. Marketing strategies should aim to expand consumer bases beyond niche markets by emphasizing the sustainability and health benefits of UPA products. Lastly, it is critical to establish supportive environments for fostering UPA innovation. Governments should integrate UPA into urban planning frameworks, offering incentives such as zoning allowances, grants, and infrastructure development for UPA initiatives. Particularly in those underdeveloped regions where UPA activities face restrictions, both national and local authorities should take responsibility in improving the policy environment and supporting livelihood strategies, including UPA practices. International agencies should foster global cooperation and knowledge exchange to ensure the global advancement of UPA technologies, promoting inclusion and sustainability. Local stakeholders should be involved in the co-design and implementation of UPA technologies to enhance the adaptability of technologies to diverse socio-economic and climatic conditions, ensuring the alignment with local needs and preferences.

In practice, emerging cases worldwide have illustrated the potential directions for leveraging technological innovations in UPA development. From an R&D perspective, research institutions and universities have initiated projects and curricula in UPA through cross-disciplinary collaborations. For instance, the University of Colorado offers a certificate program in sustainable urban agriculture, integrating subjects such as geography, agriculture, economics, and environmental sciences [213]. Wageningen University & Research has included UPA as a core research focus, facilitating collaborative research projects among various institutes and interdisciplinary teams with diverse expertise [214]. Collaboration between the public and private sectors is also expanding, exemplified by the Horizon 2020 project, the European Forum on Urban Agriculture (EFUA). The initiative has engaged universities, research institutes, and companies in this field to establish a multi-stakeholder platform for advancing UPA research and innovation within the European context [215]. In terms of UPA technology extension, universities are playing a critical role in disseminating up-to-date knowledge and practical skills. A notable example is the Cornell Cooperative Extension (CCE) in New York, supported by the national Land-Grant system and Cornell University. The CCE is an education system that connects Cornell's world-class research expertise with local educators and stakeholders. Its Harvest New York program serves local UPA practitioners through educational programming, technical assistance, and applied research [216]. For the application and commercialization of UPA technologies, practitioners in China have diversified their business models by integrating educational programs for children and science-focused agricultural tours into their operations. By leveraging the innovative UPA farming systems to generate additional revenue streams, these initiatives help to offset the high costs associated with the adoption of advanced technologies [217].

From the research perspective, technological advancements continue to evolve, offering promising prospects for UPA innovation. For instance, replacing traditional soil substrates with nano-structured materials can significantly reduce the weight of growing media, making them more suitable for rooftop farming [218]. To address the high energy costs associated with controlled-environment vertical farming systems, the integration of multiple renewable energy technologies has been tested in greenhouses, aiming to achieve net-zero energy consumption [219]. The development and application of the superabsorbent hydrogels (SAHs) in soil could enhance water retention, thus supporting efficient water management and resource recycling in UPA [220]. Meanwhile, to further advance UPA, future research should focus on bridging the technological and socio-political gaps that currently limit its widespread adoption. Research efforts need to be directed toward developing affordable, scalable UPA technologies that are tailored to the specific challenges of urban environments, such as space constraints and resource efficiency. Future studies should also explore the integration of UPA with other urban initiatives, such as green infrastructure and waste management, to create more resilient and self-sufficient urban systems.

As urbanization accelerates, UPA is not just about growing food but represents a transformative movement that leverages innovations to build more self-sufficient, equitable, and livable urban societies. These innovations, which are globally relevant, provide solutions to urban food insecurity, environmental sustainability, and economic resilience, especially in rapidly urbanizing regions. By continuously advancing technological progress and addressing socioeconomic and policy challenges through collaborative efforts, UPA can evolve into an integral and scalable component of sustainable cities, serving as a driving force for urban resilience, prosperity, and a thriving future.

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