Emerging Techniques in Urban Agriculture for Enhancing Bioactive Compounds in Plant Foods

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Abstract
Global agronomy is an emerging field of research focused on developing and implementing sustainable agricultural practices worldwide. It aims to address critical challenges such as food security, climate change, and environmental degradation. By integrating multidisciplinary approaches from plant science, soil science, ecology, and socio-economics, global agronomy seeks to optimize crop production systems, enhance resource efficiency, and promote resilience in agricultural landscapes. This field also emphasizes the importance of local and traditional knowledge, technological innovation, and policy frameworks to foster sustainable development in diverse agro-ecological contexts.

Keywords: ***Global agronomy, sustainable agriculture, food security, climate change, environmental sustainability, crop production, resource efficiency, agricultural resilience, multidisciplinary research, traditional knowledge, technological innovation, policy frameworks.***

1.Introduction
Urban agriculture is increasingly recognized not only for its role in food security and sustainability but also for its potential to enhance the nutritional quality of plant foods. Recent trends in urban agriculture focus on innovative techniques and practices aimed at boosting the bioactive content of crops grown in city environments. Bioactive compounds, which include vitamins, minerals, antioxidants, and phytochemicals, play a critical role in promoting health and preventing chronic diseases. With growing urban populations and limited space, urban agriculture is leveraging vertical farming, hydroponics, aquaponics, and aeroponics to maximize yield and nutritional value. These methods enable the cultivation of plants in controlled environments where variables such as light, temperature, and nutrient availability can be optimized to enhance the synthesis of bioactive compounds(1).
In addition, the integration of smart technology and data analytics is revolutionizing urban farming practices. Sensors and automation systems provide real-time monitoring and adjustments, ensuring that plants receive the precise conditions they need for optimal growth and nutrient production. Urban farms are also experimenting with the use of organic and biodegradable inputs, such as compost and biochar, to improve soil health and promote the uptake of beneficial nutrients. Moreover, community-based initiatives and urban gardens are playing a pivotal role in educating urban dwellers about the importance of fresh, nutrient-rich produce, fostering a culture of health and well-being.
The emphasis on local and sustainable food production is driving research into crop varieties that are particularly suited to urban farming conditions and that exhibit high levels of bioactive compounds. Breeding programs and genetic modification are also being explored to develop plants that naturally contain higher concentrations of these beneficial substances. As a result, urban agriculture is not only addressing the challenge of food availability in cities but is also contributing to the improvement of dietary quality by enhancing the bioactive content of the food supply. This holistic approach to urban farming is poised to make a significant impact on public health, offering city dwellers access to fresher, more nutritious produce grown right in their communities(2).

2.Literature Survey
The literature on recent trends in urban agriculture aimed at improving the bioactive content of plant foods reveals a multifaceted approach that incorporates advanced cultivation techniques, technological innovations, and sustainable practices. Studies have shown that vertical farming and controlled environment agriculture (CEA) significantly

enhance the levels of bioactive compounds in plants by providing optimal growing conditions. For instance, research by Kozai et al. (2019) highlights how LED lighting systems in vertical farms can be tailored to specific wavelengths that boost the production of anthocyanins and flavonoids in leafy greens. Similarly, hydroponic systems, as discussed by Pérez-Almeida et al. (2020), offer precise control over nutrient delivery, which can be adjusted to increase the concentration of vitamins and minerals in crops like tomatoes and basil(3).

Aquaponics, combining hydroponics with aquaculture, has also been noted for its ability to enhance plant bioactive content through the use of nutrient-rich fish effluent. According to Love et al. (2015), this method not only supports sustainable food production but also enriches plants with beneficial compounds such as polyphenols and antioxidants. Additionally, advancements in soil health management, including the use of biochar and organic compost, have been shown to improve the bioavailability of essential nutrients, as noted by Lehmann et al. (2011)(4).

The integration of smart technologies in urban agriculture is another key trend. IoT-based monitoring systems and AI-driven analytics enable precise environmental control and data-driven decision-making, leading to improved crop quality. Studies by Ahmed et al. (2022) demonstrate how these technologies can optimize growth conditions to enhance the bioactive content of produce. Furthermore, urban agriculture initiatives often focus on cultivating heirloom and heritage crop varieties, which are naturally richer in bioactive compounds compared to conventional varieties, as highlighted by the work of Charrondière et al. (2013).

Overall, the literature indicates that urban agriculture is evolving through a blend of traditional practices and cutting-edge technology, with a strong emphasis on improving the nutritional quality of food through enhanced bioactive content. This trend not only supports urban food security but also promotes public health by providing city dwellers with access to nutrient-dense produce.

3.Existing and Proposed System

Current urban agriculture systems encompass a variety of methods designed to maximize space efficiency and crop yield in urban environments. Vertical farming stands out as one of the most advanced existing systems. Utilizing stacked layers and controlled environment agriculture (CEA), vertical farms like those implemented by companies such as AeroFarms and Bowery Farming optimize light, temperature, and humidity to enhance plant growth and bioactive compound production. Studies have shown that LED lighting in these systems can be customized to specific wavelengths to boost the synthesis of beneficial phytochemicals such as anthocyanins and flavonoids(5).

Hydroponic and aquaponic systems are also widely used in urban agriculture. Hydroponics, which grows plants in nutrient-rich water without soil, allows for precise control over nutrient delivery, thereby increasing the concentration of vitamins and minerals in crops. Aquaponics combines hydroponics with fish farming, where fish waste provides an organic nutrient source for plants. Research indicates that aquaponic systems can significantly increase the levels of polyphenols and antioxidants in plants due to the organic nature of the nutrients.

Community gardens and rooftop farms represent another facet of existing urban agriculture systems. These projects not only contribute to local food security but also encourage the growth of heirloom and heritage crop varieties, which are often richer in bioactive compounds. Initiatives like New York’s Brooklyn Grange and Chicago’s The Roof Crop exemplify successful implementations of such systems(6).

Proposed Systems

Future trends in urban agriculture are poised to incorporate even more sophisticated technologies and sustainable practices to further enhance the bioactive content of plant foods. One promising development is the integration of artificial intelligence (AI) and Internet of Things (IoT) technologies into urban farming. These technologies can provide real-time monitoring and adjustments of environmental conditions, ensuring optimal growth conditions and maximizing the synthesis of bioactive compounds. For instance, AI-driven algorithms can analyze data from sensors to adjust light spectra, nutrient concentrations, and watering schedules dynamically(7).

Another proposed system involves the use of biofortification, a process that enhances the nutritional quality of crops through conventional breeding, genetic modification, or agronomic practices. Urban farms could implement biofortified crop varieties that are specifically engineered to contain higher levels of vitamins, minerals, and antioxidants. This approach is supported by research that indicates significant improvements in the bioactive content of biofortified crops compared to their non-biofortified counterparts.

Additionally, sustainable practices such as the use of biochar and organic amendments in urban agriculture are gaining attention. Biochar, a form of charcoal used as a soil amendment, can improve soil health and increase the bioavailability of nutrients, leading to higher bioactive compound content in plants. Research into the synergistic effects of biochar and compost on plant health and nutrient uptake is ongoing, with preliminary results showing promise.

Furthermore, vertical farming and controlled environment agriculture systems could be enhanced with renewable energy sources and closed-loop water recycling systems to make urban agriculture more sustainable and efficient. These improvements would not only increase the bioactive content of plant foods but also reduce the environmental footprint of urban farming operations.

Overall, the proposed systems aim to build on the successes of existing methods while incorporating advanced technology and sustainable practices to push the boundaries of what urban agriculture can achieve in terms of enhancing the nutritional quality of plant foods.(8)

4.Ideological Structure

4.1 Urban Agriculture's Most Recent Classification

Urban agriculture has expanded significantly in response to growing urban populations and the increasing demand for local, sustainable food sources. This sector is now more diverse than ever, encompassing a range of systems and practices tailored to urban environments. Here’s a current classification of urban agriculture based on its methods, scale, and purposes:

1. Vertical Farming

This involves growing crops in vertically stacked layers, typically within controlled environments. These systems can be housed in buildings like warehouses or skyscrapers, using artificial light and minimal soil or hydroponic systems. They are highly efficient, maximizing space and reducing water usage.

2. Rooftop Gardening

Rooftop gardens utilize the unused spaces atop residential, commercial, and public buildings. These systems can reduce building heating and cooling costs, manage stormwater, and provide accessible green spaces in densely populated areas.

3. Hydroponics and Aquaponics

Hydroponics is the practice of growing plants in a water-based, nutrient-rich solution, skipping the soil altogether. Aquaponics combines this system with aquaculture (raising fish) by using the fish waste to supply nutrients to the plants, creating a symbiotic environment. Both systems are efficient and can be used indoors, making them ideal for urban settings.

4. Community Gardens

These are collaborative projects on shared open spaces where participants share in the maintenance and products of the garden, including fruits, vegetables, and herbs. Community gardens strengthen community bonds and provide fresh produce in areas that might otherwise lack access to it.

5. Balcony and Patio Gardening

For city dwellers with limited space, balcony and patio gardening allows the cultivation of a variety of plants in containers(9). This type of urban agriculture is accessible, manageable, and can be tailored to individual needs and spaces.

6. Indoor Farming

Using indoor spaces for farming, often with advanced technologies such as grow lights and climate control, allows for year-round farming independent of external weather conditions. This category includes everything from small home setups to larger commercial operations.

7. Edible Landscaping

This practice integrates food plants within an ornamental garden. It is used in public and private spaces to beautify the urban environment while providing food. Edible landscaping can include fruit trees, berry bushes, vegetables, and edible flowers.

8. Greenhouse Gardening

Greenhouses allow for extended growing seasons and a controlled environment for growing a variety of plants, including those not native to the local climate. They can vary in size from small sheds to large-scale structures.

9. Social Urban Agriculture

This newer category focuses on the social and educational roles of urban agriculture, including programs in schools, community centers, and prisons. It emphasizes the benefits of gardening for mental health, social inclusion, and community development.

10. High-tech Urban Farms

These involve the use of cutting-edge technologies like artificial intelligence, robotics, and the Internet of Things (IoT) to enhance crop production and monitoring. Such setups are geared toward optimizing and automating the growing processes, improving efficiency and output.

Urban agriculture continues to evolve, adapting to urban environments and technological advancements. Each type of urban agriculture addresses different urban challenges such as food security, waste management, and the urban heat island effect, making it an integral part of urban planning and sustainability strategies.

4.2The biological processes involved in the production of bioactive compounds in plant foods

Understanding the mechanisms through which plants produce bioactive compounds is pivotal for enhancing the nutritional quality of crops, particularly within the framework of urban agriculture. Bioactive compounds, including vitamins, antioxidants, flavonoids, and other secondary metabolites, are vital for human health and can prevent various chronic diseases. Here's a detailed look at the biological mechanisms behind the production of these compounds in plants:

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[Sunlight] → [Photosynthesis] → [Primary Metabolites (Carbohydrates, Proteins, Lipids)]
        ↓
        |
  [Secondary Metabolism]
        |
        ├─[Phenylpropanoid Pathway]──→ [Flavonoids, Tannins]
        |
        ├─[Terpenoid Pathway]──────────→ [Carotenoids, Essential Oils]
        |
        └─[Alkaloid Path cut]──────────→ [Alkaloids]
        |
[Environmental Stresses (UV, temperature, pests)]
        ↓
  [Stress-Induced Bioactive Compounds (Phenolics, etc.)]
        |
        |
  [Hormonal Regulation (Salicylic Acid, Jasmonic Acid, etc.)]
        ↓
  [Enhanced Production of Specific Bioactive Compounds]
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Figure 1 Diagrammatic Representation of the Biosynthesis Pathways

This diagram simplifies the complex interactions and pathways involved in the synthesis of bioactive compounds in response to environmental cues and internal regulatory mechanisms.

Key Mechanisms of Bioactive Compound Synthesis in Plants

Photosynthesis and Primary Metabolism:

- Photosynthesis is the fundamental process through which plants convert light energy into chemical energy, producing primary metabolites such as carbohydrates, proteins, and lipids. These primary metabolites are vital for plant growth and development.
- During photosynthesis, light energy absorbed by chlorophyll triggers the synthesis of glucose from carbon dioxide and water, which then serves as a building block for other primary metabolites.

Secondary Metabolism:

- Secondary metabolites, which include most bioactive compounds, are not directly involved in the growth and development of plants but play crucial roles in plant defense, pigmentation, and interaction with the environment.
- These compounds are synthesized from primary metabolites through various biosynthetic pathways. Key pathways include the phenylpropanoid pathway, which leads to the synthesis of flavonoids and tannins, and the terpenoid pathway, which produces essential oils and carotenoids(10).

Environmental Stress Response:

- Plants produce many bioactive compounds in response to environmental stresses such as UV radiation, temperature extremes, and pest attacks. For example, UV light can increase the production of phenolic compounds, which protect the plant by absorbing and dissipating the harmful radiation.

Hormonal Regulation:

- Plant hormones such as gibberellins, auxins, cytokinins, and ethylene regulate the production of secondary metabolites. These hormones can modulate the activity of enzymes involved in the biosynthetic pathways of bioactive compounds.
- For instance, salicylic acid and jasmonic acid are plant hormones that enhance the synthesis of certain flavonoids and other phenolics as part of the plant's defense mechanism.

Applications in Urban Agriculture

In the context of urban agriculture, understanding these mechanisms allows for the strategic manipulation of growing conditions to enhance the concentration of beneficial bioactive compounds in plants. For instance, controlling light exposure, nutrient supply, and water stress can optimize the production of specific secondary metabolites, thereby improving the nutritional quality of the produce. Additionally, genetic engineering and plant breeding techniques can be employed to develop plant varieties with elevated levels of these compounds, tailored for urban farm environments.

4.3Methods for Enhancing Plant Foods with Bioactive Compounds via Urban Agriculture

Urban agriculture presents unique opportunities to enhance the bioactive content of plant foods, an important aspect given the increasing demand for nutritious and health-promoting crops. The strategies to achieve this revolve around optimizing growing conditions, using innovative agricultural technologies, and employing new breeding techniques. Below, we discuss these strategies in detail(11):

1. Optimal Use of Controlled Environment Agriculture (CEA)

- Controlled environment agriculture, including hydroponics, aquaponics, and aeroponics, allows for precise control over the conditions under which plants are grown. This precision significantly influences the synthesis of bioactive compounds:
- Light Management: The quality, intensity, and duration of light that plants receive can be tightly controlled in CEAs. Different wavelengths of light can stimulate the production of specific types of bioactive compounds such as anthocyanins and flavonoids. For example, blue and ultraviolet light are known to enhance phenolic compounds and antioxidants in leafy greens.
- Nutrient Recipes: The composition of nutrient solutions in hydroponic setups can be adjusted to include optimal amounts of trace minerals and other nutrients, which are crucial for the synthesis of bioactive compounds. For instance, increasing selenium or zinc in the nutrient solution can boost the respective content in the plant tissues.
- Temperature and Humidity Control: Secondary metabolite production in plants can also be influenced by adjusting the ambient temperature and humidity within growing environments. Certain stress conditions induced by altering temperature and humidity can lead to increased concentrations of protective bioactive compounds.

2. Implementing Advanced Genetic and Breeding Techniques

Urban agriculture can benefit from the application of sophisticated breeding techniques and biotechnology:

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- Genetic Modification and CRISPR: These technologies enable the modification of plant genomes to enhance their nutritional qualities. By increasing the expression of genes involved in the biosynthesis of desired bioactive compounds, plants can be engineered to produce higher levels of these nutrients.
- Traditional Breeding Techniques: Selective breeding and crossbreeding can also be used to develop plant varieties with naturally higher levels of bioactive compounds. This approach is non-GMO, which may be more acceptable to certain markets and regulatory environments.

3. Utilization of Organic and Bio-Stimulants

The use of organic farming practices and biostimulants in urban agriculture settings can promote the accumulation of **bioactive compounds:**

- Organic Amendments: Adding organic matter to soil or growing media, even in hydroponic setups, can improve nutrient uptake and stress resistance in plants, leading to enhanced synthesis of secondary metabolites.
- Biostimulants: Substances like humic acids, seaweed extracts, and microbial inoculants can stimulate plant growth and stress resilience, indirectly boosting the production of bioactive compounds.

4. Environmental Stress Induction

- Plants produce many bioactive compounds as a defense mechanism against environmental stress. Urban farmers can leverage this by deliberately inducing mild stress:
- Water Stress: Controlled drought conditions can trigger an increase in secondary metabolites like polyphenols and terpenes, which are responsible for many of the antioxidant properties of plants.
- Salinity Stress: Introducing moderate salinity stress can stimulate the production of certain antioxidants and other protective compounds in some species.

5. Smart Farming Technologies

Incorporating smart technologies can further enhance the capability of urban agriculture systems to optimize conditions for the production of bioactive compounds:

- IoT Sensors and AI: These technologies enable real-time monitoring and control of environmental variables such as light, moisture, temperature, and nutrient levels, facilitating the precise management needed to maximize the synthesis of bioactive compounds.
- Data Analytics: Using data-driven approaches to analyze plant responses to various conditions allows for the continuous improvement of growing protocols, thereby optimizing bioactive compound production.

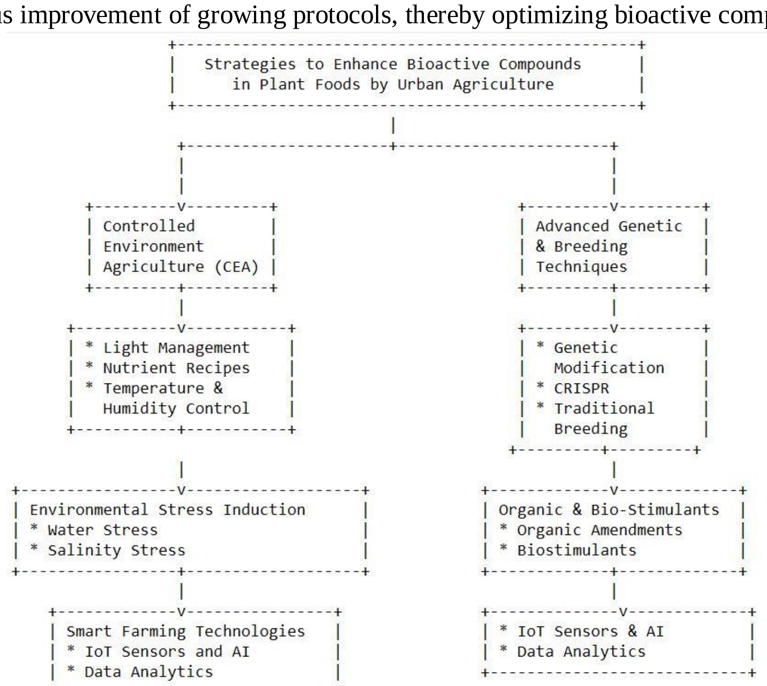

Figure 2 Strategies to Improve Bioactive Compounds

Explanation of the Diagram:

1. Central Idea: The diagram starts with a central idea, which is "Strategies to Enhance Bioactive Compounds in Plant Foods by Urban Agriculture." This serves as the header or title of the diagram.
2. Main Strategies: Two primary branches emerge from the central idea:
3. Controlled Environment Agriculture (CEA): This involves controlling internal growing environments to optimize plant growth and nutrient content.
4. Advanced Genetic & Breeding Techniques: These involve manipulating plant genetics directly or using traditional breeding to increase bioactive compounds.
5. Sub-categories and Specific Tactics:
    - Under CEA, sub-categories like light management, nutrient recipes, and climate control are detailed.
    - Under Genetic & Breeding Techniques, methods like genetic modification (including CRISPR) and traditional breeding are outlined.
    - Additional strategies branch off these main categories, including environmental stress induction to enhance bioactive production via stress response and the use of smart technologies for precise management.
    - Organic and bio-stimulants represent another approach, emphasizing soil health and biostimulants to enhance plant growth and bioactive compound synthesis.

4.4 Ground-Based, Controlled Urban Agriculture

Ground-based, controlled urban agriculture is a vital innovation, especially as urban populations grow and the strain on traditional agriculture increases due to various environmental challenges. This method of agriculture integrates plant cultivation into the urban environment, utilizing controlled settings to maximize production and efficiency. It primarily involves the development and management of allocated ground spaces within urban areas—such as gardens, vacant lots, and specially designed structures—to support plant growth under highly regulated conditions.

Utilization of Space

In urban settings where space is a premium, ground-based agriculture takes innovative forms. Traditional in-ground gardens are adapted to smaller or irregular spaces, often using techniques such as raised beds or terracing to optimize the available area. These approaches not only improve soil drainage and reduce soil compaction, thereby enhancing root growth and plant health, but they also help in managing urban soil contamination by isolating the crop's soil from the existing ground. Additionally, container gardening is widely employed, allowing for the flexible arrangement of growing spaces on rooftops, patios, or even alongside buildings, thus transforming underutilized spaces into productive agricultural zones.

Controlled Conditions

The hallmark of ground-based, controlled urban agriculture is its emphasis on controlling environmental factors to enhance growth and yield. This is achieved through various means:

1. Soil Management: Custom soil blends are used to meet specific plant requirements, optimizing pH levels and nutrient profiles to improve plant health and productivity.
2. Water Systems: Drip irrigation and other efficient watering systems ensure plants receive the precise amount of water needed to reduce waste and stress on the local water supply.
3. Pests and diseases are managed through integrated pest management (IPM) strategies that favor biological over chemical interventions, promoting a healthier urban ecosystem.

Advantages and Benefits

The benefits of this approach extend beyond simple food production. Urban agriculture can lead to significant environmental improvements, such as increased green space, which can improve air quality and urban biodiversity. Economically, it can reduce food transportation costs, lower grocery bills, and create local jobs. Socially, community gardens and other urban agriculture projects can strengthen community ties and provide educational opportunities about nutrition and the environment.

Challenges and Considerations

Despite its advantages, ground-based, controlled urban agriculture is not without challenges. The cost of establishing and maintaining such projects can be high, especially when advanced technologies and infrastructure are involved. Additionally, urban farmers often face bureaucratic hurdles, including zoning restrictions and lack of access to suitable land. Moreover, urban environments can present unique issues such as pollution and limited water availability, which can affect plant growth and require innovative solutions to overcome.

5.Conclusion and Future work

The use of hydroponics, aeropics, and controlled environment agriculture (CEA) has demonstrated that urban farming can exceed the limitations of traditional agriculture by controlling the growing environment. These systems ensure optimal plant growth conditions and enable manipulation of phytochemical content through stress induction and nutrient management, thus enhancing the concentration of beneficial bioactive compounds. Additionally, vertical farming has not only maximized space efficiency but also proven effective in reducing the farm's carbon footprint by minimizing transport logistics and associated emissions.

The employment of genetic modification and CRISPS technology also holds transformative potential for urban agriculture. By modifying plant genetics, crops can be engineered to produce higher levels of specific bioactive compounds, providing tailored health benefits to meet the nutritional demands of urban populations. Furthermore, the integration of smart technologies like IoT sensors and AI-driven data analytics into urban agricultural systems is streamlining the monitoring and management of crop growth, allowing for precise adjustments that promote the production of bioactives.

Future Work

Looking forward, the trajectory of urban agriculture requires a focused approach on several fronts:

1. Research and Development: Continued investment in research is essential to further understand the optimal conditions under which plants increase their bioactive compound production. Studies should explore the interaction between environmental factors and genetic expressions to develop more robust guidelines for crop cultivation.
2. Policy and Regulatory Frameworks: Governments and municipalities should consider supportive policies that encourage urban agricultural practices, including subsidies for urban farms, relaxed zoning laws, and incentives for sustainable farming technologies. Such policies could significantly lower entry barriers and foster innovation in urban farming techniques.
3. Education and Community Engagement: Educating urban populations about the benefits of consuming high-bioactive foods and engaging them in local farming activities can enhance public health and create more resilient communities. Programs that integrate urban agriculture into school curricula and community-based projects can foster a new generation of informed consumers and producers.
4. Technological Advancements: The future of urban agriculture will be heavily influenced by advancements in technology. Continued innovation in AI, machine learning, and IoT for agriculture will drive more efficient and effective farming methods that could personalize and scale production of bioactive-rich foods.
5. Sustainability Measures: As urban agriculture scales, sustainability must remain at the forefront. This includes optimizing resource use, reducing waste, and implementing closed-loop systems that recycle water and nutrients.

By addressing these areas, urban agriculture can continue to expand its impact, transforming urban environments into hubs of nutritional innovation that contribute positively to both local and global food systems. As we move forward, the integration of emerging techniques in urban agriculture will not only enhance the bioactive compounds in plant foods but also promote a healthier, more sustainable future for urban dwellers.

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Conflicts of interest

The authors have no conflicts of interest to declare

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