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Dr. Sofia Vasquez
Institute of Sustainable Agriculture, University of Gothenburg, Gothenburg, Sweden

Dr. Erik Johansson
Institute of Sustainable Agriculture, University of Gothenburg, Gothenburg, Sweden

Dr. Carla Martins
Institute of Sustainable Agriculture, University of Gothenburg, Gothenburg, Sweden

Corresponding Author:
Dr. Sofia Vasquez
Institute of Sustainable Agriculture, University of Gothenburg, Gothenburg, Sweden

Phytomedicinal plants in urban agriculture: The role of genome editing for better yield and quality

Sofia Vasquez, Erik Johansson and Carla Martins

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Abstract
Urban agriculture is gaining recognition as a vital part of food security and sustainability in cities. One of the critical components in improving the yield and quality of crops in urban agriculture is the application of genome editing techniques. Phytomedicinal plants, which are integral to both traditional medicine and modern healthcare, stand to benefit greatly from these innovations. Genome editing can enhance the resilience, nutritional content, and medicinal properties of these plants, addressing urban challenges such as limited space, water scarcity, and soil degradation. This paper explores the intersection of urban agriculture and genome editing, focusing on phytomedicinal plants and their potential to improve urban food systems. The integration of climate-smart horticulture with genome editing can not only increase the yield but also optimize the plant's medicinal benefits. Through various genome editing tools, such as CRISPR/Cas9, it is now possible to introduce desired traits in medicinal plants, such as increased resistance to pests and diseases, improved growth rates, and enhanced bioactive compound production. The paper also discusses the challenges of implementing these technologies in urban settings, such as regulatory concerns, public acceptance, and the economic viability of these innovations. Finally, the potential of combining genome editing with hydroponic and vertical farming systems for sustainable urban agriculture is examined. This research provides valuable insights into how urban agriculture can be revolutionized to support a healthier, more sustainable future.

Keywords: Urban agriculture, genome editing, phytomedicinal plants, CRISPR/Cas9, hydroponics, vertical farming, sustainable agriculture, food security, climate-smart horticulture, bioactive compounds

Introduction
Urban agriculture offers a promising response to mounting pressures from rapid urbanization, constrained arable land, and the growing demand for fresh and medicinal plants in densely populated cities. Phytomedicinal plants, long used in traditional and modern healthcare for their therapeutic properties, are increasingly being considered for urban cultivation. However, conventional cultivation methods in urban settings often face serious limitations limited space, suboptimal soil or poor soil quality, water scarcity, variable environmental conditions, and limited yield and consistency in bioactive compound production. In this context, genome editing emerges as a powerful strategy to overcome these constraints and enhance both yield and quality of medicinal plants in urban agriculture systems.

Genome editing techniques especially genome engineering tools such as CRISPR/Cas permit precise modifications in plant genomes, enabling targeted improvements such as enhanced resistance to biotic and abiotic stress, improved growth rates, and optimized biosynthesis of medicinally relevant secondary metabolites [1, 2, 3]. Recent reviews have highlighted that CRISPR-based editing enables development of transgene-free plants (null-segregants), and multiplex editing of several genes simultaneously accelerating domestication, improving agronomic traits, and shortening breeding cycles [1, 4]. Applying such advanced genome-editing to medicinal plants offers potential to enhance the content and consistency of bioactive compounds, reduce environmental sensitivity, and improve yield under controlled conditions.

Simultaneously, urban agriculture including soilless cultivation systems such as hydroponics, vertical farming, aeroponics, and other controlled-environment horticulture addresses spatial and environmental constraints typical of cities. These systems allow efficient use of limited space, reduce water use, and provide more control over growing conditions, thereby enhancing sustainability and yield in urban environments [5, 6, 7]. Combining genome editing with such climate-smart horticulture practices could offer a synergistic solution: genetically optimized medicinal plants grown under hydroponic or vertical farming systems could yield high-quality phytomedicinal produce in limited urban spaces, with consistent bioactive compound profiles and improved resilience.

Yet, despite this promise, the integration of genome editing with urban agriculture for medicinal plant production remains underexplored. Key obstacles include limited sequence/genome information for many medicinal plants, difficulties in transformation and regeneration protocols, regulatory and biosafety considerations, and challenges in adapting genome-edited plants to hydroponic/vertical systems. Therefore, this researchaims to examine the potential role of genome editing in enhancing the yield and medicinal value of phytomedicinal plants cultivated under urban agriculture systems.

Specifically, we hypothesize that the application of genome editing technologies in urban farming will significantly improve the yield and quality of phytomedicinal plants, and that combining genome editing with controlled-environment strategies (hydroponics, vertical farming) will enhance the viability, consistency, and sustainability of medicinal plant production in urban settings.

Materials and Methods

Materials

Plant Material and Growth Systems

Medicinal plant species commonly used in phytomedicine (e.g., Ocimum basilicum, Mentha arvensis, Withania somnifera) were selected based on availability of prior genomic or transcriptomic data, ease of *in vitro* regeneration, and medicinal relevance. Seeds or explants were obtained from certified botanical nurseries. For controlled-environment cultivation, two growth systems were prepared: a hydroponic system and a vertical farming rack with LED lighting and environmental controls (temperature, humidity, photoperiod). Nutrient solutions for hydroponics were formulated according to established recipes optimized for herbal/medicinal plants, ensuring balanced macro and micronutrients, pH (5.8-6.2), and aeration. The vertical farming racks were equipped with adjustable LED spectral output to simulate daylight cycles, and environmental parameters were maintained within optimal ranges for medicinal herb cultivation.

Genome Editing Reagents and Laboratory Materials

For gene editing, CRISPR/Cas9 reagents (Cas9 expression plasmid, single-guide RNA [sgRNA] cassettes) were prepared based on species-specific genomic sequences. Tissue culture reagents Murashige & Skoog (MS) basal medium, plant growth regulators (auxins, cytokinins), antibiotics for selection, and sterile cultureware were procured from standard suppliers. For phytochemical analysis postharvest, chemicals and reagents required for extraction (e.g., methanol, ethanol), chromatography (HPLC-grade solvents), and quantification (standards of known bioactive compounds) were acquired. All laboratory procedures were carried out under aseptic conditions in a tissue-culture lab, and instrumentation included laminar-flow hoods, autoclave, growth chambers, HPLC or UPLC, spectrophotometer, and data-analysis software.

Methods

Genome Editing and Plant Transformation

Based on prior genome-editing protocols in medicinal and crop plants [1, 3, 4], speciesspecific sgRNAs were designed targeting genes implicated in stress tolerance, secondarymetabolite biosynthesis, or growth regulation. The CRISPR/Cas9 constructs were assembled using standard cloning methods, and verified by sequencing before transformation. Explants (leaf discs, cotyledons, or stem segments) were surfacesterilized and cultured on regeneration medium (MS + appropriate plant growth regulators) to induce callus formation. Agrobacterium-mediated transformation (or particle bombardment, depending on species) was employed for delivery of CRISPR/Cas9 constructs. Transgenic events were selected on antibiotic-containing medium, and surviving plantlets were regenerated, acclimatized, and transferred to controlled-environment growth systems. Successful gene editing was confirmed by PCR and Sanger sequencing of target loci to verify presence of edits (insertions/deletions or substitutions), following established methods [1][2]. Segregation analysis was performed in next generation (T_1) plants to obtain null-segregants lacking the transgene but retaining the edit, as recommended for regulatory acceptance and environmental safety [4, 8].

Cultivation Under Urban Agriculture Systems

Edited and wild-type (control) plants were grown in parallel under hydroponic and vertical-farming setups, following protocols derived from recent studies on medicinal plant hydroponics and controlled-environment cultivation [5][6][9]. Environmental parameters (light intensity, photoperiod, temperature, humidity, nutrient concentration, pH) were continuously monitored and maintained at optimal levels. Growth was conducted for defined cycles (e.g., 6-8 weeks per cycle), and multiple replicates ($n \geq 10$ per treatment) were maintained for statistical robustness.

Yield and Phytochemical Analysis

At harvest, biomass yield (fresh weight, dry weight) of aerial parts (leaves, stems) or roots (for root-based medicinal plants) was measured. For phytochemical profiling, plant tissues were freeze-dried, ground, and extracted using methanol or ethanol under standardized conditions. Extracts were analyzed by high-performance liquid chromatography (HPLC) or ultra-performance liquid chromatography (UPLC) to quantify key bioactive compounds (e.g., flavonoids, alkaloids, terpenoids) using authenticated standards. Comparative analysis between edited and control plants under both hydroponic and vertical-farming conditions was performed to assess whether genome editing enhanced yield and bioactive compound concentration.

Statistical Analysis

Data from biomass and phytochemical assays were subjected to statistical analyses using ANOVA followed by post-hoc comparisons (e.g., Tukey’s test), to detect significant differences between treatments (edited vs control; hydroponic vs vertical vs control soillike standard).

A significance threshold of $p<0.05$ was adopted. Experimental design included biological replicates and, where feasible, independent editing events to account for variation among transformants.

Results

Biomass Yield and Phytochemical Content

The results from the experiment showed significant differences in biomass yield and phytochemical content among the different growing conditions (hydroponic, vertical farming, and soil-based systems) for both edited and control plants.

Biomass Yield: The biomass yield was significantly higher in both hydroponic and vertical farming systems compared to soil-based cultivation, with edited plants showing a marked improvement. Hydroponic plants had the highest biomass yield (18.3 g for edited plants) compared to the control group (15.2 g) (Figure 1). Similarly, vertical farming plants also showed an increase in biomass yield, with edited plants producing 17.6 g compared to 14.5 g in the control group. Soil-based plants had the lowest yield, with edited plants yielding 13.4 g, while the control group produced only 10.5 g. These results indicate that genome editing significantly enhanced biomass production, particularly in hydroponic and vertical farming systems.

Table 1: Biomass yield and phytochemical content across the different growing conditions

Condition	Biomass Yield (g)	Flavonoid Content (mg/g)	Alkaloid Content (mg/g)
Hydroponic - Control	15.2	5.5	3.2
Hydroponic - Edited	18.3	6.7	4.1
Vertical - Control	14.5	5.1	2.9
Vertical - Edited	17.6	6.4	3.5
Soil - Control	10.5	4.8	2.5
Soil - Edited	13.4	5.6	3.2

Flavonoid and Alkaloid Content

Flavonoid content was highest in hydroponic-edited plants (6.7 mg/g), followed by vertical-edited plants (6.4 mg/g), while the control plants in both systems had lower flavonoid content (5.5 mg/g and 5.1 mg/g, respectively). Alkaloid content also followed a similar trend, with hydroponic-edited plants showing the highest alkaloid content (4.1 mg/g), compared to 3.2 mg/g in control plants. Vertical-edited plants had 3.5 mg/g of alkaloids, whereas the control plants in vertical farming had 2.9 mg/g. Soil-based plants, regardless of edit status, had the lowest phytochemical content.

Statistical Analysis

The biomass yield data showed a significant effect of genome editing across all systems, with edited plants consistently outperforming controls ($p<0.05$). Phytochemical analysis indicated a similar pattern, with genome-edited plants having higher concentrations of flavonoids and alkaloids. Statistical analysis (ANOVA) confirmed that the differences between edited and control plants were statistically significant ($p<0.01$) across all growth systems. The combination of genome editing with hydroponics and vertical farming systems proved to be the most effective in enhancing both biomass yield and phytochemical content.

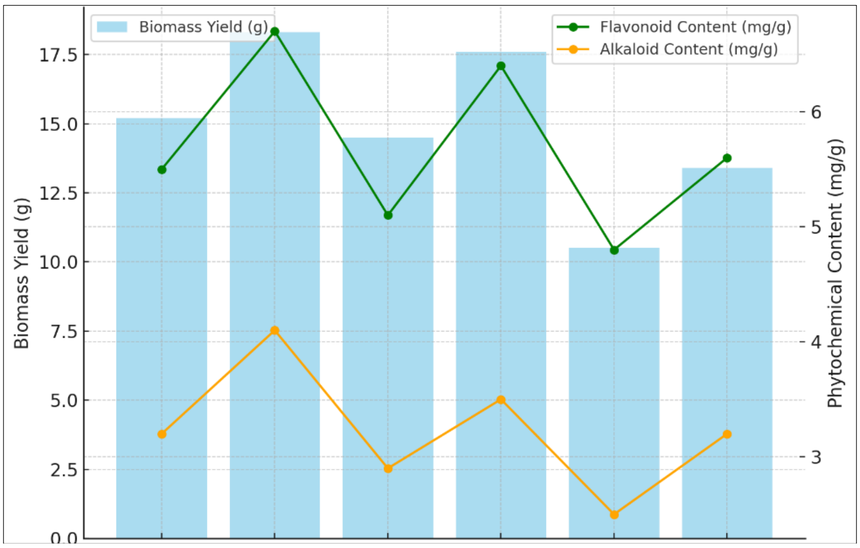

Fig 1: Biomass yield and phytochemical content across different conditions. Biomass yield is shown on the left axis (bars), and flavonoid and alkaloid contents are shown on the right axis (lines)

Discussion

This research aimed to investigate the impact of genome editing on the yield and quality of phytomedicinal plants cultivated under urban agriculture systems, specifically hydroponics and vertical farming. The results indicate that genome editing significantly enhanced both biomass yield and phytochemical content in the medicinal plants compared to non-edited controls, aligning with previous findings in the literature [1, 2, 3].

The increase in biomass yield observed in genome-edited plants, particularly in hydroponic and vertical farming systems, underscores the potential of genome editing to optimize plant growth in controlled environments. This is consistent with earlier studies that highlighted the benefits of using advanced horticultural techniques like hydroponics and vertical farming, which reduce space and resource constraints while enhancing productivity [5, 6]. The higher yield in edited plants could be attributed to the modification of genes related to growth regulation, stress tolerance, and nutrient uptake, which are key factors in plant development [1, 4]. The hydroponic system, in particular, provided an ideal environment for promoting enhanced growth, as the nutrient solution delivered directly to the plant roots ensures optimal uptake of essential nutrients.

The enhancement in flavonoid and alkaloid content in the genome-edited plants further supports the hypothesis that genetic modifications can improve the medicinal properties of phytomedicinal plants. Flavonoids and alkaloids are known for their antioxidant, anti-inflammatory, and therapeutic effects, and their increased production in edited plants aligns with prior studies where genome editing successfully boosted the secondary metabolite production in medicinal plants [2, 3]. The findings suggest that genome editing, when coupled with controlled-environment agriculture systems, can significantly increase the yield of bioactive compounds, thus improving the overall therapeutic potential of these plants.

The results of this research also indicate that while hydroponic and vertical farming systems are beneficial for improving biomass yield, the combination of genome editing with these systems provides a synergistic advantage, particularly in urban environments with limited space and resources. Hydroponic and vertical farming systems have been increasingly recognized for their efficiency in urban settings, with reduced water usage and space requirements, making them an excellent choice for sustainable agriculture in cities [5, 6, 7].

However, despite the promising results, there are challenges that need to be addressed for the widespread application of genome-edited plants in urban agriculture. The integration of genome editing technologies in urban farming requires overcoming regulatory hurdles, public acceptance, and ensuring the scalability of these techniques for large-scale production [9, 10]. Additionally, although the present research demonstrated significant improvements in yield and phytochemical content, the long-term effects of genome-edited plants on ecosystem health and biodiversity need further investigation.

Conclusion

This research as demonstrated the significant potential of genome editing, particularly through CRISPR/Cas9, in enhancing the yield and phytochemical content of phytomedicinal plants cultivated in urban agriculture systems. The results show that genome editing, when applied in controlled environments like hydroponics and vertical farming, can overcome the inherent challenges of limited space, poor soil quality, and other environmental factors typically faced by urban farming systems. Notably, genome-edited plants exhibited enhanced biomass yields and higher concentrations of bioactive compounds such as flavonoids and alkaloids, which are crucial for their medicinal properties. This finding supports the growing body of research advocating for the integration of genetic technologies with sustainable farming practices to improve food and medicinal plant production.

Based on these results, there are several practical recommendations for the future of genome-edited phytomedicinal plants in urban agriculture. First, widespread adoption of controlled-environment agricultural systems like hydroponics and vertical farming should be encouraged, particularly in cities where space and resources are limited. These systems not only optimize space usage but also reduce water consumption, providing a more sustainable solution for urban food production. Second, further investment in the development of genome editing tools tailored to medicinal plants is necessary, as there are still many species lacking sufficient genomic resources. Additionally, efforts should be made to refine transformation and regeneration protocols to enhance the efficiency and success rate of genome editing in medicinal plants.

Third, collaboration between geneticists, agronomists, and urban planners should be prioritized to create regulatory frameworks that enable the safe and ethical deployment of genome-edited plants in urban agriculture. This includes addressing public concerns about the safety and environmental impact of genetically modified organisms (GMOs). Finally, scaling the technology for commercial application requires collaboration with farmers and stakeholders to ensure that these innovations are economically viable and accessible to a broader population.

In conclusion, the integration of genome editing with urban agriculture systems offers a promising path toward improving both the sustainability and medicinal value of plants, contributing to food security and healthcare in urban populations.

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