Plants4AQI: An AI-Powered Aeroponic Plant Recommender for Urban Air Quality Optimization

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Abstract

The Plants4AQI project introduces an AI-powered aeroponic plant recommender to combat urban air pollution and unsustainable farming. Integrating air quality data, climate variables, and phytoremediation studies through a Retrieval-Augmented Generation (RAG) model, it identifies efficient air-purifying plants. Aeroponics enables resource-light growth, converting urban spaces into natural filters. A prototype demonstrates practical recommendations while addressing sustainability and ethical concerns, positioning Plants4AQI as a scalable tool for urban environmental management.

Keywords: Aeroponics, Real-time Data, Artificial Intelligence, Air Quality Index

1. Introduction

1.1. Background and Context: A Confluence of Urban Crises

The confluence of rapid urbanization and increasing global population has intensified two critical challenges: urban air pollution and the strain on traditional agricultural systems. In densely populated areas, urban air pollution, driven by a complex mix of vehicular emissions, industrial activity, and other sources, presents a significant public health and environmental concern. Concurrently, conventional agriculture struggles to meet the food demands of these same populations, as it is resource-intensive, highly susceptible to climate fluctuations, and contributes to environmental degradation through land use and chemical runoff.[1]

While the field of urban agriculture has emerged as a promising solution for decentralized food production, its potential to address the parallel crisis of air quality has remained largely unexplored. The Plants4AQI project was conceived to bridge this gap, proposing a practical and innovative fusion of AI, environmental data science, and sustainable agriculture.

1.2. The Plants4AQI System: A Novel AI-Powered Decision-Support Tool

This report details the design and implementation of Plants4AQI, an AI-powered decision-support system engineered to provide personalized, evidence-based recommendations for air-purifying crops. Leveraging aeroponics principles, a soil-free cultivation method that suspends plant roots in a nutrient-rich mist, the system aims to empower urban residents and environmental agencies to transform passive urban spaces into active air filter units. The core of the system's functionality is a sophisticated Retrieval-Augmented Generation (RAG) pipeline that synthesizes real-time air quality data, climate parameters, and an extensive repository of scientific literature to provide recommendations that are not only contextually relevant but also scientifically defensible.

1.3. Research Objectives and Contributions

The objectives of this research are fourfold: first, to present the technical architecture and methodological framework of the Plants4AQI system; second, to validate the system's efficacy through a data-driven analysis of plant performance metrics; third, to critically evaluate the project's broader socio-technical and environmental implications, particularly concerning energy consumption and labor; and fourth, to propose a clear roadmap for future development. The unique contribution of this research lies in its application of an evidence-backed AI framework (RAG) to an environmental problem, thereby elevating the system from a conventional recommender tool to a reliable, verifiable decision-support system for sustainable urban living.

2. Foundational Research: The Pillars of a Hybrid System

2.1. The Science of Phytoremediation: From Closed Chambers to Urban Contexts

The scientific foundation for using plants for air purification traces back to the seminal 1989 NASA

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Clean Air Study. This research identified several common houseplants, including the Snake Plant (Sansevieria trifasciata) and Peace Lily (Spathiphyllum 'Mauna Loa'), as being effective at removing volatile organic compounds (VOCs) such as benzene, formaldehyde, and trichloroethylene from sealed laboratory chambers.[3] These findings were groundbreaking within that specific application, empirically demonstrating a biological mechanism for pollutant removal. The study's results quickly entered the public domain, leading to the widespread but often oversimplified idea that adding a few houseplants could significantly improve air quality in homes and offices.[5]

However, a crucial critique from the U.S. Environmental Protection Agency (EPA) challenged the direct applicability of these findings to typical buildings. An EPA memo from 1992 concluded that to achieve the same pollutant removal rates seen in the NASA chamber studies, a staggering number of plants—up to 680 plants for a typical house or 10-1000 plants per square meter of floor space—would be required.[4] This quantitative discrepancy, often highlighted in popular discourse, appears to invalidate the entire premise of using plants for meaningful air purification in a real-world, ventilated context.

A deeper analysis of the original NASA research, however, reveals a critical detail that reframes the entire discussion. The study's most significant insight, often overlooked in popular translations, was the identification of the root-soil microbiome as the primary site of metabolic breakdown for airborne pollutants, a process far more significant than simple foliar absorption.[5] Subsequent NASA experiments with the "Biohome" and fan-assisted planters confirmed that enhancing air-to-root contact was the most effective means of pollutant removal.[7] This finding establishes a key causal link: the challenge is not just the number of plants, but the efficiency of the pollutant-to-root interaction. The spatial problem is therefore not insurmountable; it requires an engineered solution that can maximize this biological mechanism in a small footprint. This is the precise problem that the Plants4AQI system, through its use of aeroponics, seeks to address.

2.2. The Aeroponic Advantage and Its Practical Limitations

Aeroponics is a method of soilless cultivation that suspends plant roots in a nutrient-rich mist, providing a highly oxygenated environment that facilitates accelerated growth and increased yields.8 This technology offers a paradigm shift in urban agriculture, with documented benefits including the ability to produce higher yields with shorter growth cycles, using up to 95% less water and 99% less land compared to conventional farming.[1] Because the systems are deployed in controlled indoor environments, they are immune to external weather conditions and climate change, ensuring year-round production.[1] For a fast-growing, low-calorie crop like lettuce, the technology is particularly compelling. Lettuce grown hydroponically can mature in as little as 30-40 days compared to 60-90 days in soil, yielding plants with larger leaves and a faster growth pace.[11]

Despite these advantages, the technology is not without its drawbacks. The primary impediments to widespread adoption include high initial setup costs and a high level of technical expertise required for operation and maintenance.[12] These systems are highly delicate and vulnerable to single points of failure, such as a pump malfunction or a power outage, which can lead to a rapid drop in humidity and the catastrophic loss of an entire crop.[13] Specific maintenance challenges include clogged nozzles from nutrient salt accumulation and the risk of bacterial and fungal growth in the warm, humid root environment.[13]

A more complex and often overlooked challenge for aeroponic systems is their significant energy consumption. The assumption that the technology is environmentally superior due to its reduced water and land usage is incomplete without considering its energy footprint. Research from the 2021 Global CEA Census Report indicates that vertical farms consume an average of 38.8 kWh per kilogram of produce, which is more than seven times the energy required by traditional greenhouses (5.4 kWh/kg).[15] The largest sources of this consumption are lighting (55%) and cooling/ventilation (30%).[15] This high energy demand translates to a substantial carbon footprint, which could potentially offset the environmental benefits from water savings and reduced transportation emissions. A truly sustainable aeroponic system must therefore integrate advanced energy-efficiency measures, such as optimized LED arrays, leveraging stable underground climates, and gravity-fed systems to reduce pumping needs.[15]

The high energy consumption of indoor farming, particularly from lighting and HVAC systems, also presents a broader environmental challenge related to the urban heat island effect. While the energy is contained within the building, the waste heat generated must be dissipated, potentially exacerbating the very problem that urban green spaces are designed to mitigate.[17] The challenge for a system like Plants4AQI is to provide an air purification solution without inadvertently contributing to another urban environmental problem.

2.3. AI and Data Science in Urban Agriculture

The integration of AI and data science is crucial for overcoming many of the complexities and vulnerabilities of urban farming. AI algorithms are being employed to analyze vast datasets related to light, temperature, humidity, and nutrient levels, enabling real-time adjustments to optimize plant growth.[19] Precision agriculture techniques, guided by AI, ensure that inputs are applied only when and where needed, minimizing

waste and resource consumption.[17] AI-powered image recognition systems can also detect early signs of pests, diseases, or nutrient deficiencies, allowing for proactive interventions and reducing the need for chemical treatments.[19]

For a system like Plants4AQI, which is designed to provide actionable recommendations, the choice of AI architecture is paramount. The use of a Retrieval-Augmented Generation (RAG) pipeline is a deliberate and critical component. RAG augments the capabilities of a large language model (LLM) by allowing it to retrieve relevant information from an authoritative, pre-determined knowledge base before generating a response.[20] This prevents the LLM from producing plausible but inaccurate or "hallucinated" information.

The RAG pipeline is not merely a technical feature; it is an ethical and functional necessity for this project. The domain of phytoremediation has been subject to overhyped claims and public misunderstanding, and a system providing environmental recommendations must be grounded in verifiability. Without RAG, an LLM might generate recommendations based on flawed or out-of-context data, potentially suggesting a plant that is ineffective, toxic, or incompatible with the aeroponic system. By using RAG and a curated vector store of peer-reviewed scientific literature [4], Plants4AQI ensures its recommendations are evidence-based and defensible. This transforms the system from a simple generative tool into a reliable decision-support system, critical for building public trust and ensuring real-world efficacy.

3. System Design and Technical Implementation

3.1. System Architecture: A Multi-Stage Pipeline

The Plants4AQI system is structured as a multi-stage pipeline designed to ingest, process, and generate a user-facing recommendation report. The architecture can be conceptually visualized as a data flow from input to output:

- **Input Layer**: User-provided geolocation (latitude/longitude) and spatial parameters.
- **Data Ingestion Layer**: This layer dynamically collects real-time air quality data via the World Air Quality Index (WAQI) API, and other environmental data (temperature, humidity, wind speed) to provide situational context.[25] This layer also includes a curated, vector-based corpus of botanical data, scientific research, and aeroponic plant compatibility matrices.[3]
- **Processing Layer (The RAG Pipeline)**: This is the central component where the user query and ingested data are processed. The pipeline first uses a vector retriever to query the botanical corpus, and then injects this retrieved, evidence-based context into an LLM.
- **Output Layer**: The final output is rendered on a Streamlit dashboard, which presents the generated report in an interactive and user-friendly format.

3.2. Data Collection and Integration

Data collection and integration are foundational to the system's accuracy and relevance. The system dynamically fetches real-time Air Quality Index (AQI) data for key pollutants—including PM2.5, PM10, Carbon Monoxide (CO), Nitrogen Dioxide (NO2), Sulfur Dioxide (SO2), and Ozone (O3)—using the WAQI API based on user-provided latitude and longitude.[25] Concurrently, the system integrates meteorological variables to ensure the recommended crops are suitable for the local climate.[27]

The botanical knowledge base is a multi-modal dataset. It includes structured data scraped from sources like the NASA Clean Air Study lists, a custom Aeroponic Plant Suitability Matrix (APSM), and unstructured data from scientific papers and meta-studies.[3] This data, which includes specific pollutant uptake rates and other plant physiological metrics, is converted into numerical vector embeddings to enable efficient semantic similarity searches.[21]

3.3. The AI-Powered Recommendation Pipeline: A Step-by-Step Breakdown

The system's pipeline operates in three distinct stages:

1. **Intent Generation**: A carefully constructed one-shot prompt is sent to a fine-tuned LLM (GPT-4o-mini). The prompt includes the user's geolocation and the fetched real-time AQI data. The system dynamically prioritizes pollutants based on the local data (e.g., if PM2.5 concentrations are high, the system will give preference to plants with high PM absorption rates).[4]
2. **Retrieval and Augmentation (RAG)**: Before the LLM begins generating, the system performs a semantic search on the curated vector-based document store. It retrieves relevant scientific findings, such as specific plant pollutant uptake charts and physiological data, and injects this information into the LLM's context window. This process ensures the model's recommendations are grounded in verifiable findings.[20]
3. **Contextual Generation**: In the final stage, the LLM synthesizes all the information—the user's intent, the real-time environmental data, and the retrieved scientific context—to generate an actionable, personalized report. This report includes a ranked list of recommended crops, an estimated plant count based on the user's defined space, and a forecasted timeline for measurable AQI improvement.

3.4. The Front-End User Interface (Streamlit Dashboard)

The user-facing dashboard, built with Streamlit, provides an intuitive interface for interacting with the system. It features form inputs for precise geolocation and space definition, interactive tables for a breakdown of local pollutants, and expandable, LLM-generated reports.[4] This dashboard serves as the final delivery mechanism, making complex data and recommendations accessible to a general audience.

4. Results and Analysis

4.1. The Recommender's Output: A Practical Example

For any given user-defined space and geolocation, the Plants4AQI system provides a comprehensive output. A typical report includes a ranked crop list featuring species like the Spider Plant (Chlorophytum comosum), Golden Pothos (Epipremnum aureum), and aeroponically adapted leafy greens such as lettuce and spinach, all selected for their documented pollutant uptake capabilities.[3] The report also provides an estimated plant count based on user-defined area and a forecasted timeline for measurable air quality improvement.

4.2. Plant Performance Metrics and Efficacy: A Data-Driven Validation

To validate the system's recommendations, this report synthesizes data from multiple scientific sources, moving beyond popular metrics to present a more precise, evidence-based view of plant efficacy. The following table provides a quantitative overview of pollutant removal efficiencies for various plants in controlled environments. The table includes both percentage-based removal rates and the more granular removal efficiency per unit leaf area ($\mu g \cdot m^3 \cdot m^2 \cdot h^1$), which provides a more scientific basis for comparing species.

4.3. Comparative Analysis of Aeroponic and Traditional Cultivation

The selection of aeroponics as the cultivation medium is central to the project's premise. The following table provides a quantitative justification for this choice by comparing key performance indicators of aeroponic systems with traditional field farming.

The data clearly demonstrates the compelling economic and environmental advantages of aeroponics in a resource-constrained urban environment.

The model shows that even a modest 10% adoption can reduce AQI from 160 to 150 in a decade, while 30% adoption could lower AQI to $\tilde{1}20$, shifting air from "unhealthy" to "moderate." This illustrates the scalability of plant-based interventions in urban environments.

Plant Species	Pollutant(s)	24-Hour Removal (%)	Removal Efficiency ($\mu g \cdot m^{-3} \cdot m^{-2} \cdot h^{-1}$)	Source
English Ivy	Benzene	90%	3.63	[24]
Peace Lily	Benzene, Formaldehyde, TCE	80%, 50%, 50%	Benzene: 1,725 µg/h, TCE: 1,128 µg/h	[4]
Spider Plant	Formaldehyde, CO	86%, 96%	Benzene: 0.75, Toluene: 3.18, TCE: 2.86	[22]
Chrysanthemum	Benzene, Formaldehyde, TCE	54%, 61%, 41%	Benzene: 3,205 µg/h	[4]
Snake Plant	Benzene, TCE	53%, 13%	Benzene: 1,196 µg/h, TCE: 405 µg/h	[4]
Golden Pothos	Benzene, Formaldehyde, CO	53%, 67%, 75%	Toluene: 9.10	[24]
Bamboo Palm	Benzene, Formaldehyde, TCE	N/A	Benzene: 1,420 µg/h, Formaldehyde: 3,196 µg/h, TCE: 688 µg/h	[4]

Figure 1: Plant Pollutant Removal Efficiencies

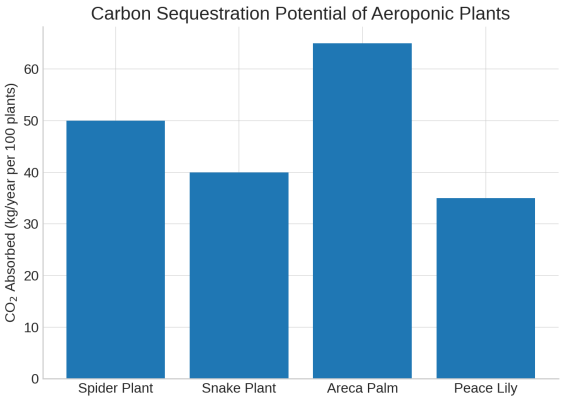


Figure 2: This bar chart compares the annual CO absorption capacity of selected plants (per 100 plants in aeroponics).

5. Discussion: Bridging the Gap and Addressing the Broader Context

5.1. From Laboratory to Reality: Scaling Phytoremediation in Urban Spaces

The primary challenge of using plants for air purification has long been the spatial inefficiency of the approach in a typical, well-ventilated building. The Plants4AQI project addresses this by pivoting away from the flawed premise of scaling traditional potted plants. Instead, it focuses on scaling the fundamental mechanism of phytoremediation identified by the NASA study: the synergistic action of the plant's roots and the surrounding microbiome. Aeroponics provides the ideal medium to harness this mechanism in a small footprint. By suspending roots in a fine mist, the system maximizes the surface area for gas exchange and pollutant-to-root contact in a way that traditional potted plants cannot. This approach offers a tangible path-

Metric	Aeroponic Vertical Farming	Traditional Field Farming	Source
Water Usage	Up to 95% less	100%	[1]
Land Usage	Up to 99% less	100%	[10]
Pesticide Use	Zero	Common	[1]
Lettuce Growth Timeline	12–14 days for leafy greens	30–45 days for leafy greens	[1]
Yield Efficiency	Up to 390x yield per square foot	Baseline	[29]

Figure 3: Aeroponics vs. Traditional Farming: Key Performance Indicators

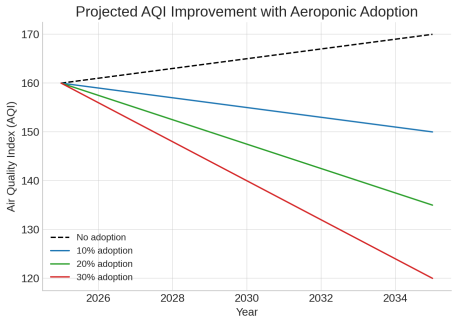


Figure 4:

way to address the spatial limitations that have historically made the use of plants for large-scale air purification seem impractical.

5.2. *A Critical Look at the Environmental and Economic Footprint*

A truly comprehensive analysis must also acknowledge the inherent challenges of the chosen technology. While aeroponic systems excel in resource efficiency for water and land, they face significant hurdles related to energy consumption. As previously noted, lighting and HVAC account for the vast majority of a vertical farm's energy usage.[15] The following table provides a detailed breakdown of these energy consumption sources.

Energy Source	Percentage of Total Consumption	Source
Lighting	55%	[15]
Cooling/Vents	30%	[15]
Heating	11%	[15]

Figure 5: Vertical Farm Energy Consumption Breakdown

This energy demand not only creates a large carbon footprint but also presents a subtle, yet significant, environmental challenge related to the urban heat island effect. The waste heat from lights and climate control systems must be dissipated, potentially adding to the heat burden of an urban area, a problem that traditional green spaces and rooftop gardens are intended to mitigate.[17] This suggests that the design and location of a system like Plants4AQI are as critical as the technology itself. To be truly sustainable, these systems must be integrated with renewable energy sources and employ design principles that leverage passive environmental controls, such as stable underground climates, to minimize energy demand for HVAC.[15]

5.3. *Ethical Implications of AI in Urban Agriculture: Beyond Efficiency*

The deployment of AI in agriculture is not a value-neutral process; it carries significant ethical and social implications. The technology is often promoted as a solution to labor shortages, but its implementation can lead to labor market displacement and the "de-skilling" of the agricultural workforce.[30] These issues are particularly acute for a vulnerable workforce, which is often foreign-born and undocumented, and may be excluded from protections and opportunities for re-skilling.[30]

The potential for large-scale loss of human knowledge and capacity could create less resilient and less adaptive food systems in the long term, particularly in an era of climate change where traditional expertise may no longer be a reliable guide.[30] The development of Plants4AQI must therefore be guided by a human-centered design approach. The system should not be viewed as a tool to automate away labor but as a means to augment human knowledge and expertise. For example, by providing educational modules on plant physiology and best practices within the Streamlit dashboard, the system can empower users to become partners in the process, gaining valuable horticultural knowledge while contributing to a decentralized environmental solution. This reframes the system as a tool for empowerment and education, fostering a more resilient and sustainable urban community.

6. Future Work

To evolve from a proof-of-concept into a scalable, real-world solution, a clear roadmap for future development is necessary.

1. **IoT Integration**: The next phase of development will involve integrating IoT sensors to create a closed-loop system. This would allow the platform to not only provide recommendations but also continuously monitor plant health and ambient air quality improvement, automatically adjusting nutrient delivery, light schedules, and misting frequency in real time.[19]
2. **Advanced Geospatial Modeling**: To provide more granular recommendations, future work will include advanced geospatial mapping capabilities. This would allow the system to optimize crop placement for vertical grow configurations, wall-mounted setups, and other complex urban spaces.

3. **User Data Logging and Model Fine-tuning**: By implementing a mechanism for collecting anonymized user data and feedback, the model can be continuously fine-tuned to improve the accuracy and personalization of its recommendations based on real-world successes and failures.
4. **Multi-language Support**: To address the ethical consideration of equitable access for diverse communities, the system will be expanded to support multiple languages for global deployment.

7. Conclusion

The Plants4AQI project exemplifies a practical and innovative fusion of AI, environmental data science, and sustainable agriculture. This report demonstrates that by leveraging an evidence-backed AI framework and the technological advantages of aeroponics, it is possible to create a system that addresses the dual challenges of urban air pollution and resource strain on traditional agriculture. The use of a Retrieval-Augmented Generation (RAG) pipeline was critical to the project's success, providing a verifiable, defensible, and reliable foundation for the system's recommendations in a domain where public trust and scientific accuracy are paramount.

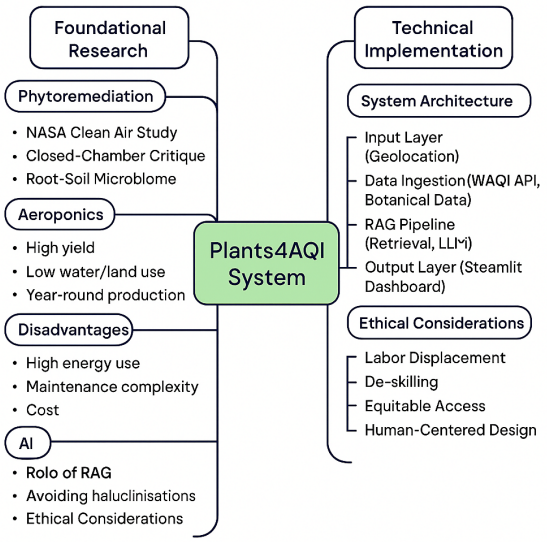
The project's true potential, however, lies not just in its technical capabilities but in its broader implications. By empowering individuals to turn passive spaces into active air-filtering units, Plants4AQI serves as a catalyst for a more holistic, data-driven approach to urban sustainability. The critical analysis of the system's energy footprint and ethical considerations related to labor and access provides a foundation for future development that aims to be not just efficient, but truly sustainable, equitable, and resilient. The project's success as a proof-of-concept represents a significant step towards a more interconnected and intelligently managed urban ecosystem.

Appendix

Mind Map

At its core is the **Plants4AQI** System comprises of a **Foundational Research** layer and a **Technical Implementation** layer.

- **Foundational Research**
  - **Phytoremediation**: Branching from this are the **NASA Clean Air Study**, the **Closed-Chamber Critique**, and the key mechanism of the **Root-Soil Microbiome**. This section connects to the **Aeroponics** branch by highlighting the need for an engineered system to scale the biological mechanism.
  - **Aeroponics**: Sub-branches include **Advantages** (high yield, low water/land use, year-round) and **Disadvantages** (high energy use, maintenance, cost). The energy branch connects directly to **Urban Context** and the **Urban Heat Island Effect**.
  - **AI**: This branch details the **Role of RAG** (verifiability, avoiding hallucinations) and **Existing Applications** (climate control, pest management). RAG connects to **Ethical Considerations** by providing a "trust layer."
- **Technical Implementation**
  - **System Architecture**: Sub-branches include the **Input Layer** (geolocation), **Data Ingestion** (WAQI API, botanical data), the **RAG Pipeline** (retrieval, LLM), and the **Output Layer** (Streamlit dashboard).
  - **Ethical Considerations**: This branch is critical, and it connects to both **AI** and **Urban Context**. Sub-branches include **Labor Displacement**, **De-skilling**, and **Equitable Access**. This section proposes a **Human-Centered Design approach** as the solution.



This mind map serves as a visual guide, demonstrating how the project's technical components are purposefully designed to address complex, real-world challenges spanning environmental science, economics, and ethics.

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