

Agriculture on Wheels

A BioE3 Vision for Green, Sustainable and Resilient Cities

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Abstract

Urban environments are increasingly challenged by rising pollution levels, limited land availability, and sustainability constraints, particularly along high-density transport corridors. While urban agriculture and vegetation-based interventions offer environmental and socio-economic advantages, their expansion in dense cities is restricted by static deployment and space limitations. This study introduces *Agriculture on Wheels (AoW)*, a mobility-integrated framework that embeds agricultural and carbon-assimilating vegetation systems within public transport infrastructure. By utilising underused bus rooftops as modular cultivation platforms, the approach enables distributed environmental interaction across urban routes without interfering with transport functionality. A depot-centric operational model ensures safety, hygiene, and regulatory compliance. The system prioritises shallow-root crops such as leafy greens and herbs, supporting biomass generation alongside carbon dioxide absorption and oxygen release. Preliminary scenario-based estimates indicate that large-scale implementation could contribute to decentralised biomass production and local environmental benefits using existing infrastructure. In addition to environmental impact, the framework offers opportunities for green employment, skill development, and productive reuse of public assets. By combining sustainability, economic value, and employment generation, AoW presents a scalable and policy-relevant pathway aligned with the BioE3 vision for resilient urban systems.

Keywords: Agriculture on Wheels, Mobile Urban Agriculture, BioE3 Framework, Net-Zero Cities, Urban Carbon Mitigation, Sustainable Public Transport

1. Introduction

The rapid expansion of urban areas has intensified environmental, spatial, and socio-economic pressures, particularly in densely populated metropolitan regions. Transport corridors, where vehicular emissions intersect with high human exposure, represent critical zones of environmental concern. Addressing these challenges requires innovative approaches that operate effectively within existing urban constraints, especially where land availability is limited.

Urban agriculture and vegetation-based strategies have been widely recognised for their ability to enhance food security, improve urban microclimates, and deliver ecological benefits. However, their large-scale implementation in dense cities remains restricted due to dependence on fixed locations and competition for valuable land resources. As a result, these interventions often fail to interact dynamically with pollution patterns associated with urban mobility systems.

Recent developments in modular design and controlled cultivation systems demonstrate

that biological processes can function efficiently in compact and engineered environments. At the same time, mobility-linked infrastructure has emerged as a strategy to improve spatial efficiency and system utilisation. Despite these advances, the integration of biological systems directly into moving public transport infrastructure remains largely unexplored.

Public bus networks represent a particularly relevant yet underutilised platform for such integration. City buses operate continuously across dense urban environments, follow predictable routes, and are maintained through centralised depot systems. These characteristics create opportunities to embed biological functionality into everyday urban operations, enabling environmental interaction along the same corridors where emissions are generated, without additional land acquisition.

In this context, the present study proposes *Agriculture on Wheels (AoW)*, a transport-integrated biotechnological and bioethical framework that embeds agricultural and carbon-assimilating vegetation into city bus infrastructure. The framework repositions public transport systems as multifunctional urban assets capable of supporting environmental mitigation, productive land substitution, and socio-economic value creation, while preserving their primary mobility function.

The proposed framework is conceptual in nature and is intended to support policy evaluation, pilot implementation, and future empirical validation. It aligns with the BioE3 vision by integrating environmental sustainability, economic value creation, and employment generation within a single operational system, guided by principles of responsible innovation, public ethics, and regulatory compatibility [17].

The remainder of this paper is structured as follows. Section 2 reviews relevant literature and identifies the research gap. Section 3 defines the problem context, objectives, and hypotheses. Section 4 presents the conceptual framework. Section 5 details the system architecture and design methodology. Section 6

provides indicative quantitative estimates and scenario analysis. Section 7 examines feasibility, safety, ethical, and evaluation considerations. Section 8 discusses sustainability impacts and long-term vision, followed by concluding remarks in Section 9.

This study outlines AoW as a conceptual and policy-relevant framework rather than a fully validated experimental system, with emphasis on feasibility, scalability, and governance alignment.

2. Literature Review

2.1. Urban Agriculture, Productivity, and Environmental Relevance

Urban agriculture has gained global attention as a response to food security concerns, environmental degradation, and declining urban resilience associated with rapid urbanisation. Numerous studies demonstrate that agricultural production can be integrated into urban environments through rooftops, balconies, peri-urban land, and repurposed infrastructure. Reported yields from soil-based and substrate-based urban agriculture systems typically range between 4–12 kg/m²/year, depending on crop type, climatic conditions, and management practices [1], [10]. More intensive systems, including hydroponic and vertical farming installations, have achieved yields exceeding 40–50 kg/m²/year, though such systems often involve higher capital costs, energy requirements, and technical complexity [2].

Beyond food production, urban agriculture provides important ecosystem services, including carbon dioxide uptake through photosynthesis, oxygen generation, urban heat-island moderation, stormwater regulation, and biodiversity enhancement [11], [13]. These functions are particularly relevant in metropolitan regions experiencing persistent air-quality deterioration. However, despite demonstrated productivity and environmental benefits, the large-scale expansion of urban agriculture remains constrained by land scarcity, high real-estate costs, and structural limitations of buildings, especially in dense city centres [3]. These constraints underscore the

need for agricultural models that do not depend on permanent land allocation and that can integrate with existing urban systems.

2.2. Non-Land-Based and Shallow-Substrate Crop Cultivation

A substantial body of research indicates that many crops suitable for urban food systems—including leafy greens, herbs, microgreens, nursery plants, and short-cycle vegetables—do not require deep soil profiles or extensive land areas. Such crops can be cultivated effectively using shallow-substrate systems, modular trays, and container-based arrangements, enabling deployment on rooftops and other non-traditional urban surfaces [2], [6].

Leafy vegetables and herbs are particularly well-suited to these environments due to their low root-depth requirements, rapid growth cycles, and relatively high biomass productivity per unit area. In addition to nutritional value, these crops contribute to carbon assimilation and oxygen release, supporting urban air-quality improvement efforts [11], [14]. Research further shows that controlled irrigation, nutrient management, and partial environmental shielding can enhance crop reliability under variable urban climatic conditions.

2.3. Circular Bioeconomy and Complementary Biological Systems

The circular bioeconomy framework emphasises efficient utilisation of biological resources and the conversion of organic waste streams into value-added products. Urban regions generate substantial quantities of biodegradable waste from households, markets, and food services, much of which remains underutilised. Biotechnological interventions such as composting, bio-fertiliser production, and controlled biological processing have been shown to reduce landfill burdens while supporting agricultural productivity [4], [5].

Although crop-based urban agriculture is the primary focus of many studies, complementary biological systems play an important role in nutrient cycling and resource efficiency.

Research demonstrates that biological processes can be safely integrated into urban environments when appropriate processing, containment, and hygiene protocols are followed [5]. These findings reinforce the broader principle that biological systems can be engineered to function reliably within compact and designed urban contexts.

2.4. Controlled-Environment Agriculture in Constrained Urban Settings

Controlled environment agriculture (CEA) has been extensively studied as a strategy for stabilising agricultural production under spatial and climatic constraints. Research shows that protective enclosures, modular cultivation units, and regulated irrigation systems can significantly improve plant survival and productivity in exposed or space-limited urban locations [6]. For hardy crops such as leafy greens and herbs, full climate control is often unnecessary; instead, partial shielding from extreme heat, wind, and precipitation is sufficient to ensure consistent yields.

These studies demonstrate that agricultural production can be decoupled from traditional farmland and fixed buildings, if core biological requirements are addressed through appropriate design and management.

2.5. Mobility as a System-Level Efficiency and Environmental Strategy

Recent research in infrastructure planning, sustainability science, and systems engineering increasingly recognises mobility as a mechanism for enhancing asset utilisation, resilience, and spatial reach [7]. This perspective is particularly relevant in metropolitan environments, where environmental challenges such as air pollution are spatially dynamic and concentrated along transport corridors [12].

Vegetation-based systems mitigate air pollution through photosynthetic carbon dioxide uptake and oxygen release. While the impact of individual plants is limited, studies

indicate that large numbers of plants distributed across multiple locations can cumulatively influence local air quality and microclimatic conditions [13], [14].

The feasibility of mobility-integrated systems has been most clearly demonstrated in renewable energy research. Studies on vehicle-mounted and route-optimised solar photovoltaic systems show that electricity generation and associated technologies can operate reliably when designed for mobile deployment [9], [15], [18]. The Illumbrella 2.0 framework further illustrates how mobility, combined with modular design and appropriate operational protocols, can enhance utilisation efficiency and system resilience [8].

2.6. Synthesis of Literature and Identification of Research Gap

The reviewed literature yields several consistent insights:

- ✓ Urban agriculture can produce meaningful quantities of food and plant biomass while delivering environmental co-benefits, yet its scalability is limited by land scarcity and predominantly static deployment models [1]–[3], [10], [11], [19].
- ✓ Many crops relevant to urban food systems—particularly leafy greens, herbs, and nursery plants—are well-suited to shallow-substrate and modular cultivation systems, enabling deployment on non-traditional surfaces [2], [6].
- ✓ Biological systems can be safely and efficiently operated within controlled or semi-controlled environments, supporting integration into engineered urban contexts [4]–[6].
- ✓ Movable infrastructure systems, validated through renewable energy and decentralised technology research, demonstrate that mobility enhances utilisation efficiency, resilience, and spatial distribution of benefits [7]–[9], [15].

Despite these advances, a significant research gap remains. Urban agriculture and biological

mitigation strategies are overwhelmingly static, whereas major sources of urban pollution—particularly transport networks—are inherently mobile and dynamic. Existing studies do not examine the integration of agricultural and carbon-assimilating biological systems directly into moving public transport infrastructure, such as city bus fleets that operate daily across dense and polluted urban zones [12], [16]. This gap forms the foundation for the present research.

3. Problem Statement, Objectives and Hypotheses

3.1. Problem Statement: Urban Context

Rapid urbanisation has intensified environmental, spatial, and socio-economic pressures in metropolitan regions worldwide. Indian cities such as Delhi, Mumbai, Bengaluru, and Kolkata exemplify this convergence of challenges, where air pollution, land scarcity, underutilised public infrastructure, and the demand for sustainable employment coexist as interconnected systemic issues.

Urban transport networks are among the most persistent contributors to urban air pollution, particularly along high-traffic corridors where commuter exposure is concentrated. Public bus systems play a critical role in supporting mass mobility and reducing reliance on private vehicles; however, they operate continuously within polluted environments and therefore remain embedded within the urban emission landscape.

At the same time, dense metropolitan areas face acute limitations in available land for environmental and productive interventions. While cities invest heavily in public transport infrastructure, large surface areas—such as city bus rooftops—remain underutilised for environmental, social, or economic functions despite regular exposure to sunlight, airflow, and ambient urban conditions. This underutilisation represents a missed opportunity to leverage existing public assets for sustainability outcomes without additional land acquisition or major redevelopment.

3.2. Objectives and Research Hypotheses

The overarching aim of this research is to conceptualize and systematically evaluate a mobility-linked biotechnological framework that addresses urban environmental challenges while leveraging existing public transport infrastructure. In alignment with the BioE3 principles of Environment, Economy, and Employment, the study pursues the following objectives [17].

3.2.1. General Objective

To develop a biotechnological and bioethical framework for integrating mobile urban agriculture and carbon-assimilating biological systems into city bus infrastructure, enabling environmental mitigation, productive land substitution, and socio-economic value creation in metropolitan regions.

3.2.2. Specific Objectives

- ✓ To examine the potential of city bus rooftops as underutilised urban infrastructure for agricultural, environmental, and biotechnological applications.
- ✓ To conceptualise a modular, lightweight, and operationally safe agricultural system suitable for deployment on moving public transport vehicles.
- ✓ To assess the potential role of mobility-linked vegetation systems in contributing to carbon dioxide uptake and oxygen generation along urban transport corridors.
- ✓ To evaluate how integrating agriculture with mobility can partially address land scarcity constraints in dense metropolitan environments.
- ✓ To explore the economic feasibility and employment-generation potential of embedding agricultural systems within city transport ecosystems.
- ✓ To align the proposed framework with principles of responsible innovation, public ethics, and national BioE3 policy objectives.

3.3. Research Hypotheses

Given the conceptual and design-oriented nature of this study, the research adopts working hypotheses intended for validation through pilot implementation, simulation, or future empirical investigation. These hypotheses describe expected system behaviour based on established engineering and biological principles.

3.4. Working Hypotheses

- ✓ **H1:** Modular agricultural systems can be safely and technically integrated onto city bus rooftops without compromising vehicle stability, passenger safety, or transport operations.
- ✓ **H2:** Mobility-integrated vegetation systems deployed on public transport vehicles can deliver measurable environmental benefits through carbon dioxide uptake and oxygen generation along urban transport corridors.
- ✓ **H3:** Utilising existing bus infrastructure for mobile agriculture can partially offset land constraints that limit the scalability of conventional urban agriculture initiatives.
- ✓ **H4:** Transport-integrated agricultural systems can achieve broader spatial interaction with urban environments compared to fixed-location interventions.
- ✓ **H5:** Integrating agriculture into public transport infrastructure can generate supplementary economic value and create green employment opportunities within urban ecosystems.
- ✓ **H6:** A mobility-based agricultural framework demonstrates stronger alignment with BioE3 objectives than isolated, single-domain sustainability interventions.

3.5. Role of Objectives and Hypotheses in the Study

The stated objectives and hypotheses provide a structured foundation for the subsequent

conceptual framework, system architecture, quantitative assessment, and feasibility analysis. Together, they guide the design logic of AoW and establish clear criteria for evaluating its technical feasibility, environmental relevance, and socio-economic impact of the proposed framework.

4. Conceptual Framework: Agriculture on Wheels (AoW)

Based on the identified gap, this research proposes AoW, a novel biotechnological and bioethical framework that integrates urban agriculture and environmental mitigation directly into city bus infrastructure. The framework reimagines public transport systems not only as mobility assets but also as mobile biological platforms capable of contributing to carbon capture, oxygen generation, urban food production, and employment generation without competing for urban land or compromising transport functionality.

4.1. Core Conceptual Premise

The core premise of AoW is that urban sustainability interventions must be operationally aligned with the spatial and temporal dynamics of cities. Public transport vehicles, particularly city buses, operate continuously across dense urban environments and therefore provide a unique opportunity to embed biological functionality directly within everyday urban systems.

City buses are particularly suited for this role due to:

- Wide spatial coverage across urban transport corridors
- Predictable routes and schedules
- Centralised inspection and maintenance at depots
- Large, contiguous, and underutilised rooftop surfaces

By leveraging these characteristics, the framework transforms buses into distributed,

mobile green infrastructure integrated within the urban fabric.

4.2. System Architecture Overview

The conceptual framework comprises three interlinked layers: physical infrastructure, biological systems, and operational governance.

4.2.1. Physical Infrastructure Layer

At the physical level, the framework utilises bus rooftops as platforms for lightweight agricultural systems. A protective structural frame is envisioned to:

- Ensure safety under vibration, wind, and weather exposure
- Prevent interference with vehicle operation
- Support modular and removable cultivation units

The use of modular tray-based systems enables flexibility in crop selection, maintenance, and scalability. These trays are designed to be installed, monitored, and serviced at bus depots, ensuring that agricultural activities do not disrupt daily transport operations.

4.2.2. Biological System Layer

The biological layer focuses on vegetation-based systems optimised for urban and mobile environments. Priority is given to crops that:

- Require shallow substrates
- Have short growth cycles
- Exhibit high biomass productivity
- Contribute to carbon dioxide uptake and oxygen release

Representative crops include leafy greens, herbs, selected short-cycle vegetables, and nursery plants for urban greening. While complementary biological processes may support nutrient management, the primary emphasis remains on photosynthetically active vegetation that directly contributes to environmental mitigation and plant-based production.

Through photosynthesis, the vegetation layer functions as a distributed carbon-assimilation surface, interacting with urban air across transport routes during routine bus operations.

4.2.3. Operational and Governance Layer

Operationally, AoW is designed to integrate seamlessly with existing public transport management systems. All installation, irrigation, harvesting, inspection, and sanitation activities are conducted at bus depots as part of scheduled maintenance cycles. This ensures:

- Operational safety
- Hygienic management
- Minimal burden on transport staff

From a governance perspective, the framework supports multi-stakeholder participation, including transport authorities, municipal bodies, urban agriculture professionals, and local workforce groups. This layered governance structure aligns with principles of responsible innovation, public accountability, and ethical use of public infrastructure.

4.3. Functional Pathways and Expected Contributions

The AoW framework is designed to operate along four primary functional pathways:

- **Environmental Mitigation:** Vegetation systems absorb carbon dioxide and release oxygen, contributing to local air-quality improvement and urban microclimate regulation.
- **Urban Food and Green Resource Production:** The system produces fresh vegetables, herbs, and nursery plants within the city, reducing dependence on distant supply chains and supporting urban food resilience [19].
- **Efficient Use of Existing Infrastructure:** By utilising unused bus rooftop space, the framework delivers environmental and economic value without additional land acquisition or major construction.

- **Employment and Economic Opportunity:** The operation, maintenance, and management of mobile agricultural systems generate green jobs and support skill development aligned with emerging urban biotechnology sectors.

4.4. Conceptual Significance

AoW represents a shift from single-purpose, static sustainability interventions toward dynamic, mobility-linked biotechnological design. By unifying transport, agriculture, and environmental mitigation within a single operational concept, the framework positions public transport infrastructure as an active participant in urban ecological regeneration, rather than solely as a mobility service. This conceptual foundation informs the subsequent sections on system design, quantitative assessment, feasibility, and impact evaluation.

5. System Architecture and Design Methodology

This section describes the physical, biological, and operational realisation of the AoW framework. The focus is strictly on how the system is designed, installed, and operated, without repeating problem justification, policy arguments, or impact narratives discussed in earlier and later sections.

5.1. Design Philosophy

The AoW system is governed by the following design principles:

1. **Non-interference** with transport operations, ensuring vehicle safety, passenger comfort, and regulatory compliance
2. **Modularity and scalability**, enabling phased deployment across city bus fleets
3. **Lightweight and low-profile** construction, minimising structural load and aerodynamic impact
4. **Depot-centric operation**, avoiding any agricultural activity during transit

5. Bioethical and environmental responsibility, ensuring hygiene, biosafety, and responsible use of public infrastructure

At the system level, the framework follows established principles of transport-integrated infrastructure, where functional systems are embedded into moving platforms to improve utilisation efficiency and spatial reach. The interaction between mobility, biological processes, and environmental outcomes is illustrated in **Figure 1**.



Figure 1. System-level conceptual framework of AoW, illustrating the integration of mobility, biological processes, and environmental outcomes aligned with BioE3 principles (AI Generated).

5.2. Physical Architecture: Integration with Public Transport Infrastructure

The AoW framework adopts a modular, infrastructure-integrated architectural approach, designed to utilise existing public transport assets for urban agriculture and environmental mitigation. The physical architecture is centred on the deployment of lightweight cultivation systems on city bus rooftops, with direct extensibility to fixed public transport infrastructure such as bus stops and shelters. This dual integration enables both mobile and stationary greening, maximising environmental reach without additional land acquisition.

5.2.1. Structural Configuration: Bus Rooftop Integration

The primary deployment platform for the framework is the rooftop of city buses, which provides a large, contiguous, and underutilised surface area. A secondary, detachable rooftop superstructure is mounted using non-invasive fastening mechanisms compatible with existing vehicle design constraints.

A perimeter safety enclosure, fabricated from galvanised steel rods or perforated metal plates, surrounds the cultivation area to:

- Prevent displacement of modules during motion
- Maintain stability under vibration and wind loads
- Ensure safety during routine inspection and maintenance

The structural configuration maintains a low-profile design to comply with vehicle height regulations and minimise aerodynamic impact. A conceptual representation of this configuration is shown in **Figure 2**.

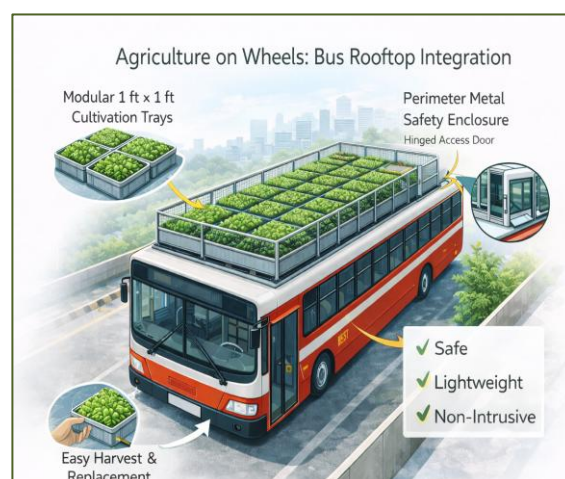


Figure 2. Conceptual architecture of the AoW system implemented on a Mumbai BEST city bus rooftop, illustrating modular 1 ft × 1 ft cultivation trays arranged within a perimeter metal safety enclosure. The design demonstrates safe, lightweight, and non-intrusive integration of urban agriculture modules on existing public transport infrastructure.

5.2.2. Modular Cultivation Tray System

Agricultural production is organised into uniform modular cultivation trays, each approximately 1 ft × 1 ft in surface area with a shallow substrate depth. These trays function as independent units and are arranged in a grid layout across the available rooftop area.

Key characteristics of the modular tray system include:

- Lightweight growing media suitable for mobile deployment
- Integrated drainage and water-retention layers
- Ease of removal and replacement during scheduled depot maintenance

The modular approach supports standardisation across different bus models and enables flexible crop management without altering the underlying structural system. A plan-view layout of the tray arrangement is illustrated in **Figure 3**.

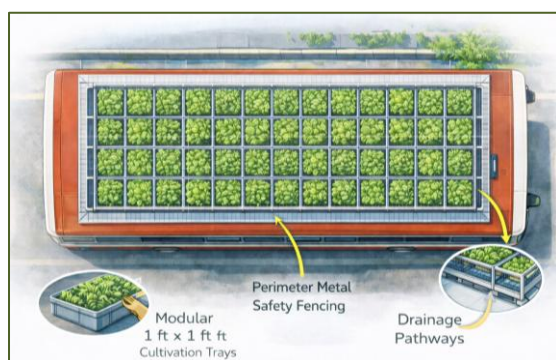


Figure 3. Plan (top) view of the AoW rooftop layout, depicting a grid arrangement of uniform 1 ft × 1 ft cultivation trays, perimeter safety fencing, and drainage pathways. This layout supports quantitative estimation of usable area, tray density, and potential crop yield.

5.2.3. Extension to Fixed Public Transport Infrastructure (Bus Stops)

The same modular tray architecture can be deployed on fixed public transport infrastructure, particularly city bus stops and

shelters with flat or semi-covered roofs. Using identical tray dimensions and support structures ensures architectural continuity between mobile and stationary installations.

Bus stop-based installations:

- Operate as static complements to rooftop systems
- Expand total green surface area without new construction
- Maintain standardised maintenance and irrigation protocols

This dual deployment enhances system robustness and spatial coverage within public transport corridors. The conceptual application of the system on a bus stop structure is illustrated in **Figure 4**.



Figure 4. Conceptual application of the AoW modular cultivation tray system on a city bus stop structure, illustrating the extension of the same architectural design from mobile bus rooftops to fixed public transport infrastructure.

5.3. Biological System Design

5.3.1. Crop Selection

Crop selection prioritises species that are biologically suited to shallow substrates and mobile environments. Selection criteria include:

- Low root-depth requirements
- Short growth cycles
- High biomass productivity
- Contribution to carbon dioxide uptake and oxygen release

Representative crops include leafy greens, herbs, selected short-cycle vegetables, and nursery plants intended for urban greening. Crop diversity is maintained to support operational flexibility across seasons and climatic conditions.

5.3.2. Environmental Protection

The cultivation system incorporates partial protective covers or mesh enclosures to shield plants from excessive wind, rainfall, and thermal stress while maintaining airflow. This approach balances biological requirements with mobility constraints and avoids the need for full climate control, thereby reducing energy and maintenance demands.

5.4. Irrigation and Resource Management

Irrigation is designed using low-water, high-efficiency techniques, such as drip or wick-based systems. Watering and nutrient replenishment occur exclusively during depot halts, ensuring safety and operational simplicity. Where permissible, bio-fertilisers aligned with circular bioeconomy principles may be employed under strict hygiene and regulatory controls.

5.5. Operational Workflow

All agricultural activities including inspection, irrigation, harvesting, and sanitation—are conducted exclusively at bus depots as part of scheduled maintenance cycles. During transit, buses function solely as environmental interaction pathways, with no human intervention in the agricultural system.

This depot-centric workflow ensures:

- Passenger safety
- Hygienic management
- Minimal disruption to transport schedules

The sequential operational process is illustrated in **Figure 5**, which highlights safe handling and maintenance practices.



Figure 5. Depot-centric operational workflow of the AoW system, illustrating sequential stages of bus arrival and inspection, irrigation and harvesting, sanitation and cleaning, and safe redeployment of the vehicle for transit. All agricultural activities are confined to bus depots, while bus routes function solely as environmental interaction pathways, ensuring passenger safety, hygiene compliance, and uninterrupted transport operations.

5.6. Safety, Hygiene, and Regulatory Compliance

Safety considerations are integral to system design and include:

- Load compliance with vehicle design limits
- Secure fastening and perimeter fencing
- Hygienic separation between cultivation units and passenger areas
- Alignment with municipal transport and food safety regulations

The system is designed as a non-intrusive add-on, reinforcing public trust and regulatory acceptability.

5.7. Methodological Approach for Evaluation

Evaluation of the proposed system follows a phased methodology:

1. Structural and operational feasibility assessment

2. Pilot-scale deployment on selected city buses
3. Monitoring of environmental, operational, and economic indicators
4. Iterative refinement prior to scale-up

This approach enables evidence-based validation, responsible innovation, and informed decision-making prior to large-scale implementation.

6. Quantitative Estimates and Scenario Analysis

This section presents indicative quantitative estimates for the AoW framework, focusing on usable area, cultivation capacity, biomass yield, carbon assimilation potential, and indicative economic value. The estimates are intended to support scenario analysis and early policy evaluation, rather than to claim precise experimental outcomes. Conservative assumptions are adopted throughout to ensure feasibility and credibility.

6.1. Assumptions and Basis of Estimation

To maintain transparency, the following baseline assumptions are used:

- Average city bus rooftop usable area: **18–22 m²**
- Effective cultivable area after structural clearance: **~15 m² per bus**
- Modular tray size: **1 ft × 1 ft × 1 ft depth** (~0.093 m² per tray)
- Cultivable trays per bus: **~150–160 trays**
- Crop types: leafy greens, herbs, and nursery plants (mixed cycle)
- Cultivation approach: soil/substrate-based, low-input, non-hydroponic
- Yield range for shallow-substrate urban systems: **4–12 kg/m²/year** (conservative)

All calculations represent order-of-magnitude estimates suitable for pilot-scale assessment.

6.2. Usable Area and Tray Density per Bus

Assuming an average effective rooftop area of 15 m², the number of modular cultivation trays per bus is estimated as:

$$\text{Number of trays per bus} = \frac{15}{0.093} \approx 161$$

Rounded conservatively, each bus can support approximately 150 cultivation trays, allowing adequate spacing for structural supports, drainage pathways, and maintenance access.

6.3. Estimated Annual Biomass and Crop Yield

Using conservative yield estimates:

- **Lower-bound yield:**

$$15 \text{ m}^2 \times 4 \text{ kg/m}^2/\text{year} = 60 \text{ kg/year}$$

- **Upper-bound yield:**

$$15 \text{ m}^2 \times 12 \text{ kg/m}^2/\text{year} = 180 \text{ kg/year}$$

Thus, each bus rooftop can produce approximately 60–180 kg of fresh biomass per year, depending on crop selection, seasonal conditions, and maintenance quality.

6.4. City-Scale Scenario: Mumbai BEST Bus Network

Mumbai's BEST transport system operates approximately 3,000–3,500 buses (diesel, CNG, and electric combined).

Using a conservative deployment scenario of 3,000 buses:

- **Total cultivable area:**

$$3,000 \times 15 = 45,000 \text{ m}^2 \approx 4.5 \text{ hectares}$$

- **Annual biomass production:**

✓ Lower bound: **180 tonnes/year**

- ✓ Upper bound: **540 tonnes/year**

This represents a **substantial distributed urban production system**, achieved **without any new land acquisition**.

6.5. Indicative Carbon Dioxide Uptake and Oxygen Generation

Photosynthetically active vegetation absorbs carbon dioxide and releases oxygen as part of biomass formation. While precise sequestration depends on species and growth conditions, indicative values from urban vegetation studies suggest:

- **CO₂ uptake:** ~1.5–2.5 kg CO₂ per kg of dry biomass
- Assuming ~15–20% dry matter content in fresh biomass

Based on these conservative assumptions, the system can contribute to measurable localised carbon assimilation, particularly along high-emission transport corridors. These estimates provide indicative environmental interaction rather than precise sequestration values.

6.6. Extension Scenario: Integration with Bus Stops

If the same modular tray system is deployed on **bus stops and shelters**, additional cultivable area can be achieved. Assuming:

- Average bus stop rooftop area: **6–8 m²**
- Deployment across **2,000 bus stops**

This yields an additional **12,000–16,000 m²** of green surface area, further increasing aggregate biomass production capacity.

6.7. Indicative Economic and Employment Potential

While revenue generation is not the primary objective of the framework, indicative economic value may arise from:

- Utilisation of vegetables and herbs

- Nursery plants for municipal greening programs
- Skill-based employment for system maintenance and harvesting

When aggregated across city-scale deployment, even modest per-bus value can support partial maintenance costs and contribute to green employment pathways.

6.8. Interpretation and Limitations

The presented estimates are **indicative and conservative**, intended to demonstrate feasibility at the order-of-magnitude level. Actual outcomes will depend on:

- Crop selection and seasonal variation
- Maintenance practices
- Local climatic conditions
- Regulatory and operational constraints

These limitations highlight the importance of pilot-scale deployment and iterative refinement, as outlined in subsequent sections.

7. Feasibility, Safety, and Ethical Considerations

This section assesses the *AoW* framework from the perspectives of technical feasibility, operational safety, regulatory compliance, ethical responsibility, and evaluation methodology. These considerations are essential for responsible deployment on public transport infrastructure and for informed policy decision-making.

7.1. Technical Feasibility

The proposed framework is technically feasible due to its modular, lightweight, and non-intrusive design. The rooftop agricultural system is engineered to remain within permissible vehicle load limits and does not require modification of the bus chassis, drivetrain, or passenger compartments. Key feasibility attributes include:

- Compatibility with existing bus designs and maintenance regimes

- Use of shallow substrates and lightweight materials
- Detachable structural components allowing phased deployment

These characteristics support pilot-scale implementation without disrupting routine transport operations.

7.2. Operational Safety

Operational safety is ensured through a depot-centric handling model, in which all agricultural activities are confined to bus depots and conducted during scheduled maintenance cycles. No irrigation, harvesting, or manual intervention occurs during transit. Safety measures include:

- Secure fastening of cultivation modules and perimeter safety fencing
- Stability under vibration, wind load, and braking conditions
- Compliance with vehicle height and clearance regulations

This approach ensures passenger safety, protects transport staff, and preserves service reliability.

7.3. Hygiene and Public Health Considerations

Hygiene and biosafety are integral to system design and operation. Cultivation units are physically separated from passenger areas, and only non-pathogenic, non-invasive plant species are selected.

Key biosafety measures include:

- Use of clean, controlled growing substrates
- Controlled irrigation and drainage to prevent spillage
- Regular sanitation of trays and support structures at depots

These measures ensure that agricultural operations do not compromise public health or sanitation standards.

7.4. Regulatory and Legal Considerations

The framework is designed as a non-intrusive add-on to existing public transport infrastructure, reinforcing regulatory acceptability and public trust. It aligns with regulatory domains governing:

- Municipal transport operations
- Vehicle safety and load compliance
- Urban horticulture and food safety
- Environmental protection standards

Pilot deployment can be enabled through inter-agency coordination between transport authorities, municipal bodies, and relevant state or national agencies, without requiring major regulatory restructuring.

7.5. Ethical Use of Public Infrastructure

From an ethical perspective, AoW follows principles of responsible innovation and public accountability. The framework enhances public infrastructure to deliver environmental and social benefits without compromising its primary function. Ethical considerations addressed include:

- Prioritisation of public benefit over commercial exploitation
- Transparency in system purpose and operation
- Inclusive access to employment and skill-development opportunities

This approach supports ethical governance of shared urban assets.

7.6. Environmental and Biosafety Considerations

The system avoids genetically modified organisms and hazardous biological agents. Plant species selection prioritises:

- Native or widely cultivated varieties
- Low ecological risk
- Minimal invasive potential

Substrate and nutrient use follow environmentally safe practices, preventing runoff or contamination. The system functions as a low-risk biological intervention, consistent with sustainable urban ecology principles.

7.7. Risk Mitigation and Adaptive Governance

Potential risks associated with the framework are assessed as low to moderate and are mitigated through design and operational controls:

- **Structural risk:** Mitigated through conservative load design and secure mounting
- **Operational risk:** Mitigated through depot-only handling
- **Biological risk:** Mitigated through crop selection and hygiene protocols
- **Public perception risk:** Mitigated through visible safety measures and transparent communication

Overall, the risk profile is suitable for controlled pilot deployment.

7.8. Methodological Approach for Evaluation

Evaluation of the AoW framework follows a phased and evidence-based methodology, designed to validate feasibility and inform scaling decisions:

1. Structural and operational feasibility assessment under real-world conditions
2. Pilot-scale deployment on selected city buses
3. Monitoring of environmental, operational, and economic indicators, including system stability, maintenance effort, and biomass output
4. Iterative refinement of design and operational protocols prior to scale-up

This methodological approach supports responsible innovation, reduces implementation risk, and enables data-driven

decision-making for municipal and policy stakeholders.

8. Sustainability, Impact, and Long-Term Vision

The AoW framework is conceived as a systems-level intervention that integrates environmental sustainability, socio-economic value creation, and urban resilience. By embedding biological productivity into existing public transport infrastructure, the framework advances a resource-efficient and low-impact model of urban innovation aligned with the BioE3 principles of Environment, Economy, and Employment.

8.1. Environmental Sustainability and Climate Relevance

At the environmental level, AoW contributes to urban sustainability by integrating distributed vegetation directly into mobility systems, particularly along transport corridors with high pollution intensity. By placing photosynthetically active vegetation on city bus rooftops and associated public transport infrastructure, the framework enables localized carbon dioxide uptake and oxygen generation within everyday urban movement patterns.

The system is not positioned as a standalone solution to urban air pollution; rather, it functions as a complementary biological augmentation layer that operates continuously across space and time. Combined deployment across mobile installations (bus rooftops) and stationary installations (bus stops) expands the effective green surface area of cities without requiring additional land conversion or structural expansion. Key environmental contributions include:

- Localised carbon assimilation and oxygen release along public transport routes
- Improvement of urban microclimates through spatially distributed greenery
- Productive reuse of underutilised built infrastructure
- Increased visibility of environmental stewardship in daily urban life

Through this integration, the framework supports climate adaptation, urban heat moderation, and ecological balance, while complementing broader strategies such as transport electrification, emission control, and urban afforestation.

8.2. Social Impact and Public Health Dimensions

The *AoW* framework generates multi-dimensional socio-economic and public health benefits by converting public transport infrastructure into a productive, bio-based urban asset. Key impacts include:

8.2.1. Socio-Economic Value Creation

- Creation of green employment opportunities in system installation, routine maintenance, harvesting, and monitoring
- Skill development in urban agriculture, bio-based system management, and circular bioeconomy practices
- Supplementary revenue and cost-offset potential for transport authorities through productive reuse of existing infrastructure
- Localised production of vegetables, herbs, and nursery plants for municipal greening programs and community use

8.2.2. Public Health and Social Equity Benefits

- Introduction of visible and functional greenery into everyday public spaces, enhancing environmental awareness and commuter engagement
- Indirect contributions to public health, including improved air-quality perception and psychological well-being
- Support for urban food resilience, particularly in land-constrained and underserved neighbourhoods
- Mitigation of disproportionate impacts of air pollution and limited green access on vulnerable urban populations

8.2.3. Inclusive and Scalable Development

- Distributed and inclusive livelihood generation, aligned with urban employment and skill-building initiatives
- Strengthening of circular bioeconomy ecosystems through bio-based urban production
- Reinforcement of equitable and responsible utilisation of public infrastructure

Collectively, these outcomes position *AoW* as a socially inclusive, economically viable, and public health-supportive intervention aligned with BioE3 objectives.

8.3. Economic Sustainability and Employment Generation

The framework advances **economic sustainability and urban resilience** by transforming underutilised public transport infrastructure into productive biological assets, without additional land acquisition or capital-intensive redevelopment. Key impacts include:

8.3.1. Economic Sustainability and Value Creation

- Productive reuse of existing infrastructure for bio-based outputs
- Aggregated economic value generation at city scale through agricultural production
- Partial cost-offset potential for transport authorities
- Reduced reliance on land-intensive urban greening interventions

8.3.2. Employment and Skill Development

- Green job creation across multiple stages of the system lifecycle, including:
 - Fabrication of modular trays and support structures

- Installation, inspection, and routine maintenance at bus depots
- Crop management, harvesting, and handling of biological outputs
- Data monitoring, documentation, and system optimisation during pilot and scale-up phases
- Development of urban bioeconomy skills and decentralised employment opportunities

8.3.3. Urban Resilience and System Redundancy

- Diversification of the functional role of public infrastructure beyond transport alone
- Creation of hybrid systems combining mobility, biological productivity, and environmental services
- Enhanced system redundancy through dual deployment on mobile (bus rooftops) and stationary (bus stops) infrastructure, ensuring continuity during fleet downtime or route changes

These combined outcomes demonstrate how AoW enables co-production of economic value, employment, and resilience within urban systems.

8.4. Institutional, Policy, and BioE3 Alignment Impact

AoW presents a policy-relevant and institutionally feasible model for embedding biotechnology into urban systems without major redevelopment. Its compatibility with existing public transport infrastructure makes it attractive for municipal governments seeking low-risk, high-visibility sustainability interventions.

8.4.1. Institutional and Governance Relevance

- Productive augmentation of public infrastructure without structural modification

- Support for incremental pilot implementation and evidence-based scaling
- Enhanced coordination across transport, environment, and urban development agencies
- Strengthened public trust through ethical and non-intrusive use of shared assets

8.4.2. Policy Convergence and Systems-Level Integration

The framework supports convergence across:

- Urban transport planning and sustainable mobility
- Climate action plans and clean air missions
- Circular bioeconomy and resource efficiency initiatives
- Employment generation and urban skill development programs

This convergence advances a systems-level governance approach for sustainable cities.

8.4.3. Alignment with BioE3 Vision

The framework operationalises BioE3 by translating biotechnology into visible, implementable urban practice [17]:

- **Environment:** Carbon assimilation, urban greening, and land-efficient mitigation
- **Economy:** Value creation through productive reuse of infrastructure
- **Employment:** Generation of green jobs and urban bioeconomy skill pathways.

8.5. Long-Term Vision and Scalability

The long-term vision of AoW positions urban mobility systems as active agents of ecological regeneration, extending public transport beyond mobility to participation in sustainable urban transformation.

8.5.1. Scalability Across Contexts

- Expansion from pilot deployments to city-scale implementation
- Adaptability across transport modes, including electric buses and future mobility platforms
- Applicability across diverse climatic, regulatory, and socio-economic contexts
- Transferability to international urban transport systems facing land scarcity and pollution challenges

8.5.2. Technological and System Evolution

- Integration of sensor-based monitoring for plant health and system performance
- Data-driven optimisation of crop selection and route-based environmental interaction
- Convergence with renewable energy systems and smart city platforms
- Extension to additional forms of public mobility and shared infrastructure

8.5.3. Transformative Urban Impact

- Reframing public transport as a multifunctional, productive urban asset
- Strengthening the role of biotechnology in everyday urban systems
- Enabling a shift from static greening to dynamic, mobility-linked sustainability solutions

Ultimately, *AoW* represents a paradigm shift in how cities conceive and deploy infrastructure-integrating mobility, biotechnology, and sustainability to support long-term ecological regeneration, economic opportunity, and urban resilience.

While the conceptual framework demonstrates strong theoretical feasibility, its real-world performance remains subject to validation under varying operational, climatic, and regulatory conditions. Further empirical studies and pilot-scale implementations are

required to establish long-term system stability and environmental impact.

9. Conclusion

This study introduces *Agriculture on Wheels (AoW)* as a mobility integrated biotechnological framework that reimagines public transport infrastructure as a platform for urban agriculture and environmental mitigation. By utilising bus rooftops and associated transport assets, the framework aligns biological systems with the dynamic spatial patterns of urban mobility, addressing key limitations of conventional urban greening such as land dependence and static deployment. The proposed system adopts a modular, lightweight, and depot-centric design that prioritises operational safety, hygiene, and regulatory compatibility. Indicative assessments suggest that, if implemented at scale, the framework could contribute to distributed biomass production and localised environmental interaction without requiring additional land or major infrastructure modification. However, these outcomes remain subject to validation through pilot implementation and empirical study.

In addition to environmental potential, *AoW* highlights opportunities for socio-economic value creation through green employment, skill development, and the productive use of existing public assets. By integrating environmental, economic, and employment dimensions within a single operational concept, the framework demonstrates a systems-level approach to urban sustainability. Future work should focus on pilot-scale deployment, performance monitoring, and iterative refinement to establish technical feasibility and inform policy adoption. As a conceptual and policy-oriented model, *AoW* offers a promising direction for transport-integrated biotechnology to support the transition toward more sustainable, resilient, and resource-efficient cities.

Author Contributions

The original concept, framework, and research idea presented in this paper were conceived by **Author 1** (Arjit Amol More). **Author 2** (Rani

Amol More) provided academic writing support, manuscript organization, language editing, and publication preparation. Both authors approved the final manuscript.

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