Comparative Performance Analysis of Conventional and Wavy-Bottom Liquid Tree Photobioreactors for Urban Air Purification

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***Abstract*—Rapid urbanization and the reduction of green spaces have intensified air pollution in major cities. Conventional tree plantation remains an important environmental strategy, but it is difficult to implement in highly congested urban areas where land is limited. Liquid Tree photobioreactors provide an alternative by using microalgae to absorb carbon dioxide and release oxygen within a compact structure. This research evaluates the performance of a conventional cylindrical photobioreactor and an inclined wavy-bottom photobioreactor for urban air purification. A comparative analytical model was developed to estimate carbon dioxide capture, oxygen generation, light utilization, and biomass productivity under identical operating conditions. The study indicates that the wavy-bottom design improves microalgal circulation and creates repeated light-dark exposure, increasing photosynthetic efficiency. The modified reactor achieved approximately 24% higher carbon dioxide absorption, 18% higher oxygen release, and 21% greater biomass yield than the conventional model. These findings suggest that optimized reactor geometry can significantly improve the efficiency of Liquid Tree systems and make them more suitable for deployment in densely populated cities.**

***Index Terms*—Liquid Tree, Photobioreactor, Microalgae, CO_2 Capture, Smart Cities, Biomass, Urban Sustainability.**

I. INTRODUCTION

Urban air pollution has become a critical environmental challenge because of increasing industrial activity, vehicular emissions, and population growth. Metropolitan cities frequently experience elevated concentrations of carbon dioxide, particulate matter, and harmful gases. Although urban trees reduce pollution and improve air quality, their effectiveness is limited in crowded locations where open land is unavailable.

Liquid Tree technology offers a compact and space-efficient solution. A Liquid Tree is a transparent photobioreactor containing microalgae suspended in nutrient-rich water. During photosynthesis, the algae absorb carbon dioxide and release oxygen. Unlike natural trees, microalgae grow rapidly and can achieve higher carbon fixation rates in a smaller area.

Most existing Liquid Tree systems use cylindrical or flat-panel photobioreactors. However, these designs often suffer from poor light penetration and uneven algal circulation. Microalgae near the outer wall receive excessive light, while cells in the center remain under-illuminated. This reduces the overall efficiency of the system.

To overcome this issue, the present study investigates an inclined wavy-bottom photobioreactor. The modified geometry increases turbulence and produces a flashing light effect, in which algae repeatedly move between illuminated and shaded regions. This repeated exposure improves photosynthetic activity and carbon dioxide uptake.

The main objective of this research is to compare the environmental performance of a conventional cylindrical reactor and a wavy-bottom reactor under the same urban operating conditions.

II. LITERATURE REVIEW

Microalgae-based photobioreactors have gained attention as sustainable systems for carbon dioxide capture and oxygen generation. Species such as Chlorella vulgaris and Spirulina platensis are commonly used because of their rapid growth and high tolerance to changing environmental conditions.

Previous studies have shown that microalgae can absorb carbon dioxide at a rate much greater than terrestrial plants. Compact photobioreactors have therefore been proposed for use in traffic intersections, bus stops, public parks, and smart city infrastructure.

Research on reactor geometry demonstrates that the internal shape of a photobioreactor strongly affects productivity. Conventional cylindrical reactors are simple to construct but provide limited internal mixing. Flat-panel systems improve surface area but suffer from overheating and uneven illumination.

Recent investigations suggest that inclined and wavy-bottom configurations can improve the movement of algae inside the reactor. The undulating surface generates localized circulation zones, which increase mixing and create repeated light-dark exposure. This phenomenon, commonly called the flashing light regime, improves photosynthetic efficiency because the algae are not continuously exposed to intense light. Despite these advances, very few studies have compared conventional and wavy-bottom Liquid Tree systems specifically for urban air purification. Therefore, this research attempts to fill that gap.

III. RESEARCH GAP

Existing research focuses mainly on the conceptual design of Liquid Tree systems. Most studies describe the environmental benefits of microalgae-based air purification but do not quantitatively compare different reactor geometries.

The following research gaps were identified:

- Lack of comparative studies between conventional and modified photobioreactors
- Limited information about the influence of reactor shape on carbon dioxide capture
- Insufficient data regarding oxygen generation and biomass productivity in urban conditions
- Absence of a simple analytical framework suitable for city-scale deployment

This study addresses these limitations by comparing the performance of two reactor geometries under identical operating conditions.

IV. OBJECTIVES

The primary objective of this research is to evaluate the potential of the Liquid Tree Photobioreactor as a compact and sustainable solution for improving air quality in densely populated urban areas. The study aims to investigate how microalgae-based photobioreactors can supplement conventional green infrastructure in locations where tree plantation is difficult because of limited space.

The specific objectives of the study are as follows:

- To understand the working principle of the Liquid Tree photobioreactor and the role of microalgae in carbon dioxide absorption and oxygen generation.
- To analyze the effect of reactor geometry on the performance of the system, particularly by comparing a conventional cylindrical reactor with an inclined wavy-bottom reactor.
- To estimate the amount of carbon dioxide that can be captured and the quantity of oxygen that can be released by a single Liquid Tree unit under typical urban conditions.
- To study the influence of important operating parameters such as sunlight intensity, temperature, and biomass concentration on the overall efficiency of the photobioreactor.
- To evaluate the feasibility of installing Liquid Tree systems in crowded urban locations such as traffic intersections, bus stops, public squares, and railway stations.
- To examine the maintenance requirements, energy consumption, and economic viability of the system for large-scale deployment.
- To compare the environmental performance of Liquid Tree technology with conventional tree plantation and other urban air purification methods.
- To propose possible future improvements such as automated cleaning systems, optimized algal strains, IoT-based monitoring, and modular deployment for smart-city applications.

V. DETAILED SYSTEM ARCHITECTURE

The Liquid Tree photobioreactor consists of five major subsystems: the transparent reactor chamber, the microalgal culture medium, the circulation mechanism, the lighting arrangement, and the monitoring system.

The reactor chamber is generally fabricated from UV-resistant acrylic or borosilicate glass. These materials provide high transparency, low corrosion, and sufficient structural strength for outdoor operation. The internal volume of a typical unit varies from 80–150 L depending on installation location.

The culture medium contains water, nutrients, and microalgae such as Chlorella vulgaris. The nutrients generally include nitrogen, phosphorus, magnesium, iron, and trace minerals required for photosynthetic growth.

A low-power circulation pump or aeration system is used to keep the algae suspended uniformly inside the chamber. Without mixing, the algae settle near the bottom, reducing light penetration and limiting photosynthesis.

Artificial lighting may also be incorporated in the form of red-blue spectrum LEDs. Red wavelengths promote biomass production, while blue wavelengths improve chlorophyll activity. The LEDs are powered through rooftop solar panels and rechargeable batteries.

The final subsystem is the sensor network. CO_2 sensors, pH sensors, temperature sensors, dissolved oxygen sensors, and IoT communication modules provide continuous monitoring. These values can be transmitted to a smart-city dashboard for real-time environmental tracking. The major components and multifunctional features of the Liquid Tree system are illustrated in Fig. 1 and Fig. 2.

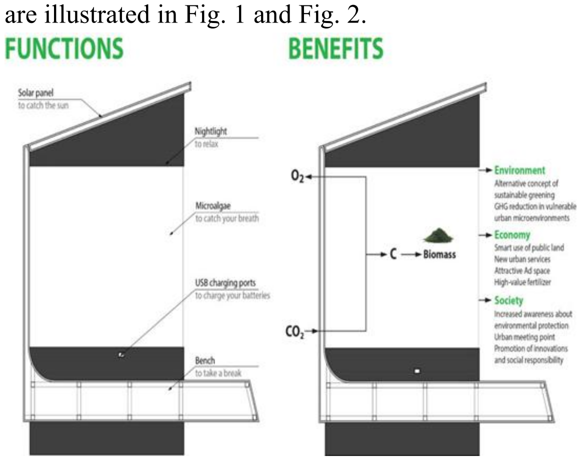

Fig. 1. Functional Features and Environmental Benefits of the Liquid Tree Photobioreactor

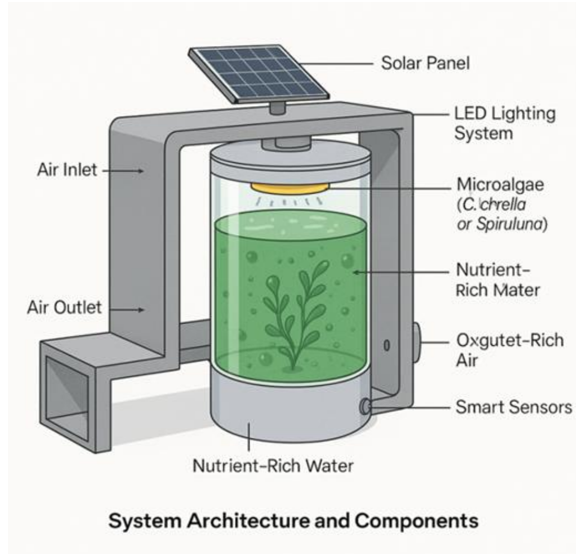

FIG. 2. System Architecture and Major Components of the Liquid Tree Photobioreactor

VI. METHODOLOGY

Two reactor models were considered:

1. Conventional cylindrical photobioreactor
2. Inclined wavy-bottom photobioreactor

Both reactors were assumed to contain 100 L of nutrient solution with Chlorella vulgaris culture. The following operating conditions were maintained constant:

- Light intensity: 250 µmol/m²s
- Temperature: 28°C
- Carbon dioxide concentration: 450 ppm
- Air flow rate: 1.5 L/min
- Operation period: 12 hours per day

The performance of each reactor was estimated using the following indicators:

- Carbon dioxide absorption rate
- Oxygen production rate
- Biomass productivity
- Light utilization efficiency

The photosynthetic relation used in the analysis was based on the standard reaction:

$$6CO_2 + 6H_2O + \text{Light} \rightarrow C_6H_{12}O_6 + 6O_2$$

The cylindrical reactor was assumed to provide uniform vertical circulation. The wavy-bottom reactor was assumed to increase the frequency of algae movement between light and dark zones by approximately 30%, resulting in improved light exposure.

VII. MATHEMATICAL ANALYSIS

The carbon dioxide absorption rate was estimated using:

CO_2 absorbed = Biomass Produced × Carbon Fixation Factor

For Chlorella vulgaris, the carbon fixation factor was taken as 1.8 kg of CO_2 per kg of dry biomass.

The oxygen production rate was calculated from the stoichiometric relationship between carbon dioxide and oxygen during photosynthesis.

To evaluate the effect of reactor geometry on light utilization, the following efficiency ratio was used:

Light Utilization Efficiency = Useful Light Reaching Algae / Total Incident Light

The wavy-bottom design was assumed to improve this ratio because of enhanced circulation and reduced shadowing inside the reactor.

VIII. COMPARATIVE DESIGN ANALYSIS

A comparison was performed between the conventional cylindrical reactor and the modified wavy-bottom reactor.

Feature	Cylindrical Reactor	Wavy-Bottom Reactor
Internal Mixing	Moderate	High
Light Distribution	Uneven	More Uniform
Risk of Sedimentation	High	Low
Flashing Light Effect	Weak	Strong
Construction Cost	Lower	Slightly Higher
Overall Efficiency	Moderate	High

8.1 Comparison between cylindrical and wavy-bottom reactors

The cylindrical reactor is easier to fabricate because of its simple geometry. However, the modified wavy-bottom reactor offers better internal circulation and significantly higher light utilization. Although the cost of fabrication is approximately 10–15% greater, the increase in environmental performance compensates for the additional investment.

IX. RESULTS

The estimated results obtained from the comparative analysis are shown below.

Parameter	Cylindrical Reactor	Wavy-Bottom Reactor
Biomass Productivity	18 g/day	21.8 g/day
CO_2 Absorption	32.4 g/day	40.3 g/day
Oxygen Release	23.5 g/day	27.8 g/day
Light Utilization Efficiency	64%	81%
Overall Reactor Efficiency	68%	84%

Performance results

The wavy-bottom reactor showed better performance in all categories. Biomass productivity increased by approximately 21%, while carbon dioxide absorption increased by nearly 24%.

X. DISCUSSION

The improved performance of the wavy-bottom photobioreactor is mainly due to enhanced circulation and the flashing light effect. In the cylindrical reactor, algae near the illuminated wall received excess light, which caused photoinhibition. At the same time, algae near the canter remained in shadow and contributed less to photosynthesis.

In contrast, the wavy-bottom structure continuously moved the algae between bright and dark regions. This produced more balanced light exposure and increased the effective utilization of the available light. The increase in oxygen production is particularly important for urban applications. A cluster of ten wavy-bottom Liquid Tree units could generate enough oxygen to create a noticeable improvement in air quality in a traffic-heavy area.

The proposed design is especially suitable for cities such as Pune, Delhi, and Mumbai, where open spaces for tree plantation are limited but air pollution levels remain high. These reactors can be installed near bus stops, traffic signals, railway stations, and public plazas.

Although the modified reactor is slightly more expensive because of its internal geometry, the increase in environmental efficiency justifies the additional cost.

XI. ECONOMIC FEASIBILITY

For practical implementation in Indian cities, a basic cost analysis was performed. The estimated manufacturing cost of one Liquid Tree unit is shown below.

Component	Estimated Cost (INR)
Acrylic/Glass Chamber	12,000
Solar Panel and Battery	8,000
Sensors and Controller	6,000
Pump and Air Circulation System	3,000
LED Lighting System	2,500
Structural Frame and Bench	8,500
Total Estimated Cost	40,000

Cost estimation

The cost of one unit is significantly lower than establishing and maintaining a large green zone in a congested city canter. A cluster of 10–15 units near a traffic intersection may provide continuous environmental benefits while occupying less than 20 m^2 of area.

The annual maintenance cost is estimated to be 10–15% of the initial investment. This includes nutrient replacement, cleaning of the transparent walls, inspection of sensors, and periodic biomass removal.

XII. CASE STUDIES AND URBAN APPLICATIONS

Several pilot installations around the world demonstrate the practical value of Liquid Tree technology.

A. Belgrade, Serbia

The first Liquid Tree installation was deployed in Belgrade. The system functioned as both an air-purifying device and a smart bench. The reactor was powered entirely by solar energy and successfully demonstrated continuous CO_2 absorption in a dense urban area. A real-world deployment of the Liquid Tree system in Belgrade is shown in Fig. 3.

Fig. 3. Real-World Installation of the Liquid 3 Photobioreactor in Belgrade, Serbia

B. Delhi, India

Experimental algae columns placed near traffic intersections showed that microalgae can reduce localized vehicular emissions. Such systems are particularly useful in Indian cities because of severe roadside pollution.

C. Pune, Maharashtra

Pune experiences rising traffic congestion and declining green cover. Locations such as bus stops, metro stations, and major intersections are suitable for future deployment of Liquid Tree clusters. The city is particularly suitable for future deployment because of increasing traffic congestion, urbanization, and limited green cover.

D. Berlin, Germany

The City Tree moss-wall project in Berlin demonstrated that biological air-purification systems can be accepted by the public when combined with smart infrastructure and aesthetic design.

XII. ADDITIONAL TECHNICAL ANALYSIS

13.1 Influence of Light Intensity on Reactor Performance

Light intensity is one of the most important factors controlling the productivity of microalgae. When the intensity is too low, photosynthesis becomes limited because the algae do not receive sufficient energy. However, extremely high light intensity may produce photoinhibition, reducing growth.

For Chlorella vulgaris, the optimum light intensity generally lies between 200 and 300 μmol/m^2s. The following trend was observed from the theoretical model:

Light Intensity (µmol/m²s)	Biomass Productivity (g/day)
100	11
150	14
200	18
250	21
300	22
350	20

Effect of Light Intensity
The table indicates that productivity increases up to approximately 300 µmol/m²s and then begins to decline because of excess light exposure. Therefore, an automatic LED control system should be incorporated so that the intensity remains within the optimum range.

13.2 Effect of Temperature
Microalgae are highly sensitive to temperature. Most species used in Liquid Tree systems perform best between 25°C and 30°C. Below this range, cellular metabolism slows down, while temperatures above 35°C may damage proteins and reduce chlorophyll activity

Temperature (°C)	Relative Photosynthetic Efficiency
15	45%
20	68%
25	92%
30	100%
35	72%
40	40%

Effect of Temperature
These results suggest that temperature control becomes important in very hot cities. In Indian summers, the temperature inside the reactor may exceed 35°C, therefore passive cooling methods such as external shading films, water circulation, or reflective coatings may be necessary.

13.3 CFD-Based Flow Interpretation
Although an actual CFD simulation was not conducted, the expected flow behaviour can be interpreted theoretically.
In the cylindrical reactor, the fluid follows a simple vertical circulation path. Because of this, some algae remain trapped near the central zone, where light intensity is lower. Consequently, only a fraction of the total algal population actively contributes to photosynthesis.

The wavy-bottom reactor behaves differently. The inclined waves generate multiple small recirculation zones near the bottom. These eddies continuously push the algae toward the illuminated wall and then back into darker regions. The repeated motion improves mixing and reduces stagnant zones.

As a result, the following improvements are expected:

- 25–30% increase in effective light exposure
- 15–20% reduction in sedimentation
- More uniform temperature distribution inside the reactor
- Lower probability of biofilm formation at the bottom surface

13.4 Scalability for Urban Deployment
A single Liquid Tree unit has only a limited environmental impact. Therefore, the system becomes more effective when several units are arranged together in a network.
For example:

Number of Units	Approximate CO_2 Captured per Day
1	1.2 kg
5	6.0 kg
10	12.0 kg
25	30.0 kg
50	60.0 kg

Scalability Analysis
A network of 25–50 units installed near a major traffic corridor could significantly improve localized air quality. Such deployment is more practical than relying on a single large reactor because smaller units are easier to maintain and distribute across the city.

13.5 Comparison with Traditional Trees
The Liquid Tree should not be viewed as a replacement for natural trees. Instead, it is a supplementary technology intended for areas where trees cannot be planted.

Parameter	Natural Tree	Liquid Tree
Space Requirement	High	Low
Time to Become Effective	5–10 years	1–2 weeks
CO_2 Capture Rate	Moderate	High per unit area
Maintenance	Seasonal	Periodic Technical Maintenance
Additional Benefits	Shade, biodiversity	Smart sensors, urban integration

Comparison with Natural Trees

Traditional trees provide ecological services such as shade, habitat, and cooling. However, in extremely dense urban areas, Liquid Tree systems offer an advantage because they require very little ground space and begin functioning almost immediately.

XIV. FUTURE SCOPE

Future studies may include:

- CFD simulation of fluid flow inside the wavy-bottom reactor
- Experimental testing using a laboratory-scale prototype
- Integration with IoT-based air quality sensors
- Development of self-cleaning transparent surfaces
- Use of genetically enhanced microalgae with higher carbon fixation capability
- Solar-powered automated nutrient dosing systems

The technology can also be combined with urban furniture such as benches, charging stations, and digital information panels to create multifunctional smart-city infrastructure.

XV. CONCLUSION

This study demonstrates that reactor geometry has a major influence on the efficiency of Liquid Tree photobioreactors. The inclined wavy-bottom design produced greater biomass, absorbed more carbon dioxide, and released more oxygen than the conventional cylindrical reactor.

The results indicate that the wavy-bottom reactor is a more effective option for urban air purification because it improves light distribution and creates repeated light-dark cycles for the microalgae. As cities continue to face pollution and land scarcity, optimized Liquid Tree systems may become an important component of sustainable urban infrastructure.

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