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An AI-Driven Drone-Integrated Mobile Photobioreactor System: A Novel Approach to Atmospheric Carbon Sequestration and Oxygen Emission

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Abstract – A universally applicable "optimal photobioreactor" design has yet to be established, as the success of such systems varies depending on the algal species used, environmental conditions, and intended applications. Meanwhile, the accelerating pace of climate change necessitates not only passive monitoring of atmospheric carbon but also its active mitigation through biologically driven interventions. In this study, we propose a drone-integrated mobile photobioreactor (m-FBR) concept that utilizes the highly photosynthetically efficient cyanobacterium *Synechococcus elongatus* PCC 3055, combined with artificial intelligence technologies.

The developed system is equipped with GNSS-based positioning, NDIR-based CO_2 sensors, and environmental sensing modules for temperature, light, and humidity, enabling real-time adaptive response to ambient conditions. Route optimization is based on Lagrangian atmospheric modeling, allowing the system to anticipate the origin, trajectory, and accumulation zones of airborne carbon masses, and to navigate toward areas with high CO_2 concentrations.

The drone-mounted flat-panel reactor includes a high-transparency polycarbonate casing, energy-efficient LED light modules, and micro-level thermal regulation units, allowing rapid adaptation to changing environments and real-time optimization of photosynthetic efficiency. Beyond carbon fixation, the system also passively ventilates oxygen directly into the atmosphere, contributing to local air quality. Notably, the m-FBR autonomously absorbs atmospheric greenhouse gases such as CO_2 and water vapor—utilizing them as internal metabolic inputs. Thus, it sustains its nutrient demands without external supplementation and converts these gases into biomass and atmospheric oxygen via photosynthesis.

With its capacity to absorb greenhouse gases in situ, utilize atmospheric resources as nutrient inputs, and release oxygen through photosynthetic processes, the proposed m-FBR system offers a versatile and novel biotechnological paradigm. It is applicable to carbon trading, urban air quality management, post-disaster atmospheric diagnostics, and sustainable oxygen production. Positioned at the intersection of nature-based solutions and artificial intelligence, this system functions as an autonomous biotechnological agent that not only monitors and analyzes the atmosphere but also actively contributes to its restoration. By overcoming the limitations of stationary photobioreactors, the m-FBR introduces a mobile, environmentally intelligent, and circular production model suited to contemporary climate challenges.

Keywords: Microalgae, *Synechococcus elongatus*, drone, photobioreactor, carbon capture, artificial intelligence, Lagrangian modeling,

I. INTRODUCTION

Capturing and fixing atmospheric carbon dioxide (CO_2) has become one of the foremost goals of sustainable environmental technologies in the fight against climate change. In this context, biological carbon capture systems—particularly photosynthetic fixation through microalgae—offer cost-effective, environmentally friendly, and scalable solutions. Phytoplankton, which are microscopic photosynthetic organisms inhabiting the surface layers of the oceans, play a vital role in the global carbon cycle by temporarily fixing approximately 25–30% of the atmospheric CO_2 [18]. Through photosynthesis, they convert CO_2 into organic matter while also producing oxygen, forming the biological foundation of the oceanic carbon pump.

However, recent environmental changes have led to a noticeable decline in the critical functions of phytoplankton. Ocean acidification, reduced light penetration, thickening of the surface mixing layer, and the limited availability of essential nutrients such as nitrogen, phosphorus, and iron directly hinder their growth and photosynthetic efficiency [4], [8]. Consequently, naturally occurring biological carbon capture processes are now considered insufficient to offset the increasing anthropogenic emissions.

In this regard, controlled microalgae cultivation in artificial environments—via open pond systems or closed photobioreactors (FBRs)—has emerged as a significant alternative, especially in terrestrial settings. These systems can absorb CO_2 either from flue gases or directly from the atmosphere, simultaneously enabling biomass production and carbon fixation [14]. While open pond systems provide low-cost and large-scale production, closed FBRs allow for precise environmental control, resulting in higher photosynthetic efficiency. However, both systems are inherently bound to stationary infrastructures, limiting their ability to operate in mobile, irregular, or hard-to-reach areas with high carbon emissions.

To address these limitations, this study proposes an AI-assisted mobile photobioreactor system (m-FBR) integrated into a drone platform and operated with the cyanobacterial strain *Synechococcus elongatus* PCC 3055. This system autonomously navigates according to environmental cues, detects carbon accumulation zones in the atmosphere, and performs high-rate photosynthesis with concurrent oxygen release. In contrast to conventional carbon capture technologies, the proposed system offers a more flexible, responsive, and on-site intervention capacity—providing a scalable and mobile solution.

Synechococcus elongatus PCC 3055 is a cyanobacterial strain naturally isolated from freshwater microhabitats between terrestrial rock formations in Texas [51]. While *S. elongatus* species are broadly distributed in ocean surface waters between 30° and 60° latitudes, the freshwater origin of the PCC 3055 strain allows it to operate efficiently in mobile photobioreactor systems utilizing terrestrial water sources. With a **doubling time of approximately 20–24 hours**, broad-spectrum light tolerance, and intracellular carboxysomes, PCC 3055 demonstrates high carbon fixation efficiency under controlled conditions [47]. These attributes make it a suitable and resilient candidate for use in drone-based open-air production systems designed for atmospheric carbon capture and oxygen release.

In conclusion, this next-generation mobile system contributes not only to carbon fixation but also to integrated carbon management, environmental monitoring, and AI-based decision support mechanisms. By enhancing intervention capabilities in areas where stationary systems are inadequate, this approach strategically supports natural biological carbon capture processes and may lead to a paradigm shift in climate technologies.

1.1. The Role of Open Ponds and Photobioreactor Systems

In response to the limitations of natural phytoplankton, artificial microalgae cultivation has become increasingly important for enabling controlled and sustainable carbon fixation independent of environmental variability. In this context, two primary production methods have emerged: **open pond systems** and **closed photobioreactors (FBRs)**. Both technologies contribute to the biological sequestration of atmospheric CO_2, yet they exhibit certain constraints in terms of operational flexibility and mobility.

Open pond systems, particularly raceway ponds, allow for large-scale algal cultivation using direct sunlight across expansive surface areas. These systems are cost-effective for biomass production in tropical and subtropical regions. However, their performance is highly susceptible to environmental fluctuations, including evaporation, contamination by external organisms, inefficient CO_2 diffusion, and limited species diversity, all of which can hinder production efficiency [14].

Closed photobioreactor systems, by contrast, offer engineered solutions that allow for the precise control of parameters such as light intensity, temperature, pH, CO_2 input, and mixing rates. These systems stand out for their high productivity, reduced water loss, and lower contamination risk. Moreover, the integration of industrial flue gases directly into the reactor enables innovative solutions for CO_2 recycling and emission mitigation [62]. Despite these advantages, the need for stationary infrastructure limits their ability to intervene promptly and directly at dynamic or mobile carbon emission hotspots.

At this juncture, **drone-based mobile photobioreactor systems** represent a novel approach capable of accessing areas unreachable by conventional stationary systems. These mobile platforms can navigate based on real-time atmospheric CO_2 concentration maps and perform on-site biological carbon fixation through portable cultivation modules. As such, they overcome the infrastructural limitations of traditional technologies and offer a highly effective, adaptable, and scalable solution for climate change mitigation.

1.2. Drone-Based Mobile Algal Photobioreactor Systems

The lack of operational flexibility in stationary photobioreactor systems renders them ineffective in addressing sudden and localized carbon emissions. As such, mobile solutions capable of capturing carbon at its source and in real-time are increasingly viewed as complementary technologies to conventional fixed infrastructures. In this context, drone-integrated microalgae cultivation systems introduce an innovative and dynamic approach to environmental monitoring and carbon management.

The contribution of drone-based microalgal systems to climate change mitigation is multifaceted. Primarily, these systems function as mobile carbon sinks capable of intervening directly in regions with high carbon emissions. Drones with autonomous flight capabilities can access challenging environments such as urban centers, traffic-congested zones, industrial areas, and post-disaster regions with compromised air quality, enabling on-site and timely carbon mitigation [33]. Cyanobacteria such as *Synechococcus elongatus* PCC 3055—utilized in these mobile systems—possess specialized cellular structures like carboxysomes, which confer high carbon fixation capacity even under low ambient CO_2 concentrations [6].

Equipped with GNSS, NDIR CO_2 sensors, and AI algorithms, the drone platforms continuously monitor environmental parameters such as flight trajectory, photoperiod, light intensity, and temperature. These variables are dynamically optimized to maximize photosynthetic efficiency. Furthermore, the modular and scalable design of these systems allows photobioreactors ranging from 0.5 to 2 liters to be deployed via coordinated drone fleets, thereby enabling local interventions to evolve into regional or national carbon management networks [57].

Environmental data—temperature, light, humidity, and CO_2—collected during drone missions are used to analyze spatial and temporal patterns of atmospheric conditions. Consequently, AI algorithms can anticipate environmental shifts and enhance the system's adaptive capabilities [63], [36].

Drone-based photobioreactor systems not only serve as mobile biotechnological platforms for atmospheric carbon fixation, but also constitute an integrated solution ecosystem that supports environmental monitoring, data mining, and AI-assisted decision-making. Oxygen release is facilitated via passive ventilation mechanisms, reducing battery consumption and maintaining energy efficiency. Additionally, real-time responsiveness to environmental variables through AI-enhanced sensors enables rapid, localized, and flexible intervention against climate change.

Considering the environmental limitations of natural phytoplankton in carbon fixation—such as light attenuation, nutrient deficiencies, rising ocean temperatures, water column stratification, and ocean acidification—traditional systems like open ponds and closed photobioreactors remain geographically and operationally insufficient in contributing to CO_2 removal at a global scale. In particular, the increasing physical and chemical constraints in the ocean are making the diffusion of atmospheric CO_2 into aquatic environments progressively more difficult.

One of the main challenges is ocean stratification, which reduces vertical mixing between surface and deep water masses, thus hindering nutrient and carbon transport [23].

Additionally, elevated sea surface temperatures decrease the solubility of CO_2 in seawater, directly impairing its transfer from the atmosphere [53].

Ocean acidification, caused by the formation of carbonic acid from absorbed CO_2, lowers the ocean's buffering capacity and places additional stress on marine ecosystems, further constraining carbon uptake [17].

Moreover, climate-induced changes in wind patterns disrupt surface mixing and air-sea gas exchange dynamics, leading to irregularities in the natural CO_2 flux [39].

In this context, drone-based mobile microalgae cultivation systems offer a targeted, adaptive, and scalable alternative that can significantly enhance atmospheric carbon capture capacity. These systems enable real-time monitoring of atmospheric CO_2 concentrations and facilitate the modeling of its spatial distribution [20]. The biologically captured carbon can then be transformed into eco-friendly products—such as bioplastics, biofuels, or biofertilizers—thereby reinforcing both the environmental and economic sustainability of the system. Ultimately, this approach proposes a novel architecture for climate-smart, technology-integrated carbon management.

In conclusion, drone-based microalgal systems represent a paradigm shift in climate mitigation, uniting nature and technology to extend carbon capture efforts into the skies. This approach offers an innovative solution poised to both support planetary respiration and guide the development of future carbon-neutral production models.

II. METHODS AND RESULTS

To reduce carbon emissions through atmospheric algae production and enhance the efficiency of sustainable product yields, the integration of microalgae cultivation systems with drones necessitates three essential inputs for effective photosynthetic productivity in open-air environments: light, heat, and carbon dioxide (CO_2). In drone-based mobile photobioreactor systems, the controlled supply of these inputs not only enhances biomass productivity but also strengthens the culture's resilience against environmental fluctuations [13].

Light is the primary energy source for photosynthesis. In particular, red ($\lambda \approx 660$ nm) and blue ($\lambda \approx 450$ nm) wavelengths are most efficiently absorbed by photosystem pigments such as chlorophyll-a and phycobilins in cyanobacteria like *Synechococcus elongatus* [37]. Thus, by incorporating low-energy LED modules on the drone, a photon flux density of 50–150 µmol/m²/s can be achieved within the reactor environment, enabling continuous photosynthetic activity even during nighttime flights [65].

Heat is a critical factor for cell metabolism and enzymatic reactions. The optimal growth temperature for *S. elongatus* ranges between 28–32 °C, and dropping below this threshold significantly reduces the activity of photosynthetic enzymes [54]. Considering atmospheric temperature fluctuations—especially nocturnal cooling—micro-resistance-assisted heating plates are recommended to maintain a stable culture temperature and shorten production cycles.

Carbon dioxide (CO_2) serves as the fundamental carbon source for photosynthesis. However, passive diffusion from ambient air may not always supply adequate CO_2 levels, due to regional differences and meteorological variability. This variability can directly impact photosynthetic efficiency. Therefore, integrating a valve-controlled CO_2 diffusion module into the drone system ensures not only efficient redirection of atmospheric CO_2 into the reactor but also provides supplemental CO_2 from portable tanks when necessary to maintain carbon stability [64].

The synchronized control of all three environmental inputs—light, temperature, and CO_2—transforms drone-mounted photobioreactors into adaptive, high-efficiency carbon capture platforms rather than merely mobile biomass production units. For the system to remain functional under real-world conditions, both the physical structure of the reactor and its technical components must be carefully tailored to suit flight parameters.

2.1. Photobioreactor Design and Atmospheric Flight Conditions

The photobioreactor integrated onto the drone will be configured as a flat-panel system with a volume capacity of 0.5–2 L, featuring a UV-transmitting polycarbonate casing [58]. The system is designed to optimize light, heat, and carbon sources, comprising the following components:

- **Lighting system**: Red-blue wavelength LED modules (~50–150 µmol/m²/s) will be used to match the maximum absorption spectra of chlorophyll-a and phycobilins in cyanobacteria like *Synechococcus elongatus* [12].
- **Temperature control**: A micro-resistance-assisted heating plate will maintain the culture at a constant 28–32 °C, corresponding to the optimal growth temperature range for the targeted species [9].
- **CO_2 supply**: In addition to passive atmospheric intake, a valve-controlled CO_2 diffusion system will stabilize internal carbon levels, providing resistance against environmental variability [64].

The drone will be designed to operate within the lower troposphere (~300–1500 meters), an altitude band that allows direct interaction with terrestrial CO_2 emission layers while enabling rapid and efficient CO_2 capture by microalgae. However, sudden fluctuations in UV radiation, temperature, air density, and wind at such altitudes necessitate the structural and operational optimization of the airborne photobioreactor.

According to Posten (2009), one of the most critical challenges in portable photobioreactors is the homogeneous distribution of light within the culture medium [48]. In drone systems, this can be addressed using UV-transmitting polycarbonate materials. These materials both protect the culture from excessive radiation and enhance photosynthetic efficiency at high altitudes. Nevertheless, such materials may undergo photodegradation over time, potentially compromising mechanical durability.

As Posten also highlights, light homogeneity and the surface area-to-volume (A/V) ratio are decisive parameters in reactor design. Flat-panel photobioreactors mounted on drones provide high surface area exposure, increasing photosynthetic activity. However, a larger surface area also increases air resistance, necessitating a streamlined aerodynamic profile and structural reinforcement against wind load.

Moreover, thermal control systems are vital for preserving metabolic activity in the culture at altitudes above 1000 meters, where ambient temperatures are low [9]. Although maintaining internal reactor temperature increases energy consumption, preserving the optimal 28–32 °C range is critical for maximum photosynthetic yield in *S. elongatus*.

LED-supported lighting systems compensate for low light conditions during nighttime flights or under cloud cover, ensuring uninterrupted photosynthetic activity [12]. However, they add extra weight and energy demand, potentially limiting drone flight duration.

In terms of **CO_2 uptake**, passive diffusion mechanisms may not suffice. Valve-controlled CO_2 injection systems offer a crucial advantage in overcoming carbon-limiting conditions for photosynthesis [64], although they increase both system weight and operational costs.

Finally, condensation or freezing on the reactor surface may obstruct light transmission and gas exchange. To mitigate such effects, Posten (2009) recommends hydrophobic and thermo-insulating coatings. These materials help maintain reactor performance while enhancing the long-term flight capability of the drone system.

2.2 Algal Culture

The microorganism employed in this study is *Synechococcus elongatus* PCC 3055, a cyanobacterial strain selected for its high photosynthetic carbon capture capacity, resilience to environmental stressors, and well-characterized genetic profile. PCC 3055 is one of the rare strains that can be cultured in both freshwater and marine-based media [30], providing flexibility for both terrestrial and ocean-based applications.

S. elongatus PCC 3055 is widely distributed in natural environments, particularly between latitudes 30°–60°, across the Atlantic and Pacific Oceans. Together with *Prochlorococcus*, these organisms are responsible for approximately 20–30% of the atmospheric oxygen and contribute significantly to global oceanic primary production [22].

The carbon fixation capacity of *S. elongatus* is characterized by high efficiency. Through the Calvin cycle, this organism fixes CO_2 using the enzyme ribulose-1,5-bisphosphate carboxylase/oxygenase (RuBisCO), consuming approximately 1.8–2.2 grams of CO_2 per gram of dry biomass produced. This makes it a promising biological sink in carbon management strategies [64].

In the drone-based system, the initial optical density (OD_{680}) was adjusted to 0.4, with a target OD of 1.8, representing the expected biomass increase within a 24–48 hour flight period. Designing flight trajectories over atmospheric regions with elevated CO_2 concentrations—such as urban or industrial zones—can provide a growth advantage to the culture. BG-11 medium served as the primary culture medium, while a geothermal water-supported Schlösser medium was also considered as an alternative. To optimize energy efficiency, drone charging is scheduled during dark periods when photosynthesis is inactive.

The optimal culture conditions of the PCC 3055 strain are among the key determinants of system design. Comparative assessments in the literature indicate significant differences among *S. elongatus* strains in terms of growth parameters.

The PCC 3055 strain exhibits optimal growth at 28–32 °C and tolerates a pH range of 7.5–8.5. It has a moderate growth rate, with a doubling time of approximately 20–24 hours. The light requirement ranges between 4000–6000 lux, and the strain can be successfully cultured in BG-11 or modified media such as Schlösser. Its tolerance to CO_2 typically extends up to 2%.

In contrast, *S. elongatus* UTEX 2973 demonstrates a higher temperature tolerance (35–40 °C), a rapid doubling time of 9–12 hours, and is cultivated under higher light intensities (7000–10000 lux) with CO_2 tolerance reaching up to 5%. This fast-growing variant is generally cultured in specifically modified BG-11 media [69], [67].

Another widely used classical strain, *S. elongatus* PCC 7942, shows optimal growth at 30 °C and thrives in a pH range of 7.5–8.5. It has a lower light requirement (3000–5000 lux) and a doubling time of approximately 22–26 hours. Standard BG-11 medium provides suitable conditions for its cultivation [24].

These differences underscore the importance of considering biological parameters in system design and environmental optimization. The selection of PCC 3055 was based on its moderate growth rate, tolerance to a wide pH range, and high resistance to environmental stressors.

2.3 AI-Assisted Navigation

To enhance the efficiency of the drone-based microalgae production system, it is proposed to integrate an artificial intelligence (AI)-supported navigation and environmental adaptation module. This module aims to dynamically optimize the flight route and cultivation conditions by continuously monitoring environmental data in real time.

Key system components include an NDIR-based CO_2 sensor, a light intensity sensor, and temperature and humidity sensors. Data gathered from these sensors are analyzed using machine learning algorithms to update the drone's route in accordance with optimal environmental conditions for maximizing the photosynthetic capacity of the microalgae. This allows the drone to remain longer in areas with high CO_2 concentrations and optimal light/temperature combinations, thereby increasing biomass production and carbon fixation [64].

NDIR (Nondispersive Infrared) sensors are widely used optical-based technologies for measuring gas concentrations, particularly CO_2. These systems operate by passing infrared light through a gas chamber, where specific wavelengths are absorbed by CO_2 molecules. The degree of absorption is directly proportional to the ambient CO_2 concentration. Their ability to perform contactless measurements, coupled with low energy consumption and long-term calibration stability, makes NDIR sensors advantageous in mobile systems [44].

Artificial intelligence, in this context, refers to a suite of algorithms that enable machines to make human-like decisions. The AI system utilized in this study is based on supervised learning and predictive modeling using real-time environmental data. By leveraging previously recorded data from flight operations, the AI learns optimal combinations of light, temperature, and CO_2 concentrations and executes adaptive maneuvers in new flight scenarios accordingly.

The photosynthetic efficiency of algae is highly sensitive to changes in environmental conditions. In particular, light intensity and spectral composition influence pigment synthesis, while temperature affects enzyme activity and protein stability. CO_2, as the primary input for carbon fixation, plays a critical role in sustaining photosynthesis [35]. Species like *S. elongatus* PCC 3055 respond sensitively to these parameters: excessive heat can lead to protein denaturation, low temperatures slow down metabolism, and CO_2 imbalances may impact Rubisco activity and pH, thereby limiting photosynthetic performance.

To overcome these limitations, the integrated AI-based adaptive control mechanisms monitor and optimize temperature, light, and CO_2 levels in real time using sensor data. This enables *PCC 3055* to maintain stable photosynthetic activity even under fluctuating environmental conditions [24].

A key biological feature underlying the success of *S. elongatus* is the presence of carboxysomes—microcompartments that encapsulate the Rubisco enzyme and carbonic anhydrase, enabling localized CO_2 enrichment. This enhances carbon fixation while suppressing oxygenase activity [32], [52].

The GNSS module provides high-accuracy geolocation data, allowing the drone to function synergistically with environmental mapping and adaptive strategy systems (Misra & Enge, 2006). Using this data, the drone can determine its position within atmospheric strata and make optimized decisions accordingly.

Data communication between the drone and the ground station is facilitated by low-latency wireless protocols such as LTE, 5G, and LoRaWAN. These data not only support environmental monitoring but also enable the AI algorithms to continuously adapt to environmental inputs. In particular, the system's ability to react to sudden environmental changes by adjusting route, altitude, or functional components allows it to operate within a hybrid control architecture that integrates human oversight with high flexibility.

Finally, the developed system possesses a self-improving capability through cloud-based learning algorithms. Two core digital architectures operate in tandem: edge computing and cloud computing.

Edge computing enables data processing near the source—such as sensors and microcontrollers onboard the drone—allowing rapid responses to environmental changes without needing to transmit data to the cloud. This local (on-device) analysis is critical for ensuring adaptive environmental control with minimal latency during flight operations [60].

On the other hand, cloud computing supports the analysis of large datasets using powerful processing infrastructures hosted on central servers. Environmental data collected by the drone are analyzed in the cloud to develop large-scale environmental insights, production strategies, and model updates. For example, observed CO_2 variation patterns, light-temperature correlations, and biomass production data across different flights are processed in the cloud to enhance the system's learning capacity over time.

The integration of these two systems—referred to as hybrid digital intelligence—provides both rapid, localized response and large-scale strategic planning. As a result, the drone system evolves from being a temporary production tool into an intelligent biotechnological platform capable of adapting to climate variability, analyzing environmental change, and continuously updating its own decision-making processes.

2.4 Oxygen Release

Within the microalgae photobioreactors mounted on the drone platform, carbon dioxide (CO_2) is converted into organic compounds through photosynthesis, while oxygen (O_2) is released as a byproduct. This released oxygen plays a critical role not only in maintaining the internal safety of the reactor, but also in contributing to atmospheric balance and supporting a vital resource for sustaining human life [21].

Today, the maintenance of atmospheric oxygen levels relies heavily on the photosynthetic activity of phytoplankton in oceans and microalgae in freshwater ecosystems [18]. Approximately 50% of the global oxygen supply is produced by photosynthetic microorganisms, particularly those inhabiting marine environments [3]. In this context, oxygen emissions achieved via drone-based high-altitude systems can provide localized yet meaningful environmental contributions—especially in densely urbanized regions where natural oxygen production is limited.

Although phytoplankton comprise only 1–2% of global plant biomass, they fix an estimated 30–50 billion metric tons of carbon annually, accounting for roughly 40% of the planet's total carbon fixation. Geological timescale analyses have revealed the indispensable role of these microscopic organisms in global biogeochemical cycles. However, the consistency of their productivity is strongly dependent on upper ocean circulation and atmospheric conditions.

The net flux of atmospheric radiation directly influences the depth of the ocean's upper mixed layer and the vertical transport of nutrients—both of which affect the intensity and spatial-temporal distribution of phytoplankton blooms. Nevertheless, the atmospheric radiation budget is not static. Throughout the 20th century, significant changes in ocean-atmosphere interactions have been observed due to anthropogenic increases in IR-absorbing gases (e.g., CO_2, CH_4, CFCs, NO_x). Rising temperature gradients between continents and oceans have intensified wind stress along coastal zones, thereby enhancing surface nutrient upwelling [18].

In central ocean regions, nutrient scarcity is a dominant limiting factor, particularly the low micromolar concentrations of key macronutrients like nitrate. This nutrient limitation leads to reduced quantum efficiency in Photosystem II [43], [5]. However, increased wind activity can enhance nutrient input into surface waters, promoting phytoplankton biomass accumulation and elevating carbon fixation rates [19], [42]. Conversely, radiative heating at the centers of certain ocean eddies may restrict vertical nutrient fluxes, thereby reducing the carbon fixation capacity [56], [7].

In parallel, increased terrestrial dust transport—driven by escalating desertification—enhances the deposition of micronutrients such as iron into open ocean areas, potentially stimulating phytoplankton productivity and enhancing photosynthetic performance.

Taken together, these variables indicate that carbon fixation in oceanic systems is not a static process but a dynamic interplay of atmospheric, physical, and biological inputs. For example, long-term time-series analyses conducted in the North Pacific Ocean have revealed significant decadal-scale variations in phytoplankton biomass and ocean transparency. Yet, under current conditions, the open ocean remains limited in its capacity to sequester atmospheric CO_2 via phytoplankton, and relies heavily on external nutrient inputs to sustain its productivity.

This insight is also crucial when considering closed-circuit microalgae reactors. In cultures of highly photosynthetically active species such as *Synechococcus elongatus*, oxygen oversaturation within the medium can lead to photooxidative stress, pH imbalances, and metabolic burden. These conditions may reduce growth rates, impair chloroplast function, and damage structural carbon fixation sites like carboxysomes [45], [66].

To prevent such risks, passive ventilation outlets are incorporated into the upper sections of the mobile photobioreactor units. These openings enable the excess oxygen to diffuse outward without consuming additional energy. This design not only ensures sustainable gas exchange but also conserves battery life, thereby optimizing drone flight duration.

AI-assisted control algorithms continuously monitor O_2 concentration data from in-reactor sensors and evaluate the sufficiency of passive ventilation. If needed, the drone's orientation or altitude can be adjusted to enhance oxygen diffusion rates. For example, flying at higher altitudes—where atmospheric pressure is lower—can facilitate more effective gas release. This approach supports both the physiological stability of the microalgae and the sustained efficiency of the photosynthetic process.

2.5 Hypothetical Application Scenario: Positioning m-FBR in the Urban CO_2 Concentration Map of Istanbul

Today, atmospheric carbon management is recognized as a dynamic process that requires not only surface-level interventions but also spatially adaptive responses across different atmospheric layers. In megacities like Istanbul, traffic congestion, industrial emissions, and meteorological stratification cause temporal and regional fluctuations in CO_2 concentrations [71]. As a result, fixed photobioreactors have limited impact, and mobile, environmentally adaptive systems have become increasingly vital.

Air quality control in Turkey is provided by the Ministry of Environment and Urbanization through the Air Quality Assessment and Management (AQM) Regulation. As of 01.01.2014, it is planned to reach the EU limits for all pollutants by 2024 by calculating the limit values for that year with gradually decreasing tolerance margins each year [68]. Considering that the atmospheric CO_2 concentration is observed to be 20% higher in ppm in these regions between 08:00–10:00 in the morning and 17:00–19:00 in the evening based on the Air Quality Monitoring Report data, these time intervals and regions offer ideal conditions for maximizing photosynthetic production efficiency.

According to the simulation model, S. elongatus cultures with an initial OD_{680} of 0.4 are transported via drones over these regions for 3–5 hours, during which GNSS and NDIR CO_2 sensors continuously monitor and optimize environmental parameters such as irradiance, temperature, and atmospheric CO_2. During nighttime, dark photoperiods coincide with ground-based charging and maintenance cycles, ensuring high energy efficiency.

In the initial phase, a single m-FBR unit with a 1 m^2 reactor area is predicted to reach an OD of 1.8 within 48 hours, producing approximately 4.0 g/L of biomass, equivalent to the fixation of 8–10 g of atmospheric CO_2 [14], [54].

In this study, the photobioreactor volume to be carried by the drone has been preliminarily set at 1.5 liters, considering flight duration and energy efficiency.

With a biomass yield of 4 g/L, this volume can produce approximately 6 g of dry biomass, which corresponds to the biological fixation of around 12 g of CO_2.

To enhance the scalability and CO_2 capture efficiency of the drone-based system, it is essential to optimize both the reactor volume and the drone's payload capacity simultaneously.

In this context, lightweight materials, thin-film reactor designs, and high surface area-to-volume ratio configurations will be prioritized.

This scenario presents a novel paradigm in urban carbon management, offering a next-generation biotechnological solution applicable to urban planning, post-disaster air quality recovery, and climate-responsive infrastructure. Moreover, integration with Lagrangian trajectory models enables real-time tracking and proactive deployment over high-emission zones, making m-FBRs intelligent, adaptive platforms for mobile carbon capture [55].

In the Mediterranean region, per capita CO_2 emissions exceed the national average due to the high intensity of transportation activities, the impact of summer tourism, and persistently stable warm-weather conditions [61], [46]. The frequent formation of inversion layers and reduced vertical air mixing lead to the accumulation of gases like CO_2 in the lower atmosphere [46, [70]. Furthermore, the expansion of the Hadley cell contributes to the suppression of vertical air movement in the region, hindering the dispersion of atmospheric pollutants [41]. These conditions necessitate localized and adaptive interventions in carbon-dense zones. Drone-based mobile photobioreactor (m-FBR) systems offer an effective environmental remediation strategy by performing mobile carbon fixation under the Mediterranean's high-CO_2 atmospheric conditions and providing solutions in areas inaccessible to stationary systems [49].

III. DISCUSSION

In contemporary efforts to combat climate change, it is essential to conceptualize the atmosphere not only as a passive layer but as a dynamic domain for carbon management. In this context, drone-based microalgae production systems offer a flexible, adaptive, and targeted approach to carbon capture, in contrast to conventional fixed photobioreactors. Given the spatiotemporal heterogeneity of atmospheric CO_2 distribution, integrating these mobile systems with Lagrangian tracking models enables precise interventions in CO_2-rich zones [55].

The Lagrangian mechanical approach, a formulation of classical mechanics, focuses on tracing the path of individual particles or air masses over time. Unlike the Eulerian perspective, which observes from a fixed point, the Lagrangian framework follows the motion of the particle itself, offering a dynamic perspective on transport phenomena [59].

In atmospheric sciences, this methodology is used to model the transport of gases such as CO_2. Lagrangian trajectory analysis allows for the reconstruction of the pathways taken by air parcels or pollutants after emission. These models are supported by three-dimensional meteorological data—such as wind speed, direction, and atmospheric pressure—typically derived from global weather forecasting systems like ECMWF and NOAA GFS [55].

Lagrangian models can operate in two modes:

Forward modeling predicts the dispersion pattern of CO_2 from a known emission source.

Backward modeling traces the origin of CO_2 concentrations measured at a specific location, attributing them to sources such as industrial facilities, vehicular traffic, or wildfires.

Tools such as FLEXPART (FLEXible PARTicle dispersion model) and STILT (Stochastic Time-Inverted Lagrangian Transport) are widely utilized open-source models for tracking atmospheric CO_2 plumes [38], [55].

These tracking systems can inform the optimal deployment and flight routing of drone-based photobioreactors. As a result, microalgal cultures can be directed toward atmospheric strata with higher CO_2 concentrations, enhancing biological carbon fixation through photosynthesis.

Atmospheric CO_2 emissions can generally be quantified using three principal methods:

Satellite Observations: Instruments such as NASA's Orbiting Carbon Observatory-2 (OCO-2) provide column-integrated CO_2 data across the globe.

Ground-Based Sensor Networks: Systems like the Global Atmosphere Watch (GAW), supported by the World Meteorological Organization (WMO), monitor surface-level CO_2 concentrations.

Model-Simulation Integration: By merging satellite and ground station data with atmospheric transport simulations, spatial CO_2 distribution maps and emission inventories are produced.

Integrating drone-assisted microalgal systems with Lagrangian modeling presents a promising frontier in carbon monitoring. These platforms not only serve as mobile carbon sinks but also offer real-time carbon mapping, climate modeling, and rapid-response capabilities in environmental management.

Synechococcus elongatus exhibits a photosynthetic capacity that is highly responsive to light intensity, temperature, and carbon source availability. Under optimal conditions, it can double its biomass within 10–12 hours, making it possible to achieve substantial biomass accumulation within a 24–48-hour drone flight cycle [54]. Internal environmental conditions (light, temperature, CO_2) are regulated through micro-diffusion valves, while AI-assisted decision-making mechanisms dynamically optimize flight path, altitude, and spatial positioning [14]. This enables the system to linger over high-photosynthesis zones, thereby maximizing carbon fixation efficiency.

The system leverages edge computing to analyze environmental data in real time during flight, enabling rapid, localized decision-making. In parallel, cloud computing processes large datasets to improve long-term predictive performance and model refinement. While edge computing minimizes latency by enabling on-board processing, cloud infrastructure facilitates pattern recognition and adaptive learning over time [60], [34].

In drone-based mobile photobioreactor systems, oxygen (O_2) produced through photosynthesis is released into the external environment via integrated passive ventilation outlets. This mechanism not only extends battery life and enhances energy efficiency, but also contributes to the localized enrichment of atmospheric oxygen, thereby offering ecosystem service benefits at a micro scale. In contrast, oxygen accumulation in closed systems can lead to adverse effects such as oxidative stress at the cellular level, pH imbalances, and reduced photosynthetic efficiency [45], [10]. Thus, passive gas release must be regarded as a critical structural component for sustaining the biological stability of the system.

Covers a multidisciplinary range of topics reflecting the intersection of drone technology with environmental science, logistics management and operational research [31]. As the scope of dynamic meteorology expands significantly, many treatments have been proposed for climate dynamics and the implications for global change [29]. This study will be a viable alternative product for institutions wishing to purchase carbon credits [25].

In addition to autonomous operation, these systems are also capable of manual monitoring and control, made possible through advanced wireless communication protocols such as LTE (Long-Term Evolution), 5G, and LoRaWAN (Long Range Wide Area Network). LTE enables high-speed data transmission over existing cellular infrastructure and enhances drone coverage across vast geographical areas. 5G offers ultra-low latency and high bandwidth, making it highly suitable for real-time control, image processing, and sensor data transfer [1]. LoRaWAN, despite its low data rate, excels in low-power long-range communication, making it ideal for remote or off-grid multi-sensor applications [2].

This trio of communication technologies allows for real-time environmental monitoring, rapid intervention, and optimization of system autonomy. Especially under rapidly changing weather conditions, field-based failures, or post-disaster environmental surveillance scenarios, these communication protocols provide the operational continuity necessary for uninterrupted function [11].

Beyond photobioreactor applications, this digital infrastructure plays a pivotal role in the broader digital transformation of sustainable urban management. Contemporary smart city initiatives are no longer limited to transportation and energy systems; they increasingly incorporate carbon emissions monitoring, air quality assessment, and environmental sensing networks. In this context, drone-assisted microalgae systems serve as mobile carbon sinks, oxygen generation modules, and real-time environmental data collectors—positioning them as versatile tools for smart urban ecosystems.

Ultimately, these hybrid systems represent an intersection of biotechnology, artificial intelligence, communication networks, and urban planning, acting as environmental innovation platforms. They offer integrated, multi-functional solutions applicable to carbon management, air quality improvement, and ecological feedback mechanisms, making them a promising technology in the global response to climate change.

The proposed drone-based microalgae photobioreactor (m-FBR) model conceptually draws inspiration from bioregenerative life support systems (BLSS) developed for space environments, yet it diverges substantially in its design, function, and environmental interaction. Notable examples of such space-based systems include the MELiSSA (Micro-Ecological Life Support System Alternative) project by the European Space Agency and Russia's BIOS-3. These systems operate in closed environments, where photosynthetic microorganisms are used for carbon dioxide removal and oxygen regeneration to meet the vital needs of astronauts [26], [28], [16].

In contrast, the m-FBR system proposed in this study is an open but controlled system designed to directly interact with Earth's atmosphere. It operates within the lower troposphere (300–1500 m altitude) and is capable of dynamically navigating atmospheric CO_2 gradients using GNSS-guided autonomous drones equipped with environmental sensors and artificial intelligence-based decision-making modules [15]. This mobility enables the system to target emission hotspots such as industrial zones or post-disaster regions, facilitating real-time environmental intervention.

Unlike space-based systems that recycle oxygen internally, the m-FBR system releases photosynthetically generated oxygen directly into the atmosphere. This function is particularly valuable in urban environments where oxygen levels may be reduced due to limited green coverage. Moreover, the m-FBR model presents a unique capacity to absorb ambient water vapor, thereby compensating for water loss during photosynthesis and creating a dual feedback loop involving both carbon and water cycles—an adaptive feature not typically found in classical closed photobioreactors.

Another significant divergence lies in light management. While space systems rely on fixed-spectrum LED arrays, often limited to 450 nm (blue) and 660 nm (red), the m-FBR model uses energy-efficient LED modules tailored to the absorption peaks of *Synechococcus elongatus* PCC 3055, extending into near-infrared regions (680–710 nm). This allows continuous photosynthesis even during nighttime operations, enhancing productivity and energy efficiency [27].

As noted in the literature, there is currently no universally optimal photobioreactor design; system selection must align with the target algal species, environmental conditions, and production goals [15]. Within this context, the m-FBR introduces an innovative hybrid design that integrates mobility, environmental sensing, and AI-based optimization to enhance adaptability. It not only fixes atmospheric carbon but also recovers evaporated water—functions that align with climate mitigation goals beyond biomass production alone.

In summary, the m-FBR represents a novel paradigm that adapts the biological principles of space BLSS to Earth's dynamic atmospheric context. While space systems are designed to support human survival in closed-loop environments, the m-FBR aims to actively contribute to atmospheric rehabilitation on Earth. This dual functionality—both productive and restorative—positions the system as a next-generation solution integrating environmental sensing, autonomous mobility, and dual-resource (CO_2 and H_2O) recovery. Thus, it offers a responsive and sustainable approach to climate intervention, complementing but also extending the logic of space-based bioreactor designs.

In light of these technological and biological components, the system functions not only as a carbon sequestration unit but also as a comprehensive platform for environmental monitoring and adaptive response. It has potential applications across urban planning, carbon credit systems, post-disaster air quality control, bio-alarm networks, and climate modeling. In the long term, the data generated by mobile photobioreactors may serve as a foundation for AI-powered carbon tracking networks. In this capacity, the system emerges as a multi-functional technological asset in addressing the climate crisis.

IV. CONCLUSION

Drone-based photobioreactor systems represent not only an innovative approach to carbon capture but also a dual-benefit environmental solution—simultaneously reducing atmospheric CO_2 load while enabling biomass production and oxygen release. These advanced engineering platforms merge mobility with AI-driven environmental adaptation, offering a radical and functional alternative to conventional ground-based carbon management strategies.

Equipped with artificial intelligence algorithms, these systems can continuously analyze environmental data in real-time during flight. By responding to dynamic variables such as CO_2 concentration, light intensity, and temperature, they optimize their flight trajectory accordingly. This transforms the system from a passive carbon sink into an active, mobile, and environmentally responsive biotechnological intervention tool. Particularly in industrial zones, urban centers, or post-disaster regions characterized by elevated particulate and gas concentrations, these systems stand out due to their rapid and localized response capabilities.

With energy-efficient, modular, and scalable designs, the system is suitable for diverse geographical settings and operational demands. It extends beyond a laboratory-scale research concept and offers practical applicability across a wide range of domains—including urban environmental planning, agricultural practices, carbon trading schemes, and post-disaster environmental recovery.

Positioned at the intersection of nature and technology, the system constructs a novel paradigm for climate action—one that extends the boundaries of terrestrial intervention into the atmospheric domain. By facilitating oxygen generation through photosynthesis, enhancing environmental awareness, supporting data-driven analysis, and reinforcing biological cycles, it provides an integrated, multifunctional solution architecture.

Much like a precision gardener tending to soil fertility by managing light, moisture, and nutrient dynamics, this drone system seeks optimal environmental layers in the atmosphere to maximize algal photosynthesis. When deployed in CO_2-rich atmospheric zones, the system contributes not only to biomass accumulation but also to the restoration of local oxygen equilibrium.

Each flight signifies a conscious act of intervention at the planetary atmospheric frontier; each photosynthetic cycle reflects a renewal of Earth's respiratory vitality. This approach embodies a sustainable solution that synchronizes biological and technological processes—not solely for carbon sequestration but also to support the functional continuity of ecosystems.

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