**HEATWAVE ACTION**

**AIR POLLUTION ACTION**

**RENEWABLE ENERGY ACTION**

**GREEN CITY ACTION**

**SUSTAINABILITY ACTION**

**CARBON-NEUTRALITY ACTION**

A PILOT

PROJECT PROPOSAL

ON

**Algae-Infused Green Roof: A Nature-Based Solution for Climate-Resilient Cities**

Proposed by

CHANCHAL TIWARI

A logo of a school

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**Indian Institute of Technology(Indian School of Mines),Dhanbad**

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To

A close-up of a logo

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**Avery Dennison Foundation & Institute of International Education(IIE)**

**Problem Statement**

Cities worldwide are facing the combined challenges of intensifying heatwaves, rising CO₂ emissions, unsustainable energy demand, and deteriorating urban air quality and all of which threaten human health, infrastructure resilience, and climate stability. Rooftops, which cover a significant share of urban surface areas, remain underutilized assets despite their potential to mitigate these interconnected crises through nature-based, low-carbon, and technologically integrated solutions. Addressing these issues requires an innovative, scalable, and multifunctional approach that can simultaneously reduce urban heat, capture CO₂, generate renewable energy, and promote a circular bioeconomy.

As average rise in temperatures are set to reach 1.5 degrees, the number of heatwave spells in the country are rising rapidly(*Cool-Roof-Handbook.Pdf*, n.d.). During peak summer seasons, indoor temperature can rise-up to 45 degrees. With heat island effect in urban areas, the impact is far more severe on people's health, family expenditure, and productivity(*Cool-Roof-Handbook.Pdf*, n.d.).

A graph showing the growth of the stock market

AI-generated content may be incorrect. It’s a global problem for example over the last century, India has experienced a consistent rise in average surface temperatures, as evidenced by IMD’s temperature anomaly data (1901–2019), showing a +0.61°C increase per 100years. This warming trend is directly linked to the increasing frequency and intensity ofheatwaves, urban heat island effects, and higher energy demands for cooling systems such as air conditioners. These cooling systems, while essential for comfort, emit greenhouse gases (GHGs) and further intensify climate change. Combined with rapid urbanization and air quality deterioration due to industrial CO₂ emissions, the situation creates a vicious cycle of heat, energy demand, andemissions, threatening human health, ecosystem stability, and energy security(*IMD*, n.d.).

A Case Study of DELHI-NCR:

A new study by Greenpeace India has revealed a troubling link between Delhi’s intensifying heat stress and thousands of unrecognised deaths, particularly among the homeless and outdoor workers. The report, “Death and Degree: Establishing a Relationship of Death and Heat in Scorched Delhi,” uses the Universal Thermal Climate Index (UTCI) to show how extreme heat has become a silent public health crisis.

According to the findings, monsoon months that once brought relief now register dangerously high humidity and temperature levels. Between 2015 and 2024, June, July, and August consistently recorded UTCI values above 31.5 degrees Celsius, with July 2019 peaking at 34.4 degrees, conditions previously linked only to peak summer. The report highlights a sharp seasonal rise in stress, with March-to-April UTCI levels spiking by over 30 per cent, marking the onset of extreme summer-danger.  
This rise has coincided with a surge in deaths. In 2019 alone, 5,341 unidentified deaths were recorded during months of record heat. From 2022 to 2024, Delhi reported 11,819 such deaths, the highest three-year toll on record. June has emerged as the deadliest month, with 657 deaths in June 2019 at a UTCI of 34.2 degrees. The homeless have been worst hit: in June 2024, 192 homeless people died within just nine days, while July 2024 recorded 401 deaths—the highest monthly toll in two decades(*Case Study*, n.d.).

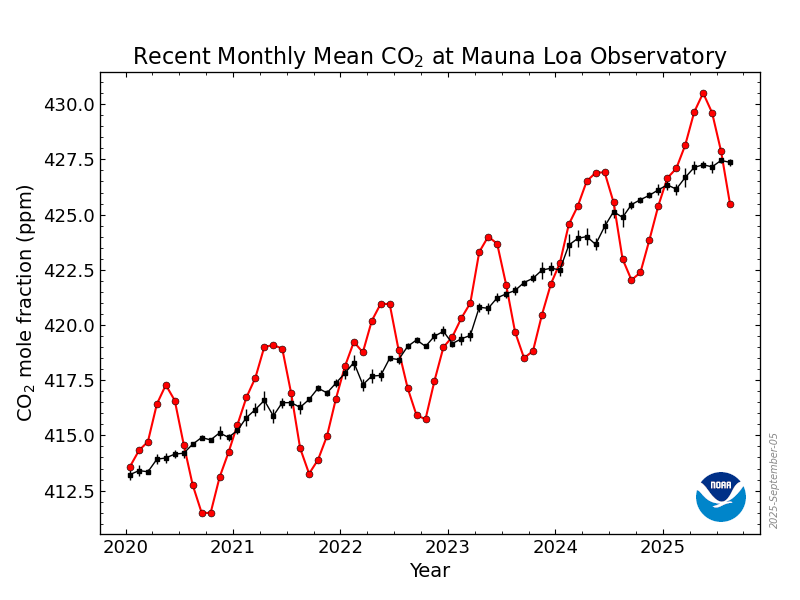
India, where extreme environmental exposures intersect with unplanned urbanization, poor-quality housing, declining urban green cover and other vulnerabilities in the world’s most populous country(de Bont, n.d.). A national assessment of climate change conducted by the Indian government predicts increasing temperatures in India throughout the 21st century with an increase in extreme heat events(de Bont, n.d.).

“On an average, electricity bills increases by 15%-20% during heatwave for an urban household !!(*Cool-Roof-Handbook.Pdf*, n.d.)”

To address the growing challenge of heat waves in summer, the integration of microalgae-based photobioreactors in buildings offers a sustainable and nature-based solution. Green microalgae selectively absorb red solar radiation, and when housed within glass photobioreactors, they function as dynamic bio-shading systems. This not only controls light penetration but also reduces indoor temperatures, thereby lowering the reliance on non-renewable energy sources such as air conditioning. As a result, electricity consumption and energy bills are significantly reduced, while citizens benefit from improved thermal comfort and better health.

Moreover, during winters, the photobioreactor panels act as thermal insulating layers, storing solar energy that can be harnessed to warm the buildings. This dual functionality ensures year-round energy efficiency, highlighting the crucial role of nature-based solutions in reducing energy demand, enhancing climate resilience, and promoting sustainable urban living.

Another threatening problem of current time is the excessive release of greenhouse gases (GHG) and the increase in the concentration of carbon dioxide (CO2) (approximately 75% of greenhouse gases GHG) in the last two centuries have aroused the attention of all countries, due to the serious threat they represent to the environment and human health. According to the World Health Organization (WHO), it is estimated that seven million deaths a year are the product of environmental pollution arising from GHGs, and it is predicted that these deaths may amount to up to nine million in 2060 if the growing trend in CO2 and GHG emissions continues(*Trends on Co2*, n.d.).

To reduce increasing trend of CO2, Algae is one of the most effective organisms in the domain of carbon sequestration and photosynthesis. They are classified into microalgae and microalgae, which vary in size and structure(*Regulation of Microclimate*, n.d.). The CO2 sequestration mechanism is done during photosynthesis, via bioconcentration. Performance evaluation revealed that the efficiency of capture and sequestration of CO2 by microalgae ranges between 40% and 93.7%(*Regulation of Microclimate*, n.d.).

Microalgae are of high interest for CO2 sequestration, as the biomass can be used widely, such as supplementing as animal feed, biofertilizer or as a feedstock for biofuel; thus, it can introduce the resource recycling(*Algal Biomass Utilization toward Circular Economy*, n.d.; *Potential of Microalgae*, n.d.). In the food and pharmaceutical industries, microalgae are a proven source essential amino-acids and long–chain polyunsaturated fatty-acids with antimicrobial, anti–cancer and antioxidant activities(*Microalgae in Food-Health Nexus*, n.d.).

**Goals and Objectives**

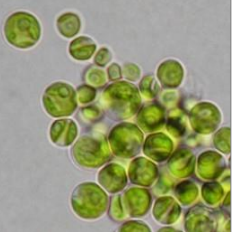
* Mitigate urban heat stress by reducing building energy demand and indoor overheating

during summer heatwaves.

* Lower greenhouse gas emissions through enhanced CO₂ and reduced reliance on fossil fuel-based cooling and heating systems.
* Promote sustainable cities by integrating nature-based and technologically advanced solutions into urban infrastructure.
* Enhance public health and well-being by improving indoor thermal comfort, reducing air pollution, and lowering energy costs.
* Promote Industries for optimizing Advance circular bioeconomy pathways by utilizing algal biomass for value-added applications.
* To design and install a rooftop pilot closed photobioreactor in Delhi-NCR, integrating semi-transparent solar panels, an automated temperature–humidity control, inline optical density monitoring, and a thermal insulating layer, to test its feasibility, seasonal efficiency, and urban applicability under real conditions.
* Quantify energy savings by monitoring reductions in electricity consumption for cooling/heating before and after system installation (expecting 15-20% energy savings per annum).
* Measure CO₂ sequestration efficiency (expecting achievement of 40-45%) of the microalgae strains used (kg CO₂ captured per m² of panel per day).
* Evaluate thermal regulation benefits by recording changes in indoor temperature (°C reduction in summer, °C retention in winter).
* Analyse biomass potential (amount of generation) and encourage industries to utilize biomass for various innovative products.

**APPROACH**

This pilot project will be implemented in five phases over 12 months, combining design, cultivation, installation, monitoring, and evaluation. The selected strain, Chlorella vulgaris, is chosen for its high biomass productivity, rapid growth, and strong carbon dioxide (CO₂) sequestration capacity. The integrated approach ensures that the photobioreactor system contributes simultaneously to urban cooling, renewable energy generation, CO₂ mitigation, and circular bioeconomy.

Chlorella vulgaris-Microalgae(*Microalgae Strain Catalogue*, n.d.)

A eukaryotic marine Trebouxiophyceae strain that has large-scale commercial cultivation in Asia as a high protein-rich food and feed source, a nutritional supplement, and biofuel source. It can be cultivated autotrophically, mixotrophically or heterotrophically 37–39 . It has quite robust growth for cultivation in open ponds as well as photobioreactors 40(*Microalgae Strain Catalogue*, n.d.).

Commonly cultivated strains include: CCAP 211/8K, CCAP 211/11B, CCAP 211/21A, CCAP 211/21B, CCAP 211/79, UTEX 2805, UTEX 2714(*Microalgae Strain Catalogue*, n.d.).

**Project Initiation and Design (Months 0–2)**

* Conduct rooftop site survey, structural assessment, and stakeholder consultations.
* Perform baseline environmental assessment (mini-EIA) to identify potential impacts, mitigation measures, and socio-economic benefits and update it over the next phases.
* Finalise the design of a closed photobioreactor (PBR) integrated with semi-transparentphotovoltaic (PV) solar panels and phase change material (PCM) insulation layer.
* Develop the cultivation protocol for Chlorella vulgaris, using BG-11 medium (Blue-GreenMedium 11) or Bold’s Basal Medium, with controlled supply of nitrogen, phosphorus, and trace metals.
* Bench-scale testing of Chlorella vulgaris for growth curves, optical density thresholds, and thermal tolerance.
* Deliverable: Final design package, Bill of Materials (BOM), and bench-test results.

**Procurement and Fabrication (Months 3–4)**

* Procure semi-transparent photovoltaic panels, modular photobioreactor panels, pumps, sensors, and controllers.
* Fabricate rooftop units designed as inclined shade-type modules to maximise sunlight use and cooling benefits.
* Install systems for CO₂ supply (enriched 1–5% CO₂ or ambient air with high flow), aeration, and automated nutrient dosing.

CO₂ Supply Strategy:

The photobioreactor (PBR) will utilize a multi-source CO₂ supply strategy to ensure reliable and sustainable operation. At the building scale, indoor CO₂ from human respiration and HVAC exhaust will be redirected into the PBR, improving indoor air quality while feeding algal growth. For larger systems, purified industrial flue gases from power plants or cement industries, CO₂ fractions from biogas plants, and emissions captured from urban transport hubs can all serve as inputs. By integrating domestic, industrial, and urban CO₂ streams, the system not only enhances carbon sequestration but also creates a circular pathway where waste emissions become a valuable resource for biomass production.

* Calibrate inline sensors for optical density (OD at 680 nanometres), pH, temperature, light intensity (Photosynthetically Active Radiation, PAR), and dissolved oxygen (DO).
* Deliverable: Fully fabricated and tested modules ready for rooftop installation.

**Installation and Commissioning (Months 5–6)**

* Install the rooftop photobioreactor–PV(Photovoltaic) hybrid system in Delhi-NCR under real urban conditions.
* Connect PV panels to building power supply for electricity generation.
* Inoculate reactors with Chlorella vulgaris starter cultures.
* Stabilise cultures under the following operating window:
* Temperature: 22–32 °C (not exceeding 35 °C)
* Light intensity (PAR): 100–300 micromoles photons per square metre per second
* pH: 6.8–8.5
* Dissolved oxygen (DO): maintained at safe levels through aeration
* CO₂: continuous dosing via sparging or venturi mixing
* Record baseline building cooling load and indoor comfort.
* Deliverable: Operational rooftop system with established baseline performance.

**Monitoring, Optimisation, and Harvesting (Months 7–11)**

* Continuously monitor OD, pH, DO, temperature, CO₂ uptake, and PV(Photovoltaic) energy output.
* Trigger harvesting when OD 680 nanometres = 0.8–1.2, avoiding excessive self-shading (OD > 1.5).
* When the algae culture reaches optimal growth, as indicated by the optical density (OD)sensor, 30–50% of the culture is harvested. Natural flocculation using chitosan aggregates the cells, which then settle by sedimentation, followed by centrifugation or membranefiltration to concentrate the biomass. The resulting slurry can be used for biofertilizer, animal feed,orbiofuel, making the process cost-effective, environmentally friendly, and scalable, while ensuring continuous growth and CO₂ capture in the rooftop photobioreactor system.
* Replenish nutrient medium after each harvest to maintain culture growth.
* Release excess oxygen (O₂) safely through gas vents, ensuring indoor air safety.
* Analyse harvested biomass for applications such as bio-fertiliser or anaerobic digestion forbiogas.
* Optimise system parameters (nutrient supply, CO₂ dosing, shading, insulation) seasonally for maximum efficiency.
* Deliverable: Monthly datasets on biomass productivity, CO₂ sequestration, indoor cooling, and energy savings.

**Final Evaluation and Dissemination (Month 12)**

* Analyse one-year performance data for:
* Biomass productivity (grams per litre per day).
* CO₂ captured per square metre.
* Reduction in indoor temperature and cooling load.
* Electricity savings from reduced air conditioning and PV power generation.
* Conduct a cost–benefit analysis (CBA) and life cycle assessment (LCA) to determine scalability.
* Organise a stakeholder workshop with policymakers, urban planners, and industry representatives.
* Develop a replication roadmap for scaling in other Indian cities and globally.
* Deliverable: Final technical report, scale-up manual, and policy brief.

**IMPACT MEASUREMENTS**

Impacts of this project can be seen in three spheres of environmental sustainability as:

* Reduction of indoor and rooftop surface temperatures: The photobioreactor panels with microalgae act as bio-shading devices, reducing direct solar heat gain and contributing to lower indoor temperatures, thereby easing the urban heat island effect.

Measurement-Process:

Embedded temperature sensors installed within the algae photobioreactor panels andon therooftop-surface continuously monitor rooftop and ambient air temperature as well as indoor air temperature is also measured using thermal sensors, this IoT-based system helps in generating heat-maps also so, combination of both automated and thermal sensors will be beneficial.

* Significant CO₂ sequestration: Chlorella vulgaris actively absorbs ambient CO₂ during photosynthesis, with a high biomass productivity rate, making it a reliable tool for reducing carbon concentrations in cities.

This captured carbon can be quantified and certified, forming the basis for carbon credits.

Measurement-Process:

Uptake is tracked using an inline CO₂ sensor and mass-balance growth model, ensuring accurate measurement of carbon capture.

* Enhanced oxygen release: During photosynthesis, the algae release O₂, which is vented out through an automated degassing system monitored by a dissolved oxygen (DO) probe, directly improving surrounding air quality.
* Reduction in energy demand and GHG emissions: Thanks to the semi-transparent solarpanel layer, part of the incoming solar radiation is converted to clean electricity, while the PBR reduces building cooling demand. This dual mechanism cuts dependence on fossil-fuel-based electricity.
* Promotion of circular bioeconomy: Biomass is harvested when the optical density (OD)meter indicates optimum growth. After harvesting through natural flocculation/sedimentation orcentrifugation, the biomass can be used for various purposes, closing the resource loop.

Measurement:

* Monitor algae growth continuously; harvest is triggered automatically at a pre-set ODthreshold.
* Collect harvested biomass and measure wet weight and dry weight (oven drying at 60–70°C until constant weight).
* Track biomass productivity:

Productivity (g/L/day)=(Volume of culture × cultivation days)/Dry weight harvested​

* CO₂ Sequestration Calculation:

CO₂ captured (g)=Dry biomass (g)×1.8

(Chlorella vulgaris typically fixes ~1.8 g CO₂ per g dry biomass)

* Improved thermal comfort and health: Cooler indoor environments are achieved through bio-shading panels and PCM integration, reducing risks of heat stress and enhancing occupant well-being.
* Reduction in heat-related illnesses and deaths: The system provides continuous real-time monitoring of indoor and outdoor temperatures via embedded temperature sensors(IoT-based) or simply using thermal sensors or combination of both, ensuring preventive action during peak heatwaves.
* Increased awareness and participation: The visible rooftop PBR modules serve as community demonstration sites, while digital dashboards and IoT-based data sharing engage citizens in climate-smart practices.
* Skill development opportunities: Training programmes will teach students and technicians to operate automated control systems (PLC/microcontrollers), manage biomass harvesting equipment, and interpret sensor data, fostering a green-tech skill base.
* Creating both green jobs and long-term employment in urban biotechnology and renewable energy sectors.
* Green Jobs Creation

Skilled technicians will be required for design, installation, and operation of rooftop photobioreactors.  
This generates new urban employment in the renewable energy and green technology sector.  
It strengthens local capacity for sustainable urban infrastructure projects.

* Microalgae Cultivation & Processing Workforce

Staff will manage strain cultivation, nutrient preparation, harvesting, biomass handling, and quality monitoring.

Creates lab-label and semi-skilled jobs in urban biotechnology. Supports growth of local expertise in algae-based solutions and circular bioeconomy.

* Maintenance & Service Industry

Routine system maintenance includes cleaning, optical density calibration, CO₂/O₂checks,and thermal sensor servicing.

Generates jobs for local service providers and small businesses.

* Research & Innovation Jobs

Universities, startups, and research organizations employ people for R&D, modelling, andprocess optimization.

Increases knowledge-based employment in biotechnology, environmental engineering, and smart building design. Encourages innovation and sustainable urban solutions.

* Indirect Economic Opportunities
* Biomass production leads a good supply for various industries as a raw material to make necessary bio-products and then they will generate revenue form the local markets and various small-scale industries and promoting circular economy concept.
* Carbon credits earned from verified CO₂ reductions can be traded in voluntary carbon markets, creating an additional revenue stream that improves long-term financial sustainability.

This pilot project aligns with and actively contributes to multiple Sustainable Development Goals (SDGs), including SDG 3 (Good Health and Well-being)(*SDG Goals*, n.d.), SDG 7 (Affordable and Clean Energy)(*SDG Goals*, n.d.), SDG 11 (Sustainable Cities and Communities)(*SDG Goals*, n.d.), SDG 12 (Responsible Consumption and Production)(*SDG Goals*, n.d.), SDG 13 (Climate Action)(*SDG Goals*, n.d.), and SDG 15 (Life on Land)(*SDG Goals*, n.d.), by integrating nature-based solutions, renewable energy, and circular bioeconomy principles to improve urban resilience, public health, and environmental sustainability.

**BUDGET ANALYSIS**

Cost-Matrix:



The present budget primarily reflects the one-time costs(~USD 25,500) of establishing a pilot closed photobioreactor system integrated with semi-transparent photovoltaic (PV) panels and monitoring devices. Since this is an R&D demonstration in Delhi-NCR, costs are relatively high due to custom fabrication, precision sensors, and small-scale procurement. However, these expenses are strategic investments to evaluate technical feasibility and optimize system performance under real urban conditions.

**“Here are some ways to enhance economic feasibility and Long-Term Sustainability of this project”**

1..

Cost-Reduction & Scalability Strategy

* Modular photobioreactor (PBR) units for rooftop deployment, enabling mass production and lowering costs.
* Use of local materials and algae strains to reduce procurement expenses.
* Government support through programs such as the National Green Hydrogen Mission and Smart Cities Mission.

Industry Partnerships for Biomass Utilization

2..

To avoid wastage and ensure value generation, harvested algal biomass can be absorbed into existing industrial supply chains. Potential pathways and partners include:

* Fertilizer: IFFCO, KRIBHCO (India); Nutrien (Canada).
* Animal Feed: Godrej Agrovet, Suguna Feeds (India); Cargill, ADM (global).
* Bioenergy: Indian Oil (algae biofuel pilots), Praj Industries (India); Algenol (USA).
* Nutraceuticals & Cosmetics: Himalaya, Patanjali (India); Corbion (Netherlands), Cyanotech (USA).
* Biochar: Takachar (India), Carbon Craft Design (India); Charm Industrial (USA), Carbon Gold (UK), Pacific Biochar (USA).

3..

Recycling of Culture Medium & Wastewater Reuse

The project adopts a closed-loop water and nutrient management system to reduce input costs and environmental impact:

* Process of Nutrient Recycling: After algae harvesting, biomass is separated by settling/filtration. The remaining liquid still contains nitrogen, phosphorus, and trace minerals. Only the depleted nutrients are topped up before reuse in the photobioreactor.
* Wastewater Integration: Treated greywater or STP effluent can be used as nutrient-rich input, reducing freshwater demand.

This combined approach can reduce nutrient and water costs by 40–60%, while achieving near zero-liquid discharge.

4..

Carbon Credit Potential

* CO₂ sequestration achieved through algal growth and biochar stabilization can be quantified and certified.
* Credits can be traded in voluntary carbon markets such as Verra, Gold Standard, and Puro. Earth.
* This creates an additional revenue stream, making the project financially sustainable while contributing to India’s Net Zero 2070 goals.

Looking ahead, the future budget will benefit from economies of scale. Once the pilot proves successful, the per-unit cost of photobioreactors, semi-transparent solar panels, and harvesting units will decrease significantly with bulk manufacturing and modular rooftop designs. Additionally, the system itself offsets part of the investment through renewable electricity generation, reduced energy bills (by lowering air conditioning demand), and valorisation of harvested biomass into biofertilizers, feed, or bioenergy.

The cost–benefit trend is highly favourable in the short term; investment leads to measurable reductions in electricity bills (20–30% lower cooling demand during peak summer). In the medium term, biomass reuse and solar energy generation provide additional returns. In the long term (5–10 years), payback is achieved, and the system continues to provide environmental benefits, carbon credits, and energy independence at relatively low maintenance cost. Importantly, this project aligns with multiple Sustainable Development Goals (SDGs), strengthens corporate sustainability profiles, and enhances social goodwill, making it a future-ready green investment.

This pilot rooftop photobioreactor can be scaled from individual buildings to entire urban areas, integrating renewable energy, smart monitoring, and automated biomass harvesting. By utilizing industrial and domestic CO₂ sources, it promotes a circular bioeconomy, reduces energy demand, and creates green jobs, while helping cities achieve multiple Sustainable Development Goals (SDGs) and move toward carbon-neutral, climate-resilient infrastructure.

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