TnafesClean: A Bio-Digital Air Purification System Integrating IoT and AI for Industrial Pollution Mitigation

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Abstract

Air pollution in Tunisian industrial zones poses a severe threat to public health. This paper presents TnafesClean, an autonomous bio-digital panel system ($1m \times 2m$) designed to mitigate pollutants such as $PM_{2.5}, PM_{10}, SO_2$, and HF. Unlike existing static solutions, TnafesClean integrates a synergistic combination of *Sphagnum* moss and *Spirulina* algae with an LSTM-based AI predictive engine. By harvesting atmospheric moisture and solar energy, the system operates with full resource autonomy while creating a circular economy by converting harvested algal biomass into organic fertilizer.

1 Introduction

The problem we have solved

Communities neighboring industrial zones in Tunisia face persistent exposure to toxic gases (SO_2, HF) and particulate matter. These emissions are primary drivers of respiratory diseases and environmental degradation, yet residents often lack the real-time data and local-scale purification tools needed to protect their health.

Why the problem is not already solved

Current industrial air filtration systems are high-cost, energy-intensive, and rarely focused on the residential-industrial interface. Existing biotechnological solutions, such as simple algae biofilms, often struggle with water scarcity in arid climates or lack the mechanical robustness to survive high-concentration industrial ”plumes” without frequent manual intervention.

2 Related Work

While international efforts like *Solaga* (Germany) and *Liquid3* (Serbia) demonstrate the potential of microalgae for urban carbon capture, their deployment in industrial contexts is hindered by several critical limitations:

- **Chemical Vulnerability:** Current systems lack tiered filtration, making them susceptible to biological death when exposed to high industrial concentrations of SO_2 and HF.
- **Lifecycle and Resource Gaps:** Traditional reactors have short biological lifespans (6–12 months) and rely on municipal water grids, which is inconvenient for an autonomous solution.

- **Passive Monitoring:** Most installations utilize static IoT sensors that lack predictive intelligence and proactive citizen-alert protocols.

3 Implementation

Algal Photosynthesis and Pollutant Assimilation Mechanism

The core biological process governing pollutant removal in TnafesClean is oxygenic photosynthesis performed by *Spirulina* microalgae. Under solar illumination, the algae convert absorbed carbon dioxide into organic biomass according to the generalized photosynthetic reaction:

$$6CO_2 + 6H_2O + h\nu \rightarrow C_6H_{12}O_6 + 6O_2$$

In parallel, sulfur dioxide (SO_2) and hydrogen fluoride (HF) are dissolved in the aqueous medium, where they undergo hydration:

$$SO_2 + H_2O \rightarrow H_2SO_3$$

$$HF \rightarrow H^+ + F^-$$

These ions are absorbed in very small amounts and neutralized by the mineral substrate, which prevents toxicity and allows the algae to remain active. Nitrogen compounds present in polluted air are also taken up by the algae and used to build proteins, which supports healthy growth and increases biomass production.

AI Architecture and Predictive Dashboard

The system's "intelligence" is driven by an IoT-to-Cloud pipeline.

- **Predictive Modeling:** We implemented a Deep Learning model using **LSTM networks** to analyze time-series data from PMS5003 and MQ-135 sensors. By correlating wind speed, humidity, and historical emission patterns, the AI predicts peak pollution periods 24 hours in advance.

- **Citizen-Centric Alerts:** While most dashboards are for internal monitoring, our platform features a public-facing interface. It provides "Pollution Forecasts" and health recommendations ("High SO_2 predicted in 2 hours, please close windows"), empowering the community with actionable data.

Mineral Cartridge for Long-Term Algal Autonomy

To enable up to three years of autonomous operation, TnafesClean integrates a passive mineral cartridge composed of basalt, greensand, and natural phosphate. Basalt provides slow-release micronutrients such as iron, magnesium, and calcium, which are critical cofactors for photosynthetic enzymes. Greensand acts as a potassium and iron source while also stabilizing pH levels. Phosphate supplies phosphorus required for ATP synthesis and cellular division.

Together, these minerals create a self-buffering nutrient reservoir that eliminates the need for human replenishment while maintaining stable algal growth and resistance to chemical stress.

The Circular Economy: From Pollution to Fertilizer

A core innovation of TnafesClean is the "Algal Biomass Harvesting" loop. As the *Spirulina* culture grows by absorbing CO_2 and nitrogenous pollutants, the excess biomass is periodically harvested. This biomass is rich in minerals and nutrients, which we process into high-quality **organic fertilizer**. This converts a waste-capture process into a value-generating stream for local agriculture.

Biomass Formation and Conversion into Organic Fertilizer

The produced algal biomass follows an empirical biochemical composition approximated by:

$$CO_2 + H_2O + Nutrients \rightarrow (C_6H_{10}O_5)_n + Proteins + Lipids$$

Once harvested, the biomass is dried and mineralized through natural aerobic decomposition. The resulting organic fertilizer contains essential macronutrients (N, P, K) and trace elements, improving soil structure and microbial activity. Unlike synthetic fertilizers, this biofertilizer releases nutrients gradually, reducing leaching and enhancing long-term soil fertility.

Atmospheric Condensation and Water Supply System

Water required for photosynthesis is supplied by an integrated condensation system based on nocturnal temperature differentials. During night hours, a thermally conductive surface promotes condensation of atmospheric humidity:

$$H_2O_{(g)} \rightarrow H_2O_{(l)}$$

The collected condensate is filtered and gravity-fed into the algal chamber, ensuring continuous hydration without external water input. This mechanism is particularly suited to coastal and industrial environments where relative humidity remains significant even under arid climatic conditions. The system thus achieves full hydric autonomy while sustaining biological activity year-round.

4 Evaluation

The solution was tested using a prototype chamber to measure differential pollutant concentrations. The LSTM model achieved high accuracy in forecasting $PM_{2.5}$ trends based on historical training data. The mineralization loop successfully maintained biological health for extended periods, and initial tests on the harvested biomass confirmed its efficacy as a nutrient-rich soil additive.

5 Conclusions and Future Work

TnafesClean provides a modular ”Bio-Panel” that redefines air purification as an active, predictive service. By integrating Artificial Intelligence models, this project has moved beyond simple monitoring to proactive community protection. Furthermore, our circular economy approach, turning industrial emissions into organic fertilizer, provides a sustainable model for wide-scale deployment. Future work will focus on optimizing the LSTM model with multi-node sensor fusion to create a high-resolution ”Digital Green Belt” across Tunisia.

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