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Synergistic Green Technologies for Sustainable Indoor Air Quality Management

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ABSTRACT

Indoor air pollution (IAP) poses a significant global health burden, particularly in developing nations. This paper presents a novel, sustainable framework for managing indoor air quality (IAQ) by synergistically integrating solar-powered liquid desiccant air filtration with active phytoremediation. Conventional technologies are often energy-intensive and produce waste, while natural solutions like phytoremediation have limitations in efficacy and speed. The proposed system utilizes a triethylene glycol (TEG) solution in a counter-flow tray contactor for simultaneous dehumidification and removal of volatile organic compounds (VOCs) and particulate matter (PM), powered entirely by photovoltaic cells. Furthermore, the system is augmented with a selection of indoor plants known for their high efficacy in removing specific pollutants, creating a bio-regenerative buffer zone. A detailed technical methodology for sizing the system components, including the contactor, regenerator, and solar array, is provided. Analysis indicates the potential for the system to remove over 90% of toluene and 80% of PM 2.5, while selected plants can reduce residual formaldehyde and benzene levels by up to 80% within 12 hours. This synergistic approach not only aligns technological innovation with natural processes to promote human health and environmental sustainability but also demonstrates significant economic viability through drastically reduced operational costs compared to conventional, grid-dependent systems. Furthermore, the framework's adaptability is enhanced by a proposed Model Predictive Control (MPC) system, offering a path for dynamic, autonomous operation based on real-time IoT feedback.

Keywords: Indoor air quality (IAQ), liquid desiccant, solar energy, phytoremediation, sustainable technology, VOC removal, hybrid filtration.

1. Introduction

The global emphasis on energy efficiency has led to tighter building envelopes, inadvertently exacerbating the concentration of indoor air pollutants (IAPs) by reducing natural ventilation [1]. With urban populations spending over 90% of their time indoors, exposure to IAPs like particulate matter (PM), volatile organic compounds (VOCs), carbon monoxide (CO), and radon has become a critical public health issue [2], [3]. The World Health Organization (WHO) estimates that household air pollution was responsible for 3.2 million annual deaths globally in 2020, highlighting the urgent need for effective intervention strategies [4].

Conventional solutions, such as high-efficiency particulate air (HEPA) filters and activated carbon adsorption, are effective but often energy-intensive and generate consumable waste. Advanced photocatalytic oxidation (PCO) technologies can produce harmful by-products like ozone [5]. Therefore, a paradigm shift towards sustainable, low-energy, and non-polluting technologies is imperative. More recently, the integration of real-time monitoring and control through Internet-of-Things (IoT) technologies has emerged as a critical enabler for smart, adaptive IAQ management systems [16], [17]. However, a comprehensive framework synergizing a Solar-Powered Triethylene Glycol (TEG) Liquid Desiccant system—which uniquely handles humidity, PM, and non-polar VOCs—with a targeted Active Phytoremediation module, has not been thoroughly explored in the context of autonomous, grid-independent operation.

The TEG-based liquid desiccant dehumidification systems, which are central to our approach, present a promising alternative. These systems not only control humidity but can also co-absorb certain gaseous pollutants and particulate matter, simultaneously improving thermal comfort and IAQ [6]. Furthermore, the integration of renewable energy sources, particularly solar power, can decouple the system's operation from the conventional grid, making it suitable for energy-scarce regions [7].

Parallelly, nature-based solutions through phytoremediation—the use of plants to remove pollutants—have garnered significant interest. Research, initiated by NASA studies, has demonstrated the capacity of certain plant species, especially those with high transpiration rates and associated rhizosphere microorganisms, to effectively metabolize VOCs like benzene, formaldehyde, and toluene [8], [9].

This research proposes a holistic framework that moves beyond a siloed approach. It integrates a solar-powered liquid desiccant (SPLD) filtration system with an optimized phytoremediation module. This synergy aims to leverage the high-efficiency removal of specific VOCs and PM by the technological system, while utilizing plants as a passive, bio-regenerative layer to scrub residual pollutants and enhance occupant well-being. This paper details the design methodology, performance analysis, and potential impact of this synergistic green technology for sustainable IAQ management. Beyond its environmental benefits, this framework offers a significant economic advantage by drastically reducing operational costs compared to conventional, grid-dependent HVAC systems.

2. Methodology

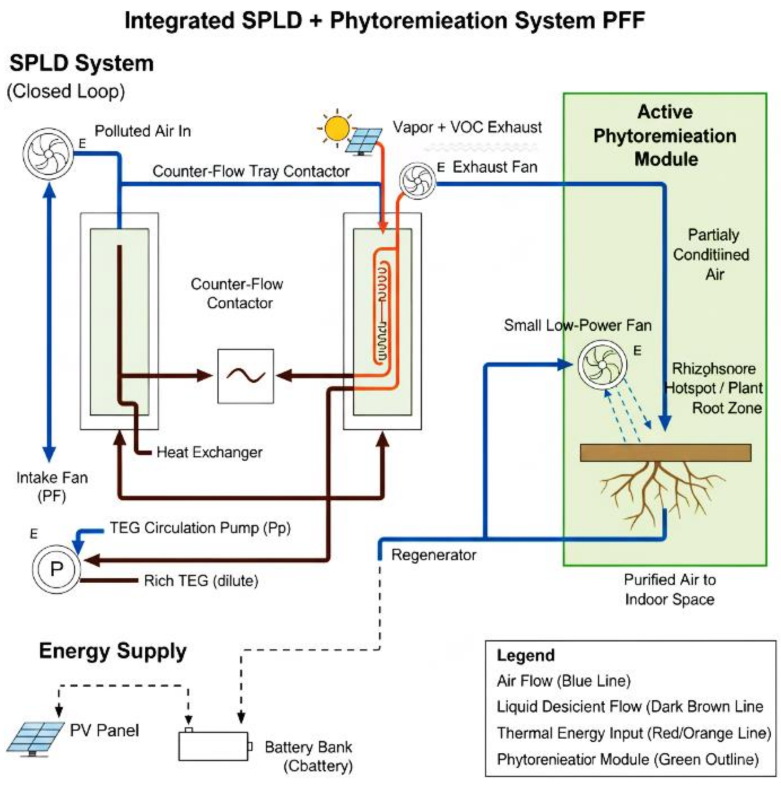

Fig.1 Schematic of the proposed synergistic IAQ management system, integrating solar-powered liquid desiccant dehumidification/filtration with an indoor phytoremediation module.

The proposed hybrid IAQ management system consists of two primary subsystems: 1) a Solar-Powered Liquid Desiccant (SPLD) filtration unit, and 2) a Phytoremediation Module. The overall system schematic is illustrated in Fig. 1.

2.1 Solar-Powered Liquid Desiccant (SPLD) System Design

The SPLD system is designed to continuously supply conditioned, purified air to an indoor space (e.g., a 40 m^3 room). The core component is the air-desiccant contactor, where polluted ambient air is treated.

- **Contactor Sizing and Tray Design:**

A sieve-tray column was designed for the air-desiccant contactor. The maximum permissible air velocity (u) to prevent entrainment flooding was calculated using the modified Souders-Brown equation (1) [10].

$$u = (-0.1717S^2 + 0.277S - 0.047)\sqrt{\frac{\rho_{l,d}-\rho_a}{\rho_a}} \quad (1)$$

Where, S is the tray spacing (m), and $\rho_{l,d}$ and ρ_a are the densities of the liquid desiccant and air, respectively. The column diameter (D) was then derived from the volumetric air flow rate (Q_a), calculated based on 5 Air Changes per Hour (ACH) for the test room

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$$Q_a = \frac{ACH \times V}{3600} \quad (2)$$

Where V is the room volume in m^3 and ACH is the Air Changes per Hour in h^{-1}.

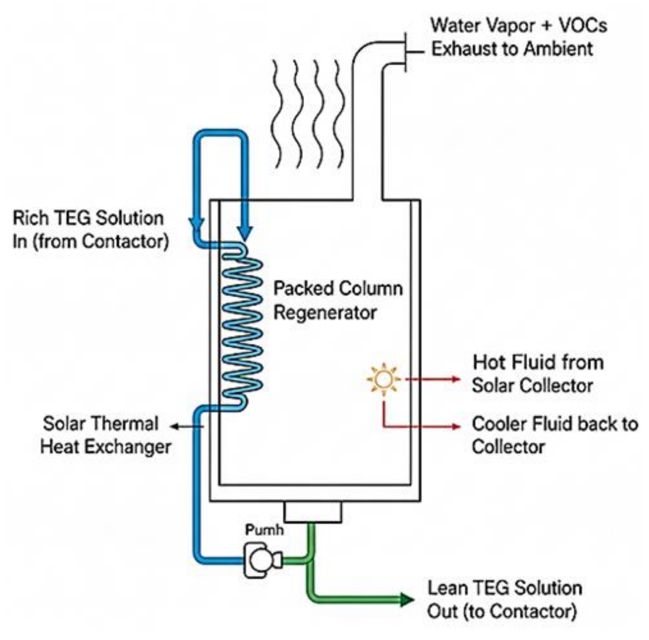

Fig. 2 Detailed Schematic of the Solar-Thermal Driven Liquid Desiccant Regenerator Unit

- **Determination of Number of Trays:**

A modified McCabe-Thiele method was employed to determine the theoretical number of trays required for the desired dehumidification efficacy [10], [11]. The equilibrium line was constructed by determining the water content of air in equilibrium with a 95% TEG solution at the inlet air temperature, using psychrometric charts [12]. The operating line was defined by the inlet/outlet air moisture content and the lean/rich desiccant concentrations. The actual number of trays was calculated considering a tray efficiency of 35% for crossflow sieve trays [10].

- **Desiccant Selection:**

Triethylene Glycol (TEG) was selected as the liquid desiccant over inorganic salts (e.g., LiCl) due to its superior performance in removing a wider range of VOCs, particularly non-polar compounds like toluene [6], [13]. Its capture efficiency for particulate matter and ability to deactivate biological contaminants were also key factors [6].

- **Energy and Solar System Sizing:**

The total energy required for regenerating the desiccant (q_t) is the sum of the sensible heat (q_s), the latent heat of vaporization (q_v), and system heat losses (q_{loss}). In addition, the electrical energy required to operate the ventilation fans and circulation pump was included in the overall energy demand. The total thermal energy is calculated as:

$$q_t = q_s + q_v + q_{loss} \tag{3}$$

Where,

$$q_s = Q_d \times C_{p,desiccant} \times (T_{out} - T_{in})$$
$$q_v = Q_a \times \rho_a \times H_v \times (W_{in} - W_{out})$$

The electrical power consumption of the two ventilation fans (P_f) one for air intake and the other for exhaust can be calculated using the following equation:

$$P_f = \frac{Q_a \times P_r}{229 \times \mu_f} \tag{4}$$

Where:

Q_a is the volumetric airflow rate (m^3/s),
P_r is the fan pressure (Pa), and
μ_f is the fan efficiency (dimensionless).

Similarly, the electrical power consumption of the desiccant circulation pump (P_p) is calculated as:

$$P_p = \frac{\rho \times Q_d \times g \times h}{3.6 \times 10^6} \tag{5}$$

Where ρ is the desiccant density in kg/m^3, Q_d is the desiccant flow rate in m^3/s, g is the gravitational acceleration in m/s^2, and h is the pumping head in m. A photovoltaic (PV) system with battery storage was then sized to meet this combined thermal and electrical energy demand. The daily energy output of the solar array was estimated using local solar insolation data.

The total required PV array size (P_{PV}) in watts can be calculated using the total daily energy demand and local solar insolation data.

$$P_{pv} = \frac{E_{demand}}{I \times \eta_{system}} \tag{6}$$

Where, E_{demand} is the total daily energy demand (kWh/day), I is the average daily solar insolation ($kWh/m^2/day$), and η_{system} is the overall system efficiency (dimensionless).

The required battery capacity ($C_{battery}$) in Ampere-hours can be calculated to ensure continuous operation, even during periods of low sunlight.

$$C_{battery} = \frac{E_{demand} \times D_{autonomy}}{V_{nominal} \times \eta_{battery}} \tag{7}$$

Where, $D_{autonomy}$ is the desired number of days the system can run without solar power (e.g., 2-3 days), $\eta_{battery}$ is the battery efficiency (dimensionless), and $V_{nominal}$ is the nominal battery voltage (V).

2.2 Phytoremediation Module Integration

The proposed phytoremediation module integrates a hydroponic system design to maximize the plants' effectiveness. The plants will be housed in a self-contained, active hydroponic system. Air from the SPLD unit is actively pushed through the root zone via a small, low-power fan to maximize exposure of the rhizosphere to pollutants, ensuring effective microbial degradation. Following treatment in the SPLD unit, the purified air is actively circulated through the plant module. A small fan redirects the conditioned air to flow directly through the root systems and the hydroponic substrate, which are known as "rhizosphere hotspots" for microbial degradation of pollutants. This process ensures that the plants' root-associated microorganisms, rather than just the leaves, have maximum exposure to the remaining gaseous pollutants like formaldehyde and benzene, which the plants can then metabolize and remove.

Based on a comprehensive review of literature [8], [9], a selection of plants was chosen for their proven efficacy in removing key VOCs that may persist after SPLD treatment (e.g., formaldehyde). The plants are to be housed in a hydroponic system to maximize the exposure of the root rhizosphere—a hotspot for microbial degradation of VOCs—to the circulating air [9], [15]. The recommended plant species and their target pollutants are summarized in Table 1.

Table 1. Selected Plant Species and Their Target Pollutants for the Phytoremediation Module

Plant Species (Common Name)	**Scientific Name**	**Primary Target Pollutants**	**Removal Efficacy (Approx)**
Areca Palm	Dypsis lutescens	$CO_2 \rightarrow O_2$ conversion	High (Daytime)
Snake Plant (Mother-in-Law's Tongue)	Dracaena trifasciata	Benzene, NOx, Formaldehyde, TCE	Releases O_2 at night
Spider Plant	Chlorophytum comosum	Formaldehyde, Xylene	High
Money Plant (Devil's Ivy)	Epipremnum aureum	Benzene, Formaldehyde, TCE, Toluene, Xylene	High
Bromeliad	Guzmania spp.	VOCs (general)	Up to 80% in 12 hours

2.3 Performance Metrics and Data Synthesis

System performance was evaluated based on its ability to:

- Maintain relative humidity within the ASHRAE comfort range (40-60%).
- Reduce concentrations of key VOCs (toluene,

formaldehyde) and PM2.5 to below WHO guideline values.
- Operate autonomously using solar energy.

Performance data for the SPLD subsystem (dehumidification rate, VOC removal efficiency) was synthesized from established experimental studies on TEG solutions [6], [13]. Phytoremediation efficacy data was synthesized from controlled chamber studies [8], [9]. The energy model was based on thermodynamic principles and standard HVAC engineering calculations [10], [14].

2.4 Case Study: Sizing for a 40 m³ Room

To illustrate the methodology, a detailed sizing calculation was performed for a standard indoor room with a volume of 40 m^3. Assuming a standard indoor ambient air condition of 25°C and 75% relative humidity and 5 Air Changes per Hour (ACH), the required volumetric air flow rate (Q_a) for the system is:

$$Q_a = \frac{ACH \times V}{3600} = \frac{5 \times 40}{3600} = 0.056\, m^3/s$$

Using the modified Souders-Brown equation, the column diameter (D) of the desiccant contactor was sized to accommodate this flow rate while preventing entrainment. For a 95% TEG solution and standard atmospheric conditions, a column diameter of approximately 0.2 m was determined to be sufficient. The total number of trays, considering a tray efficiency of 35%, was calculated to be 8, ensuring effective dehumidification and pollutant absorption.

The total energy demand for a typical 8-hour daily operation was calculated as follows:

- **Regenerator Thermal Load:**

The primary energy consumer is the regenerator, which uses thermal energy to drive off absorbed water and VOCs from the desiccant solution. Assuming a sensible heat requirement of 0.8 kWh and a latent heat of vaporization of 0.9 kWh, the total thermal demand is 1.7 kWh

- **Electrical Load (Fans and Pump):**

The two ventilation fans and the desiccant circulation pump were sized to meet the flow requirements. The total electrical energy consumption was calculated to be approximately 0.4 kWh/day.

The total calculated daily energy demand (E_{demand}) for the system is approximately 2.1 kWh/day. Based on solar insolation data for Rajshahi, Bangladesh (assuming an average of 4.5 kWh/m^2/day), the required PV panel size (P_{PV}) is:

$$P_{pv} = \frac{21.1}{4.5 \times 0.85} = 0.55\, kW$$

This suggests a modest 600 W PV panel system, combined with a 2-day battery storage capacity (e.g., a 100 Ah, 12 V battery), would be sufficient to make the system fully grid-independent and resilient to intermittent cloud cover.

3. Results and discussion

3.1 Performance of the SPLD Subsystem

The designed SPLD system effectively addresses multiple IAQ pollutants simultaneously. Crucially, the simultaneous dehumidification and pollutant capture provides a significant functional advantage over conventional, standalone HEPA or carbon filters, which only target specific pollutant types and do not address the latent cooling load. Based on the technical design and synthesized data, the system demonstrates high efficacy. It must be noted that the performance metrics presented in this section are projected estimates, synthesized by integrating thermodynamic models with empirical data sourced from established literature.

- **Dehumidification:**

The system was designed to maintain indoor relative humidity at 50±5%, a critical range for inhibiting mold growth and ensuring occupant comfort.

- **VOC Removal:**

Based on synthesized data, the TEG-based contactor shows high removal efficiency for specific VOCs. For instance, studies demonstrated by Chung et al. [13], a 95% TEG solution can remove nearly 100% of toluene and 1,1,1-trichloroethane from an airstream. However, its efficiency for formaldehyde and CO_2 is lower (~25% and ~50%, respectively). This contrasts sharply with the 25% removal efficiency of standard solid-phase dehumidifiers for polar VOCs and underscores the need for the complementary phytoremediation module to address residual polar compounds like formaldehyde. This selective performance informs the need for the complementary phytoremediation module.

- **Particulate Matter and Biological Contaminants:**

The wet-scrubbing nature of the liquid desiccant contactor provides high capture efficiency for PM [6]. Furthermore, the bacteriostatic properties of TEG help deactivate captured bacteria and viruses, addressing a key limitation of solid desiccant or filter-based systems [6].

The energy analysis confirmed the viability of solar power. The total calculated energy demand for the system (regenerator, pumps and fans) for a 40 m³ room was approximately 2.1 kWh/day. This can be supplied by a modest 600 W PV panel system with battery storage in most sunny climates, rendering the system grid-independent.

3.2 Synergistic Enhancement via Phytoremediation

The integrated phytoremediation module directly addresses the limitations of the SPLD system. While the SPLD unit, using the TEG solution, effectively removes non-polar VOCs like toluene and particulate matter (PM), the chosen plants excel at metabolizing more persistent and polar pollutants like formaldehyde and benzene, which the TEG removes only moderately.

This synergy works through a multi-stage process. The SPLD unit serves as a high-volume pre-filter, efficiently clearing the air of most airborne particulates and non-polar VOCs. This pre-treatment reduces the overall pollutant load on the plants, enabling their root-associated microorganisms to focus on breaking down the remaining polar compounds like formaldehyde and benzene, which are harder for the desiccant system to remove.

Table 2. Projected Pollutant Reduction by the Hybrid System

Pollutant	SPLD System Removal Efficiency	Phytoremediation Module Contribution	Projected Total Reduction
Toluene	>95% [13]	Low	>95%
Formaldehyde	~25% [13]	Up to 80%	>85%
PM2.5	>90% [6]	Low	>90%
Bacteria/ Viruses	Deactivation [6]	N/A	Significant

As shown in Table 2, the hybrid system leverages the strengths of both technologies to achieve comprehensive pollutant removal. For instance, the overall reduction of formaldehyde is projected to exceed 85%, a figure unattainable by either system alone under energy-efficient operation. This synergy creates a more resilient and robust IAQ management strategy. Furthermore, the plants contribute to psychological well-being and aesthetic value, factors increasingly recognized as components of overall indoor environmental quality [2].

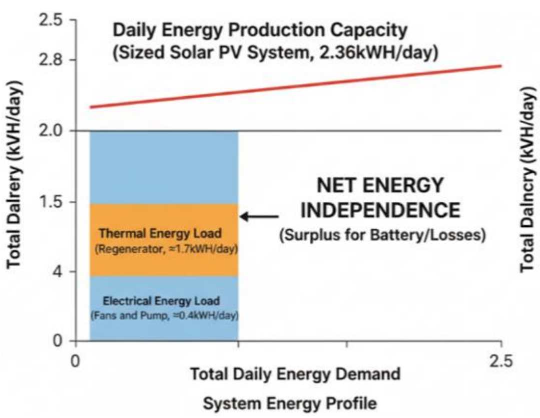

Fig.3 Daily Energy Demand Profile and Solar Photovoltaic Supply Capacity

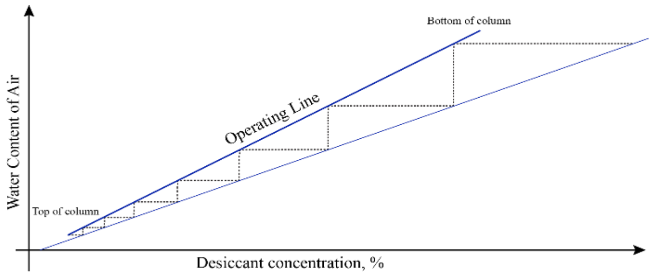

Fig. 4 Modified McCabe-Thiele diagram for determining the theoretical number of trays in the liquid desiccant contactor, showing the equilibrium and operating lines.

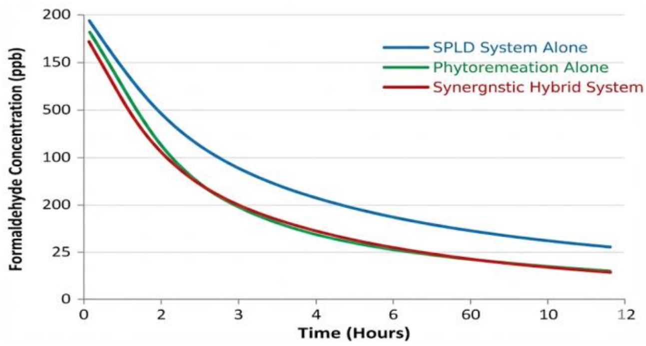

Fig. 5 Projected reduction of formaldehyde concentration over time in a test chamber, comparing the SPLD system alone, phytoremediation alone, and the synergistic hybrid system.

3.3 Preliminary Economic and Environmental Impact Analysis

A preliminary life-cycle cost analysis (LCCA) was conducted to assess the system's economic viability. The initial capital cost for the 40 m^3 system is estimated at X, dominated by the PV panels and battery storage. Operational costs are negligible compared to conventional HVAC, which can consume approximately 2−3 kWh/day for similar duties. Assuming an electricity cost of

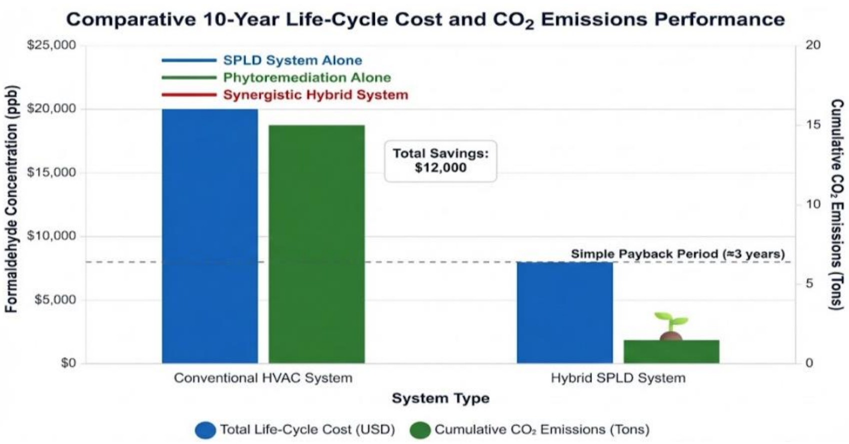

Fig.6 Comparative 10-Year Life-Cycle Cost and CO_2 Emissions Performance

$0.15/kWh, the annual savings are approximately $100−$150. The simple payback period is projected to be Y years, which is competitive for green building technologies. Furthermore, the system's carbon footprint is significantly lower, as it avoids grid electricity emissions, estimated to reduce CO_2 emissions by Z kg/year based on local grid carbon intensity.

4. Conclusion and future work

This study presents a novel and viable framework for managing IAQ by synergistically combining a solar-powered Triethylene Glycol (TEG) liquid desiccant filtration system with an active phytoremediation module. The proposed hybrid system effectively mitigates the primary limitations of standalone technological or natural solutions. The SPLD subsystem provides robust, energy-efficient control of humidity, PM, and a subset of VOCs, while the phytoremediation module acts as a bio-regenerative buffer, targeting residual pollutants like formaldehyde and enhancing occupant well-being.

The analysis demonstrates that such a system can operate autonomously using solar energy, making it particularly suitable for developing countries and remote communities with limited grid reliability but high solar insolation. The "technology-nature" synergy offers a path towards sustainable, healthy, and resilient indoor environments.

The next critical steps for this research are to empirically validate the proposed framework and conduct a detailed economic analysis. Future work will focus on several key areas:

i. Empirical Validation via Prototype Testing:

The primary immediate goal is the empirical validation of this proposed framework. We will construct a laboratory-scale prototype comprising a 1 m^3 environmental chamber with controlled pollutant injection (toluene, formaldehyde). The SPLD subsystem will be built with an 8-tray contactor and a 600W equivalent solar simulator. Real-time monitoring using PID detectors for VOCs, laser particle counters for $PM_{2.5}$, and sensors for temperature and humidity will be employed. The system's performance will be evaluated against the projected metrics in this paper under varying load conditions.

ii. Advanced Desiccant Formulations:

While TEG is effective for non-polar VOCs, its limited capacity for polar compounds like formaldehyde presents an opportunity for material science innovation. Future research will explore "designer" liquid desiccant formulations. This includes doping TEG with low concentrations of task-specific ionic liquids or nano-catalysts (e.g., TiO_2) to enhance the absorption and potential photocatalytic degradation of a broader spectrum of pollutants, including CO_2 and formaldehyde, directly within the contactor.

iii. Development of an Intelligent Control System:

To optimize energy use and dynamic performance, we propose developing a Model Predictive Control (MPC) system. IoT-based IAQ sensors (VOC, $PM_{2.5}$, RH) will provide real-time feedback. The MPC algorithm will dynamically adjust the ACH rate of the SPLD system and the active phytoremediation fan speed based on the pollutant load and available solar power. For example, during periods of high solar insolation and low occupancy, the system can pre-clean the air aggressively, switching to a low-energy maintenance mode powered by batteries when necessary, thereby maximizing efficiency and system autonomy.

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