On the Feasibility of a Plant-based Air Quality System Modeled via Molecular Communication for Green Smart Homes

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***Abstract*—Indoor air quality in urban homes is influenced by multiple airborne pollutants, including volatile organic compounds (VOCs), carbon dioxide (CO_2), and fine particulate matter (PM) originating from indoor activities and outdoor sources such as vehicular traffic. Although mechanical air filtration systems are effective, they are energy-intensive and offer limited spatial awareness of pollutant dynamics. In this paper, we explore the feasibility of a plant-based indoor–outdoor air quality system modeled through the lens of molecular communication (MC). Pollutants are abstracted as information-carrying molecular species, plants as spatially distributed receivers with absorption and sensing capabilities, and residential spaces as bounded diffusion-dominated channels. This abstraction enables the reuse of MC models to reason about pollutant propagation, assess the feasibility of plant placement, and explore early-stage design trade-offs. Unlike large-scale urban or industrial environments, residential settings operate in confined geometries where diffusion-driven modeling is more applicable, making them well-suited for MC-inspired analysis. Rather than optimizing plant species or placement, this work positions MC as a unifying framework to evaluate feasibility and identify open challenges toward greener, bio-integrated smart home environments.**

***Index Terms*—Molecular Communication, Plant Network, Air filtering, Urban Pollution, Ideation**

I. Introduction

Air pollution has become a persistent reality in major cities worldwide, with urban residents routinely exposed to elevated levels of particulate matter, volatile organic compounds (VOCs), and carbon dioxide (CO_2) both outside and inside their homes. In addition, indoor air quality is increasingly affected by everyday human activities, such as cooking, cleaning, and respiration. Although mechanical ventilation and filtration systems can mitigate these effects, they are energy-intensive and provide limited spatial awareness of pollutant distribution within residential spaces [1]. In recent times, increasing emphasis on sustainable and energy-efficient living has renewed interest in bio-integrated solutions for environmental monitoring and mitigation. Indoor and balcony plants are known to passively absorb airborne pollutants, contribute to thermal regulation, and improve indoor comfort [2]. Beyond filtration, plants have the potential to act as environmental biosensors. However, the use of plants for air quality management remains largely heuristic, with limited frameworks to assess feasibility or guide spatial deployment [2].

Molecular communication (MC) provides a natural abstraction for modeling biological systems [3]. In MC, information is conveyed through molecules propagating within a medium, a paradigm that maps directly to indoor air quality scenarios where pollutants act as molecular species carrying information, residential spaces form bounded diffusion channels, and plants behave as distributed receivers with absorption and sensing capabilities [4]. Residential environments are characterized by confined geometries and limited spatial extents, making diffusion-based modeling assumptions particularly suitable.

In this paper, we assess the feasibility of a plant-based indoor air quality system using MC as our analytical lens. Instead of delivering an optimized design, we present MC as a unified modeling framework to analyze pollutant dynamics, plant deployment, design trade-offs, and to highlight open challenges on the path to greener smart homes.

II. MC-Based System Model and Considerations

We model the residential environment as a bounded indoor space in which airborne pollutants propagate over short spatial scales characterized by a mixed diffusion–advection mechanism: diffusion dominates in most regions and enclosed rooms, while weak advection arises from ventilation, thermal gradients, and human activity. Within an MC abstraction, pollutant emissions are treated as molecular signals released by multiple transmitters, the indoor space forms the communication channel, and plants act as spatially distributed receivers as seen in Fig. 1. Plants absorb and respond to these molecules according to species specific biological properties, which can be mapped to receiver parameters such as absorption efficiency, saturation behavior, and operational lifetime. Plant survivability and response to pollutants can be partially characterized through indices such as the Air Pollution Tolerance Index (APTI) [5].

Beyond pollutant-to-plant interactions, the framework also accommodates plant-to-plant MC. Plants are known to exchange chemical signals through airborne volatiles and other

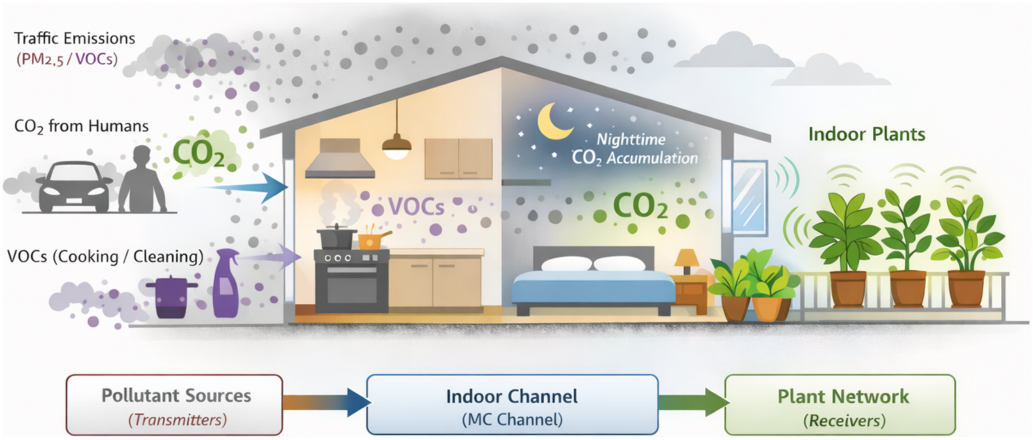

Fig. 1. Overview of a plant-based indoor air quality system modeled as a MC framework.

mechanisms, particularly under stress conditions. In an MC context, this interaction can be interpreted as secondary molecular signaling between receivers, enabling indirect information exchange across the plant network. Such interactions introduce cooperative and interference effects, where the response of one plant may influence neighboring plants, effectively forming a distributed sensing and signaling network.

From a network perspective, the system naturally maps to multi-input multi-output (MIMO) MC scenarios, with multiple pollutant sources interacting with a heterogeneous plant network and with inter-receiver signaling. Established MC models can be used to analyze how receiver density, spatial placement, and inter-plant coupling affect system behavior. Furthermore, information theoretic metrics commonly used in MC, such as received molecule count or mutual information, can be repurposed to evaluate placement strategies in terms of coverage, sensitivity, and robustness.

In terms of methodology, we plan to implement a hybrid COMSOL–Python workflow. COMSOL Multiphysics is used to model the indoor environment as a bounded transport domain with diffusion–advection dynamics for the concentration of particles. The resulting concentration time series will be transferred to Python, where each plant will be modeled as a heterogeneous transceiver with species-specific parameters derived from descriptors such as leaf area and APTI. Python will also be used to represent plant-to-plant signaling, evaluate cumulative stress and purification performance, and compute network-level metrics such as coverage, detection reliability, and mutual information for preliminary placement analysis.

This approach demonstrates that MC provides a coherent framework not only to model pollutant propagation but also to analyze cooperative behavior within plant networks, thus supporting early-stage feasibility assessment and guiding future optimization efforts.

III. Open Challenges and Research Direction

Although the proposed framework demonstrates the feasibility of modeling plant-based indoor air quality systems using MC, there remain open challenges that motivate future research.

- Plant modeling and biological variability: Indices such as the APTI provide a useful abstraction, but long-term effects including saturation, adaptation, and others require detailed bio-physical models and experimental validation.
- Transport regime transitions: Use of hybrid diffusion–advection models and stochastic airflow effects to improve realism while maintaining analytical tractability.
- Plant-to-plant MC: While the framework allows for inter-plant signaling, the strength, range, and reliability of airborne plant-to-plant communication in indoor environments remain largely unexplored. Characterizing these interactions is essential for understanding network behavior.
- Network-level optimization: Optimizing device placement in realistic homes involves balancing multiple objectives, including pollutant removal, sensing performance, durability, and others. Information theoretic measures from MC can provide a principled basis for capturing these trade-offs tailored to each scenario.
- Experimental validation and hybrid systems: Future work should prioritize validating MC-based models in controlled indoor testbeds and investigating systems that integrate plant signals with low cost sensors. These improve reliability and speed up the adoption of MC inspired design principles in real-world smart home applications.

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