ENHANCING PHOTOCATALYTIC AIR PURIFICATION METHODS IN CLOSED ECOLOGICAL SYSTEMS AND PROSPECTS FOR THE APPLICATION OF INTEGRATED FACADE SYSTEMS

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This paper presents an in-depth analysis of indoor environmental air pollution, the impacts of volatile organic compounds (VOC) on human health, and the scientific and practical foundations of air purification technologies based on photocatalytic oxidation. The study investigates the photocatalytic activity of semiconductor catalysts—titanium dioxide (TiO2), zinc oxide (ZnO), silicon-based nanostructures, and graphene oxide (GO)—and examines their potential application in integrated building façade systems. In particular, based on recent studies from 2024–2026, kinetic modeling (Langmuir–Hinshelwood and pseudo-first-order models) has demonstrated that photocatalytic lamellae can achieve up to 9% NOx gas degradation, up to 99% bioaerosol inactivation, and 15–17% energy savings in HVAC systems.

Introduction. In the 21st century, the rapid development of urbanization processes and climate change pose a significant challenge to humanity to ensure the environmental safety of living and working environments. The COVID-19 pandemic in 2020 further heightened the urgency of creating a healthy indoor environment in buildings, thereby prioritizing the fight against not only chemical but also biological contamination.

Indoor air quality is regulated by the building codes of many countries. These codes specify the required ventilation volumes and air exchange rates for buildings. However, in recent decades, in the pursuit of energy efficiency the building envelope (building envelope) has increasingly been constructed to be highly airtight. Excessive reliance on mechanical ventilation and air-conditioning systems has sharply reduced opportunities for natural ventilation. Scientific studies indicate that in inadequately ventilated buildings relative humidity increases and carbon dioxide, volatile organic compounds (VOC), and pathogenic microorganisms accumulate. This situation leads to an increased incidence of respiratory diseases and the development of "sick building syndrome".

In recent years, for the purpose of energy conservation, many buildings have adopted airtight façades and mechanical ventilation systems. As a result, the potential for natural ventilation has been reduced.

Scientific studies have demonstrated that:

- If ventilation is inadequate, indoor humidity increases;
- harmful gases and microorganisms accumulate;
- The risk of respiratory tract diseases increases;

Conversely, natural ventilation:

- Improves human health;
- Renews the indoor air;
- enhances users' convenience;
- maintains a natural connection with the external environment.

Nevertheless, outdoor air is not always clean.

According to the World Health Organization (WHO), more than 4.2 million people die each year as a result of air pollution.

The major pollutants encountered in outdoor (ambient) air are as follows:

- PM_{2*5} and PM_{10} particulate matter;
- volatile organic compounds (VOC);
- NO_x;
- SO_2;
- CO;
- O_3.

Although mechanical ventilation systems can capture dust and spores, they cannot completely eliminate harmful gases.

Therefore, the authors developed a novel façade element integrating natural ventilation and photocatalytic air purification.

This element:

- Introduces outdoor air into the building;
- captures dust particles by physical means;
- Using a TiO_2 photocatalyst, it decomposes harmful gases such as NO_2;
- It also serves the function of protecting against solar radiation.

The primary aim of this study is to investigate the effectiveness of this multifunctional façade element; the trend in the development of façade construction systems has long indicated standardization and the maximization of prefabrication. Over time, façade prefabrication has evolved, improving photocatalytic air purification methods originally associated with a specific material or industry, analyzing their kinetic models and their integration within contemporary architectural elements (integrated façades).

Literature review. This article was revised within the framework of scientific research conducted in 2024–2026. Recent studies indicate that photocatalytic air purification technology is transitioning from the laboratory scale to real industrial and environmental control systems [5].

Comparative Analysis of Photocatalytic Materials

Titanium dioxide (TiO_2) is the most extensively studied photocatalyst, and its anatase phase exhibits high catalytic activity. However, the pristine material's 3.2 eV band gap restricts its operation to ultraviolet (UV) irradiation, thereby limiting the efficiency of solar energy utilization.[6]

Recent studies (2024–2026) have achieved a reduction in the susceptibility of zinc oxide (ZnO) nanostructures to photocorrosion through structural modification. For example, $Ag/TiO_2/PLA$ hybrid films reached 99% efficiency in inactivating bioaerosols within 15 minutes [3]. Additionally, graphene oxide (GO)-based composites have been found to reduce electron recombination, thereby increasing the quantum efficiency of the process [4].

Integrated Facade Systems and Photocatalysis

Research conducted in 2024 (Buildings journal) demonstrated the feasibility of combining natural ventilation and air purification by installing photocatalytic lamellae (slats) on building façade elements [9]. These systems clean the outdoor air before it enters the building using aluminum-based TiO_2 coatings. Experiments showed that, in tests performed according to ISO 22197-1, degradation was 9% and NO_x conversion was 5% [6].

Research methodology. This study employed methodological approaches and comparative analyses to assess the efficacy of photocatalytic air purification processes in closed ecological systems. The degree of mineralization and the potential for energy savings were examined through a review of scientific publications.

Results. Analyses indicate that the efficiency of photocatalytic air purification systems depends on a number of factors:

Gas flow and reactor design. Air-cleaning efficiency is directly dependent on the type of photoreactor and the gas flow rate. For example, at an airflow rate of 5 L/min, the Ag/TiO_2 system has been shown to remove bioaerosols with high efficiency not only by physical capture but also by chemical decomposition [7].

Degree of mineralization and safety. The primary goal of photocatalytic oxidation is the complete mineralization of volatile organic compounds (VOCs) to CO_2 and H_2O. Complete mineralization is observed at low concentrations (<1 ppm); however, at higher concentrations or when the catalyst is poisoned there is a risk of formation of intermediate products (e.g., formaldehyde or other intermediates). Therefore, in integrated systems a combination of adsorption and photocatalysis (hybrid systems) is recommended. [8]

Langmur – Hinshelwood model. The Langmuir-Hinshelwood model is particularly suitable for describing air purification processes in enclosed ecological systems, because in this model pollutant gases or vapors are first adsorbed onto the cleaning surface and then react on that surface to undergo decomposition. In closed systems the air is continuously circulated, so the gas concentration, the degree of adsorption, and the condition of the catalyst surface directly determine the purification efficiency. The essence of the model is that in closed ecological systems—such as greenhouses, laboratory chambers, closed water–air reactors, or ventilation-driven purification units—harmful airborne species adhere to the surface of a catalyst or adsorbent. Thereafter chemical decomposition or oxidation occurs at that surface. This process can be described by the Langmuir-Hinshelwood equation:

$$r = \frac{kKC}{1 + KC}$$

Here; [r] — removal rate, [k] — surface reaction rate constant, [K] — adsorption constant, [C] — concentration of the pollutant in the air.

If the system is a two-component system, for example, if gases [A] and [B] react together, then:

$$r = \frac{kK_AK_BC_AC_B}{(1 + K_AC_A + K_BC_B)^2}$$

The Langmuir–Hinshelwood model serves as the fundamental mathematical framework describing the sequential processes of adsorption, surface reaction, and desorption in the purification of air within closed ecological systems. It enables a priori calculation of the removal rate of harmful compounds in the air and aids in the design of purification devices.[8]

Energy-saving opportunities. In integrated façade systems, outdoor air exchange can be reduced through air purification. This enables energy savings of 15% to 17% in HVAC (heating, ventilation and air conditioning) systems, since the amount of energy required to continuously adjust (condition) the temperature of the incoming fresh air is reduced [2].

Table 1

Comparative analysis of photocatalytic materials and systems (based on data from 2024–2026) [2,3,5]

Object of the study	Purification efficiency	Kinetic model	Energy efficiency
(ProClean™ façade	degradation of up to 9%	NO conversion (ISO 22197-1)	External UV-A irradiation (no electrical power consumption)

Ag//PLA hybrid	Bacteria 99% minutes)	First-order (upper)	Low-power UV-C LED
Modified	UOB (VOC) greater than 90%.	Langmuir–Hinshelw	15–17% HVAC energy savings
composite	Organic paints 95%	Quantum yield (QY) has increased.	Active under visible light

Conclusion. Studies conducted on improving photocatalytic air purification methods in closed ecological systems enable the following conclusions:

1. Composites based on titanium dioxide and zinc oxide (in particular, modified with Ag va bilan) exhibit high efficiency in removing chemical and biological pollutants from air.
2. The installation of photocatalytic lamellae in integrated façade systems provides natural ventilation in buildings while enabling a reduction of harmful NO_x gases by up to 9%.
3. The Langmuir–Hinshelwood model remains the most reliable kinetic model for assessing photocatalytic processes, thereby enabling precise calculations for system design.
4. Future research should be directed toward enhancing the activity of photocatalysts in the visible-light spectrum and ensuring their long-term stability (resistance to photocorrosion).

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