Surface Coating with Advanced Nanocomposites: Photocatalytic Applications in Degradation of Environmental Pollutants for Urban Environments

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Abstract

This study addresses the critical issue of air pollution in major metropolitan areas, including Tehran, and emphasizes the need for advanced surface coating technologies to reduce environmental contaminants in urban settings. The paper provides a comprehensive analysis of surface coating with advanced nanocomposites and their photocatalytic applications for the degradation of environmental pollutants. Nanocomposites composed of various materials, particularly semiconductor metal oxides such as TiO_2, ZnO, and g-C_3N_4, demonstrate high efficiency in decomposing micro-pollutants and atmospheric contaminants under light irradiation. Several coating techniques, including spray coating, electrophoretic deposition, and electrospinning, are reviewed, each offering distinct advantages depending on specific environmental conditions and surface requirements. Moreover, the integration of nanomaterials with emerging components such as graphene and MXenes enhances photocatalytic performance, corrosion resistance, and long-term stability of the coatings. Innovative synthesis techniques, such as plasma-based and electrochemical methods, also play a significant role in improving the efficiency of these coatings for air and water purification. Harnessing the photocatalytic properties of these materials using solar and other renewable energy sources, particularly in urban environments, offers a promising pathway for reducing air pollution and improving urban living standards.

Kewwords:

Building Surface Coating, Advanced Materials Engineering, Micro-pollutants, Photocatalyst, Renewable Energy

Introduction

Urban air pollution, particularly in megacities such as Tehran, poses a severe threat to public health, exacerbating respiratory, cardiovascular, and other chronic diseases. Traditional indoor air control strategies (source control, ventilation, filtration) have limitations, creating a need for advanced, passive, and durable air purification solutions. Photocatalytic nanocomposite coatings, primarily based on semiconductor oxides such as TiO_2, ZnO, and g-C_3N_4 , can degrade harmful gaseous pollutants and volatile organic compounds (VOCs) into harmless products under UV or visible light. These coatings also offer self-cleaning, anti-fouling, and solar-reflective properties, contributing to reduced energy use and urban heat island mitigation. Enhancements using graphene, MXenes, and hybrid heterojunctions have addressed limitations such as restricted visible-light absorption and high electron–hole recombination rates, enabling improved environmental remediation performance[1, 2].

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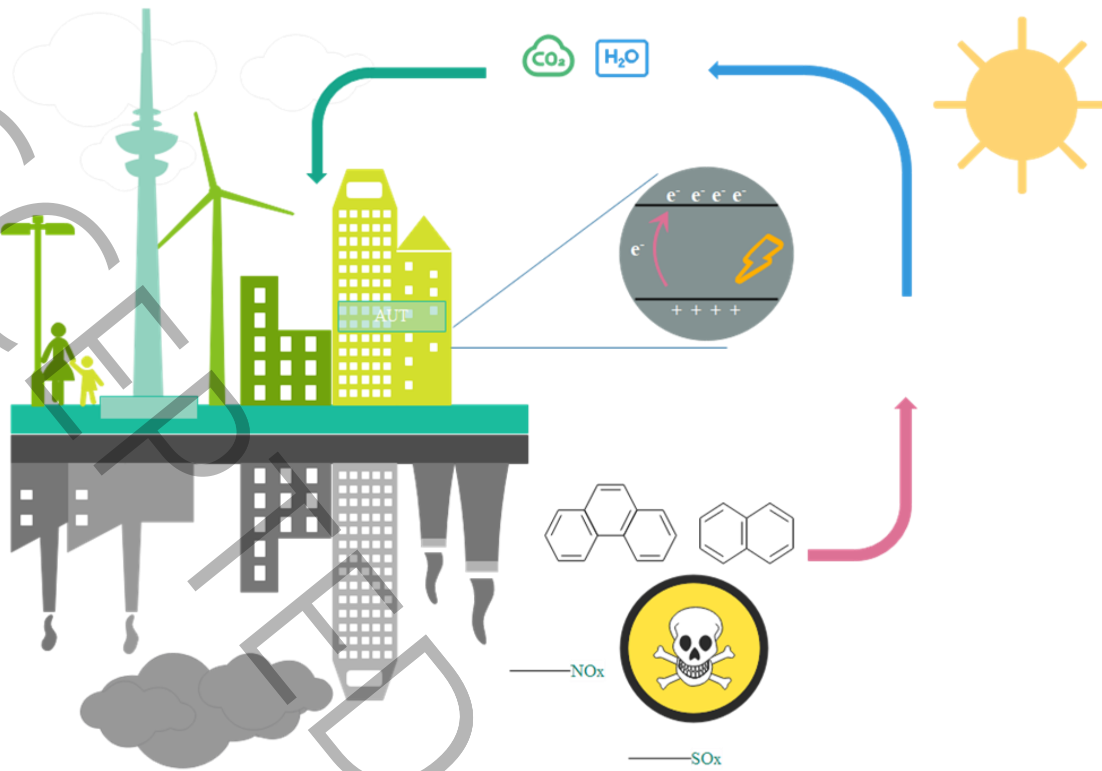

Figure 1 Advanced photocatalytic coatings with urban applications

Methodology

Multiple fabrication methods were reviewed, each tailored to substrate type and application. Spray coating provides high-speed, large-area deposition, particularly for TiO_2-based layers, with performance dependent on phase composition, morphology, and hydroxylation degree[3]. Electrophoretic deposition (EPD) enables precise thickness control and uniform coverage, including on complex geometries, useful for ceramic or metal surfaces in environmental applications[4]. Electrospinning produces nanofibrous mats with high surface area, beneficial for air and water filtration. Cold plasma offers solvent-free deposition with simultaneous surface modification, compatible with heat-sensitive substrates.

Results and Discussion

Photocatalytic coatings applied to urban building facades, pavements, and infrastructure demonstrated significant reductions in NO_x, SO_x, and VOC levels under natural sunlight. For instance, TiO_2-based facade coatings in London achieved seasonal NO_x reductions from 3.5–9.8% in winter to 18–37.5% in summer[5]. Graphene/TiO_2 nanocomposite cement coatings exhibited high self-cleaning ability and maintained photocatalytic activity after prolonged sunlight exposure[6]. ZnO nanostructures showed strong VOC mineralization capability, while g-C_3N_4 and MXene hybrids extended spectral response into the visible region and enhanced electron transport[7]. Secondary benefits included reduced surface fouling, lower building cooling loads via solar reflection[8], and mitigation of the urban heat island effect. However, field performance is influenced by environmental factors such as humidity, pollutant load, and surface aging, which can reduce catalytic efficiency over time. Cleaning or surface refresh methods can restore activity. Hybrid approaches combining photocatalysis with adsorption, photothermal, or plasma treatment have shown promise in improving pollutant removal rates for resistant[9].

Table 1 Challenges and proposed solutions for the development and widespread application of photocatalytic nanocomposite coatings in urban environments

Challenge	Explanation	Proposed Solution
Low Durability in Real-World Conditions	Reduced performance against UV radiation, humidity, heat, and surface pollutants.	Designing protective coatings, using resistant additives, and optimizing surface structure.
High Cost of Synthesis and Coating Application	Use of pure materials and advanced equipment for applying coatings.	Utilizing inexpensive alternative materials (e.g., bioplastics) and developing simple, scalable synthesis methods.
Limited Performance in Visible Light	Many photocatalysts are only activated by UV light.	Using visible light-active nanocomposites like TiO_2/MXene or TiO_2/g-C_3N_4.
Decreased Efficiency Over Time	Performance drop due to surface blockage or contamination.	Designing durable nanocoatings, adding inhibitors, and performing photochemical stabilization.
Low Efficiency in Short-Term Pollutant Removal	Long reaction times for removing resistant compounds like VOCs.	Integrating with complementary technologies such as adsorption, photothermal, or plasma to increase efficiency.
Complexity and Cost of Industrial Coating Methods	Need for precise equipment and controlled conditions to apply coatings on large surfaces.	Using simpler industrial methods like spray coating, dipping, and roll-coating.
Lack of Performance Data in Real-World Conditions	Most data is obtained in laboratory environments.	Conducting urban and industrial-scale field studies for a realistic evaluation.
Poor Performance on Specific Surfaces (Porous Concrete, Glass, Rough Metals)	Incompatibility of the coating with the substrate's material or texture.	Careful selection of the coating composition based on the type of substrate.

Conclusion

Advanced photocatalytic nanocomposite coatings offer a viable, passive strategy for urban air and surface pollution control, with additional energy-saving and structural protection benefits. Materials such as TiO_2, ZnO, g-C_3N_4, and their hybrids with graphene or MXenes deliver enhanced visible-light activity, stability, and multifunctionality. While laboratory results are encouraging, large-scale adoption is limited by performance degradation in real conditions, high production costs, and substrate-specific challenges. Future work should focus on:

1. Developing visible-light-active, durable, and low-cost composites.
2. Optimizing scalable, low-energy coating methods.
3. Conducting long-term field evaluations in varied urban climates.

Given their synergy with renewable energy use and smart-city infrastructure, these coatings have high potential to become integral to sustainable urban design.

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