Innovative Approaches to Mitigate Urban Air Pollution: A Comprehensive Review on Photocatalytic Technologies and Biomass-Derived Materials in Concrete

Darwish Adil[1*], Hamad Ahmad[1], Muneeza Naheem[1], Syeda Rabiya Abid[1], Nadia Riaz[2], Muhammad Arbab Faisal Javed[3]

[1] Department of Civil Engineering, COMSATS University Islamabad, Abbottabad Campus, Abbottabad, Khyber Pakhtunkhwa, Pakistan
[2] Department of Environmental Sciences, COMSATS University Islamabad, Abbottabad Campus, Abbottabad, Khyber Pakhtunkhwa, Pakistan
[3] Department of Civil Engineering, GIK Institute of Engineering Sciences and Technology, Topi 23460, Khyber Pakhtunkhwa, Pakistan.
fa20-cve-002@cuiatd.edu.pk; arbabfaisal@cuiatd.edu.pk; nadiariazz@gmail.com

Abstract. This review article provides an overview of the prevalent problem of air pollution in metropolitan and urban areas, emphasizing the imperative for innovative technologies to mitigate pollutants. It explores the application of photocatalytic technology, utilizing nanoparticles such as meal oxides, to effectively address air pollution stemming from vehicle emissions. Additionally, the article investigates the use of metal oxides and activated carbon derived from biomass in the context of photocatalytic concrete, with the overarching goal of developing environmentally conscious building materials for urban environments. The review encompasses significant findings from various studies, highlighting advancements in durability, efficiency in photocatalysis, positive impacts on public health, sustainability, and contributions to scientific progress.

Keywords: Air pollution, Metal oxides, Photocatalyst, Biomass derived-activated carbon, semiconductor photocatalysis, concrete

1 Introduction

Metropolitan and urban areas confront a significant issue: air pollution as a result of industrial and transportation activity [1]. The consequences are far-reaching, affecting a person's health and the entire well-being of their communities. The effects on the environment include contributing to climate change and ecological problems [2]. Addressing this issue requires an integrated approach that includes strict emission legislation, promotion of sustainable mobility, and investment in cleaner technologies [3]. Several approaches have been proposed for addressing air pollution, among which photocatalytic technology employing nanoparticles, such as TiO_2, has shown effective in reducing the airborne pollutants emitted by various sources [4].

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In photocatalysis, a semiconductor is crucial for generating electron-hole pairs through the absorption of photons, initiating a chemical reaction [5-7]. This process triggers a redox chemical potential within the semiconductor, as electrons and holes migrate to the material's surface [5, 7-9]. Subsequently, these electrons and holes actively participate in dismantling molecules adsorbed on the material's surface. Heterogeneous photocatalysts, which use semiconductor TiO_2 (Advanced Oxidation Processes (AOP)), are an up-and-coming field among the various treatment methods that can break down a range of organic air and water contaminants. These photocatalysts are strong semiconductors that have several advantages, including being non-toxic, having the ability to absorb visible light and/or UV, chemical stability, and being relatively inexpensive. Zinc sulfide (ZnS), zinc oxide (ZnO), tungsten oxide (WO_3), titanium dioxide (TiO_2), and iron oxide (Fe_2O_3) are few examples of photoactive semiconductors that have been described [10-12]. Among heterogeneous semiconductors, titanium dioxide is a versatile, cost-effective, and extensively used photocatalytic material because of its chemical stability and non-toxic nature. Other polymorphs of TiO_2, such as rutile, anatase, and brookite, are even more dominant, with anatase and rutile being the most stable, while the former is known for its unique photoactive features. During the reaction, titania remains stable and does not disintegrate, while changing in oxidation state [13].
Photocatalytic concrete is a structural concrete mix that contains titanium dioxide (TiO_2) as an additive or surface layer. Photocatalytic substances expedite this process and, when used in concrete, actually enable for the treatment of pollutants by employing a self-cleaning concept: decomposing organic molecules, microbes, and contaminants into simple or harmless molecules [14]. A novel and effective approach to materials engineering has proved that cementitious building materials such as paints, mortars, concrete products, pavements, and so on may be characterized with photocatalytic activity [15]. Photocatalytic concrete (PC) has been used in several research studies as presented in the following sections.

2 TiO_2 based photocatalytic concrete

Previous research has focused on the photocatalytic behaviour of cementitious materials containing TiO_2, emphasizing the significance in enhancing photocatalyst availability on concrete surfaces [16, 17]. In a study by Wu et al., [18], a significant decrease in compressive strength was observed, reducing from 26 MPa to 13.5 MPa at 28 days as the TiO_2 concentration increased from 0% to 8%, reflecting a 48% loss in compressive strength [18]. Excessive TiO_2 adversely affects cement hydration, raises cement matrix flaws, and hampers mechanical qualities. Replacing 80% of brand-name sand with M-sand, 16% POFA, and 10% TiO_2 results in a notable 12.16% increase in compressive quality and an 11.10% improvement in flexure quality at 28 days [19]. MacPhee and Folli [17] examined the application of TiO_2 -based photocatalysts to concrete and came to the assumption that concrete surface should increase photocatalyst accessibility; Yang [20] synthesized a TiO_2 porous microspheres material for photocatalytic depollution purpose; When applied to concrete surfaces, photocatalytic coatings of TiO_2 nanoparticles were found by Faraldos et al., (2016) [21] to be very successful at treating NOx pollution. Table 1 reports the various studies reported on photocatalytic degradation of NOx under various reaction conditions using TiO_2 supported photocatalytic concrete.

Table 1. Degradation of NOx as model pollutant using TiO_2 supported photocatalytic concrete

Reaction conditions	References
Degradation of NOx by UV-A	[1]
For TiO_2 UV with wavelength lower than 387 nm	[22]
It can be used in different areas for abatement of NOx.	[23]
It is used in road pavements for abatement of NOx.	[24]
To mitigate NOx pollution by using photocatalytic pavements.	[25]

3 Limitations and modifications of TiO_2

Titanium and other nanoparticles are being researched worldwide for their remarkable qualities, affordability, and low environmental effect when it comes to improving dye removal. Nevertheless, using visible light for photocatalytic applications is hampered by their inability to respond under UV light, which makes up only 4% of the visible light spectrum. Despite this, they are a preferred choice for the removal of dye from wastewater due to their huge surface area, strong adsorption properties, quick equilibrium rates, and low diffusion resistance. Because of this, numerous research teams all over the world are concentrating on figuring out how to get beyond nanoparticles' restrictions when it comes to using visible light for photocatalytic reactions. [23, 26]. By addressing these constraints and investigating potential improvements, the integration of TiO_2 with biomass-derived activated carbon can be optimised for improved photocatalytic performance in environmental applications.

Activated carbon, acknowledged for its porous structure and large surface area, is an effective adsorbent for a variety of pollutants in water and air treatment, specifically organic contaminants. When mixed with titanium dioxide (TiO_2) nanoparticles, the resulting composite has increased photocatalytic activity, allowing it to break down organic contaminants under light exposure. This improvement is due to the activated carbon's role in providing adequate surface area for TiO_2 dispersion, reducing agglomeration, and acting as a sensitizer by absorbing and transferring light energy to TiO_2 nanoparticles. Activated carbon/TiO_2 composites have been shown to be effective at degrading organic pollutants and removing heavy metals from water and air, demonstrating their versatility and efficiency as an environmental remediation technique. Table 2 illustrates the different types of biomasses along with enhanced characteristics and related environmental remediation.

Table 2. Different types of biomass along with enhanced characteristics and related environmental remediation.

Biomass Source	Research Summary	Ref.
Soybean oil cake	- Pyrolysis at 600 and 800 °C - Chemical activation (K_2CO_3 and KOH) - Resultant AC with the highest surface area at 800 °C (1352.86 m^2/g)	[27]
Alpha cellulose, xylan from beech	- Thermal stability and activation below 600 °C - Xylan exhibited lower surface area and adsorption - CO_2 isotherms indicated that the mixture impacts ultra-micro porosity. - Activated carbon qualities influenced by initial feedstock's presence and makeup	[28]
Orange peel	- highly porous activated carbon - Chemical activation ($ZnCl_2$ & K_2CO_3) - Optimal activation temperatures identified for surface area and pore volume optimization (400–500 °C for $ZnCl_2$ activation and 900–950 °C for K_2CO_3)	[29]
Gelatin and starch	- Chemically activation - Increasing activating agent concentration enhances porous structure of produced activated carbon materials. - The combination significantly improved specific surface area and CO_2 capture. - Increased porosity resulted from heteroatoms (O and N) in the precursor material	[30]
Rice Husk	- Chemical activation (H_3PO_4) - Correlation observed between H_3PO_4 amount at 500 °C and HA uptake. - Endothermic process with enhanced HA uptake in the presence of Ca^{2+} ions. - Incomplete reversibility suggests a significant energy barrier for desorption. - "Electrostatic attraction" and "surface complex formation" identified as key adsorption mechanisms on the carbon surface.	[31]
Pineapple	- Investigation explores activated carbon from pineapple leaves for dye removal. - Demonstrated ability to remove methylene blue, showcasing efficacy. Saturated activated carbon finds utility in pyrolysis for charcoal or pyroligneous acid production.	[32]

4 Biomass-Derived Activated Carbons

Researchers are diligently investigating the environmentally friendly utilisation of various biomass sources for activated carbon production while considering environmental concerns. Materials such as soybean oil cake, orange peel, gelatin, starch, rice husk, and pineapple leaves have all been investigated for their potential. Numerous investigations have shown that chemical activation of these biomass sources produced activated carbons with varying porosity and tailored adsorption capacities. For example, soybean oil cake activated carbon had various characteristics when activated with K_2CO_3 and

KOH at different temperatures. Similarly, orange peel was discovered to be suitable for making extremely porous activated carbon via chemical activation. Rice husk-derived activated carbon was effective at removing humic acid from wastewater, but activated carbon derived from pineapple leaves exhibited versatility in colour removal. This collaborative investigation illustrates the extensive use of biomass-derived activated carbons in environmental remediation. Figure 1 explains various methods for preparation and activation processes for activate carbon whereas Table 3 illustrates the ratio of biomass to molar solution that's is definitely considered effective to enhance the physico-chemical properties of the activated carbon.

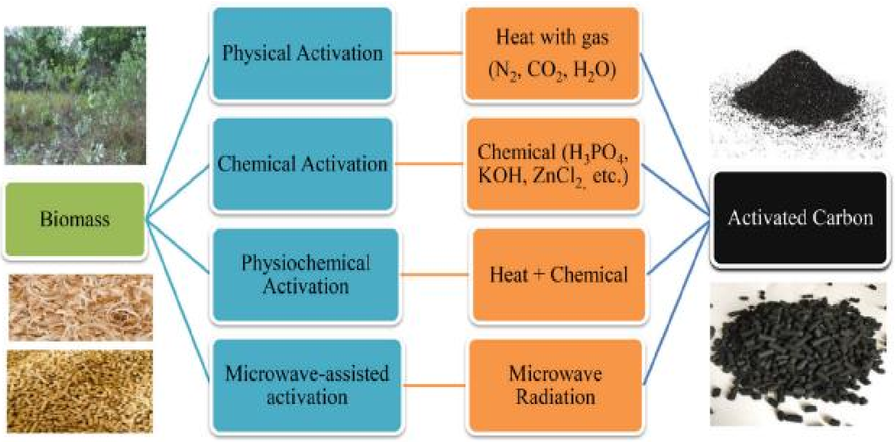

Fig. 1. Methods of the activation processes [33]

Table 3. Ratio of biomass to molar solution

Biomass	Biomass to Molar Solution Ratios			
	Impregnation Ratios	Activation Temperature	Chemical Reagent	Ref.
Alpha Cellulose, xylan	Weight ratio char:KOH was 1:4	600°C	KOH	[28]
Orange peel	01:01	500-1000°C	K_2CO_3 and $ZnCl_2$	[28]
Gelatin and starch	porous carbon/KOH = 1/4	700°C	KOH	[29]
Rice husk	30, 40, 50, 60 and 70 wt.%.	400, 500, 600, and 700 °C for 2.5 h.	H_3PO_4	[30]
seeds of local date fruits	KOH- 3:1, 4:1, 5:1 and H2SO4 - 0.5:1, 1:1, 2:1	600, 700, 800, 900 °C	KOH and H_2SO_4	[31]
Pineapple	01:01	500 °C, 1 h	$ZnCl_2$	[34]

5 Activated Carbon-Loaded Titanium Dioxide Nanoparticles

Studies have showed the rapid removal/photocatalysis of a variety of organic pollutants in the presence of TiO_2/AC, making use of the synergistic effects of TiO_2's high photocatalytic activity and AC's large surface area[35]. The efficacy is related to the presence of a substantial amount of contaminants near the semiconductor surface materials when adsorbed. Combining AC as an adsorbent and TiO_2 as a photocatalyst yields a nanocomposite with superior characteristics over the individual precursors. However, anchoring TiO_2 on AC has proven difficult, reducing the composite's ability to absorb pollutants and therefore its photocatalytic efficacy. The available research suggests that altering AC with chemical activation and covalently connecting it with TiO_2 improves pollutant adsorption capacity[36].

6 Conclusion

Semiconductor-based photocatalytic processes, particularly those involving titanium dioxide (TiO_2), have received interest for improving the durability of cement-based materials and combating global environmental pollution. TiO_2 integration with cement-based materials helps to reduce urban pollution concentrations. AC/TiO_2-infused cementitious composites can be employed in self-cleaning buildings, antimicrobial surfaces, and air-purifying structures. This paper provides a comprehensive analysis of TiO_2-based photocatalysis along with the possible coupling with biomass derived activated carbon, focusing on practical applications and highlighting research gaps for the improvement of photocatalytic cement materials.

Disclosure of Interests Author declare no conflict of interest.

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