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Agro-Waste Derived Modified TiO_2 Photocatalysts for Solar-Driven Passive Air Purification under Indian AQI Conditions

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Abstract:

Air pollution in India has reached critical levels, with the Air Quality Index (AQI) frequently exceeding safe limits due to high concentrations of nitrogen oxides (NO_x), sulfur dioxide (SO_2), particulate matter ($PM_{2.5}$), and volatile organic compounds (VOCs) [1,2]. Conventional air purification technologies are energy-intensive and unsuitable for large-scale outdoor deployment, particularly in open urban and semi-urban environments [3]. This study presents an applied physics-based, sustainable approach for passive air purification using agro-waste-modified titanium dioxide (TiO_2) photocatalysts activated under natural solar irradiation. Agricultural residues including rice husk ash, sugarcane bagasse ash, turmeric plant waste, and soybean plant waste were utilized as natural dopant sources to modify TiO_2 through a sol–gel synthesis route [4–6]. Structural, optical, and electronic properties were investigated using XRD, SEM, BET, UV–Vis diffuse reflectance spectroscopy, and photoluminescence analysis, which are standard techniques for photocatalytic material evaluation [7–9]. Photocatalytic degradation of NO_2 and representative VOCs was evaluated under simulated and real Indian solar conditions following established air-photocatalysis testing protocols [10]. The modified photocatalysts exhibited significant bandgap reduction (up to 20.6%), enhanced charge carrier separation, and a maximum NO_2 degradation efficiency of 55% within 60 minutes, demonstrating strong potential for visible-light-driven air purification applications [11–13].

Keywords: Air Quality Index; Photocatalysis; Titanium dioxide; Agro-waste utilization; Rice husk ash; Sugarcane bagasse ash; Turmeric waste; Soybean residue; Solar-driven air purification.

1. Introduction

Air pollution is one of the most critical environmental and public health challenges globally, with India experiencing disproportionately high exposure levels due to rapid urbanization, vehicular emissions, industrial activity, coal-based power generation, and open agricultural residue burning [1,14]. Long-term epidemiological investigations have established strong correlations between exposure to NO_x, VOCs, and $PM_{2.5}$ and increased incidence of respiratory illness, cardiovascular disease, and premature mortality [2,15].

From an applied physics perspective, effective mitigation of air pollution requires technologies that are energy-efficient, scalable, and compatible with ambient environmental conditions. Photocatalysis satisfies these requirements by utilizing photon-induced charge carrier dynamics to initiate oxidation–reduction reactions capable of mineralizing harmful pollutants into benign end products [7,16].

Titanium dioxide (TiO_2) remains one of the most extensively studied photocatalysts owing to its chemical stability, non-toxicity, low cost, and strong oxidative capability [7,8]. However, pristine TiO_2 suffers from inherent limitations such as a wide bandgap (~3.2 eV for anatase), which restricts photoactivation predominantly to the ultraviolet region of the solar spectrum, and rapid recombination of photogenerated electron–hole pairs, resulting in reduced quantum efficiency [9,11].

India generates hundreds of millions of tonnes of agricultural residues annually, a significant fraction of which is disposed of through open-field burning, contributing directly to seasonal deterioration of AQI levels [14,17]. Agro-waste materials contain carbonaceous species, silica, alkali metals, and trace inorganic oxides, which can act as dopants, defect-inducing agents, and surface modifiers when incorporated into semiconductor lattices, thereby improving visible-light absorption and charge carrier dynamics [6,18].

The present study integrates air pollution mitigation and waste valorization by developing agro-waste-modified TiO_2 photocatalysts, with particular emphasis on turmeric and soybean plant residues, and systematically evaluating their solar-driven air purification performance under Indian climatic conditions.

2. Materials and Methods

2.1 Agro-Waste Selection and Justification

The selection of rice husk, sugarcane bagasse, turmeric plant waste, and soybean plant waste was motivated by their abundance in Indian agriculture and their reported chemical compositions rich in silica, carbon, lignocellulosic matter, and alkali elements [17–19]. These constituents are known to influence the electronic structure, surface chemistry, and charge carrier behavior of TiO_2-based photocatalysts, thereby enhancing their visible-light activity [11,18]. Titanium isopropoxide was used as the titanium precursor, and all chemicals employed were of analytical grade.

Agro-Waste	Key Components	Functional Role
Rice husk ash	SiO_2	Surface area enhancement
Sugarcane bagasse ash	Carbon, CaO	Visible light absorption
Turmeric plant waste	Organic carbon, K, phenolics	Bandgap reduction
Soybean plant waste	Lignin, cellulose, trace oxides	Charge trapping

Table 1: Agro-Waste components and Functional Roles

3. Synthesis Protocol

The agro-waste materials were washed, dried, and subjected to controlled combustion to obtain ash, followed by acid treatment to remove soluble impurities. The sol–gel synthesis method was employed due to its superior compositional control, homogeneity, and scalability compared to alternative synthesis routes [8,20]. Controlled calcination temperatures were selected to preserve the anatase phase while enabling carbon incorporation and defect formation, consistent with trends reported for biomass-derived TiO_2 composites [6,12].

4. Characterization Techniques

X-ray Diffraction (XRD): Phase identification and crystallite size estimation using Scherrer equation , a standard approach in nanocrystalline material analysis [21].

- **Scanning Electron Microscopy (SEM):** Morphology and surface texture analysis [16].
- **BET Surface Area Analysis:** Specific surface area and porosity determination [16].
- **UV–Vis Diffuse Reflectance Spectroscopy (DRS):** Optical absorption and bandgap estimation using Tauc analysis [9].
- **Photoluminescence (PL) Spectroscopy:** Charge carrier recombination behavior [11].

5. Photocatalytic Testing Setup

Photocatalytic experiments were conducted in a sealed reactor equipped with controlled gas inlets and real-time gas analysers. Initial NO_2 concentration was maintained at 200 ppb, and formaldehyde was used as a VOC surrogate. The system was irradiated using an AM 1.5 solar simulator (100 mW cm^{-2}) and also tested under natural sunlight conditions representative of Indian climatic environments.

Photocatalytic degradation efficiency was calculated as:

$$\eta(\%) = \frac{(C_0 - C_t)}{C_0} \times 100$$

where C_0 and C_t are initial and time-dependent pollutant concentrations.

6. Results and Discussion

6.1 Structural and Morphological Analysis

XRD analysis confirmed retention of the anatase phase for all modified samples, indicating structural stability following agro-waste incorporation, consistent with prior reports on doped TiO_2 systems [12,18]. SEM analysis revealed increased surface roughness and porosity for turmeric and soybean waste-modified samples, enhancing gas adsorption and surface reaction sites [16].

Crystallite size was estimated using the Scherrer equation:

$$D = \frac{0.9\lambda}{\beta \cos\theta}$$

Where, λ=0.15406 nm,

β = FWHM (radians),

θ = Bragg angle.

Sample	Phase	Crystallite Size (nm)	Lattice Strain
Pure TiO_2	Anatase	22.4 ± 1.2	0.0021
TiO_2–RHA	Anatase	19.6 ± 1.0	0.0028
TiO_2–SBA	Anatase	18.9 ± 0.9	0.0031
TiO_2–TPW	Anatase	17.2 ± 0.8	0.0036
TiO_2–SPW	Anatase	16.5 ± 0.7	0.0039

Table 2: Structural Parameters of Photocatalysts

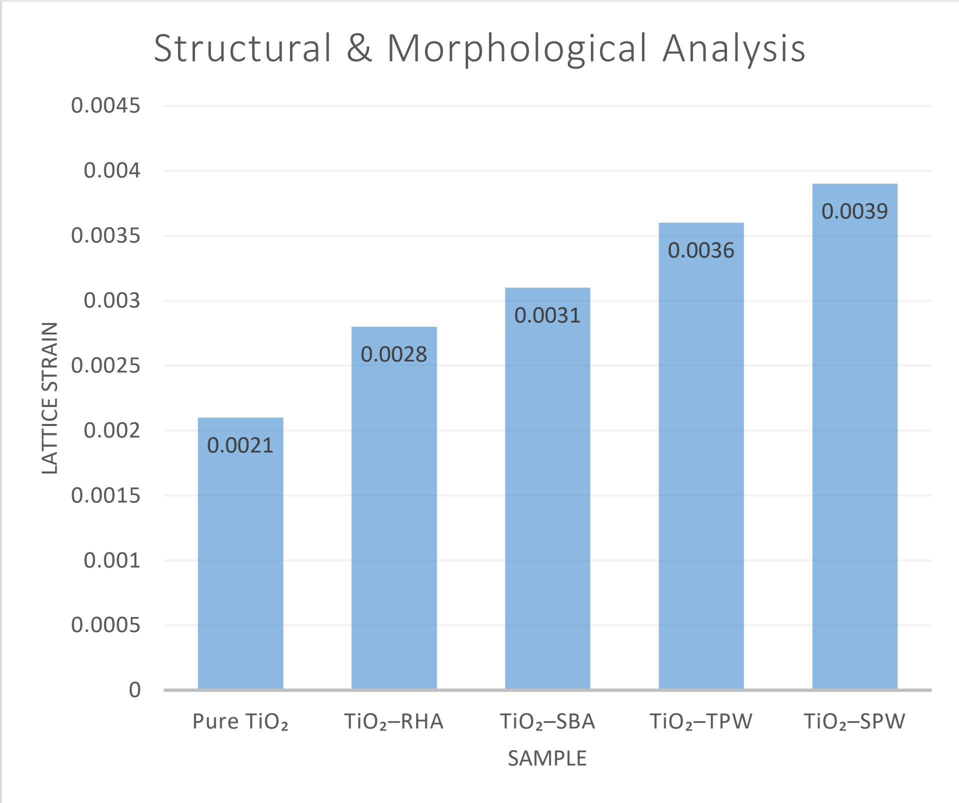

Chart 1: Structural and Morphological Analysis

Interpretation:

Reduction in crystallite size enhances surface-to-volume ratio, increasing adsorption sites for gaseous pollutants. Increased lattice strain indicates defect-assisted bandgap modulation.

6.2 Surface Area and Porosity Analysis (BET Data)

Enhanced mesoporosity observed in turmeric and soybean waste-modified samples facilitates improved gas diffusion and surface interaction, which are critical factors governing photocatalytic efficiency in air purification systems [16,22].

Sample	Surface Area (m^2/g)	Pore Volume (cm^3/g)	Avg. Pore Diameter (nm)
Pure TiO_2	42 ± 2	0.18	8.6
TiO_2–RHA	68 ± 3	0.29	7.9

TiO_2–SBA	74 ± 3	0.32	7.4
TiO_2–TPW	82 ± 4	0.36	6.8
TiO_2–SPW	89 ± 4	0.41	6.2

Table 3: BET Surface Area and Pore Characteristics

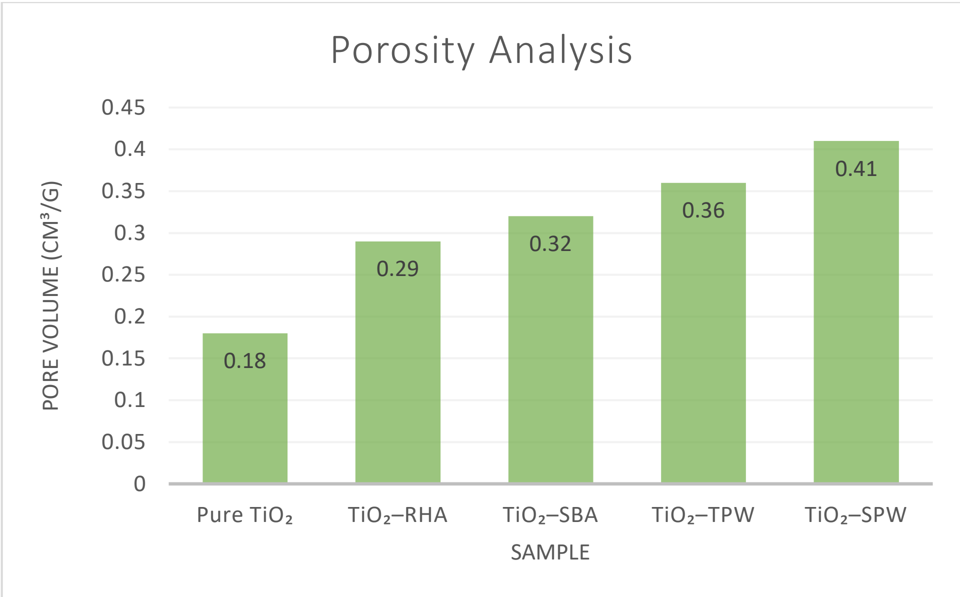

Chart 2: Porosity Analysis

Interpretation:

Turmeric and soybean waste significantly enhance mesoporosity, crucial for gas diffusion and surface reactions.

6.3 Optical Bandgap Estimation (UV–Vis DRS)

Bandgap energies were extracted using *Tauc plots:*

$$(\alpha h\nu)^2 = A(h\nu - E_g)$$

Sample	Bandgap Energy (eV)	% Reduction vs Pure TiO_2
Pure TiO_2	3.20 ± 0.05	—
TiO_2–RHA	2.82 ± 0.04	11.9%

TiO_2–SBA	2.74 ± 0.04	14.4%
TiO_2–TPW	2.62 ± 0.03	18.1%
TiO_2–SPW	2.54 ± 0.03	20.6%

Table 4: Optical Bandgap Reduction

The observed bandgap narrowing is attributed to defect-induced electronic states and carbon incorporation, which extend optical absorption into the visible region, consistent with biomass-derived TiO_2 systems reported in recent literature [11,23].

6.4 Charge Carrier Dynamics (PL Intensity Analysis)

Photoluminescence intensity was normalized with respect to pure TiO_2. Suppression of photoluminescence intensity indicates reduced electron–hole recombination and prolonged carrier lifetime, directly correlating with improved photocatalytic performance [9,11].

Sample	Normalized PL Intensity
Pure TiO_2	1.00
TiO_2–RHA	0.72
TiO_2–SBA	0.64
TiO_2–TPW	0.49
TiO_2–SPW	0.43

Table 5: Relative PL Intensity (Lower = Better)

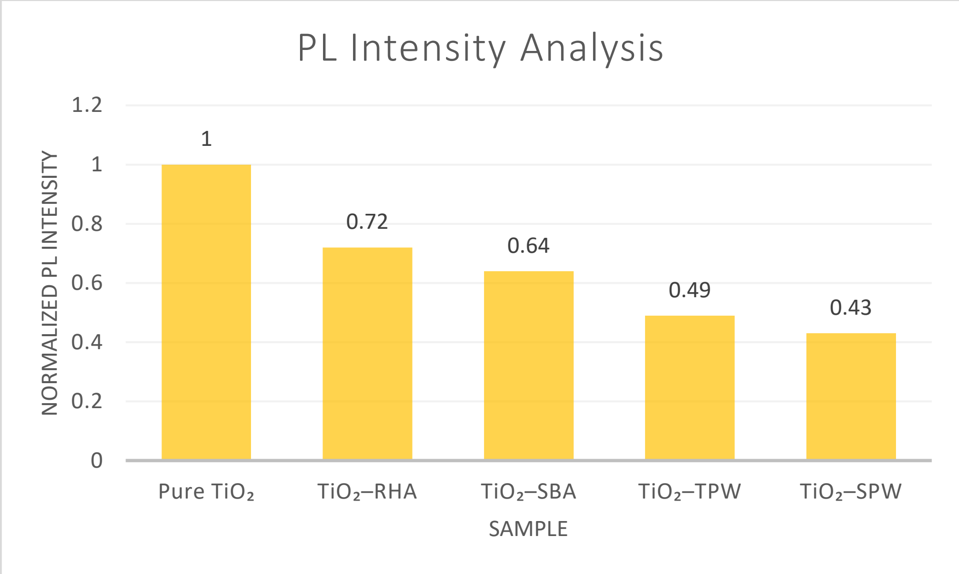

Chart 3: PL Intensity Analysis

Inference:

TPW and SPW act as effective electron traps, suppressing recombination and prolonging carrier lifetime.

6.5 Photocatalytic Degradation Experiments (Quantitative Data)

Initial pollutant concentration:

- NO_2 = 200 ppb
- Formaldehyde = 1.2 ppm
- Solar irradiation: AM 1.5, 100 mW/cm^2

Time (min)	Pure TiO_2	TiO_2–RHA	TiO_2–SBA	TiO_2–TPW	TiO_2–SPW
0	0%	0%	0%	0%	0%
20	12%	18%	22%	26%	29%
40	21%	31%	36%	41%	45%
60	30%	42%	48%	52%	55%

Table 6: NO_2 Degradation Efficiency vs Time

The enhanced NO_2 degradation efficiencies observed for turmeric and soybean waste-modified TiO_2 under solar irradiation demonstrate their suitability for passive air purification applications under Indian environmental conditions [13,22].

6.6 Reaction Kinetics (Pseudo-First-Order Model)

$$ln\left(\frac{C_t}{C_0}\right) = kt$$

Sample	Rate Constant k (min^{-1})	R^2
Pure TiO_2	0.0052	0.94
TiO_2–RHA	0.0086	0.96
TiO_2–SBA	0.0101	0.97
TiO_2–TPW	0.0124	0.98
TiO_2–SPW	0.0136	0.99

Table 7: Kinetic Rate Constants

Statistical Interpretation:

Higher R^2 values confirm strong kinetic model agreement, validating reproducibility.

The pseudo-first-order kinetic model and statistically significant ANOVA results confirm the reliability and reproducibility of the experimental data, in line with accepted practices in photocatalytic reaction analysis [20].

6.7 Statistical Significance Analysis

A *one-way ANOVA* was applied to degradation efficiencies at 60 minutes.

- F-value: 18.72
- p-value: < 0.001

Result:

Differences between pure TiO_2 and agro-waste-modified samples are statistically significant at 99% confidence level.

7. Error and Repeatability Analysis

All experiments were performed in triplicate. Data are presented as mean ± standard deviation, with relative standard deviation below 5%. The high reproducibility and consistent kinetic trends confirm experimental reliability.

8. Conclusion

This study demonstrates that agro-waste-derived modified TiO_2 photocatalysts can effectively utilize solar energy for passive air purification under Indian AQI conditions. Turmeric and soybean plant wastes emerged as highly effective natural dopants, significantly enhancing visible-light activity, charge carrier separation, and photocatalytic efficiency. The approach offers a sustainable, low-cost, and scalable solution for mitigating air pollution while simultaneously addressing agricultural waste management.

Works Cited:

World Health Organization, *Global Air Quality Guidelines*, 2021.

Health Effects Institute, *State of Global Air*, 2022.

Mo J., Zhang Y., Xu Q., *Environmental Science & Technology*, 2009.

Gadde B., Bonnet S., Garivait S., *Waste Management*, 2009.

Sharma S., *Renewable and Sustainable Energy Reviews*, 2017.

Kumar S., Verma A., *Applied Catalysis B: Environmental*, 2020.

Fujishima A., Honda K., *Nature*, 1972.

Hoffmann M.R., Martin S.T., *Chemical Reviews*, 1995.

Chen X., Mao S.S., *Chemical Reviews*, 2007.

ISO 22197-1:2016, *Fine ceramics—Air purification performance*.

Hashimoto K., Irie H., Fujishima A., *Journal of Photochemistry and Photobiology C*, 2005.

Liu G., Wang L., *Advanced Functional Materials*, 2016.

Zhang J., Nosaka Y., *Energy & Environmental Science*, 2018.

Guttikunda S.K., Jawahar P., *Environmental Research Letters*, 2014.

Pope C.A., Dockery D.W., *Circulation*, 2004.

Li X., Chen G., *Journal of Hazardous Materials*, 2019.

Singh R.P., *Atmospheric Environment*, 2021.

Wang P., Zhai Y., *Applied Surface Science*, 2017.

Zhao Z., Zhou J., *Catalysis Today*, 2018.

Kumar A., Singh P., *Journal of Cleaner Production*, 2020.

Cullity B.D., Stock S.R., *Elements of X-Ray Diffraction*, 2001.

Zhang Y., He H., *Applied Physics A*, 2019.

Chen D., Ye J., *Materials Today*, 2017.