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Carbon-based nanomaterials (CNMs) modified TiO_2 nanotubes (TNTs) photo-driven catalysts for sustainable energy and environmental applications: A comprehensive review

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ABSTRACT

Photo-driven catalysis is an appealing way to concurrently tackle the issues of environmental pollution and energy scarcity sustainably. Among other photocatalysts, TiO_2 nanotubes (TNTs) have emerged as a highly preferred candidate due to their unique structural orientation, notable surface area, fast electron mobility, and tunable morphology. It has been observed carbon-based nanomaterials (CNMs) are extensively explored to enhance the performance of TNTs because of their distinctive attributes including availability, porous nature, diverse structures, well-dispersed active sites, quantum effectiveness, band gap narrowing ability, flexibility for co-catalysis, and photosensitization capacity. Considering myriads of research based on CNMs-modified TNTs, there is a lack of systematic analysis and summary of key aspects such as synthesis pathways and the synergistic mechanism of promising CNMs to enhance the efficiency of constructed composite. This review systematically summarized the fundamentals of TNTs and CNMs, the principle of photocatalysis and photo-electrocatalysis, fabrication methods of TNTs and CNMs, and modification strategies of CNMs-TNTs. Moreover, an in-depth investigation based on CNMs-TNTs composite has been performed to comprehensively describe nearly every aspect of the recent photo-driven energy and environmental applications such as water splitting, CO_2 utilization, pollutants removal and detection, photovoltaic cells, and photocathodic protection. The literature reveals that research on modifying TNTs with emerging carbon-based functional materials such as MXenes and MOF-derived carbons is still at rudimentary level. Although CNMs-TNTs composites have displayed excellent photoactivity, their yield remains limited to the laboratory scale. Therefore, more efforts should be exerted on enhancing the commercial viability of CNMs-TNTs composites for large-scale industrial applications.

1. Introduction

Energy scarcity and environmental pollution have been the utmost concerning issues for future generations due to the increasing rate of fuel consumption, dependency on fossil fuels, unplanned rapid industrialization, and unregulated pollutant discharge. By 2060, it is anticipated that the world's energy consumption will increase by one-third to keep pace with the current economic expansion, drastically depleting the availability of fossil fuels [1–3]. Moreover, the increasing severity of emerging contaminants in the environment, including heavy metals, pharmaceuticals, industrial dyes, and microbes, which have recently been proven to be very hazardous to ecosystems and human health, is a source of great concern for researchers and policymakers [4–6]. Addressing these pivotal energies and environmental issues are crucial and immediate measures have to be taken to ensure a better world for the foreseeable future. Henceforth, different technologies considering

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