**QUEEN'S
UNIVERSITY
BELFAST**

Photocatalytic oxidation of pollutants in gas-phase via Ag₃PO₄-based semiconductor photocatalysts: Recent progress, new trends, and future perspectives

Naciri, Y., Hsini, A., Bouziani, A., Djellabi, R., Ajmal, Z., Laabd, M., Navio, J. A., Mills, A., Bianchi, C. L., Li, H., Bakiz, B., & Albourine, A. (2022). Photocatalytic oxidation of pollutants in gas-phase via Ag₃PO₄-based semiconductor photocatalysts: Recent progress, new trends, and future perspectives. *Critical Reviews in Environmental Science and Technology*, 52(13), 2339-2382. <https://doi.org/10.1080/10643389.2021.1877977>

Published in:

Critical Reviews in Environmental Science and Technology

Document Version:

Peer reviewed version

Queen's University Belfast - Research Portal:

[Link to publication record in Queen's University Belfast Research Portal](#)

Publisher rights

Copyright 2021 Taylor & Francis Group

This work is made available online in accordance with the publisher's policies. Please refer to any applicable terms of use of the publisher.

General rights

Copyright for the publications made accessible via the Queen's University Belfast Research Portal is retained by the author(s) and / or other copyright owners and it is a condition of accessing these publications that users recognise and abide by the legal requirements associated with these rights.

Take down policy

The Research Portal is Queen's institutional repository that provides access to Queen's research output. Every effort has been made to ensure that content in the Research Portal does not infringe any person's rights, or applicable UK laws. If you discover content in the Research Portal that you believe breaches copyright or violates any law, please contact openaccess@qub.ac.uk.

Photocatalytic oxidation of pollutants in gas-phase via Ag₃PO₄-based semiconductor photocatalysts:
Recent Progress, New Trends, and Future Perspectives

Y. Naciri^{1,2, †,*}, A. Hsini^{1,†}, A. Bouziani³, R. Djellabi^{4,5}, Z. Ajmal⁶, M. Laabd¹, J. A. Navío^{7,*}, A. Mills⁸, C.L. Bianchi⁴, H. Li², B. Bakiz¹, A. Albourine¹.

¹ *Laboratoire Matériaux et Environnement LME, Faculté des Sciences, Université Ibn Zohr, BP 8106, Cité Dakhla, Agadir, Morocco.*

² *Institute for Energy Research, School of Chemistry and Chemical Engineering, Jiangsu University, Zhenjiang, 212013 P. R. China.*

³ *Chemical Engineering Department, Middle East Technical University, Ankara, Turkey*

⁴ *Department of Chemistry, Università degli Studi di Milano, Via Golgi 19, Milano, Italy.*

⁵ *Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences, Beijing, 100085, People's Republic of China Beijing, 100085, China*

⁶ *College of Engineering, China Agricultural University, 100083, Beijing, PR China.*

⁷ *Instituto de Ciencia de Materiales de Sevilla, Centro Mixto Universidad de Sevilla-CSIC, Américo Vespucio 49, 41092 Sevilla, Spain.*

⁸ *School of Chemistry and Chemical Engineering, Queens University Belfast, David Keir Building, Stranmillis Road, Belfast, BT9 5AG, UK.*

[†] These authors contributed equally to this work.

* Corresponding authors:

(Y. Naciri) E-mail address: yassine.naciri@edu.uiz.ac.ma

(J.A.Navio). E-mail address: navio@us.es

Abstract

As a solemn dilemma, due to numerous fatal diseases such as cancer, respiratory, heart attack, and brain stroke, air pollution has become a significant challenge for both developing and developed nations. The scientific community makes many offers to solve

air pollution issues. The heterogeneous photocatalysis technique has emerged as an effective air remediation strategy due to its field-scale application via free-solar light and photoactive catalysts. The photocatalytic efficacy is utterly associated with the optical and physical characteristics of the photocatalyst. Unlike conditional photocatalysts (e.g., TiO_2 , ZnO), recent studies showed that Ag_3PO_4 semiconductors with a 2.43 eV bandgap exhibit an excellent photocatalytic efficiency for the removal of many types of pollutants in the gas phase.

Nevertheless, there are certain limitations with Ag_3PO_4 (i.e., photo-corrosion and the inability to produce $\bullet\text{O}_2^-$), which restricts its application. These limitations are critically evaluated and outlined thoroughly in this review. Recent studies on the modification of Ag_3PO_4 via combination with the conventional heterojunctions or Z-scheme junctions, as well as the photocatalytic mechanistic pathways for enhanced gas-pollutants removal, were summarized and discussed. Finally, an outlook on future development is proposed to overcome challenges and stimulate further research into this promising field.

Keywords: Ag_3PO_4 ; photocatalytic oxidation process; Z-scheme junctions; conventional heterojunctions; gaseous pollutants.

1. Introduction

Currently, soil, aquatic, and air environment are severely affected by rapid population expansion and the industrial revolution. As we know, there are a wide variety of pollutants

annually entering into the natural environment (Aarab et al., 2020a, 2020b; Abdellaoui et al., 2021; Ajmal et al., 2018; Ba Mohammed et al., 2020; Essekri et al., 2020; Hsini et al., 2020a, 2020b; Qadeer et al., 2020, 2019). The typical indoor air pollutants are generally volatile organic compounds (VOCs), particulate matter (PM), and inorganic oxides (CO₂, NO_x, and SO_x). Moreover, according to the world health organization survey, air pollution results in the death of about 7 million people around the globe. Among them, 4.3 million people were severely affected by indoor air pollution. That is one in eight total global deaths, which indicates that air pollution is now the world's most considerable single environmental health risk (da Costa Filho and Vilar, 2019; Hyuntae Cho, 2017).

To curb the pollution, most standard air purifying systems use air filters to remove particulate matter. Others use adsorbents (e.g., magnetite, almond shell derived biomass, granular activated carbon) for gaseous adsorption over their surface sites. However, these technologies cannot remove pollutants altogether but only transfer them from one phase to another (Ajmal et al., 2020b, 2020a; Benafqir et al., 2019; Hsini et al., 2020c; Sansotera et al., 2019; Zhao and Yang, 2003). Hence, it has become an urgent hot topic for policymakers and scientists to explore and introduce new cost-effective treatment strategies to overcome the existing air pollution problem.

Heterogeneous photocatalytic degradation due to numerous facets over conventional treatment strategies is regarded as an effective alternative remediation technology (S. (Ahsaine et al., 2018; Barebita et al., 2020; Bouziani et al., 2020; Erdogan et al., 2019; Naciri et al., 2020b; S. Ferraa et al., 2020; Shaim et al., 2019). Generally, it could be classified into two categories according to environmental implications. (**Fig.1**) (i) Aqueous phase organic pollutants degradation (Deng et al., 2020; Fiorenza et al., 2020; Naciri et

al., 2020a, 2019b, 2019a, 2018) and (ii) Gaseous phase pollutants removal (Aramendía et al., 2007; Araña et al., 2004; Liao et al., 2017; Reyna-Cavazos et al., 2020).

Fig.1. Heterogeneous photocatalytic remediation systems for various pollutants.

This technology is considered the newest generation of air cleaning technology. It has attracted considerable research interest over the last few decades owing to their great potential to eliminate continuously gaseous pollutants even at low concentrations and operating at low or room temperature (Aramendía et al., 2007; Araña et al., 2009, 2004; Murcia et al., 2012). Interestingly, it has been noted that this technique is proved to be most efficient for various gaseous pollutants (i.e., volatile organic compound, simple and chlorinated hydrocarbon) (Aramendía et al., 2007; Araña et al., 2009, 2004; Murcia et al., 2012; Zhou et al., 2019), as well as different carbon, hydrogen, and sulfur-based oxides-dioxides (Kato et al., 2005; Liao et al., 2017; Reyna-Cavazos et al., 2020). Since the first report on gas-solid heterogeneous photocatalytic oxidation conducted in the 1970s with the work of Djeghri's and Bickley's group (Bickley et al., 1973; Djeghri, N., Formenti, M.,

Juillet, F., Teichner, 1974), the photocatalytic oxidation of gaseous contaminants has been extensively studied, to confirm the validity and attractiveness of that remediation strategy for degrading a myriad of gaseous pollutants.

Among various semiconductors, the use of TiO_2 is considered as one of the most renowned photocatalysts due to its low cost, higher chemical stability, and good surface structure characteristics. However, its application is restricted due to numerous facets, i.e., wide bandgap (approximately 3.2 eV). As well- know, the UV light occupies just around 5% of the solar light, while the visible light occupies 43%. Therefore, the development of visible-light-driven photocatalysts has become a subject of prime importance in the field of photocatalytic pollutants degradation (Chenchana et al., 2019; Likodimos, 2018; Mazierski et al., 2018; Puga et al., 2020).

Up to date, several Ag-based photocatalysts, including AgX ($\text{X} = \text{Cl}, \text{Br}, \text{I}$) (Wang et al., 2019; Wen et al., 2020; Xin et al., 2019), Ag_2O (Liang et al., 2019), Ag_2CO_3 (Y. Liu et al., 2018), and Ag_3PO_4 (Martín-Gómez et al., 2020), have demonstrated an outstanding photocatalytic performance under natural sunlight or the visible light. Among them, Ag_3PO_4 is extremely attractive since it could attain 90% efficiency over the 400-800 nm wavelength (Chen et al., 2015, 2013). However, further reports on the origin of Ag_3PO_4 photocatalytic activity indicated that both the inductive effect of PO_4^{3-} and the large dispersion of the conduction band are considered the major contributor to the separation of the electron-hole pairs for Ag_3PO_4 (Chen et al., 2013). Unfortunately, there are still some inherent shortcomings in the photoactivity of Ag_3PO_4 for photodecomposition gaseous organic contaminates. One reason is that the Ag_3PO_4 could not produce $\cdot\text{O}_2^-$ radicals, just because of the existence of its conduction band at +0.45 V vs. NHE (pH 0)

is lower than the reduction potential of O_2 ($O_2 + e^- \rightarrow \cdot O_2^-$, -0.33 V vs. NHE) (Wood, 1988). As a result, the generated electrons cannot be consumed by O_2 , which is very important for the photo-oxidation of various gaseous organic pollutants. Moreover, Ag particle by-product formation in the absence of electron acceptor during Ag_3PO_4 photodecomposition is considered a significant factor affecting its photocatalytic activity and stability and ultimately restricts its potential practical application (Chai et al., 2015; Li et al., 2014, 2015). Therefore, it is crucial to introduce efficient approaches for improving Ag_3PO_4 photocatalytic activity without any reagents (Chai et al., 2015; Li et al., 2014, 2015). Thus, numerous strategies have been applied to enhance the stability of Ag_3PO_4 under visible light irradiation. Providentially, numerous studies verified that the formation of hybrid or heterojunction between Ag_3PO_4 and semiconductor having proper band structure is a promising strategy for enhancing the stability of Ag_3PO_4 for the reduction/removal of inorganic gas pollutants (Chen et al., 2015; Guo et al., 2013; Huang et al., 2019; Jia et al., 2019; Rao et al., 2020; Rawal et al., 2012).

To the best of our knowledge, this is the first review addressing the reported research progress on the photocatalytic remediation of air using Ag_3PO_4 -based semiconductor photocatalytic systems. Thus, this review article focuses on investigating the recent strategies for the photocatalytic oxidation of pollutants in gas-phase in the presence of Ag_3PO_4 -based conventional and Z-scheme heterojunctions. Moreover, we introduce a general overview of the current control techniques for gas-phase pollutants removal and their limitations. Then, the photocatalytic properties of Ag_3PO_4 and its limitations as a photocatalyst are discussed in detail. The improving photocatalytic activities of Ag_3PO_4 photocatalyst towards gaseous-phase pollutants by constructing conventional

heterojunctions or Z-scheme junction photocatalytic systems are then addressed as the main part of this review. Finally, numerous ways are presently proposed for future research to overcome the existing challenges and design the most promising heterojunctions based photocatalyst for air pollution reduction strategy.

2. General overview of the current control techniques for the removal of pollutants in gas-phase

The stability of gas pollutants and their severe toxic effects on human beings and the ecological system are of prime importance. Many physicochemical abatement methods such as adsorption (Li et al., 2020), absorption (Rodriguez Castillo et al., 2019), condensation (Belaissaoui et al., 2016), botanical purification (Pettit et al., 2019, 2018), catalytic combustion (Fino et al., 2016), photocatalytic oxidation (Kamal et al., 2016), bio-filtration (Malakar et al., 2017), plasma oxidation (Malakar et al., 2017), biodegradation (Malakar et al., 2017), and membrane separation (Malakar et al., 2017) have been used extensively for the effective removal of gaseous pollutants. Based on the removal mechanism, we can further classify these abatement techniques into two categories: recovery techniques (adsorption, absorption, filtration, and condensation) and destructive techniques (catalytic combustion, plasma oxidation, biodegradation, and botanical purification). The destructive gas cleaning techniques are mainly based on the conversion of gas-phase organic contaminants into water vapor, carbon dioxide, and other smaller molecules by-products (Ehn et al., 2014), which consume a large amount of energy to generate high temperature for the reaction, and they inevitably produce some toxic byproducts such as NO_x, O₃, HO• radicals, secondary organic aerosols, etc. (Ehn et al.,

2014; Li et al., 2020). In contrast, recovery technologies have often been reported as more efficient and economical gas cleaning strategies (Zhang et al., 2017). Among them, adsorption is recognized as one of the most promising strategies to abate the gas-phase pollutants, which do not produce the secondary by-products (Li et al., 2020). In the adsorption process, the storage of gaseous pollutants on the surface of adsorbent material is commonly carried out via a pore-filling mechanism combined with the eventual formation of physical and/or chemical gas-adsorbent bindings (Zhu et al., 2020). Thus, the effectiveness and real applicability of adsorption techniques for gas pollutants abatement are ultimately associated with adsorbent surface proprieties include functional groups and porous texture (Li et al., 2020). In this regard, a large variety of adsorbents, including carbon-based materials (Azzouz et al., 2018; Zhang et al., 2017), organic polymers (Azzouz et al., 2018; Zhu et al., 2020), aluminosilicates (Swetha et al., 2017; Zhang et al., 2018), resins (Qiu et al., 2018), silica gels (Amonette and Matyáš, 2017; Sui et al., 2017) and metal-organic frameworks (Barea et al., 2014; Xian et al., 2015) have been recently developed to sequestrate gas-phase contaminants. The activated carbon is a popular filter material with excellent gas sequestration ability because of its high surface area, microporous structure, surface chemistry, etc. (Shammy et al., 2016; Suresh and Bandosz, 2018). Nevertheless, the adsorption is a transfer process of pollutants from the gas phase to the solid phase, which requires a post-treatment to mineralize the adsorbed pollutants (Jo and Yang, 2009; Thevenet et al., 2014). Besides, the contaminant load variations and regeneration costs, also the high humidity, restrict the effectiveness of the adsorption process (Jo and Yang, 2009). Overall, the conventional gaseous contaminants abatement techniques present the main limitations

of the generation of secondary waste and high operation costs (Krishnamurthy et al., 2019; Luengas et al., 2015). The merits and demerits of some aforementioned conventional processes for gaseous pollutants removal (see **Supplementary Table. S1**). Therefore, it is urgent to explore and introduce alternative, cost-effective and environmental strategies for gas-phase pollutants removal.

3. General overview of the removal of gaseous pollutants via photocatalytic oxidation

3.1. General mechanism of photocatalysis

People spend almost 80% of their life in indoor places such as residential units, offices, workshops, etc. Therefore, indoor air quality (IAQ) is vital for human health. On top of that, the outdoor air quality (OAQ) resulted from natural sources and mostly industrial pollution/human activities can cause several environmental, medium-term, and long-term health problems such as respiratory diseases (e.g., emphysema), heart damage, lung cancer, sudden death and cognitive alterations (Olmo et al., 2011). As already reported in section 2, we see that the conventional gaseous contaminants abatement techniques encompass a wide range of limitations. Thus, they are considered to be uneconomical, less effective as they further produce secondary toxic by-products. In order to address these issues, it is an urgent need to explore the most advanced removal of gaseous pollutants rather than conventional methods. The photocatalytic oxidation of gaseous pollutants, including volatile organic compounds (VOCs) (Ardizzone et al., 2008; Ganesh et al., 2011; Lopes et al., 2012; Monteiro et al., 2015) or inorganic gaseous (e.g., NO_x (Ballari et al., 2010; Zouzelka and Rathousky, 2017), SO_x (Li et al., 2016) and H₂S

(Navakoteswara Rao et al., 2019) on the surface of a photocatalyst under light into less-toxic and odorless compounds is a fascinating technology. The photocatalytic oxidation reaction is focused on the production of reactive oxygen species (ROSs) having high oxidizing potentials such as $\text{HO}\cdot$, $\text{O}_2\cdot^-$, $\text{HO}_2\cdot^-$, and H_2O_2 , which can oxidize pollutants being adsorbed on the photocatalyst in water or air phases; also, direct oxidation of pollutants via positive holes (h^+) on the surface of the photo-excited photocatalyst can take place as well (Djellabi et al., 2020). As showed in **Fig.2A**, unlike the extensive use of photocatalysis for water treatment, less attention has been given to the application of heterogeneous photocatalysis for air purification over the last two decades. **Fig.2B** shows the mechanistic pathways of organic pollutants photocatalytic oxidation over photocatalyst surface sites.

Fig. 2. (A) Publications trends in photocatalysis, photocatalysis for water and air treatment over the last two decades, obtained from PubMed (up to Apr. 2020) **(B).** Photocatalytic oxidation of

organic pollutants, including gas substances, by heterogenous photocatalysis process (Adapted with permission from ref (Shayegan et al., 2018), copyright 2017 Elsevier).

3.2. Parameters affected the photocatalytic efficiency

The efficiency of photocatalytic degradation of gas pollutants highly depends upon many factors. Since the production of $\text{HO}^\bullet$ is carried out via the reaction of water molecules or HO^- species with positive holes, in air medium, relative humidity (RH) is a very beneficial resource for the generation of $\text{HO}^\bullet$ radicals for the oxidation of gas pollutants (Amaterz et al., 2020; Amaterz et al., 2020; Guo et al., 2008; Mamaghani et al., 2017). It is essential to point out that water vapor concentration over the photocatalyst surface is a very influencing parameter for the photocatalytic performance (Aghighi and Haghighat, 2015). A high quantity of water adsorbed on the surface can prevent/inhibit the adsorption of gas compounds, reducing their chance of being oxidized. C.A. Korologos et al. reported that the presence of water enhances the oxidation of benzene and toluene effectively (Korologos et al., 2011). It was reported that gaseous phase pollutants (to CO_2) mineralization without humidity is impossible. Airflow is another important factor that showed a dual antagonistic effect on gas contaminants' photocatalytic oxidation (Shayegan et al., 2018). In low airflow rates, the higher residence time of pollutants gives the pollutant species in the gas phase the opportunity to be adsorbed on the photocatalyst and further oxidized by photo produced ROSs and h^+ . However, at higher airflow rates, the residence time and mass transfer decrease on the photocatalyst's surface, resulting in lower oxidation/mineralization efficiency. Therefore, in the photocatalytic reactor, the airflow should be optimized to obtain an enhanced photocatalytic efficiency depending on the reactor and the operating conditions such as the gas contaminant concentration. In

addition, the airflow rate may also affect the formation of the by-product during photo-oxidation of contaminants and the total mineralization to CO₂ (Farhanian et al., 2013; Sleiman et al., 2009; Yang et al., 2015). The type of photocatalyst is also an important key for the photocatalytic oxidation in water or air phases. Therefore, over more than three decades, most scientific research has been carried out to develop photoactive materials and nanomaterials for environmental remediation and energy production, especially to enhance the adsorption capacity, improve the visible light response, and reduce the recombination of electron/hole charges. Several strategies have been employed, such as the modification of photocatalysts (e.g., TiO₂) by metal (Karafas et al., 2019; Nie et al., 2019) and non-metal doping (Jo and Kim, 2009; Patil et al., 2019), the combination of semiconductors with high adsorbing materials (Shayegan et al., 2020), photosensitizing (Park et al., 2013; Xiao et al., 2008) and coupling of semiconductors (Djellabi et al., 2019b, 2019a). So far, a wide variety of titania and non-titania-based photocatalysts have been employed for air purification (Boyjoo et al., 2017). Many physicochemical factors must be taken into consideration for developing a photocatalyst for air treatment, such as the enlargement of visible light response, enhancing the selectivity towards some pollutants (i.e., NO_x), and also to enhance the gaseous phase pollutants mineralization into preferred products (CO₂, H₂O, and inorganic species) and to avoid the formation of unwanted coke on the surface of the photocatalyst, resulting in its deactivation. The type and the concentration of the gas pollutant significantly affect the photocatalytic oxidation efficiency. Indeed, the photooxidation efficiency depends on the photocatalyst's affinity towards the type of pollutant, wherein species showing good adsorption on the photocatalyst have more possibility to be oxidized. Furthermore, the

concentration of gas species on the photocatalyst's surface plays an essential factor (Jafarikojour et al., 2015; Mamaghani et al., 2017; Zhong et al., 2013). More by-products are likely to be adsorbed on the photocatalyst at higher gas species concentration, impeding gas species' oxidation progress. Therefore, photocatalysis for air purification is more effective in lower concentrations of contaminants depending on the photocatalyst's surface chemistry and porosity.

One of the successful applications of photocatalysis for air treatment was the development of self-cleaning photo-materials. These smart materials have been applied for different purposes, such as house furniture and glasses, roofs, solar panel cleaning, cement, and self-cleaning building (Banerjee et al., 2015; Ganesh et al., 2011). Under solar light, self-cleaning materials can remove adsorbed gas contaminants/or bacteria via photocatalytic action, and then by the action of rain, clean themselves. Claudia Bianchi's group has developed many self-cleaning materials to remove several types of contaminants in the gas phase (Ardizzone et al., 2008, 2007; Bianchi et al., 2020, 2016, 2014; Cappelletti et al., 2009).

Many semiconductor composite photocatalysts with different geometrical configurations and compositions have been extensively synthesized and applied to the oxidation of various gaseous phase pollutants. **Table. S2 (see Supplementary)** summarizes the recent studies of representative composite semiconductor photocatalysts for removing many types of pollutants in the gas phase.

3.3. Photocatalytic reactors for air treatment

The photocatalytic reactor type and its geometry are also significant factors for air purification since they can directly influence the contact of contaminants and the immobilized photocatalyst (Boyjoo et al., 2017). For this purpose, many photo-reactor configurations have been designed for contaminants oxidation in the gas phase, such as packed bed (Lopes et al., 2012), annular reactor (Monteiro et al., 2015), flat plate reactor (Passalía et al., 2017), honeycomb monolith (Taranto et al., 2009), and multi-plate/annular (Zazueta et al., 2013). In order to improve the surface of coated photocatalyst per volume of the reactor, which in turn enhances the uniform irradiated photocatalyst surface and the mass transfer, da Costa Filhoa's group (da Costa Filho et al., 2019a, 2019b, 2017) have developed a new microreactor based on NET mix technology (see **Supplementary Fig. S1**) for the oxidation of VOCs in the gas phase.

4. General overview of Ag_3PO_4 photocatalyst

4.1. Crystal structure of Ag_3PO_4 photocatalyst

Ag_3PO_4 is a cubic crystal structure with a space group ($P4-3n$) and parameter lattice $\approx 6.004 \text{ \AA}$. Isolated, regular PO_4 tetrahedral creates a body-centered cubic lattice, with a P-O distance is $\approx 1.539 \text{ \AA}$. The Ag^+ ions are dispersed between twelve sites with double symmetry (Ng et al., 1978). Every Ag atom on the 2-fold axis mainly uses one of the two sites at $(x, 0, 0.50)$ and $(0.5-x, 0, 0.50)$. The Ag atom has 4-fold coordination by four O atoms (Ma et al., 2011). The P atoms experience 4-fold coordination encircled by four

atoms of O, while O atoms experience 4-fold coordination encircled by three atoms of Ag and one atom of P (Kahk et al., 2014) (**see Supplementary Fig. S2**).

Kahk et al. (Kahk et al., 2014) reported that the lattice parameter of Ag_3PO_4 acquired theoretically from DFT calculations is 6.072 Å. In addition, Ma et al. (Ma et al., 2011) concluded that Ag_3PO_4 with polyhedron configuration mainly contains tetrahedral AgO_4 and PO_4 . They stated that three AgO_4 and one PO_4 are joint over the corner oxygen. They explained that Ag_3PO_4 photocatalytic activity is due to PO_4^{3-} ions owing to its higher negative charge, thus maintaining a large dipole in the Ag_3PO_4 , resulting in the distortion of AgO_4 (Ma et al., 2011).

4.2. Electronic structure of Ag_3PO_4 photocatalyst

In order to have a better understanding of the source of the photocatalytic activity of Ag_3PO_4 , a thoroughly electronic study is essential. Assumed from the ultraviolet-visible diffuse reflectance spectrum, the indirect and direct transition bandgap energy of Ag_3PO_4 is 2.36 eV and 2.43 eV, respectively (Yi et al., 2010). Therefore, Ag_3PO_4 can adsorb illumination under visible light with an average wavelength (< 530 nm). Using density functional theory (DFT), several studies have been done to understand Ag_3PO_4 high photocatalytic activity (**see Supplementary Fig. S3.A**).

Ma et al. (Ma et al., 2011) reported that Ag_3PO_4 has a conduction band with large dispersion that enables the separation of charge carriers. Furthermore, the vacancies present in Ag_3PO_4 could play a significant role in the separation of the electron-hole pairs.

Liu et al. (Liu et al., 2011) also reported that Ag_3PO_4 has a bandgap energy of 2.43 eV (**see Supplementary Fig. S3.B**). The conduction and valence bands are mainly

consisting of (Ag 5s, 5p) and (O2p, Ag 4d) states, respectively. A VBM potential of 2.67 eV implies a sufficient driving force for the oxidation of water and pollutants' degradation.

Xu et al. (Xu et al., 2014) studied Ag₃PO₄ and graphene (GR) surface interaction and established good stability and electron transfer mechanism along with the photocatalytic activity. The strength of interfacial interaction is attributed to the geometry and separation of Ag₃PO₄/GR.

Kahk et al. (Kahk et al., 2014) studied the relation between the experiment and theoretical results. They demonstrated that the prediction of the electronic, structural, and optical characteristics of Ag₃PO₄ using DFT calculations was of excellent precision. The molecular orbital (MO) theory was used to propose an interpretation of the electronic structure of Ag₃PO₄ (**see Supplementary Fig. S3.C**). Based on the MO theory, the electronic structure of Ag₃PO₄ was simplified. The covalent interactions between silver and oxygen are weaker than those between phosphorus and oxygen, commencing from an isolated (PO₄)³⁻ unit, a molecular orbital diagram for Ag₃PO₄ was created.

Moreover, only sigma interactions between orbitals over O and P were considered for (PO₄)₃⁻, two orbitals of sigma symmetry were provided by four oxygen atoms: 2s and one of the three 2p. The two triply degenerate ligand group orbital (LGO) is t₂ symmetry, and two LGO of a₁ symmetry in a tetrahedral environment. These overlap with the P 3s (a₁) and P 3p (t₂) orbitals and form twelve molecular orbitals, as demonstrated in (**see Supplementary Fig. S3.C**).

4.3. Photocatalytic properties of Ag₃PO₄ photocatalyst

In general, there are some factors that can effectively evaluate the photocatalyst activity during organic pollutants oxidation into water or gas phases such as: (i) the successful photo-excitation and the formation of separated electron/hole pairs during visible or UV light, wherein, a better visible light responsive photocatalyst was recommended; (ii) the ability of photocatalyst conduction band to condense dissolved O_2 to yield oxidizing $\cdot O_2^-$ species ($E_0(O_2/O_2^{\cdot-}) = -0.33$ V vs. the NHE at pH 7) (Wood, 1988); (iii) the valance band of the photocatalyst is able to oxidize H_2O or $\cdot OH$ into $\cdot OH$ hydroxyl radicals ($E_0(H_2O/HO^{\cdot}) = 2.73$ V vs the NHE; $E_0(HO^{\cdot}/HO^{\cdot}) = 1.9$ V vs the NHE) (Schneider et al., 2014); (iv) photocatalyst surface area is a crucial parameters since the most photocatalytic action takes place over photocatalyst surface sites, therefore, adsorbed pollutants have more chance of being oxidized via ROSs (Djellabi et al., 2020); (v) the stability of the photocatalyst is also considered as a critical key for practical application. Since 2010, Ag_3PO_4 has been identified as a photocatalyst for organic pollutant oxidation and water splitting (Yi et al., 2010). Ming Ge *et al.* (Ge et al., 2012) reported that the scavenging of $HO^{\cdot}$ and $\cdot O_2^-$ species by isopropyl alcohol and benzoquinone, respectively, does not affect visible-light-driven RhB photocatalytic degradation using Ag_3PO_4 . It further points out that these ROSs do not contribute much to the oxidation of RhB. In other words, the photo-production of $HO^{\cdot}$ and $\cdot O_2^-$ via the Ag_3PO_4 /visible light system is not very efficient. They reported that the CB and VB are not thermodynamically able to convert O_2 and H_2O into $O_2^{\cdot-}$ and $HO^{\cdot}$, respectively. However, the photocatalytic degradation of RhB was utterly inhibited when EDTA was added to the reaction, which confirms that direct oxidation of RhB by photoinduced h^+ on Ag_3PO_4 is the primary oxidation mechanism. Dong et al. (Dong et al., 2016) also showed that the direct hole oxidation of MB by Ag_3PO_4 (oxidized

373 at 200°C) is the most crucial pathway, while there is also the participation of HO• species.
374 As shown in **Fig. 3A**, Ag₃PO₄ is very effective for oxygen evolution via the conversion of
375 H₂O molecules into O₂ by the VB (Bierman et al., 2008). The photo produced electrons
376 on the CB reduce Ag⁺ to Ag.

377 One of the main hindrances of Ag₃PO₄ for environmental remediation is the photo-
378 corrosion issue due to Ag⁺ reduction into metallic Ag (Martin et al., 2015), thus leading to
379 the deactivation of the photocatalyst. On the other hand, due to the CB and VB potential
380 edges, the efficiency of Ag₃PO₄ photocatalyst for photo-producing ROSs is very low. Thus
381 only the pollutants that are adsorbed on the Ag₃PO₄ surface have more possibility of being
382 oxidized and mineralized directly by positive holes. It is essential to point out that the
383 surface area of Ag₃PO₄ is tiny as reported by some studies, e.g., 0.98 m²/g (Yi et al.,
384 2010); 0.16-1.02 m²/g (Dong et al., 2016); 2 m²/g (Ge et al., 2012).

Fig.3 (A). Mechanistic pathway of photocatalytic oxidation of organic pollutants in Ag_3PO_4 /visible light; **(B)** Schematic of the conventional type-II heterojunction; **(C)** Schematic of the Ag_3PO_4 -Based Z-scheme heterojunction photocatalyst (inspired from (Xue et al., 2020; Yi et al., 2010)).

5. Improving photocatalytic activities of Ag_3PO_4 photocatalyst towards the degradation of pollutants in gas-phase

The generation of by-products during the photocatalytic treatment in both water and air mediums is a serious issue that faces the application of photocatalysis systems in the

real-world (Pichat, 2019). However, the photocatalytic system under sunlight can continuously produce ROSs to mineralize such by-products further or decrease their medium concentration. Mostly, photocatalysis cannot be used as a single treatment process when it comes to the real application due to its shortcoming in terms of the formation of by-products. Therefore, the combination of photocatalysis with other systems is crucial to help the appropriate treatment of air.

The formation of heterojunctions between Ag_3PO_4 and other semiconductors is an attractive option to vary interfacial interactions, further offers a series of novel characteristics rather than that by single nanomaterial characteristics (Cai et al., 2020; Tang et al., 2020). A prolonged carrier lifetime and an enhancing interfacial charge transfer can be obtained from such heterostructures. However, it is also well understood that this is not easy to get the desired properties of heterojunctions material with well-matched valence and conduction band level in the two semiconductors (Lu et al., 2015; Wang et al., 2015).

Ag_3PO_4 -Based Z-scheme and conventional heterojunctions have already been extensively investigated to enhance photo-generated charges responsible for photocatalysis reactions and ultimately inhibited its photo-corrosion (Chen et al., 2014; Lu et al., 2015; Rao et al., 2020; Tang et al., 2020). The type II junction is the most common in conventional heterojunctions (**Fig. 3B**). In contrast, the newly emerged direct Z-scheme heterojunction (**Fig. 3C**) is regarded as the most efficient in Z-scheme systems to explore photo-generated carriers (He et al., 2018). Both heterojunctions have different charge carrier transport mechanisms, but the structure of both direct Z-scheme and type-II heterojunctions is the same.

The formation of conventional type-II heterojunction is mainly dependent on combining the proper two different semiconductors (SC-I) and (SC-II) having proper CB and VB band structure for proper electron-hole pairs transferring **Fig. 3B**. During light irradiation, the produced electron and holes from SC-I and SC-II will move towards SC-II (CB) and SC-I (VB), respectively. Thus, the photogenerated electron-hole pair recombination possibility would be reduced, and oxidation and reduction reactions without interfering occur over two semiconductors. (Huang et al., 2019; Lam et al., 2012; Pirhashemi et al., 2018). In contrast, a completely different mechanism of charge carrier migration was observed for direct Z-scheme heterojunctions. During light irradiation, the electron produced on semiconductor II (SC-II) would automatically transfer towards the higher reduction potential of semiconductor I (SC-I) (**Fig. 3C**), while the photogenerated holes remain on semiconductor II (SC-II), resulting in the spatial separation of charge carriers. Therefore, spatial separation of useful charge carrier in direct Z-scheme heterojunction will remove useless charge carriers by optimizing SC-I and SC-II composition system redox ability. Therefore, a direct Z-scheme heterojunction photocatalyst could enhance the photocatalytic activity more specifically (He et al., 2018; Huang et al., 2019). Moreover, the direct Z-scheme photocatalyst fabrication cost seems to be significantly reduced. Substantially, the direct Z-scheme heterojunction prepared photocatalyst offers two obvious merits, a highly efficient photocatalytic reduction (high redox ability) and a low-cost fabrication (Huang et al., 2019; Low et al., 2017; Zhou et al., 2014).

The bottom of the Ag_3PO_4 conduction band (CB) energy level is more positive than the reduction potential of O_2 ($\text{O}_2 + e^- \rightarrow \cdot\text{O}_2^-$, - 0.33 V vs. NHE) (Wood, 1988). Therefore, introducing another semiconductor to produce the Z-scheme system is beneficial for the

degradation of gaseous pollutants and the extension of Ag_3PO_4 lifetime if the photo-excited electrons in the CB of Ag_3PO_4 can be transferred to the newly introduced semiconductor.

A wide range of Ag_3PO_4 -based heterojunctions photocatalysts by exhibiting various composition and structural characteristics have been proposed through various well-established synthesis protocols for photocatalytic oxidation gas-phase pollutants. It is systematically summarized in this section.

5.1. Coupling Ag_3PO_4 with graphitic carbon nitride ($\text{g-C}_3\text{N}_4$)

Graphitic carbon nitride ($\text{g-C}_3\text{N}_4$) has gained considerable interest as a metal-free polymer n-type semiconductor due to favorable characteristics such as its 2D structure, tunable electric structure, and good chemical stability. It is a visible-light-driven semiconductor with (2.7 eV bandgap), and the CB and VB energy position exist at -1.1 and 1.6 eV vs. standard hydrogen electrode (NHE), respectively (Che et al., 2020; Dong et al., 2014; He et al., 2020; Masih et al., 2017; Tian et al., 2017). These characteristics make ($\text{g-C}_3\text{N}_4$) the most attractive candidate for highly efficient photocatalysis of gas-phase volatile pollutant degradation.

There are several reports regarding the degradation of gaseous pollutants. They include volatile organic pollutants (toluene, Ethylene, isopropanol, formaldehyde) and nitrogen oxide (NO_x) by $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ composite photocatalyst (Chen et al., 2014; Rao et al., 2020; Shen et al., 2018; Zhao et al., 2017). For instance, Chen and his co-workers (Chen et al., 2014) recently prepared a direct Z-scheme configuration-based novel $\text{g-C}_3\text{N}_4$ - Ag_3PO_4 composite for visible-light-driven (300 W Xe lamp) photocatalytic oxidation of

ethylene (C_2H_4). The results indicate that the introduction of g- C_3N_4 in Ag_3PO_4 resulted in enhanced gas adsorption. Notably, by using (30:70%) ratio of Ag_3PO_4 and g- C_3N_4 composite, the complete decomposition of C_2H_4 (90 μ L) was achieved after 3h under visible light, whereas bare Ag_3PO_4 needs 20 h for complete decomposition of C_2H_4 under visible light irradiation (**Fig. 4A**). Moreover, it was noted that g- C_3N_4 - Ag_3PO_4 composites exhibited higher k values ($1.0464\ h^{-1}$) than by pristine g- C_3N_4 (12.38 times) and Ag_3PO_4 (3.7 times). Hence, it is confirmed that the synergetic Ag_3PO_4 and g- C_3N_4 effect eases photogenerated charge carriers separation and their mobility thereby, resulting into superior photocatalytic performance. Furthermore, It was observed that during the photo-oxidation of C_2H_4 , no other products except CO_2 were detected (**Fig. 4B**). The fact that the CO_2 yields for all g- C_3N_4 -containing samples were greater than that which can be generated from C_2H_4 reveals an obvious adsorption effect of g- C_3N_4 . Moreover, this composite was stable for the photocatalytic oxidation of C_2H_4 and it can be recycled upto 5 cycles without significant decrease in its activity.

According to their investigation, the reaction mechanism under sunlight illumination during ethylene photocatalytic oxidation using 70% g- C_3N_4 -30% Ag_3PO_4 catalysts may be elucidated by the model presented in **Fig. 4C**.

During sunlight irradiation, a photo-excited electron of Ag_3PO_4 (CB) will transfer towards g- C_3N_4 (VB) by recombining with holes or excited over g- C_3N_4 CB, thus resulting in efficient charge separation of the photo-generated electron with no Ag_3PO_4 sacrificing. Thus, the photo-excited electrons present over the g- C_3N_4 conduction band are captivated by atmospheric O_2 near the g- C_3N_4 surface site and generate more reactive superoxide radical anions ($O_2^{\bullet-}$). Conversely, the presence of holes over the Ag_3PO_4 VB

site automatically react with Ag_3PO_4 surface site adsorbed water molecules (or surface hydroxyl groups) to produce hydroxyl radicals ($\cdot\text{OH}$), thus resulting in the highly efficient oxidation of C_2H_4 into water and carbon dioxide via reactive $\cdot\text{OH}$ and $\text{O}_2\cdot^-$ radicals and ultimately give higher stability of Ag_3PO_4 (Chen et al., 2014).

Similarly, the formation of $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ composite by adopting a simple in-situ solvothermal process with different mass ratios (1:0, 19:1, 9:1, 17:3, 4:1, 7:3, and 1:1) of C_3N_4 have already been reported under different light wavelength for the decomposition of NO_x (Zhao et al., 2017). The result indicated no apparent NO_x destruction was observed at 510 nm wavelength using both Ag_3PO_4 or $\text{g-C}_3\text{N}_4$ (**Fig. 4D**). Although, the photocatalytic activity of $\text{Ag}_3\text{PO}_4/20\%\text{gC}_3\text{N}_4$, $\text{Ag}_3\text{PO}_4/30\%\text{g-C}_3\text{N}_4$, and $\text{Ag}_3\text{PO}_4/50\%\text{g-C}_3\text{N}_4$ composites catalysts was observed to be preferable for NO_x decomposition under irradiation of >400 nm with an average performance rate (15.52%), (4.35%), (10.64%) (**Fig. 4D**). Also, the fixing of irradiation wavelength at 290 nm leads to an incremental increase of all $\text{Ag}_3\text{PO}_4/20\%\text{gC}_3\text{N}_4$, $\text{Ag}_3\text{PO}_4/30\%\text{g-C}_3\text{N}_4$, and $\text{Ag}_3\text{PO}_4/50\%\text{g-C}_3\text{N}_4$ composites activity for photocatalytic decomposition of NO_x and an average decomposition rate (41.76, 51.09, 47.87%), respectively was obtained (**Fig. 4D**). However, these decomposition rates were comparatively higher than the pristine $\text{g-C}_3\text{N}_4$, Ag_3PO_4 , and P25, thus demonstrating the promising efficiency of $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ composite under both ultraviolet and visible irradiation due to enhanced light absorption after Ag_3PO_4 and $\text{g-C}_3\text{N}_4$ composite formation (**Fig. 4E**). Moreover, the authors stated that composite materials with an average $\text{g-C}_3\text{N}_4$ content of 20% and 30% demonstrate the best visible light and UV light-driven decomposition of NO_x , respectively. Additionally, it is also noted that under irradiation >290 nm, excellent stability, and the remarkable

efficiency of the $\text{Ag}_3\text{PO}_4/30\%\text{g-C}_3\text{N}_4$ catalyst even after four cycles. Simultaneously, the NO_x decomposition rate of Ag_3PO_4 somehow decreased (**Fig. 4F**). Hence, it is undeniable that the $\text{g-C}_3\text{N}_4$ addition automatically improves Ag_3PO_4 stability and thus inhibiting its photo-corrosion.

The photocatalytic mechanistic pathways on $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ photocatalysts under visible light is illustrated in **Fig. 4G**. When $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ photocatalysts composite is irradiated by visible light (Eq. 1), the transfer of photoexcited electron occurs from $\text{g-C}_3\text{N}_4$ CB to Ag_3PO_4 , inhibiting electron and holes recombination behavior. Thus, the hole present over the $\text{g-C}_3\text{N}_4$ valence band (VB) is scavenged by water molecules to generate more free hydroxyl radical ($\text{OH}^\bullet$) (Eq. 2). Conversely, the photogenerated and transfer electrons over the Ag_3PO_4 CB site automatically react with oxygen, thereby generating oxygen radicals (Eq. 3) and resulting in the oxidation of nitrogen monoxide via oxygen, hydroxyl radical, and water producing NO_2^- or NO_3^- . Moreover, it was noted that during light irradiation, only 20% of NO was converted into O_2 and N_2 , while the rest 80% was oxidized to NO_3^- . The overall mechanism of photocatalytic NO_x decomposition via $\text{Ag}_3\text{PO}_4/\text{gC}_3\text{N}_4$ composite under visible light is presented below (Zhao et al., 2017):

Fig.4. Time courses of (A) C_2H_4 degradation and (B) CO_2 evolution on $\text{g-C}_3\text{N}_4\text{-Ag}_3\text{PO}_4$ composites, (C) Charge transfer in the $\text{g-C}_3\text{N}_4\text{-Ag}_3\text{PO}_4$ Z-Scheme mode under sunlight illumination (Figs 4A,4B and 4C are adapted with permission from ref (Chen et al., 2014), copyright 2014 Wiley Online Library). (D) and (E) NOx destruction activities of $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ composites under the irradiation of different wavelengths of light, (F) Cycling photocatalytic degradation of NOx under 290 nm irradiation, (G) the possible mechanism of visible-light-induced photocatalysis of $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ composite (Figs 4D,4F,4E and 4G are adapted with permission from ref (Zhao et al., 2017), copyright 2016 Elsevier).

Similarly, Reo et al. (Rao et al., 2020) proposed a different mass ratio (0.5, 1.0, 1.5, to 2.0 wt%) to prepare $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ nanocomposites. In a continuous flow, at 420 nm, LED irradiation driven formaldehyde (HCHO) (0.5 mg/m^3) photocatalytic decomposition efficiency of $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ photocatalysts was tested. Their findings showed maximum formaldehyde degradation rates (8.51%, 10.60%, 22.4%, 10.60%, and 6.38%), in the order of g- C_3N_4 , 0.5AP-CN, 1AP-CN, 1.5AP-CN, and 2AP-CN, respectively **Fig. 5A**. The optimum photoactivity of the 1AP-CN heterojunction for HCHO degradation was about (2.63) times fast than g- C_3N_4 . After comprehensively evaluating the gas-phase formaldehyde photocatalytic degradation in a continuous flowing mode of corresponding composite photocatalysts, they found that when Ag_3PO_4 as an impurity semiconductor was immersed into the g- C_3N_4 lattice, the formation of type II heterojunctions semiconductor was observed (**Fig. 5B**), which can restrain photogenerated carriers recombination thereby enhancing the overflow of the photogenerated electron over photocatalyst surface to boost up the reaction. Therefore, under irradiation, the $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ nanocomposite photodegradation efficiency for formaldehyde increased. Moreover, their results reveal that under visible light irradiation, the photogenerated electrons trapped by O_2 over conduction band CB produce more $\cdot\text{O}_2^-$ radicals, and the presence of holes over the valence band (VB) directly participate in the oxidation of water/ $\cdot\text{OH}$ and/or water by generating $\cdot\text{OH}$ radicals and thereby resulting in further oxidation of HCHO into H_2O and CO_2 (Rao et al., 2020).

In another study, special attention towards the formation of Z-scheme g- $\text{C}_3\text{N}_4/\text{Ag}/\text{Ag}_3\text{PO}_4$ composite was devoted to evaluate gaseous isopropanol photocatalytic oxidation (Shen et al., 2018). The formation of g- $\text{C}_3\text{N}_4/\text{Ag}/\text{Ag}_3\text{PO}_4$ composites at room temperature was

562 carried via a simple in situ deposition method by coating regular rhombic dodecahedrons
563 Ag_3PO_4 particles over a g- C_3N_4 sheet. Later on different Ag_3PO_4 to g- C_3N_4 ratio were
564 denoted by ACx and x refer to various ratios ($x = 0.3, 0.5, 0.7, 0.9, 1.0$ and 1.2). The
565 photocatalytic oxidation efficiency of AC1.0 (90 μL) is the highest among Ag/ Ag_3PO_4 and
566 g- C_3N_4 (**Fig. 5C**). In the case of AC1.0 samples, almost 63% IPA was removed within 4
567 h, higher than that by g- C_3N_4 (14%) and Ag/ Ag_3PO_4 (40%). Their findings also showed
568 that acetone was the main outcome product during the photocatalytic oxidation of
569 isopropanol. The incremental increase in acetone concentration was attributed to
570 isopropanol's selective oxidation to acetone (**Fig. 5D**). As depicted in **Fig. 5E**, the use of
571 g- C_3N_4 /Ag/ Ag_3PO_4 for isopropanol oxidation exhibited significant efficiency over five
572 consecutive cycles, thereby indicating higher stability of the studied photocatalyst. The
573 explanation of visible-light-driven photooxidation of gaseous isopropanol possible
574 mechanism over g- C_3N_4 /Ag/ Ag_3PO_4 is shown in **Fig. 5F**. Moreover, the presence of
575 photogenerated electron and holes over CB of g- C_3N_4 and VB of Ag_3PO_4 of g-
576 C_3N_4 /Ag/ Ag_3PO_4 exhibited efficient oxidation-reduction capability due to the transfer of
577 electrons from the CB Ag_3PO_4 to Ag nanoparticles instead of remaining over Ag_3PO_4
578 lattice and thereby resulting in the inhibition of Ag_3PO_4 self-reduction and enhancing g-
579 C_3N_4 /Ag/ Ag_3PO_4 composite stability (Shen et al., 2018).

Fig. 5. (A) Degradation measurement of flowing gas-phase formaldehyde (B) Energy band schematic of $\text{Ag}_3\text{PO}_4/\text{g-C}_3\text{N}_4$ composites (Figs 5A and 5B are adapted with permission from ref (Rao et al., 2020), copyright 2019 Elsevier). (C) Photocatalytic degradation of gaseous isopropanol over $\text{AC}_{1.0}$, $\text{Ag}/\text{Ag}_3\text{PO}_4$ and $\text{g-C}_3\text{N}_4$ samples, (D) Photocatalytic degradation of gaseous isopropanol and amounts of acetone evolution yield over $\text{AC}_{1.0}$, (E) the cyclic stability tests of $\text{AC}_{1.0}$, (F) Schematic illustration for the charge transfer and separation in Z-scheme $\text{g-C}_3\text{N}_4/\text{Ag}/\text{Ag}_3\text{PO}_4$ photocatalytic composite under visible-light irradiation (Figs 5C,5D,5E, and 5F are adapted with permission from ref (Shen et al., 2018), copyright 2018 Elsevier).

5.2. Coupling Ag₃PO₄ with TiO₂

Nowadays, TiO₂, as an efficient UV light-driven photocatalyst, is getting tremendous attention due to its non-toxic nature and low cost. Many attempts have been made by many researchers to construct a heterostructure with Ag₃PO₄, not for only enhancing Ag₃PO₄ stability but also its photocatalytic activity via decreasing its bandgap (Jia et al., 2019; Rawal et al., 2012; Xie et al., 2015; Zhao et al., 2014). For example, Rawal et al. (Rawal et al. 2012) introduced a novel Ag₃PO₄/TiO₂ heterojunction by coating Ag₃PO₄ surface sites polycrystalline TiO₂. The as-prepared heterojunctions formation pathway is presented in **Fig. 6A**. Its photocatalytic performance under visible light irradiation ($\lambda \geq 420$ nm) was evaluated to remove gaseous 2-propanol (IP). Experimental reports implied that several compositions of Ag₃PO₄/TiO₂ composites photocatalytic activities were higher than bare Ag₃PO₄ and TiO₂, (**Fig. 6B**). Their findings implied that within 120 min of visible light irradiation about 65% of 2-propanol was decomposed by the composites (3/97 Ag₃PO₄/TiO₂) due to superior adsorption and higher photogenerated e⁻ transfer over interface between TiO₂ and Ag₃PO₄ (**Fig. 6B**). Furthermore, under visible light the evaluation of photocatalytic activity was investigated in term of CO₂ evolution. From the **Fig. 6C**, it can be seen that the higher CO₂ evolving efficiency is about 11.4 ppmv was achieved within 2 hour using 3/97 Ag₃PO₄/TiO₂. The pristine Ag₃PO₄ and TiO₂ demonstrated an average CO₂ evolution efficiency of about 0.9 and 2.9 ppmv, respectively. Additionally, the 3/97 Ag₃PO₄/TiO₂ reusability potential was evaluated for gaseous isopropanol decomposition and their result showed that the degradation of the 3/97 Ag₃PO₄/TiO₂ composite after 5 and 10 times recycling did not showed considerable alteration in CO₂ evolution (**Fig. 6D**), thus indicating its high photocatalytic stability.

Fig. 6. (A) Preparation strategy for $\text{Ag}_3\text{PO}_4/\text{TiO}_2$ composite; (B) Percentage of the remnant IP as a function of irradiation time in the presence of several $\text{Ag}_3\text{PO}_4/\text{TiO}_2$ composites under visible-light irradiation; (C) Amount of CO_2 evolved (ppmv) in the presence of several $\text{Ag}_3\text{PO}_4/\text{TiO}_2$ composites under visible-light irradiation, (D) Photocatalytic evolution of CO_2 by the repeated use of $3/97 \text{ Ag}_3\text{PO}_4/\text{TiO}_2$. (Figs. 6A, 6B, 6C, and 6D are adapted with permission from ref (Rawal et al.,

2012), copyright 2011 Elsevier). Acetone **(E)** and **(F)** CO₂ evolution through degradation of 2-propanol by TiO₂-Ag₃PO₄ photocatalysts (Fig. 6E,6F are adapted with permission from ref (Jia et al., 2019), copyright 2019 Elsevier). **(G)** Diagram for the charge carrier transfer and formation of •OH radical in the Ag₃PO₄/TiO₂ under visible light irradiation (Adapted with permission from ref (Rawal et al., 2012). copyright 2011 Elsevier).

Another study from Jia *et al.* (Jia et al., 2019) reported the preparation and utilization of (Ag₃PO₄/TiO₂) nanocomposites for gaseous 2-propanol decomposition. After using Ag₃PO₄/TiO₂ as a photocatalyst under visible light, the high photocatalytic activity of Ag₃PO₄/TiO₂ composites obtained was attributed to the superior surface area, which further enhances the visible light absorption capacity and thus increasing charge separation efficiency. Their results indicated a high photocatalytic performance of all hybrid TiO₂-Ag₃PO₄ nanorods for 2-propanol degradation. Among them, TiO₂-Ag₃PO₄-3 (13% molar percentage of Ag₃PO₄) proved to be the best photocatalyst and produced about 147 ppm and 424 ppm of acetone and CO₂ within the first 3 h (**Fig. 6E**) and 11 h (**Fig. 6F**), respectively.

Furthermore, to demonstrate the enhancement mechanism of photocatalytic degradation using Ag₃PO₄/TiO₂ nanocomposites, a paradigm 2-propanol photocatalytic degradation was chosen (Rawal et al., 2012). However, it was observed that Ag₃PO₄ VB electron excitement towards CB produced holes over its VB under visible light irradiation. The higher valence band position of Ag₃PO₄ (+2.9 eV vs. NHE) compared to TiO₂ enables the holes transformation from Ag₃PO₄ to TiO₂ (+2.7 eV vs. NHE) as shown in **Fig. 6G**. It indicates that the formation of holes over TiO₂ VB sites would be consumed through different oxidation reactions. During the inter-semiconductor hole-transfer mechanism, the photo-induced electron could be more stably separated, enabling the coupled system to effectively use the visible light for organic pollutant mineralization. On the other hand,

considering Ag_3PO_4 CB level +0.45 V (vs. NHE), the direct electron transfers to oxygen molecules (−0.284 V (vs. NHE) or formation of $\text{HO}_2^\bullet$ need about −0.284 V (vs. NHE) and −0.046 V (vs. NHE), respectively. would be difficult, as shown in Eqs. (7) and (8) (Krungchanuchat et al., 2017), respectively. Thus, the electrons accumulated over CB of Ag_3PO_4 multi-electron processes would be transported to oxygen species described in Eqs. (9) and (10) (Krungchanuchat et al., 2017). It is observed that the efficient photo-induced charge separation may result in the enhancement of $\text{Ag}_3\text{PO}_4/\text{TiO}_2$ composites' photocatalytic activity.

5.3. Coupling Ag_3PO_4 with SrTiO_3

SrTiO_3 is one of the most commonly studied perovskite structures for photocatalytic application (Ji et al., 2019; Kong et al., 2016; Yue et al., 2018); it exhibits high corrosion resistance (Kong et al., 2016; Yue et al., 2018), chemical stability (Kong et al., 2016), low cost (Kong et al., 2016), and non-toxicity (Kong et al., 2016; Zhang et al., 2010). It has been verified as an efficient photocatalyst for improving Ag_3PO_4 photocatalytic activity (Kong et al., 2016; Saadetnejad and Yildirim, 2018; Yue et al., 2018).

In a study conducted by Guo et al. (Guo et al., 2013), a novel $\text{Ag}_3\text{PO}_4/\text{Cr-SrTiO}_3$ new efficient heterojunction photocatalyst fabrication was performed by adopting a simple sol-gel hydrothermal method. The photocatalytic activity of $\text{Ag}_3\text{PO}_4/\text{Cr-SrTiO}_3$

heterojunction under 300 W Xe-lamp as a source of solar light production ($420\text{ nm} < \lambda < 800\text{ nm}$) was investigated for Isopropyl alcohol (IPA) (the initial concentration of IPA was about 1250–1500 ppm) photocatalytic conversions into CO_2 . According to this study, the prepared samples with varying ratios exhibited different efficiencies. In particular, $\text{Ag}_3\text{PO}_4/\text{Cr-SrTiO}_3$ heterojunction composite with (1:4) mass ratio exhibited the highest photodegradation, about 97% IPA within 3.8 h irradiation (**Fig. 7A**). In contrast, pure Ag_3PO_4 and Cr-SrTiO_3 exhibited only 9% and 12% IPA decomposition within 8 h of irradiation, respectively (**Fig. 7A**). Besides, the highest rate of CO_2 evolution was found in the presence of this heterojunction photocatalyst, and the amount of CO_2 produced was 291.2 ppm, which was 35 and 5-fold higher than the bare Ag_3PO_4 and Cr-SrTiO_3 , respectively (**Fig. 7B**). Furthermore, the effect of calcination over photocatalytic performance was also examined. Results indicated that higher photocatalytic activity was observed for the samples calcined over (500°C) than the ones calcined over (300°C) and (700°C) (**Fig. 7C**). As depicted from $\text{Ag}_3\text{PO}_4/\text{Cr-SrTiO}_3$ heterojunctions composites XRD patterns in (**Fig. 7D**), calcined over different temperatures, the incremental increase photocatalytic activity might be due to metallic silver particles presence over Ag_3PO_4 , and its behavior as photogenerated electrons trappers is more beneficial for electron aggregation and transformation. The decrease in photocatalytic performance with an increase in calcined temperature is might be due to the complete decomposition of Ag_3PO_4 at a higher temperature of 700°C .

Fig.7. (A) The concentration change of IPA and **(B)** the evolution of CO₂ over Cr-SrTiO₃, Ag₃PO₄ and Ag₃PO₄/Cr-SrTiO₃ (1:4) composite powders under visible light irradiation; **(C)** the evolution rate of CO₂ under visible light irradiation of the Ag₃PO₄/Cr-SrTiO₃ (1:4) composite powders calcined at different temperature over (420 nm < λ < 800 nm); **(D)** The XRD patterns and. Adapted with permission from ref (Guo et al., 2013), copyright 2013 Elsevier).

Another report from Ji et al. (Ji et al., 2019) investigated the Z-scheme Ag₃PO₄/Ag/SrTiO₃ (named AgPO/Ag/STO) heterojunction catalyst preparation and its applications toward visible-light-driven ($\lambda \geq 420$ nm, 150 mW/cm²) typical volatile organic compounds (xylene, toluene, and benzene) under mild heating (not higher than 90 °C). Their findings showed that visible-light-driven AgPO/Ag/STO photocatalytic conversion (> 90%) of toluene (800ppm) was observed after 6 h reaction (**Fig. 8A**), which was better than (AgPO/STO,

Ag/AgPO, and Ag/STO). The Ag NP bridge over AgPO/STO considerably enhances the photocatalytic performance. Furthermore, in their report, the effect of heat on photocatalytic behavior was also examined. As depicted in **Fig. 8B**, the toluene conversion during the photo-thermo-catalytic oxidation (PTO) process significantly increased from (65% to 94%) over AgPO/Ag/STO because of temperature increases (45 to 90 °C) for 3h. For the thermocatalytic oxidation (TCO) process, toluene conversion only increased from 3% to 14%, and 59% toluene conversion via photocatalytic oxidation (PCO) was achieved at room temperature. Additionally, the photo-thermo-catalytic oxidation (PTO) process over AgPO/Ag/STO was tested for xylene and benzene degradation. Their results showed that after 4h photo-thermo-catalytic oxidation (PTO) process at 90 °C, the conversion rates of xylene, toluene, and benzene were more than 85%, thereby suggesting its potential practical application.

Furthermore, a clear description of the possible photocatalytic mechanism and the photo-thermo-catalytic oxidation of volatile organic compounds under visible-light irradiation over Ag₃PO₄/Ag/SrTiO₃ are exhibited in **Fig. 8C**.

As proposed in **Fig. 8C**, the photogenerated electrons from the Ag₃PO₄ conduction band and the holes from the SrTiO₃ valance band recombine via Ag nanoparticles using Z-scheme Ag₃PO₄/Ag/SrTiO₃ heterojunction structure as a photocatalyst. Such a distinctive Z-scheme charges transfer route could effectively restrain photogenerated charges recombination produced in SrTiO₃ and Ag₃PO₄, thereby assuring a considerable generation of oxidative species ($\bullet\text{OH}$ and $\bullet\text{O}_2^-$). Equally, photo-generated electrons from SrTiO₃ reduction and the active $\bullet\text{O}_2^-$ generation could also be enhanced. Moreover, in the surface of Ag NP, the photo-induced electron in Ag₃PO₄ and the holes in SrTiO₃

selective recombination behavior results in the protection of Ag_3PO_4 from light corrosion (Ag^+ to Ag^0), thereby ensuring enhancement of $\text{Ag}_3\text{PO}_4/\text{Ag}/\text{SrTiO}_3$ photocatalytic stability.

Fig. 8 (A) Photocatalytic oxidation (PCO) of toluene under visible light at room temperature for 6 h; (B) Thermocatalytic oxidation (TCO), Photocatalytic oxidation (PCO), and photothermocatalytic oxidation (PTO) of toluene over $\text{Ag}_3\text{PO}_4/\text{Ag}/\text{SrTiO}_3$ for 3 h (RT refers to room temperature); (C) Charge transfer process in the photocatalytic oxidation process over $\text{Ag}_3\text{PO}_4/\text{Ag}/\text{SrTiO}_3$. (Figs. 8A, 8B, and 8C are adapted with permission from ref (Ji et al., 2019), copyright 2019 American Chemical Society); (D) Time courses of C_2H_4 photodegradation and (E) pseudo-first-order kinetics plots: a. In_2O_3 , 95-IO-Ag-5-AP, c. 90-IO-Ag-10-AP, d. 70-IO-Ag-30-AP, e. 50-IO-Ag-50-AP, f. Ag_3PO_4 ; (F) Charge transfer in the In_2O_3 -Ag- Ag_3PO_4 Z-scheme mode under sunlight illumination (Figs. 8D, 8E, and 8F are adapted with permission from ref (Chen et al., 2017), copyright 2017 Elsevier).

5.4. Coupling Ag_3PO_4 with In_2O_3

In_2O_3 is an indirect band semiconductor with a direct bandgap of 3.6 eV and an indirect bandgap of 2.8 eV. The In_2O_3 is regarded as an efficient photocatalyst, as it increases the semiconductor absorption spectra from the UV region into the visible region (W. T. Liu et al., 2018; Mu et al., 2012; Yang et al., 2017). In light of the Chen et al. investigation (Chen et al., 2017), a novel $2\text{O}_3\text{-Ag-Ag}_3\text{PO}_4$ composites formation via the Z-scheme configuration and its use for visible-light-driven ethylene (C_2H_4) photocatalytic degradation was investigated. After comprehensively evaluating the photocatalytic ethylene degradation performance by the corresponding composite photocatalysts, they found that $\text{In}_2\text{O}_3\text{-Ag-Ag}_3\text{PO}_4$ composite with 9:1 (90-IO-Ag-10-AP) mass ratio exhibited a remarkable C_2H_4 photodegradation by decomposing almost 200 ppm C_2H_4 within 2h under visible light irradiation (**Fig. 8D**). Additionally, only the production of CO_2 was detected during the photocatalytic oxidation of C_2H_4 . The pseudo-first-order reaction kinetics with the highest value of the rate constant ($52.93 \times 10^{-3} \text{ h}^{-1}$) provided the best fitting for the whole photocatalytic oxidation reactions (**Fig. 8E**), and it was found to be higher than the In_2O_3 and Ag_3PO_4 with an average fold value of 24.4-fold and 41.1-fold, respectively.

Furthermore, it was observed that during visible light irradiation, the degradation proficiency of the catalyst changed after 3 reaction cycles. The schematic diagram of charge carrier separation proposed for the photoexcited $\text{In}_2\text{O}_3\text{-Ag-Ag}_3\text{PO}_4$ composite photocatalyst is represented in **Fig. 8F**. Moreover, it was observed that the photo-excited electrons on the CB bottom of Ag_3PO_4 move to the Ag nanoparticles and then recombined with the holes which transferred from the VB edge of In_2O_3 under visible light irradiation

leading to the efficient separation of photo-generated charge carriers, which in turn slow down the Ag_3PO_4 photo-corrosion. Simultaneously, the efficient reduction of adsorbed O_2 over the In_2O_3 surface resulted in reactive superoxide radical anions $\cdot\text{O}_2^-$ due to photo-excited electrons over the CB bottom of In_2O_3 . Furthermore, the efficient oxidation of adsorbed water molecules or surface hydroxyl groups over Ag_3PO_4 resulted in hydroxyl radicals $\cdot\text{OH}$ generation due to the holes over the VB edge Ag_3PO_4 . Thus, the photo-induced strong $\cdot\text{OH}$ and O_2^- radicals efficiently degraded the ethylene into CO_2 and H_2O . Thus, this work gives a solid conclusion towards Ag_3PO_4 photo stabilization and C_2H_4 photocatalytic degradation by proving the formation of a Z-scheme composite as a promising pathway in the photocatalytic degradation field.

5.5. Coupling Ag_3PO_4 with $\text{Sr}_2\text{Nb}_2\text{O}_7$

The $\text{Sr}_2\text{Nb}_2\text{O}_7$ is viewed as the most promising visible-light-driven photocatalyst, even among many-layered perovskite materials. Moreover, besides hydrogen reduction potential, it has a lower bandgap (3.9 eV) (Adhikari et al., 2018; Guo et al., 2014; Nisar et al., 2012). In connection with that, Guo et al. (Guo et al., 2014) reported different temperature based (873 K, 923 K, 973 K, 1023 K, 1073 K, and 1173 K), novel $\text{Ag}_3\text{PO}_4/\text{nitridized Sr}_2\text{Nb}_2\text{O}_7$ (nitrided under NH_3 flow (500 mL min^{-1})) preparation throughout 3 h intending to adjust the band structures for efficient isopropyl alcohol (the initial concentration of IPA was about 1250-1500 ppm) degradation under visible light irradiation. Furthermore, the electronic structure calculations showed that the top of the valance band of $\text{Sr}_2\text{Nb}_2\text{O}_7$ might be significantly increased after nitrogen doping (**Fig. 9A**). Therefore, it was concluded that the $\text{Ag}_3\text{PO}_4/\text{nitridized Sr}_2\text{Nb}_2\text{O}_7$ photocatalysts electronic structure might be altered by controlling nitrogen dose in nitridized $\text{Sr}_2\text{Nb}_2\text{O}_7$. The report

781 showed that all the composite photocatalysts displaying superior photoactivity than the
782 pristine materials. In particular, a remarkable photoactivity was observed using
783 $\text{Ag}_3\text{PO}_4/\text{SNON-1023}$ photocatalyst which achieved a maximum CO_2 and acetone
784 evolution rates 10.32 ppm h^{-1} and 173.3 ppm h^{-1} , respectively (**Fig. 9B**) and (**Fig.**
785 **9C**). These evolution rate are comparatively higher than other composite photocatalysts.
786 Moreover, it was found that by increasing the nitridation temperature $<1023 \text{ K}$, increasing
787 evolution rate of acetone (**Fig. 9B**) and CO_2 was observed (**Fig. 9C**). However, after
788 nitridation temperature $>1023 \text{ K}$, increasing temperature resulted in the reduction of
789 acetone and CO_2 evolution rates more significantly. This is due to generated holes
790 oxidation potential. Although the separation of electron-hole pairs increased due to the
791 prepared composite band structure characteristics the produced holes oxidation ability
792 was lower after transferring, as a result of the valence band position of the nitridized
793 $\text{Sr}_2\text{Nb}_2\text{O}_7$ (**Fig. 9D**). The optimal band gap of the nitridized $\text{Sr}_2\text{Nb}_2\text{O}_7$ is almost 2.15 eV ,
794 while that of CB and VB potentials are $(-0.27 \text{ eV}$ and $+1.88 \text{ eV})$, respectively. According
795 to these findings, it was concluded that Ag_3PO_4 valance and conduction bands relative
796 potential as well as nitridized $\text{Sr}_2\text{Nb}_2\text{O}_7$ have an important effects on photoactivity.

Fig. 9. (A) The schematic band structures of nitridized $\text{Sr}_2\text{Nb}_2\text{O}_7$ (N: 0– 6.18 wt%); **(B)** The acetone evolution rates of the as-prepared composite photocatalysts; **(C)** The CO_2 evolution rates of the as-prepared composite photocatalysts; **(D)** The schematic band structure of the $\text{Ag}_3\text{PO}_4/\text{SNON-1023}$ composite photocatalyst. Adapted with permission from ref. (Guo et al., 2014) Copyright 2014 Royal Society of Chemistry).

5.6. Coupling Ag_3PO_4 with CaIn_2S_4

The CaIn_2S_4 belongs to the AB_2X_4 semiconductor family. They possess suitable band edge positions (Li et al., 2017), high chemical stability (Liu et al., 2019), and narrow bandgaps (Wan et al., 2018), which make them more effective in the photocatalysis field

808 due to their multiple potential applications (Ding et al., 2014; Jo and Natarajan, 2015; Li
809 et al., 2017; Liu et al., 2019).

810 The basis for enhancing Ag_3PO_4 photocatalysis by CaIn_2S_4 is well summarized by
811 Shipeng et al. (Wan et al., 2018). The authors prepared Z-scheme $\text{CaIn}_2\text{S}_4/\text{Ag}_3\text{PO}_4$
812 nanocomposite (called CIS/APO) via wet impregnation method, through CaIn_2S_4
813 concentration changing from 0 to 15 wt%. The photodegradation oxidation of nitric oxide
814 (NO) (~400 ppm) using a 300 W Xe-lamp as a solar light production source using the as-
815 synthesized $\text{CaIn}_2\text{S}_4/\text{Ag}_3\text{PO}_4$ composites photocatalytic behavior was also assessed. The
816 optimum NO photocatalytic oxidation using $\text{CaIn}_2\text{S}_4/\text{Ag}_3\text{PO}_4$ was achieved when CaIn_2S_4
817 content was kept constant up to (10 wt%) (**Fig. 10A**). Moreover, it was observed that
818 10%-CIS/APO nanocomposite exhibited 2-fold and 3.5-fold higher solar light-driven
819 photocatalytic oxidation (86.61%) of nitric oxide after 80 min than the pristine Ag_3PO_4 and
820 CaIn_2S_4 , respectively (**Fig. 10A**). The $\text{CaIn}_2\text{S}_4/\text{Ag}_3\text{PO}_4$ nanocomposite photocatalyst also
821 exhibits high photostability up to four photocatalytic oxidation of NO cycles (**Fig. 10B**).

822 Such kind of visible-light-driven superior photocatalytic behavior is strictly associated with
823 the separated charge carriers extended lifetime, improved light-harvesting, and
824 photogenerated e^- , h^+ pairs easy transportation at the heterojunction interfaces produced
825 from lattice match and energy level between CaIn_2S_4 and Ag_3PO_4 (**Fig. 10C**).
826 Furthermore, the results demonstrate that the coupling of CaIn_2S_4 and Ag_3PO_4 does not
827 follow the conventional $\text{CaIn}_2\text{S}_4/\text{Ag}_3\text{PO}_4$ heterojunction (type II) because of the more
828 positive potential of Ag_3PO_4 CB (+0.45 eV) (Krungchanuchat et al., 2017) than the
829 produced $\cdot\text{O}_2^-$ and $\cdot\text{OH}$ formation ($\text{O}_2/\cdot\text{O}_2^- = -0.33$ eV; $\text{H}_2\text{O}_2/\cdot\text{OH} = +0.06$ eV) redox
830 potential (Krungchanuchat et al., 2017), as well as the more negative potential of CaIn_2S_4

831 VB (+0.82 eV) (Wan et al., 2018) than the potential required for the oxidation of H_2O_2 to
832 $\bullet\text{O}_2^-$ (+1.00 eV) (Krungchanuchat et al., 2017). In contrast, provided that the coupling of
833 CaIn_2S_4 and Ag_3PO_4 could follow the Z-scheme mechanism, under visible light
834 illumination, the photogenerated electrons over the Ag_3PO_4 conduction band move
835 towards the CaIn_2S_4 valence band and recombine with holes of CaIn_2S_4 valence Band
836 (VB). As the highly negative CB potential of CaIn_2S_4 (-1.03 eV) could easily reduce (O_2
837 and H_2O_2) into ($\bullet\text{O}_2^-$ and $\bullet\text{OH}$), respectively. Similarly, the highly positive VB potential of
838 Ag_3PO_4 (+2.90 eV) facilitates oxidizing H_2O_2 to $\bullet\text{O}_2^-$. Thus, the existence of many active
839 free radicals ($\bullet\text{O}_2^-$, $\bullet\text{OH}$) resulted in the production of a strong oxidation ability of
840 $\text{CaIn}_2\text{S}_4/\text{Ag}_3\text{PO}_4$ nanocomposite photocatalysts for efficient oxidation of NO than the
841 pristine CaIn_2S_4 or Ag_3PO_4 photocatalyst.

Figure 10. (A) The NO conversion efficiency of CIS, APO, and x%-CIS/APO nanocomposites (x = 2, 5, 10, 15); (B) the stability tests of the 10%-CIS/APO nanocomposite for NO removal. The schematic band structures of nitrified $\text{Sr}_2\text{Nb}_2\text{O}_7$ (N: 0–6.18 wt%); (C) Schematic representation of the photoexcited electron-hole transfer mechanism. Adapted with permission from ref (Wan et al., 2018), copyright 2018 Royal Society of Chemistry).

6. Conclusions and Future Directions

Silver phosphate is believed to be the most effective photocatalysts recorded to date since its first application in photocatalysis in 2009. Also, it is considered to be the most efficient visible-light-driven photocatalysts exhibiting remarkable photocatalytic properties

than commonly employed oxidative photocatalysts such as TiO_2 , ZnO , BiVO_4 , and WO_3 . The only drawback for Ag_3PO_4 use as a photocatalyst is its photo-corrosion, limiting its reusability potential in photocatalytic reactions. Consequently, many research efforts have been devoted to improving Ag_3PO_4 stability and its photocatalytic performance in environmental photo remediation studies. This review reveals that the construction of a Z- scheme semiconductor by integrating Ag_3PO_4 with other photocatalyst or conventional type-II heterojunctions photocatalyst could effectively enhance its stability and photocatalytic activity towards gaseous pollutants elimination. The enhanced photocatalytic oxidation of gaseous contaminants is closely associated with narrow bandgap energy, improved absorption light range, reduce electron-hole pair recombination, faster charge transfer, and negligible photo-corrosion.

Thus, this review's main purpose is to compile the current research progress on the current strategies for enhancing Ag_3PO_4 -based composite photocatalytic activities towards gaseous pollutants elimination. Moreover, the mechanism responsible for the enhanced photocatalytic performance of the Ag_3PO_4 -based composite system has been discussed in detail, which will provide guidelines for future research. Although considerable advances in this area have already been made over the past few years, most studies in this field are still at the initial stage. Thus, future work should focus on the following aspects:

- (i) Thoughtful research efforts are urgently required in the future ahead for Ag_3PO_4 -based composite photocatalysts appliance to treat other volatile organic compounds separately and mixed. Therefore, their application must

be extended towards the degradation of other harmful gases, such as acetaldehyde, trichloroethylene...etc.

(ii) Another major objective has been proposed as a future direction to develop and improve the green and straightforward synthesis of Ag_3PO_4 -based photocatalysts. For that aim, systematic studies are urgently needed to introduce sustainable production pathways to provide a selection based material fabrication with the desired morphology, crystal phase, surface structure, as these characteristics strongly influence its photocatalytic activity.

(iii) It has been reported that constructing core@shell structure photocatalysts could effectively improve the photostability of the Ag_3PO_4 -based composite semiconductor. It is also a prerequisite to understanding better the relationship between semiconductor photocatalyst structural properties and its photocatalytic performance during experimentation when computational methods are integrated.

(iv) In a broad spectrum, it is highly required to have a better understanding to promote and evaluate the mechanism of the Ag_3PO_4 -based composite system using different novel characterization and computational techniques, such as density functional theory (DFT), which have a significant value in order to provide valuable insight towards the deep understanding of the material structural characteristics, i.e., surfaces, interfaces, nanostructures and activity at the atomic and molecular level.

(v) Bare Ag_3PO_4 showed a low surface area, which inhibits the kinetics and the photocatalytic degradation rate. Therefore, it is recommended to combine bare

Ag₃PO₄ with adsorbing/porous surface materials such as activated carbon, graphene, lignocellulosic biomass, or clays for enhanced surface area and photoactivity.

(vi) A wide range of systematic studies regarding gaseous phase pollutant remediation has been critically reviewed and elucidated in this review. Moreover, it is well understood that previously reported studies mainly focus on the performance of materials under laboratory-based controlled conditions. Although considerable performance is achieved, there are still some limitations when scaling up the system operating in real conditions.

Therefore, in conclusion, we believe that if these issues and challenges are adequately addressed, then in years to come, the use of Ag₃PO₄ based Z scheme or conventional type-II heterojunctions photocatalyst for gaseous phase contaminants photocatalytic oxidation would be tremendous and commercially feasible.

Acknowledgments

This work was supported by the Ibn Zohr University and LME laboratory (Morocco).

919 References

- 920 Aarab, N., Hsini, A., Essekri, A., Laabd, M., Lakhmiri, R., Albourine, A., 2020a. Removal of an
 921 emerging pharmaceutical pollutant (metronidazole) using PPY-PANi copolymer: Kinetics,
 922 equilibrium and DFT identification of adsorption mechanism. *Groundw. Sustain. Dev.* 11,
 923 100416. <https://doi.org/10.1016/j.gsd.2020.100416>
- 924 Aarab, N., Hsini, A., Laabd, M., Essekri, A., Laktif, T., Haki, M.A., Lakhmiri, R., Albourine, A.,
 925 2020b. Theoretical study of the adsorption of sodium salicylate and metronidazole on the
 926 PANi. *Mater. Today Proc.* 22, 100–103. <https://doi.org/10.1016/j.matpr.2019.08.103>
- 927 Abdellaoui, Y., Abou Oualid, H., Hsini, A., El Ibrahim, B., Laabd, M., El Ouardi, M., Giacomani-
 928 Vallejos, G., Gamero-Melo, P., 2021. Synthesis of zirconium-modified Merlinoite from fly ash
 929 for enhanced removal of phosphate in aqueous medium: Experimental studies supported by
 930 Monte Carlo/SA simulations. *Chem. Eng. J.* 404, 126600.
 931 <https://doi.org/10.1016/j.cej.2020.126600>
- 932 Adhikari, S.P., Hood, Z.D., Chen, V.W., More, K.L., Senevirathne, K., Lachgar, A., 2018. Visible-
 933 light-active g-C₃N₄/N-doped Sr₂Nb₂O₇ heterojunctions as photocatalysts for the hydrogen
 934 evolution reaction. *Sustain. Energy Fuels* 2, 2507–2515. <https://doi.org/10.1039/c8se00319j>
- 935 Aghighi, A., Haghighat, F., 2015. Using physical-chemical properties of reactants to estimate the
 936 performance of photocatalytic oxidation air cleaners. *Build. Environ.* 85, 114–122.
 937 <https://doi.org/10.1016/j.buildenv.2014.11.020>
- 938 Ahsaine, H.A., Slassi, A., Naciri, Y., Chennah, A., Jaramillo-Páez, C., Anfar, Z., Zbair, M.,
 939 Benlhachemi, A., Navío, J.A., 2018. Photo/Electrocatalytic Properties of Nanocrystalline ZnO
 940 and La-Doped ZnO: Combined DFT Fundamental Semiconducting Properties and
 941 Experimental Study. *ChemistrySelect* 3, 7778 – 7791.
 942 <https://doi.org/10.1002/slct.201801729>
- 943 Ajmal, Z., Muhmood, A., Dong, R., Wu, S., 2020a. Probing the efficiency of magnetically modified
 944 biomass-derived biochar for effective phosphate removal. *J. Environ. Manage.* 253, 109730.
 945 <https://doi.org/10.1016/j.jenvman.2019.109730>
- 946 Ajmal, Z., Muhmood, A., Usman, M., Kizito, S., Lu, J., Dong, R., Wu, S., 2018. Phosphate removal
 947 from aqueous solution using iron oxides: Adsorption, desorption and regeneration
 948 characteristics. *J. Colloid Interface Sci.* 528, 145–155.
 949 <https://doi.org/10.1016/j.jcis.2018.05.084>
- 950 Ajmal, Z., Usman, M., Anastopoulos, I., Qadeer, A., Zhu, R., Wakeel, A., Dong, R., 2020b. Use
 951 of nano-/micro-magnetite for abatement of cadmium and lead contamination. *J. Environ.*
 952 *Manage.* 264, 110477. <https://doi.org/10.1016/j.jenvman.2020.110477>
- 953 Amaterz, Elhassan, Tara, A., Bouddouch, A., Taoufyq, A., Bakiz, B., Benlhachemi, A., Jbara, O.,
 954 2020. Photo-electrochemical degradation of wastewaters containing organics catalysed by
 955 phosphate-based materials: a review. *Rev. Environ. Sci. Biotechnol.* 9.
 956 <https://doi.org/10.1007/s11157-020-09547-9>
- 957 Amaterz, E., Tara, A., Bouddouch, A., Taoufyq, A., Bakiz, B., Lazar, F., Gilliot, M., Benlhachemi,
 958 A., Bazzi, L., Jbara, O., 2020. Hierarchical flower-like SrHPO₄ electrodes for the
 959 photoelectrochemical degradation of Rhodamine B. *J. Appl. Electrochem.*
 960 <https://doi.org/10.1007/s10800-020-01416-1>

961 Amonette, J.E., Matyáš, J., 2017. Functionalized silica aerogels for gas-phase purification,
 962 sensing, and catalysis: A review. *Microporous Mesoporous Mater.* 250, 100–119.
 963 <https://doi.org/10.1016/j.micromeso.2017.04.055>

964 Aramendía, M.A., Colmenares, J.C., Marinas, A., Marinas, J.M., Moreno, J.M., Navío, J.A.,
 965 Urbano, F.J., 2007. Effect of the redox treatment of Pt/TiO₂ system on its photocatalytic
 966 behaviour in the gas phase selective photooxidation of propan-2-ol. *Catal. Today* 128, 235–
 967 244. <https://doi.org/10.1016/j.cattod.2007.07.009>

968 Araña, J., Alonso, A.P., Rodríguez, J.M.D., Colón, G., Navío, J.A., Peña, J.P., 2009. FTIR study
 969 of photocatalytic degradation of 2-propanol in gas phase with different TiO₂ catalysts. *Appl.*
 970 *Catal. B Environ.* 89, 204–213. <https://doi.org/10.1016/j.apcatb.2008.11.027>

971 Araña, J., Doña-Rodríguez, J.M., González-Díaz, O., Tello Rendón, E., Herrera Melián, J.A.,
 972 Colón, G., Navío, J.A., Pérez Peña, J., 2004. Gas-phase ethanol photocatalytic degradation
 973 study with TiO₂ doped with Fe, Pd and Cu. *J. Mol. Catal. A Chem.* 215, 153–160.
 974 <https://doi.org/10.1016/j.molcata.2004.01.020>

975 Ardizzone, S., Bianchi, C.L., Cappelletti, G., Gialanella, S., Pirola, C., Ragaini, V., 2007. Tailored
 976 anatase/brookite nanocrystalline TiO₂. the optimal particle features for liquid and gas-phase
 977 photocatalytic reactions. *J. Phys. Chem. C* 111, 13222–13231.
 978 <https://doi.org/10.1021/jp0741096>

979 Ardizzone, S., Bianchi, C.L., Cappelletti, G., Naldoni, A., Pirola, C., 2008. Photocatalytic
 980 degradation of toluene in the gas phase: Relationship between surface species and catalyst
 981 features. *Environ. Sci. Technol.* 42, 6671–6676. <https://doi.org/10.1021/es8009327>

982 Azzouz, A., Kailasa, S.K., Lee, S.S., J. Rascón, A., Ballesteros, E., Zhang, M., Kim, K.H., 2018.
 983 Review of nanomaterials as sorbents in solid-phase extraction for environmental samples.
 984 *TrAC - Trends Anal. Chem.* 108, 347–369. <https://doi.org/10.1016/j.trac.2018.08.009>

985 Ba Mohammed, B., Hsini, A., Abdellaoui, Y., Abou Oualid, H., Laabd, M., El Ouardi, M., Ait Addi,
 986 A., Yamni, K., Tijani, N., 2020. Fe-ZSM-5 zeolite for efficient removal of basic Fuchsin dye
 987 from aqueous solutions: Synthesis, characterization and adsorption process optimization
 988 using BBD-RSM modeling. *J. Environ. Chem. Eng.* 8, 104419.
 989 <https://doi.org/10.1016/j.jece.2020.104419>

990 Ballari, M.M., Hunger, M., Hüskén, G., Brouwers, H.J.H., 2010. NO_x photocatalytic degradation
 991 employing concrete pavement containing titanium dioxide. *Appl. Catal. B Environ.* 95, 245–
 992 254. <https://doi.org/10.1016/j.apcatb.2010.01.002>

993 Banerjee, S., Dionysiou, D.D., Pillai, S.C., 2015. Self-cleaning applications of TiO₂ by photo-
 994 induced hydrophilicity and photocatalysis. *Appl. Catal. B Environ.* 176–177, 396–428.
 995 <https://doi.org/10.1016/j.apcatb.2015.03.058>

996 Barea, E., Montoro, C., Navarro, J.A.R., 2014. Toxic gas removal-metal-organic frameworks for
 997 the capture and degradation of toxic gases and vapours. *Chem. Soc. Rev.* 43, 5419–5430.
 998 <https://doi.org/10.1039/c3cs60475f>

999 Barebita, H., Naciri, Y., Ferraa, S., Nimour, A., Guedira, T., 2020. Investigation of structural and
 1000 photocatalytic behavior of Bi₁₃B_{1-2x}V_xP_xO_{20.95+2x} (0 ≤ x ≤ 0.5). *Solid State Sci.* 108, 106389.
 1001 <https://doi.org/10.1016/j.solidstatesciences.2020.106389>

1002 Belaisaoui, B., Le Moullec, Y., Favre, E., 2016. Energy efficiency of a hybrid
 1003 membrane/condensation process for VOC (Volatile Organic Compounds) recovery from air:

1004 A generic approach. *Energy* 95, 291–302. <https://doi.org/10.1016/j.energy.2015.12.006>

1005 Benafqir, M., Hsini, A., Laabd, M., Laktif, T., Ait Addi, A., Albourine, A., El Alem, N., 2019.
 1006 Application of Density Functional Theory computation (DFT) and Process Capability Study
 1007 for performance evaluation of Orthophosphate removal process using
 1008 Polyaniline@Hematite-titaniferous sand composite (PANI@HTS) as a substrate. *Sep. Purif.*
 1009 *Technol.* 236, 116286. <https://doi.org/10.1016/j.seppur.2019.116286>

1010 Bianchi, C.L., Cerrato, G., Morandi, S., Di Michele, A., Djellabi, R., Capucci, V., 2020. Sustainable
 1011 photocatalytic porcelain grés slabs active under LED light for indoor depollution and bacteria
 1012 reduction, *Handbook of Smart Photocatalytic Materials*. INC. <https://doi.org/10.1016/b978-0-12-819049-4.00008-8>

1014 Bianchi, C.L., Gatto, S., Pirola, C., Naldoni, A., Di Michele, A., Cerrato, G., Crocellà, V., Capucci,
 1015 V., 2014. Photocatalytic degradation of acetone, acetaldehyde and toluene in gas-phase:
 1016 Comparison between nano and micro-sized TiO₂. *Appl. Catal. B Environ.* 146, 123–130.
 1017 <https://doi.org/10.1016/j.apcatb.2013.02.047>

1018 Bianchi, C.L., Pirola, C., Stucchi, M., Sacchi, B., Cerrato, G., Morandi, S., Di Michele, A., Carletti,
 1019 A., Capucci, V., 2016. A New Frontier of Photocatalysis Employing Micro-Sized TiO₂:
 1020 Air/Water Pollution Abatement and Self-Cleaning/ Antibacterial Applications. *Semicond.*
 1021 *Photocatal. - Mater. Mech. Appl.* <https://doi.org/10.5772/62892>

1022 Bickley, R.I., Munuera, G., Stone, F.S., 1973. Photoadsorption and photocatalysis at rutile
 1023 surfaces. II. Photocatalytic oxidation of isopropanol. *J. Catal.* 31, 398–407.
 1024 [https://doi.org/10.1016/0021-9517\(73\)90311-4](https://doi.org/10.1016/0021-9517(73)90311-4)

1025 Bierman, M.J., Lau, Y.K.A., Kvit, A. V., Schmitt, A.L., Jin, S., 2008. Dislocation-driven nanowire
 1026 growth and Eshelby twist. *Science* (80-.). 320, 1060–1063.
 1027 <https://doi.org/10.1126/science.1157131>

1028 Bouziani, A., Park, J., Ozturk, A., 2020. Synthesis of α -Fe₂O₃/TiO₂ heterogeneous composites by
 1029 the sol-gel process and their photocatalytic activity. *J. Photochem. Photobiol. A Chem.* 400,
 1030 112718. <https://doi.org/10.1016/j.jphotochem.2020.112718>

1031 Boyjoo, Y., Sun, H., Liu, J., Pareek, V.K., Wang, S., 2017. A review on photocatalysis for air
 1032 treatment: From catalyst development to reactor design. *Chem. Eng. J.* 310, 537–559.
 1033 <https://doi.org/10.1016/j.cej.2016.06.090>

1034 Cai, T., Zeng, W., Liu, Y., Wang, L., Dong, W., Chen, H., Xia, X., 2020. A promising inorganic-
 1035 organic Z-scheme photocatalyst Ag₃PO₄/PDI supermolecule with enhanced photoactivity
 1036 and photostability for environmental remediation. *Appl. Catal. B Environ.* 263, 118327.
 1037 <https://doi.org/10.1016/j.apcatb.2019.118327>

1038 Cappelletti, G., Ardizzone, S., Bianchi, C.L., Gialanella, S., Naldoni, A., Pirola, C., Ragaini, V.,
 1039 2009. Photodegradation of pollutants in air: Enhanced properties of nano-TiO₂ prepared by
 1040 ultrasound. *Nanoscale Res. Lett.* 4, 97–105. <https://doi.org/10.1007/s11671-008-9208-3>

1041 Chai, Y., Ding, J., Wang, L., Liu, Q., Ren, J., Dai, W.L., 2015. Enormous enhancement in
 1042 photocatalytic performance of Ag₃PO₄/HAp composite: A Z-scheme mechanism insight.
 1043 *Appl. Catal. B Environ.* 179, 29–36. <https://doi.org/10.1016/j.apcatb.2015.05.006>

1044 Che, H., Liu, C., Che, G., Liao, G., Dong, H., Li, Chunxue, Song, N., Li, Chunmei, 2020. Facile
 1045 construction of porous intramolecular g-C₃N₄-based donor-acceptor conjugated copolymers
 1046 as highly efficient photocatalysts for superior H₂ evolution. *Nano Energy* 67, 104273.

1047 <https://doi.org/10.1016/j.nanoen.2019.104273>

1048 Chen, X., Huang, X., Yi, Z., 2014. Enhanced ethylene photodegradation performance of g-C₃N₄-
 1049 Ag₃PO₄ composites with direct Z-scheme configuration. *Chem. - A Eur. J.* 20, 17590–17596.
 1050 <https://doi.org/10.1002/chem.201404284>

1051 Chen, X., Li, R., Pan, X., Huang, X., Yi, Z., 2017. Fabrication of In₂O₃-Ag-Ag₃PO₄ composites with
 1052 Z-scheme configuration for photocatalytic ethylene degradation under visible light irradiation.
 1053 *Chem. Eng. J.* 320, 644–652. <https://doi.org/10.1016/j.cej.2017.03.072>

1054 Chen, Z., Bing, F., Liu, Q., Zhang, Z., Fang, X., 2015. Novel Z-scheme visible-light-driven
 1055 Ag₃PO₄/Ag/SiC photocatalysts with enhanced photocatalytic activity. *J. Mater. Chem. A* 3,
 1056 4652–4658. <https://doi.org/10.1039/c4ta06530a>

1057 Chen, Z., Wang, W., Zhang, Z., Fang, X., 2013. High-Efficiency Visible-Light-Driven Ag₃PO₄ /AgI
 1058 Photocatalysts: Z - Scheme Photocatalytic Mechanism for Their Enhanced Photocatalytic
 1059 Activity. *J. Phys. Chem. CC* 117, 19346–19352.
 1060 <https://doi.org/https://doi.org/10.1021/jp406508y>

1061 Chenchana, A., Nemamcha, A., Moumeni, H., Doña Rodríguez, J.M., Araña, J., Navío, J.A.,
 1062 González Díaz, O., Pulido Melián, E., 2019. Photodegradation of 2,4-dichlorophenoxyacetic
 1063 acid over TiO₂ (B)/anatase nanobelts and Au-TiO₂ (B)/anatase nanobelts. *Appl. Surf. Sci.*
 1064 467–468, 1076–1087. <https://doi.org/10.1016/j.apsusc.2018.10.175>

1065 da Costa Filho, B.M., Araujo, A.L.P., Padrao, S.P., Boaventura, R.A.R., Dias, M.M., Lopes, J.C.B.,
 1066 Vilar, V.J.P., 2019a. Effect of catalyst coated surface, illumination mechanism and light
 1067 source in heterogeneous TiO₂ photocatalysis using a mili-photoreactor for n-decane
 1068 oxidation at gas phase. *Chem. Eng. J.* 366, 560–568.
 1069 <https://doi.org/10.1016/j.cej.2019.02.122>

1070 da Costa Filho, B.M., Araujo, A.L.P., Silva, G. V., Boaventura, R.A.R., Dias, M.M., Lopes, J.C.B.,
 1071 Vilar, V.J.P., 2017. Intensification of heterogeneous TiO₂ photocatalysis using an innovative
 1072 micro-meso-structured-photoreactor for n-decane oxidation at gas phase. *Chem. Eng. J.*
 1073 310, 331–341. <https://doi.org/10.1016/j.cej.2016.09.080>

1074 da Costa Filho, B.M., Silva, G. V., Boaventura, R.A.R., Dias, M.M., Lopes, J.C.B., Vilar, V.J.P.,
 1075 2019b. Ozonation and ozone-enhanced photocatalysis for VOC removal from air streams:
 1076 Process optimization, synergy and mechanism assessment. *Sci. Total Environ.* 687, 1357–
 1077 1368. <https://doi.org/10.1016/j.scitotenv.2019.05.365>

1078 da Costa Filho, B.M., Vilar, V.J.P., 2019. Strategies for the intensification of photocatalytic
 1079 oxidation processes towards air streams decontamination: A review. *Chem. Eng. J.* 123531.
 1080 <https://doi.org/10.1016/j.cej.2019.123531>

1081 Deng, X., Chen, Y., Wen, J., Xu, Y., Zhu, J., Bian, Z., 2020. Polyaniline-TiO₂ composite
 1082 photocatalysts for light-driven hexavalent chromium ions reduction. *Sci. Bull.* 65, 105–112.
 1083 <https://doi.org/10.1016/j.scib.2019.10.020>

1084 Ding, J., Hong, B., Luo, Z., Sun, S., Bao, J., Gao, C., 2014. Mesoporous monoclinic CaIn₂S₄ with
 1085 surface nanostructure: An efficient photocatalyst for hydrogen production under visible light.
 1086 *J. Phys. Chem. C* 118, 27690–27697. <https://doi.org/10.1021/jp508497a>

1087 Djeghri, N., Formenti, M., Juillet, F., Teichner, S.J., 1974. Photointeraction on the Surface of
 1088 Titanium Dioxide between Oxygen and Alkanes. *Faraday Discuss. Chem. Soc.* 58, 185–193.
 1089 <https://doi.org/https://doi.org/10.1039/DC9745800185>

1090 Djellabi, R., Fouzi Ghorab, M., Smara, A., Bianchi, C.L., Cerrato, G., Zhao, X., Yang, B., 2020.
 1091 Titania–Montmorillonite for the Photocatalytic Removal of Contaminants from Water: Adsorb
 1092 & Shuttle Process. *Green Mater. Wastewater Treat.* 291–319. [https://doi.org/10.1007/978-](https://doi.org/10.1007/978-3-030-17724-9_13)
 1093 3-030-17724-9_13

1094 Djellabi, R., Yang, B., Adeel Sharif, H.M., Zhang, J., Ali, J., Zhao, X., 2019a. Sustainable and
 1095 easy recoverable magnetic TiO₂-Lignocellulosic Biomass@Fe₃O₄ for solar photocatalytic
 1096 water remediation. *J. Clean. Prod.* 233, 841–847.
 1097 <https://doi.org/10.1016/j.jclepro.2019.06.125>

1098 Djellabi, R., Yang, B., Xiao, K., Gong, Y., Cao, D., Sharif, H.M.A., Zhao, X., Zhu, C., Zhang, J.,
 1099 2019b. Unravelling the mechanistic role of Ti–O–C bonding bridge at titania/lignocellulosic
 1100 biomass interface for Cr(VI) photoreduction under visible light. *J. Colloid Interface Sci.* 553,
 1101 409–417. <https://doi.org/10.1016/j.jcis.2019.06.052>

1102 Dong, G., Zhang, Y., Pan, Q., Qiu, J., 2014. A fantastic graphitic carbon nitride (g-C₃N₄) material:
 1103 Electronic structure, photocatalytic and photoelectronic properties. *J. Photochem. Photobiol.*
 1104 C Photochem. Rev. 20, 33–50. <https://doi.org/10.1016/j.jphotochemrev.2014.04.002>

1105 Dong, P., Hou, G., Liu, C., Zhang, X., Tian, H., Xu, F., Xi, X., Shao, R., 2016. Origin of activity
 1106 and stability enhancement for Ag₃PO₄ photocatalyst after calcination. *Materials (Basel)*. 9,
 1107 1–17. <https://doi.org/10.3390/ma9120968>

1108 Ehn, M., Thornton, J.A., Kleist, E., Sipilä, M., Junninen, H., Pullinen, I., Springer, M., Rubach, F.,
 1109 Tillmann, R., Lee, B., Lopez-Hilfiker, F., Andres, S., Acir, I.H., Rissanen, M., Jokinen, T.,
 1110 Schobesberger, S., Kangasluoma, J., Kontkanen, J., Nieminen, T., Kurtén, T., Nielsen, L.B.,
 1111 Jørgensen, S., Kjaergaard, H.G., Canagaratna, M., Maso, M.D., Berndt, T., Petäjä, T.,
 1112 Wahner, A., Kerminen, V.M., Kulmala, M., Worsnop, D.R., Wildt, J., Mentel, T.F., 2014. A
 1113 large source of low-volatility secondary organic aerosol. *Nature* 506, 476–479.
 1114 <https://doi.org/10.1038/nature13032>

1115 Erdogan, N., Bouziani, A., Park, J., Micusik, M., Kim, S.Y., Majkova, E., Omastova, M., Ozturk,
 1116 A., 2019. Synthesis and enhanced photocatalytic activity of nitrogen-doped triphasic TiO₂
 1117 nanoparticles. *J. Photochem. Photobiol. A Chem.* 377, 92–100.
 1118 <https://doi.org/10.1016/j.jphotochem.2019.03.047>

1119 Essecri, A., Hsini, A., Naciri, Y., Laabd, M., Ajmal, Z., El Ouardi, M., Ait Addi, A., Albourine, A.,
 1120 2020. Novel citric acid-functionalized brown algae with a high removal efficiency of crystal
 1121 violet dye from colored wastewaters: insights into equilibrium, adsorption mechanism, and
 1122 reusability. *Int. J. Phytoremediation* 0, 1–11.
 1123 <https://doi.org/10.1080/15226514.2020.1813686>

1124 Farhanian, D., Haghighat, F., Lee, C.S., Lakdawala, N., 2013. Impact of design parameters on
 1125 the performance of ultraviolet photocatalytic oxidation air cleaner. *Build. Environ.* 66, 148–
 1126 157. <https://doi.org/10.1016/j.buildenv.2013.04.010>

1127 Fino, D., Bensaid, S., Piumetti, M., Russo, N., 2016. A review on the catalytic combustion of soot
 1128 in Diesel particulate filters for automotive applications: From powder catalysts to structured
 1129 reactors. *Appl. Catal. A Gen.* 509, 75–96. <https://doi.org/10.1016/j.apcata.2015.10.016>

1130 Fiorenza, R., Di Mauro, A., Cantarella, M., Iaria, C., Scalisi, E.M., Brundo, M.V., Gulino, A.,
 1131 Spitaleri, L., Nicotra, G., Dattilo, S., Carroccio, S.C., Privitera, V., Impellizzeri, G., 2020.
 1132 Preferential removal of pesticides from water by molecular imprinting on TiO₂
 1133 photocatalysts. *Chem. Eng. J.* 379, 122309. <https://doi.org/10.1016/j.cej.2019.122309>

- 1134 Ganesh, V.A., Raut, H.K., Nair, A.S., Ramakrishna, S., 2011. A review on self-cleaning coatings.
1135 J. Mater. Chem. 21, 16304–16322. <https://doi.org/10.1039/c1jm12523k>
- 1136 Ge, M., Zhu, N., Zhao, Y., Li, J., Liu, L., 2012. Sunlight-assisted degradation of dye pollutants in
1137 Ag₃PO₄ suspension. Ind. Eng. Chem. Res. 51, 5167–5173.
1138 <https://doi.org/10.1021/ie202864n>
- 1139 Guo, J., Ouyang, S., Li, P., Zhang, Y., Kako, T., Ye, J., 2013. A new heterojunction Ag₃PO₄/Cr-
1140 SrTiO₃ photocatalyst towards efficient elimination of gaseous organic pollutants under visible
1141 light irradiation. Appl. Catal. B Environ. 134–135, 286–292.
1142 <https://doi.org/10.1016/j.apcatb.2012.12.038>
- 1143 Guo, J., Zhou, H., Ouyang, S., Kako, T., Ye, J., 2014. An Ag₃PO₄/nitridized Sr₂Nb₂O₇ composite
1144 photocatalyst with adjustable band structures for efficient elimination of gaseous organic
1145 pollutants under visible light irradiation. Nanoscale 6, 7303–7311.
1146 <https://doi.org/10.1039/c4nr00537f>
- 1147 Guo, T., Bai, Z., Wu, C., Zhu, T., 2008. Influence of relative humidity on the photocatalytic
1148 oxidation (PCO) of toluene by TiO₂ loaded on activated carbon fibers: PCO rate and
1149 intermediates accumulation. Appl. Catal. B Environ. 79, 171–178.
1150 <https://doi.org/10.1016/j.apcatb.2007.09.033>
- 1151 He, F., Wang, Z., Li, Y., Peng, S., Liu, B., 2020. The nonmetal modulation of composition and
1152 morphology of g-C₃N₄-based photocatalysts. Appl. Catal. B Environ. 118828.
1153 <https://doi.org/10.1016/j.apcatb.2020.118828>
- 1154 He, R., Xu, D., Cheng, B., Yu, J., Ho, W., 2018. Review on nanoscale Bi-based photocatalysts.
1155 Nanoscale Horizons 3, 464–504. <https://doi.org/10.1039/c8nh00062j>
- 1156 Hsini, A., Essekre, A., Aarab, N., Laabd, M., Addi, A.A., Lakhmiri, R., Albourine, A., 2020a.
1157 Elaboration of novel polyaniline@Almond shell biocomposite for effective removal of
1158 hexavalent chromium ions and Orange G dye from aqueous solutions. Environ. Sci. Pollut.
1159 Res. 1–14. <https://doi.org/10.1007/s11356-020-08039-1>
- 1160 Hsini, A., Naciri, Y., Benafqir, M., Ajmal, Z., Aarab, N., Laabd, M., Navío, J.A., Puga, F.,
1161 Boukherroub, R., Bakiz, B., Albourine, A., 2020b. Facile synthesis and characterization of a
1162 novel 1,2,4,5-benzene tetracarboxylic acid doped polyaniline@zinc phosphate
1163 nanocomposite for highly efficient removal of hazardous hexavalent chromium ions from
1164 water. J. Colloid Interface Sci. <https://doi.org/10.1016/j.jcis.2020.10.036>
- 1165 Hsini, A., Naciri, Y., Laabd, M., El Ouardi, M., Ajmal, Z., Lakhmiri, R., Boukherroub, R., Albourine,
1166 A., 2020c. Synthesis and characterization of arginine-doped polyaniline/walnut shell hybrid
1167 composite with superior clean-up ability for chromium (VI) from aqueous media: Equilibrium,
1168 reusability and process optimization. J. Mol. Liq. 316, 113832.
1169 <https://doi.org/10.1016/j.molliq.2020.113832>
- 1170 Huang, D., Chen, S., Zeng, G., Gong, X., Zhou, C., Cheng, M., Xue, W., Yan, X., Li, J., 2019.
1171 Artificial Z-scheme photocatalytic system: What have been done and where to go? Coord.
1172 Chem. Rev. 385, 44–80. <https://doi.org/10.1016/j.ccr.2018.12.013>
- 1173 Hyuntae Cho, 2017. An Air Quality and Event Detection System with Life Logging for Monitoring
1174 Household Environments. Smart Sensors IoT Front. 251–270. https://doi.org/10.1007/978-3-319-55345-0_10
- 1176 Jafarikojour, M., Sohrabi, M., Royaei, S.J., Hassanvand, A., 2015. Evaluation and Optimization

1177 of a Novel Immobilized Photoreactor for the Degradation of Gaseous Toluene. *Clean - Soil,*
1178 *Air, Water* 43, 662–670. <https://doi.org/10.1002/clen.201300985>

1179 Ji, W., Rui, Z., Ji, H., 2019. Z-scheme $\text{Ag}_3\text{PO}_4/\text{Ag}/\text{SrTiO}_3$ Heterojunction for Visible-Light Induced
1180 Photothermal Synergistic VOCs Degradation with Enhanced Performance. *Ind. Eng. Chem.*
1181 *Res.* 58, 13950–13959. <https://doi.org/10.1021/acs.iecr.9b02176>

1182 Jia, Y., Ma, Y., Zhu, L., Dong, J., Lin, Y., 2019. Efficient visible-light-responsive photocatalyst:
1183 Hybrid $\text{TiO}_2\text{-Ag}_3\text{PO}_4$ nanorods. *Chem. Phys.* 521, 1–4.
1184 <https://doi.org/10.1016/j.chemphys.2019.01.015>

1185 Jo, W.-K., Natarajan, T.S., 2015. Facile Synthesis of Novel Redox-mediator-free Direct Z-scheme
1186 CaIn_2S_4 Marigold Flower-like TiO_2 Photocatalysts with Superior Photocatalytic Efficiency.
1187 *ACS Appl. Mater. Interfaces* 7, 17138–17154.
1188 <https://doi.org/https://doi.org/10.1021/acsami.5b03935>

1189 Jo, W.K., Kim, J.T., 2009. Application of visible-light photocatalysis with nitrogen-doped or
1190 unmodified titanium dioxide for control of indoor-level volatile organic compounds. *J. Hazard.*
1191 *Mater.* 164, 360–366. <https://doi.org/10.1016/j.jhazmat.2008.08.033>

1192 Jo, W.K., Yang, C.H., 2009. Granular-activated carbon adsorption followed by annular-type
1193 photocatalytic system for control of indoor aromatic compounds. *Sep. Purif. Technol.* 66,
1194 438–442. <https://doi.org/10.1016/j.seppur.2009.02.014>

1195 Kahk, J.M., Sheridan, D.L., Kehoe, A.B., Scanlon, D.O., Morgan, B.J., Watson, G.W., Payne, D.J.,
1196 2014. The electronic structure of silver orthophosphate: Experiment and theory. *J. Mater.*
1197 *Chem. A* 2, 6092–6099. <https://doi.org/10.1039/c3ta14191h>

1198 Kamal, M.S., Razzak, S.A., Hossain, M.M., 2016. Catalytic oxidation of volatile organic
1199 compounds (VOCs) - A review. *Atmos. Environ.* 140, 117–134.
1200 <https://doi.org/10.1016/j.atmosenv.2016.05.031>

1201 Karafas, E.S., Romanias, M.N., Stefanopoulos, V., Binas, V., Zachopoulos, A., Kiriakidis, G.,
1202 Papagiannakopoulos, P., 2019. Effect of metal doped and co-doped TiO_2 photocatalysts
1203 oriented to degrade indoor/outdoor pollutants for air quality improvement. A kinetic and
1204 product study using acetaldehyde as probe molecule. *J. Photochem. Photobiol. A Chem.*
1205 371, 255–263. <https://doi.org/10.1016/j.jphotochem.2018.11.023>

1206 Kato, S., Hirano, Y., Iwata, M., Sano, T., Takeuchi, K., Matsuzawa, S., 2005. Photocatalytic
1207 degradation of gaseous sulfur compounds by silver-deposited titanium dioxide. *Appl. Catal.*
1208 *B Environ.* 57, 109–115. <https://doi.org/10.1016/j.apcatb.2004.10.015>

1209 Kong, J., Rui, Z., Ji, H., 2016. Enhanced Photocatalytic Mineralization of Gaseous Toluene over
1210 SrTiO_3 by Surface Hydroxylation. *Ind. Eng. Chem. Res.* 55, 11923–11930.
1211 <https://doi.org/10.1021/acs.iecr.6b03270>

1212 Krishnamurthy, A., Adebayo, B., Gelles, T., Rownaghi, A., Rezaei, F., 2019. Abatement of
1213 gaseous volatile organic compounds: A process perspective. *Catal. Today* 0–1.
1214 <https://doi.org/10.1016/j.cattod.2019.05.069>

1215 Krungchanuchat, S., Ekthammathat, N., Phuruangrat, A., Thongtem, S., Thongtem, T., 2017.
1216 High UV-visible photocatalytic activity of Ag_3PO_4 dodecahedral particles synthesized by a
1217 simple hydrothermal method. *Mater. Lett.* 201, 58–61.
1218 <https://doi.org/10.1016/j.matlet.2017.04.131>

- 1219 Lam, S.M., Sin, J.C., Abdullah, A.Z., Mohamed, A.R., 2012. Degradation of wastewaters
1220 containing organic dyes photocatalysed by zinc oxide: A review. *Desalin. Water Treat.* 41,
1221 131–169. <https://doi.org/10.1080/19443994.2012.664698>
- 1222 Li, G., Wang, Y., Mao, L., 2014. Recent progress in highly efficient Ag-based visible-light
1223 photocatalysts. *RSC Adv.* 4, 53649–53661. <https://doi.org/10.1039/c4ra08044k>
- 1224 Li, J., Fang, W., Yu, C., Zhou, W., Zhu, L., Xie, Y., 2015. Ag-based semiconductor photocatalysts
1225 in environmental purification. *Appl. Surf. Sci.* 358, 46–56.
1226 <https://doi.org/10.1016/j.apsusc.2015.07.139>
- 1227 Li, J., Meng, S., Wang, T., Xu, Q., Shao, L., Jiang, D., Chen, M., 2017. Novel Au/CaIn₂S₄
1228 nanocomposites with plasmon-enhanced photocatalytic performance under visible light
1229 irradiation. *Appl. Surf. Sci.* 396, 430–437. <https://doi.org/10.1016/j.apsusc.2016.10.172>
- 1230 Li, X., Zhang, L., Yang, Z., Wang, P., Yan, Y., Ran, J., 2020. Adsorption materials for volatile
1231 organic compounds (VOCs) and the key factors for VOCs adsorption process: A review.
1232 *Sep. Purif. Technol.* 235, 116213. <https://doi.org/10.1016/j.seppur.2019.116213>
- 1233 Li, X., Zhang, Z., Yao, C., Lu, X., Zhao, X., Ni, C., 2016. Attapulgite-CeO₂/MoS₂ ternary
1234 nanocomposite for photocatalytic oxidative desulfurization. *Appl. Surf. Sci.* 364, 589–596.
1235 <https://doi.org/10.1016/j.apsusc.2015.12.196>
- 1236 Liang, S., Zhang, D., Pu, X., Yao, X., Han, R., Yin, J., Ren, X., 2019. A novel Ag₂O/g-C₃N₄ p-n
1237 heterojunction photocatalysts with enhanced visible and near-infrared light activity. *Sep.*
1238 *Purif. Technol.* 210, 786–797. <https://doi.org/10.1016/j.seppur.2018.09.008>
- 1239 Liao, L., Heylen, S., Sree, S.P., Vallaey, B., Keulemans, M., Lenaerts, S., Roeffaers, M.B.J.,
1240 Martens, J.A., 2017. Photocatalysis assisted simultaneous carbon oxidation and NO_x
1241 reduction. *Appl. Catal. B Environ.* 202, 381–387.
1242 <https://doi.org/10.1016/j.apcatb.2016.09.042>
- 1243 Likodimos, V., 2018. Photonic crystal-assisted visible light activated TiO₂ photocatalysis. *Appl.*
1244 *Catal. B Environ.* 230, 269–303. <https://doi.org/10.1016/j.apcatb.2018.02.039>
- 1245 Liu, B., Liu, X., Li, L., Zhuge, Z., Li, Y., Li, C., Gong, Y., Niu, L., Xu, S., Sun, C.Q., 2019. CaIn₂S₄
1246 decorated WS₂ hybrid for efficient Cr(VI) reduction. *Appl. Surf. Sci.* 484, 300–306.
1247 <https://doi.org/10.1016/j.apsusc.2019.03.322>
- 1248 Liu, J.J., Fu, X.L., Chen, S.F., Zhu, Y.F., 2011. Electronic structure and optical properties of
1249 Ag₃PO₄ photocatalyst calculated by hybrid density functional method. *Appl. Phys. Lett.* 99,
1250 2011–2014. <https://doi.org/10.1063/1.3660319>
- 1251 Liu, W.T., Wu, B.H., Lai, Y.T., Tai, N.H., Perng, T.P., Chen, L.J., 2018. Enhancement of water
1252 splitting by controlling the amount of vacancies with varying vacuum level in the synthesis
1253 system of SnO_{2-x}/In₂O_{3-y} heterostructure as photocatalyst. *Nano Energy* 47, 18–25.
1254 <https://doi.org/10.1016/j.nanoen.2018.02.037>
- 1255 Liu, Y., Kong, J., Yuan, J., Zhao, W., Zhu, X., Sun, C., Xie, J., 2018. Enhanced photocatalytic
1256 activity over flower-like sphere Ag/Ag₂CO₃/BiVO₄ plasmonic heterojunction photocatalyst for
1257 tetracycline degradation. *Chem. Eng. J.* 331, 242–254.
1258 <https://doi.org/10.1016/j.cej.2017.08.114>
- 1259 Lopes, F.V.S., Monteiro, R.A.R., Silva, A.M.T., Silva, G. V., Faria, J.L., Mendes, A.M., Vilar,
1260 V.J.P., Boaventura, R.A.R., 2012. Insights into UV-TiO₂ photocatalytic degradation of PCE

for air decontamination systems. *Chem. Eng. J.* 204–205, 244–257.
<https://doi.org/10.1016/j.cej.2012.07.079>

Low, J., Jiang, C., Cheng, B., Wageh, S., Al-Ghamdi, A.A., Yu, J., 2017. A Review of Direct Z-Scheme Photocatalysts. *Small Methods* 1, 1700080.
<https://doi.org/10.1002/smtd.201700080>

Lu, B., Ma, N., Wang, Y., Qiu, Y., Hu, H., Zhao, J., Liang, D., Xu, S., Li, X., Zhu, Z., Cui, C., 2015. Visible-light-driven $\text{TiO}_2/\text{Ag}_3\text{PO}_4/\text{GO}$ heterostructure photocatalyst with dual-channel for photo-generated charges separation, *Journal of Alloys and Compounds*.
<https://doi.org/10.1016/j.jallcom.2015.01.008>

Luengas, A., Barona, A., Hort, C., Gallastegui, G., Platel, V., Elias, A., 2015. A review of indoor air treatment technologies. *Rev. Environ. Sci. Biotechnol.* 14, 499–522.
<https://doi.org/10.1007/s11157-015-9363-9>

Ma, X., Lu, B., Li, D., Shi, R., Pan, C., Zhu, Y., 2011. Origin of photocatalytic activation of silver orthophosphate from first-principles. *J. Phys. Chem. C* 115, 4680–4687.
<https://doi.org/10.1021/jp111167u>

Malakar, S., Saha, P. Das, Baskaran, D., Rajamanickam, R., 2017. Comparative study of biofiltration process for treatment of VOCs emission from petroleum refinery wastewater—A review. *Environ. Technol. Innov.* 8, 441–461. <https://doi.org/10.1016/j.eti.2017.09.007>

Mamaghani, A.H., Haghighat, F., Lee, C.S., 2017. Photocatalytic oxidation technology for indoor environment air purification: The state-of-the-art. *Appl. Catal. B Environ.* 203, 247–269.
<https://doi.org/10.1016/j.apcatb.2016.10.037>

Martín-Gómez, A.N., Navío, J.A., Jaramillo-Páez, C., Sánchez-Cid, P., Hidalgo, M.C., 2020. Hybrid $\text{ZnO}/\text{Ag}_3\text{PO}_4$ photocatalysts, with low and high phosphate molar percentages. *J. Photochem. Photobiol. A Chem.* 388, 112196.
<https://doi.org/10.1016/j.jphotochem.2019.112196>

Martin, D.J., Liu, G., Moniz, S.J.A., Bi, Y., Beale, A.M., Ye, J., Tang, J., 2015. Efficient visible driven photocatalyst, silver phosphate: performance, understanding and perspective. *Chem. Soc. Rev.* 44, 7808–7828. <https://doi.org/10.1039/c5cs00380f>

Masih, D., Ma, Y., Rohani, S., 2017. Graphitic C_3N_4 based noble-metal-free photocatalyst systems: A review. *Appl. Catal. B Environ.* 206, 556–588.
<https://doi.org/10.1016/j.apcatb.2017.01.061>

Mazierski, P., Mikolajczyk, A., Bajorowicz, B., Malankowska, A., Zaleska-Medynska, A., Nadolna, J., 2018. The role of lanthanides in TiO_2 -based photocatalysis: A review. *Appl. Catal. B Environ.* 233, 301–317. <https://doi.org/10.1016/j.apcatb.2018.04.019>

Monteiro, R.A.R., Miranda, S.M., Rodrigues-Silva, C., Faria, J.L., Silva, A.M.T., Boaventura, R.A.R., Vilar, V.J.P., 2015. Gas phase oxidation of n-decane and PCE by photocatalysis using an annular photoreactor packed with a monolithic catalytic bed coated with P25 and PC500. *Appl. Catal. B Environ.* 165, 306–315. <https://doi.org/10.1016/j.apcatb.2014.10.026>

Mu, J., Chen, B., Zhang, M., Guo, Z., Zhang, P., Zhang, Z., Sun, Y., Shao, C., Liu, Y., 2012. Enhancement of the visible-light photocatalytic activity of $\text{In}_2\text{O}_3\text{-TiO}_2$ nanofiber heteroarchitectures. *ACS Appl. Mater. Interfaces* 4, 424–430.
<https://doi.org/10.1021/am201499r>

1303 Murcia, J.J., Hidalgo, M.C., Navío, J.A., Vaiano, V., Ciambelli, P., Sannino, D., 2012. Ethanol
1304 partial photooxidation on Pt/TiO₂ catalysts as green route for acetaldehyde synthesis. *Catal.*
1305 *Today* 196, 101–109. <https://doi.org/10.1016/j.cattod.2012.02.033>

1306 Naciri, Y., Ait Ahsaine, H., Chennah, A., Amedlous, A., Taoufyq, A., Bakiz, B., Ezahri, M., Villain,
1307 S., Benlhachemi, A., 2018. Facile synthesis, characterization and photocatalytic
1308 performance of Zn₃(PO₄)₂ platelets toward photodegradation of Rhodamine B dye. *J.*
1309 *Environ. Chem. Eng.* 6, 1840–1847. <https://doi.org/10.1016/j.jece.2018.02.009>

1310 Naciri, Y., Bouddouch, A., Bakiz, B., Taoufyq, A., Ezahri, M., Benlhachemi, A., 2019a.
1311 Photocatalytic degradation of sulfadiazine by Zn₃(PO₄)₂/BiPO₄ composites upon UV light
1312 irradiation. *Mater. Today Proc.* 3, 8–11. <https://doi.org/10.1016/j.matpr.2019.08.071>

1313 Naciri, Y., Chennah, A., Jaramillo-Páez, C., Navío, J.A., Bakiz, B., Taoufyq, A., Ezahri, M., Villain,
1314 S., Guinneton, F., Benlhachemi, A., 2019b. Preparation, characterization and photocatalytic
1315 degradation of Rhodamine B dye over a novel Zn₃(PO₄)₂/BiPO₄ catalyst. *J. Environ. Chem.*
1316 *Eng.* 7, 103075. <https://doi.org/10.1016/j.jece.2019.103075>

1317 Naciri, Y., Hsini, A., Ajmal, Z., Bouddouch, A., Bakiz, B., Navío, J.A., Albourine, A., Valmalette,
1318 J.C., Ezahri, M., Benlhachemi, A., 2020a. Influence of Sr-doping on structural, optical and
1319 photocatalytic properties of synthesized Ca₃(PO₄)₂. *J. Colloid Interface Sci.* 572, 269–280.
1320 <https://doi.org/10.1016/j.jcis.2020.03.105>

1321 Naciri, Y., Hsini, A., Ajmal, Z., Navío, J.A., Bakiz, B., Albourine, A., Ezahri, M., Benlhachemi, A.,
1322 2020b. Recent progress on the enhancement of photocatalytic properties of BiPO₄ using π–
1323 conjugated materials. *Adv. Colloid Interface Sci.* 280, 102160.
1324 <https://doi.org/10.1016/j.cis.2020.102160>

1325 Navakoteswara Rao, V., Lakshmana Reddy, N., Mamatha Kumari, M., Ravi, P., Sathish, M.,
1326 Kuruvilla, K.M., Preethi, V., Reddy, K.R., Shetti, N.P., Aminabhavi, T.M., Shankar, M. V.,
1327 2019. Photocatalytic recovery of H₂ from H₂S containing wastewater: Surface and interface
1328 control of photo-excitons in Cu₂S@TiO₂ core-shell nanostructures. *Appl. Catal. B Environ.*
1329 254, 174–185. <https://doi.org/10.1016/j.apcatb.2019.04.090>

1330 Ng, H.N., Calvo, C., Faggiani, R., 1978. A new investigation of the structure of silver
1331 orthophosphate. *Acta Crystallogr. Sect. B Struct. Crystallogr. Cryst. Chem.* 34, 898–899.
1332 <https://doi.org/10.1107/s0567740878014570>

1333 Nie, L., Duan, B., Lu, A., Zhang, L., 2019. Pd/TiO₂ @ Carbon Microspheres Derived from Chitin
1334 for Highly Efficient Photocatalytic Degradation of Volatile Organic Compounds. *ACS Sustain.*
1335 *Chem. Eng.* 7, 1658–1666. <https://doi.org/10.1021/acssuschemeng.8b05426>

1336 Nisar, J., Pathak, B., Ahuja, R., 2012. Screened hybrid density functional study on Sr 2Nb 2O 7
1337 for visible light photocatalysis. *Appl. Phys. Lett.* 100, 181903.
1338 <https://doi.org/10.1063/1.4709486>

1339 Olmo, N.R.S., Saldiva, P.H. do N., Braga, A.L.F., Lin, C.A., Santos, U. de P., Pereirai, L.A.A.,
1340 2011. A review of low-level air pollution and adverse effects on human health: Implications
1341 for epidemiological studies and public policy. *Clinics* 66, 681–690.
1342 <https://doi.org/10.1590/S1807-59322011000400025>

1343 Park, H., Park, Y., Kim, W., Choi, W., 2013. Surface modification of TiO₂ photocatalyst for
1344 environmental applications. *J. Photochem. Photobiol. C Photochem. Rev.* 15, 1–20.
1345 <https://doi.org/10.1016/j.jphotochemrev.2012.10.001>

1346 Passalía, C., Alfano, O.M., Brandi, R.J., 2017. Integral design methodology of photocatalytic
 1347 reactors for air pollution remediation. *Molecules* 22, 1–17.
 1348 <https://doi.org/10.3390/molecules22060945>

1349 Patil, S.B., Basavarajappa, P.S., Ganganagappa, N., Jyothi, M.S., Raghu, A. V., Reddy, K.R.,
 1350 2019. Recent advances in non-metals-doped TiO₂ nanostructured photocatalysts for visible-
 1351 light driven hydrogen production, CO₂ reduction and air purification. *Int. J. Hydrogen Energy*
 1352 44, 13022–13039. <https://doi.org/10.1016/j.ijhydene.2019.03.164>

1353 Pettit, T., Bettles, M., Chapman, A.R., Hoch, L.M., James, N.D., Irga, P.J., Torpy, F.R., 2019. The
 1354 botanical biofiltration of VOCs with active airflow: is removal efficiency related to chemical
 1355 properties? *Atmos. Environ.* 214. <https://doi.org/10.1016/j.atmosenv.2019.116839>

1356 Pettit, T., Irga, P.J., Torpy, F.R., 2018. Towards practical indoor air phytoremediation: A review.
 1357 *Chemosphere* 208, 960–974. <https://doi.org/10.1016/j.chemosphere.2018.06.048>

1358 Photoadsorption, I., 1973. Photoadsorption and photocatalysis at rutile surfaces: I.
 1359 Photoadsorption of oxygen. *J. Catal.* 31, 389–397. [https://doi.org/s://doi.org/10.1016/0021-](https://doi.org/s://doi.org/10.1016/0021-9517(73)90310-2)
 1360 [9517\(73\)90310-2](https://doi.org/s://doi.org/10.1016/0021-9517(73)90310-2)

1361 Pichat, P., 2019. A brief survey of the practicality of using photocatalysis to purify the ambient air
 1362 (indoors or outdoors) or air effluents. *Appl. Catal. B Environ.* 245, 770–776.
 1363 <https://doi.org/10.1016/j.apcatb.2018.12.027>

1364 Pirhashemi, M., Habibi-Yangjeh, A., Rahim Pouran, S., 2018. Review on the criteria anticipated
 1365 for the fabrication of highly efficient ZnO-based visible-light-driven photocatalysts. *J. Ind.*
 1366 *Eng. Chem.* 62, 1–25. <https://doi.org/10.1016/j.jiec.2018.01.012>

1367 Puga, F., Navío, J.A., Jaramillo-Páez, C., Sánchez-Cid, P., Hidalgo, M.C., 2020. Microwave-
 1368 assisted sol-gel synthesis of TiO₂ in the presence of halogenhydric acids. Characterization
 1369 and photocatalytic activity. *J. Photochem. Photobiol. A Chem.* 394, 112457.
 1370 <https://doi.org/10.1016/j.jphotochem.2020.112457>

1371 Qadeer, A., Liu, S., Liu, M., Liu, X., Ajmal, Z., Huang, Y., Jing, Y., Khalil, S.K., Zhao, D., Weining,
 1372 D., Wei, X.Y., Liu, Y., 2019. Historically linked residues profile of OCPs and PCBs in surface
 1373 sediments of typical urban river networks, Shanghai: Ecotoxicological state and sources. *J.*
 1374 *Clean. Prod.* 231, 1070–1078. <https://doi.org/10.1016/j.jclepro.2019.05.203>

1375 Qadeer, A., Saqib, Z.A., Ajmal, Z., Xing, C., Khan Khalil, S., Usman, M., Huang, Y., Bashir, S.,
 1376 Ahmad, Z., Ahmed, S., Thebo, K.H., Liu, M., 2020. Concentrations, pollution indices and
 1377 health risk assessment of heavy metals in road dust from two urbanized cities of Pakistan:
 1378 Comparing two sampling methods for heavy metals concentration. *Sustain. Cities Soc.* 53,
 1379 101959. <https://doi.org/10.1016/j.scs.2019.101959>

1380 Qiu, W., Dou, K., Zhou, Y., Huang, H., Chen, Y., Lu, H., 2018. Hierarchical pore structure of
 1381 activated carbon fabricated by CO₂/microwave for volatile organic compounds adsorption.
 1382 *Chinese J. Chem. Eng.* 26, 81–88. <https://doi.org/10.1016/j.cjche.2017.04.006>

1383 Rao, X., Dou, H., Long, D., Zhang, Y., 2020. Ag₃PO₄/g-C₃N₄ nanocomposites for photocatalytic
 1384 degrading gas phase formaldehyde at continuous flow under 420 nm LED irradiation.
 1385 *Chemosphere* 244, 125462. <https://doi.org/10.1016/j.chemosphere.2019.125462>

1386 Rawal, S.B., Sung, S. Do, Lee, W.I., 2012. Novel Ag₃PO₄/TiO₂ composites for efficient
 1387 decomposition of gaseous 2-propanol under visible-light irradiation. *Catal. Commun.* 17,
 1388 131–135. <https://doi.org/10.1016/j.catcom.2011.10.034>

- 1389 Reyna-Cavazos, K.A., la Cruz, A.M. de, Longoria Rodríguez, F.E., López-Cuellar, E., 2020.
1390 Synthesis of bismuth oxyiodide (BiOI) by means of microwaves in glycerol with high
1391 photocatalytic activity for the elimination of NO_x and SO₂. Res. Chem. Intermed. 46, 923–
1392 941. <https://doi.org/10.1007/s11164-019-03998-8>
- 1393 Rodriguez Castillo, A.S., Biard, P.F., Guihéneuf, S., Paquin, L., Amrane, A., Couvert, A., 2019.
1394 Assessment of VOC absorption in hydrophobic ionic liquids: Measurement of partition and
1395 diffusion coefficients and simulation of a packed column. Chem. Eng. J. 360, 1416–1426.
1396 <https://doi.org/10.1016/j.cej.2018.10.146>
- 1397 S. Ferraa, Naciri, Y., Hsini, A., Barebita, H., Bouziani, A., A.Albourine, A.Nimour, Guedira, T.,
1398 2020. Evolution of the physicochemical and photocatalytic properties of BaO embedded in
1399 bismuth phosphovanadates glasses. Chem. Phys. Lett. 138173.
- 1400 Saadetnejad, D., Yıldırım, R., 2018. Photocatalytic hydrogen production by water splitting over
1401 Au/Al-SrTiO₃. Int. J. Hydrogen Energy 43, 1116–1122.
1402 <https://doi.org/10.1016/j.ijhydene.2017.10.154>
- 1403 Sansotera, M., Geran Malek Kheyli, S., Baggioli, A., Bianchi, C.L., Peddeferri, M.P., Diamanti,
1404 M.V., Navarrini, W., 2019. Absorption and photocatalytic degradation of VOCs by
1405 perfluorinated ionomeric coating with TiO₂ nanopowders for air purification. Chem. Eng. J.
1406 361, 885–896. <https://doi.org/10.1016/j.cej.2018.12.136>
- 1407 Schneider, J., Matsuoka, M., Takeuchi, M., Zhang, J., Horiuchi, Y., Anpo, M., Bahnemann, D.W.,
1408 2014. Understanding TiO₂ photocatalysis: Mechanisms and materials. Chem. Rev. 114,
1409 9919–9986. <https://doi.org/10.1021/cr5001892>
- 1410 Shaim, A., Amaterz, E., Naciri, Y., Taoufyq, A., Bakiz, B., Ezahri, M., Benlhachemi, A., Ouammou,
1411 A., Chahine, A., 2019. Synthesis, characterization and photocatalytic activity of
1412 titanophosphate glasses. Mediterr. J. Chem. 8, 66–73.
1413 <https://doi.org/10.13171/mjc8119032221as>
- 1414 Shammay, A., Sivret, E.C., Le-Minh, N., Lebrero Fernandez, R., Evanson, I., Stuetz, R.M., 2016.
1415 Review of odour abatement in sewer networks. J. Environ. Chem. Eng. 4, 3866–3881.
1416 <https://doi.org/10.1016/j.jece.2016.08.016>
- 1417 Shayegan, Z., Haghighat, F., Lee, C.S., 2020. Carbon-doped TiO₂ film to enhance visible and UV
1418 light photocatalytic degradation of indoor environment volatile organic compounds. J.
1419 Environ. Chem. Eng. 8, 104162. <https://doi.org/10.1016/j.jece.2020.104162>
- 1420 Shayegan, Z., Lee, C.S., Haghighat, F., 2018. TiO₂ photocatalyst for removal of volatile organic
1421 compounds in gas phase – A review. Chem. Eng. J. 334, 2408–2439.
1422 <https://doi.org/10.1016/j.cej.2017.09.153>
- 1423 Shen, Y., Zhu, Z., Wang, X., Khan, A., Gong, J., Zhang, Y., 2018. Synthesis of Z-scheme g-
1424 C₃N₄/Ag/Ag₃PO₄ composite for enhanced photocatalytic degradation of phenol and selective
1425 oxidation of gaseous isopropanol. Mater. Res. Bull. 107, 407–415.
1426 <https://doi.org/10.1016/j.materresbull.2018.08.017>
- 1427 Sleiman, M., Conchon, P., Ferronato, C., Chovelon, J.M., 2009. Photocatalytic oxidation of
1428 toluene at indoor air levels (ppbv): Towards a better assessment of conversion, reaction
1429 intermediates and mineralization. Appl. Catal. B Environ. 86, 159–165.
1430 <https://doi.org/10.1016/j.apcatb.2008.08.003>
- 1431 Sui, H., An, P., Li, X., Cong, S., He, L., 2017. Removal and recovery of o-xylene by silica gel using

vacuum swing adsorption. Chem. Eng. J. 316, 232–242.
<https://doi.org/10.1016/j.cej.2017.01.061>

Suresh, S., Bandosz, T.J., 2018. Removal of formaldehyde on carbon -based materials: A review of the recent approaches and findings. Carbon N. Y. 137, 207–221.
<https://doi.org/10.1016/j.carbon.2018.05.023>

Swetha, G., Gopi, T., Chandra Shekar, S., Ramakrishna, C., Saini, B., Rao, P.V.L., 2017. Combination of adsorption followed by ozone oxidation with pressure swing adsorption technology for the removal of VOCs from contaminated air streams. Chem. Eng. Res. Des. 117, 725–732. <https://doi.org/10.1016/j.cherd.2016.11.036>

Tang, M., Ao, Y., Wang, C., Wang, P., 2020. Facile synthesis of dual Z-scheme g-C₃N₄/Ag₃PO₄/AgI composite photocatalysts with enhanced performance for the degradation of a typical neonicotinoid pesticide. Appl. Catal. B Environ. 268, 118395.
<https://doi.org/10.1016/j.apcatb.2019.118395>

Taranto, J., Frochot, D., Pichat, P., 2009. Photocatalytic air purification: Comparative efficacy and pressure drop of a TiO₂-coated thin mesh and a honeycomb monolith at high air velocities using a 0.4 m³ close-loop reactor. Sep. Purif. Technol. 67, 187–193.
<https://doi.org/10.1016/j.seppur.2009.03.017>

Thevenet, F., Sivachandiran, L., Guaitella, O., Barakat, C., Rousseau, A., 2014. Plasma-catalyst coupling for volatile organic compound removal and indoor air treatment: A review. J. Phys. D. Appl. Phys. 47. <https://doi.org/10.1088/0022-3727/47/22/224011>

Tian, N., Zhang, Y., Li, X., Xiao, K., Du, X., Dong, F., Waterhouse, G.I.N., Zhang, T., Huang, H., 2017. Precursor-reforming protocol to 3D mesoporous g-C₃N₄ established by ultrathin self-doped nanosheets for superior hydrogen evolution. Nano Energy 38, 72–81.
<https://doi.org/10.1016/j.nanoen.2017.05.038>

Wan, S., Ou, M., Zhong, Q., Zhang, S., 2018. Z-scheme CaIn₂S₄/Ag₃PO₄ nanocomposite with superior photocatalytic NO removal performance: Fabrication, characterization and mechanistic study. New J. Chem. 42, 318–326. <https://doi.org/10.1039/c7nj03588h>

Wang, K., Liu, C., Du, P., Zheng, J., Gong, X., 2015. Bulk heterojunction perovskite hybrid solar cells with large fill factor. Energy Environ. Sci. 8, 1245–1255.
<https://doi.org/10.1039/c5ee00222b>

Wang, X., Yu, J., Fu, C., Li, T., Yu, H., 2019. Self-templated formation of AgCl/TiO₂ hollow octahedra for improved visible-light photocatalytic activity. Appl. Surf. Sci. 494, 740–748.
<https://doi.org/10.1016/j.apsusc.2019.07.221>

Wen, X.J., Shen, C.H., Fei, Z.H., Fang, D., Liu, Z.T., Dai, J.T., Niu, C.G., 2020. Recent developments on AgI based heterojunction photocatalytic systems in photocatalytic application. Chem. Eng. J. 383, 123083. <https://doi.org/10.1016/j.cej.2019.123083>

Wood, P.M., 1988. The potential diagram for oxygen at pH 7. Biochem. J. 253, 287–289.
<https://doi.org/10.1042/bj2530287>

Xian, S., Yu, Y., Xiao, J., Zhang, Z., Xia, Q., Wang, H., Li, Z., 2015. Competitive adsorption of water vapor with VOCs dichloroethane, ethyl acetate and benzene on MIL-101(Cr) in humid atmosphere. RSC Adv. 5, 1827–1834. <https://doi.org/10.1039/c4ra10463c>

Xiao, G., Wang, X., Li, D., Fu, X., 2008. InVO₄-sensitized TiO₂ photocatalysts for efficient air

1474 purification with visible light. *J. Photochem. Photobiol. A Chem.* 193, 213–221.
1475 <https://doi.org/10.1016/j.jphotochem.2007.06.027>

1476 Xie, J., Yang, Y., He, H., Cheng, D., Mao, M., Jiang, Q., Song, L., Xiong, J., 2015. Facile synthesis
1477 of hierarchical Ag₃PO₄/TiO₂ nanofiber heterostructures with highly enhanced visible light
1478 photocatalytic properties. *Appl. Surf. Sci.* 355, 921–929.
1479 <https://doi.org/10.1016/j.apsusc.2015.07.175>

1480 Xin, X., Li, S.H., Zhang, N., Tang, Z.R., Xu, Y.J., 2019. 3D graphene/AgBr/Ag cascade aerogel
1481 for efficient photocatalytic disinfection. *Appl. Catal. B Environ.* 245, 343–350.
1482 <https://doi.org/10.1016/j.apcatb.2018.12.066>

1483 Xu, L., Huang, W.Q., Wang, L.L., Huang, G.F., Peng, P., 2014. Mechanism of superior visible-
1484 light photocatalytic activity and stability of hybrid Ag₃PO₄/graphene nanocomposite. *J. Phys.*
1485 *Chem. C* 118, 12972–12979. <https://doi.org/10.1021/jp5034273>

1486 Xue, W., Huang, D., Wen, X., Chen, S., Cheng, M., Deng, R., Li, B., Yang, Y., Liu, X., 2020.
1487 Silver-based semiconductor Z-scheme photocatalytic systems for environmental pur-
1488 ification. *Journal of Hazardous Materials* 390, 122128.
1489 <https://doi.org/10.1016/j.jhazmat.2020.122128>

1490 Yang, H., Tian, J., Bo, Y., Zhou, Y., Wang, X., Cui, H., 2017. Visible photocatalytic and
1491 photoelectrochemical activities of TiO₂ nanobelts modified by In₂O₃ nanoparticles. *J. Colloid*
1492 *Interface Sci.* 487, 258–265. <https://doi.org/10.1016/j.jcis.2016.10.051>

1493 Yang, S.B., Chun, H.H., Tayade, R.J., Jo, W.K., 2015. Iron-functionalized titanium dioxide on
1494 flexible glass fibers for photocatalysis of benzene, toluene, ethylbenzene, and o-xylene
1495 (BTEX) under visible- or ultraviolet-light irradiation. *J. Air Waste Manag. Assoc.* 65, 365–
1496 373. <https://doi.org/10.1080/10962247.2014.995838>

1497 Yi, Z., Ye, J., Kikugawa, N., Kako, T., Ouyang, S., Stuart-Williams, H., Yang, H., Cao, J., Luo, W.,
1498 Li, Z., Liu, Y., Withers, R.L., 2010. An orthophosphate semiconductor with photooxidation
1499 properties under visible-light irradiation. *Nat. Mater.* 9, 559–564.
1500 <https://doi.org/10.1038/nmat2780>

1501 Yue, X., Yi, S., Wang, R., Zhang, Z., Qiu, S., 2018. Well-controlled SrTiO₃@Mo₂C core-shell
1502 nanofiber photocatalyst: Boosted photo-generated charge carriers transportation and
1503 enhanced catalytic performance for water reduction. *Nano Energy* 47, 463–473.
1504 <https://doi.org/10.1016/j.nanoen.2018.03.014>

1505 Zazueta, A.L.L., Destailats, H., Li Puma, G., 2013. Radiation field modeling and optimization of
1506 a compact and modular multi-plate photocatalytic reactor (MPPR) for air/water purification
1507 by Monte Carlo method. *Chem. Eng. J.* 217, 475–485.
1508 <https://doi.org/10.1016/j.cej.2012.11.085>

1509 Zhang, J., Bang, J.H., Tang, C., Kamat, P. V., 2010. Tailored TiO₂-SrTiO₃ heterostructure
1510 nanotube arrays for improved photoelectrochemical performance. *ACS Nano* 4, 387–395.
1511 <https://doi.org/10.1021/nn901087c>

1512 Zhang, N., Nguyen, A. V., Zhou, C., 2018. A review of the surface features and properties,
1513 surfactant adsorption and floatability of four key minerals of diasporic bauxite resources. *Adv.*
1514 *Colloid Interface Sci.* 254, 56–75. <https://doi.org/10.1016/j.cis.2018.03.005>

1515 Zhang, X., Gao, B., Creamer, A.E., Cao, C., Li, Y., 2017. Adsorption of VOCs onto engineered
1516 carbon materials: A review. *J. Hazard. Mater.* 338, 102–123.

1517 <https://doi.org/10.1016/j.jhazmat.2017.05.013>

1518 Zhao, F.M., Pan, L., Wang, S., Deng, Q., Zou, J.J., Wang, L., Zhang, X., 2014. Ag₃PO₄ /TiO₂
 1519 composite for efficient photodegradation of organic pollutants under visible light. Appl. Surf.
 1520 Sci. 317, 833–838. <https://doi.org/10.1016/j.apsusc.2014.09.022>

1521 Zhao, J., Yang, X., 2003. Photocatalytic oxidation for indoor air purification: A literature review.
 1522 Build. Environ. 38, 645–654. [https://doi.org/10.1016/S0360-1323\(02\)00212-3](https://doi.org/10.1016/S0360-1323(02)00212-3)

1523 Zhao, Z., Fan, J., Liu, W., Xue, Y., Yin, S., 2017. In-situ hydrothermal synthesis of Ag₃PO₄/g-C₃N₄
 1524 composite and their photocatalytic decomposition of NO_x. J. Alloys Compd. 695, 2812–2819.
 1525 <https://doi.org/10.1016/j.jallcom.2016.12.001>

1526 Zhong, L., Haghighat, F., Lee, C.S., 2013. Ultraviolet photocatalytic oxidation for indoor
 1527 environment applications: Experimental validation of the model. Build. Environ. 62, 155–166.
 1528 <https://doi.org/10.1016/j.buildenv.2013.01.009>

1529 Zhou, H., Wen, Z., Liu, J., Ke, J., Duan, X., Wang, S., 2019. Z-scheme plasmonic Ag decorated
 1530 WO₃/Bi₂WO₆ hybrids for enhanced photocatalytic abatement of chlorinated-VOCs under
 1531 solar light irradiation. Appl. Catal. B Environ. 242, 76–84.
 1532 <https://doi.org/10.1016/j.apcatb.2018.09.090>

1533 Zhou, P., Yu, J., Jaroniec, M., 2014. All-solid-state Z-scheme photocatalytic systems. Adv. Mater.
 1534 26, 4920–4935. <https://doi.org/10.1002/adma.201400288>

1535 Zhu, L., Shen, D., Luo, K.H., 2020. A critical review on VOCs adsorption by different porous
 1536 materials: Species, mechanisms and modification methods. J. Hazard. Mater. 389, 122102.
 1537 <https://doi.org/10.1016/j.jhazmat.2020.122102>

1538 Zouzelka, R., Rathousky, J., 2017. Photocatalytic abatement of NO_x pollutants in the air using
 1539 commercial functional coating with porous morphology. Appl. Catal. B Environ. 217, 466–
 1540 476. <https://doi.org/10.1016/j.apcatb.2017.06.009>

1541