Photocatalytic Applications of Heterostructure Graphitic Carbon Nitride: Pollutant Degradation, Hydrogen Gas Production (water splitting), and CO₂ Reduction

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Abstract: Fabrication of the heterojunction composites photocatalyst has attained much attention for solar energy conversion due to their high optimization of reduction-oxidation potential as a result of effective separation of photogenerated electrons-holes pairs. In this review, the background of photocatalysis, mechanism of photocatalysis, and the several researches on the heterostructure graphitic carbon nitride (g-C₃N₄) semiconductor are discussed. The advantages of the heterostructure g-C₃N₄ over their precursors are also discussed. The conclusion and future perspectives on this emerging research direction are given. This paper gives a useful knowledge on the heterostructure g-C₃N₄ and their photocatalytic mechanisms and applications.

Impact Statements: The paper on g-C₃N₄ Nano-based photocatalysts is expected to enlighten scientists on precise management and evaluating the environment, which may merit prospect research into developing suitable mechanism for energy, wastewater treatment and environmental purification.

Keywords: Photocatalysis, Heterostructure, Graphitic carbon nitride, Pollutant degradation, Hydrogen Gas Production, CO₂ reduction

Introduction
Background of Photocatalytic Semiconductors

In 1972, Fujishima and Honda discovered the water photolysis on a TiO₂ electrode [1] as the response to the steady increase of energy shortage and environmental pollution caused by industrialization and population growth in 1970 [2]. Their discovery was recognized as the landmark event that stimulated the investigation of photonic energy conversion by photocatalytic methods [2]. Due to population growth, high industrialization, and improvements in agricultural technologies, till the twenty-first century, energy shortage and environmental pollution are still challenges [3]. In recent decades, photocatalysis has become one of the most promising technologies owing to its potential applications in solar energy conversion to solve the worldwide energy shortage and environmental pollution alleviation [4]. Photocatalysis is the process that involves photocatalyst. “A photocatalyst is defined as a substance which is activated by adsorbing a photon and is capable of accelerating a reaction without being consumed” [5]. Photocatalysts are invariably semiconductors. Several semiconductors such as TiO₂, ZnO, Fe₂O₃, CdS, and ZnS are used as photocatalysts in environmental pollutants treatment and solar fuel production such as methane (CH₄), hydrogen (H₂), formic acid (HCOOH), formaldehyde (CH₂O), and methanol (C₂H₅OH) [6]. Due to its photocatalytic and hydrophilic high reactivity, reduced toxicity, chemical stability, and lower costs [7], TiO₂ has been mostly studied as having the high ability to break down organic pollutants and even achieve complete mineralization [8]. Due to its large band energy, TiO₂ can only absorb solar...
energy in the UV regions which only constitutes 4% of the total solar energy irradiated [9, 10].

For efficient performance, a photocatalyst semiconductor requires a suitable band gap for harvesting light [11], facile separation and transportation of charge carriers (electron and holes) [12], and proper valence band (VB) and conduction band (CB) edge potential for redox reaction being thermodynamically feasible [13]. Several semiconductor modifications such as surface modification, metal doping, and heterojunctions formations have been taken to give the best photocatalytic activity of different photocatalyst semiconductors [14–16]. Also, the plasmon-enhanced sensitization was found to be effective in improving the photocatalytic activity efficiency of some photocatalyst [17, 18]. This is caused by the oscillation of electrons in the metal nanoparticle as a result of the induced electric field after solar irradiation, a term referred to as the localized surface plasmon resonance effects (LSPRs) [19]. In counteracting on the demerits of most inorganic photocatalyst such as visible light utilization, there has been a great increase of researches on the photocatalytic graphitic carbon nitride (g-C₃N₄) in recent decades due to its special structure and properties, such as its good chemical and thermal stability under ambient conditions, low cost and non-toxicity, and facile synthesis [20, 21]. Although some single g-C₃N₄ semiconductor photocatalysts demonstrated high photocatalytic efficiency on visible light illumination [22] compared to other photocatalysts like TiO₂ [23], they suffer from high charger carrier (electron–hole pair) recombination which greatly reduce their photocatalytic efficiency [24]. The construction of heterostructured photocatalyst systems comprising multicomponent or multiphase is one of most effective strategies to balance the harsh terms, owing to the tenable band structures and efficient electron–hole separation and transportation [25], which endow them with suitable properties superior to those of their individual components [26]. Several heterostructured semiconductor modifications have been studied over the three decades.

This paper, however, centers on the ability and efficacy of the prospective applications of construction of heterostructured carbon nitride to enhance the visible light-responsive photocatalytic performance of the candidate for energy, wastewater, and environmental treatment in order to project future implementations to elucidate environmental problems and related.

Carbon Nitride

Presently, g-C₃N₄ is studied as a new-generation photocatalyst to recover the photocatalytic activity of traditional photocatalysts like TiO₂, ZnO, and WO₃. Graphitic carbon nitride (g-C₃N₄) is assumed to have a tri-s-triazine nucleus with a 2D structure of nitrogen heteroatom substituted graphite framework which include p-conjugated graphitic planes and sp² hybridization of carbon and nitrogen atoms [27]. Bulky carbon nitride can be synthesized through thermal condensation of nitrogen-rich (without a direct C-C bound) precursors such as cyanamide, dicyandiamide, thiourea, urea, and melamine. Also, it can be synthesized through polymerization of nitrogen-rich and oxygen-free precursors (comprising the pre-bonded C-N core structure) by physical vapour deposition, chemical vapour deposition, solvothermal method, and solid-state reactions. Having the band gap of 2.7 eV and the conduction and valence band position at −1.4eV and 1.3 eV, respectively, versus NHE (normal hydrogen electrode), g-C₃N₄ have shown great ability to carry photocatalytic activity in the visible light irradiation without the addition of any noble-metal co-catalyst [28]. Apart from visible light utilization, bulky carbon nitride is hampered by high-charge carrier recombination which reduces its photocatalytic activity. Different researchers have studied on the modification of g-C₃N₄ to counteract the challenge of charge carrier recombination and band engineering. Several modifications have been studied over decades including structural modification, doping, modification with carbonaceous and plasmonic material, and heterojunction composite formation.

Structural Modification

Changing the morphology of the synthesized photocatalysts plays a significant effect in its photocatalytic activity [29]. Optical, electronic, mechanical, magnetic, and chemical properties of carbon nitride materials are highly dependants on the change of size, composition, dimension, and shape. Hard and soft templating methods, template-free methods, and exfoliation strategies are among the methods used to modify the structure of the synthesized carbon nitride photocatalysts [30]. Templating modifies the physical properties of carbon nitride semiconductor materials by varying morphology and introducing porosity. Template-free method creates vacancies in carbon nitride photocatalysts resulting to introduction of additional energy levels or acting as reactive sites, and thus profoundly changing the overall photocatalytic activity. Exfoliation modifies the bulky carbon nitride into nano-sheet carbon nitrides which increase the surface area for active sites, hence increasing its photocatalytic activity. Also, carbon nitride can be modified into nano-rods and nanotubes which all have effects on the photocatalytic activity of the synthesised photocatalyst.

Doping

One and the most popular modification of a single semiconductor is the metal/non-metal doping [31] and
surface modification forming metal/semiconductor-heterostructured photocatalysts [32]. Different researchers have studied doping g-C\(_3\)N\(_4\) with different metals or non-metals for band gap engineering and overcoming the challenge of charge carrier (electrons-holes pair) recombination [33]. Yan et al. [34] reported the study on the impact of doped metal (Na, K, Ca, and Mg) on g-C\(_3\)N\(_4\) for the photocatalytic degradation of enrofloxacin (ENR), tetracycline (TCN), and sulfamethoxazole (SMX) as representatives of common antibiotics under visible light irradiation. In their study, it was observed that in all the degradation of three representative antibiotics the degradation activity followed the same sequence of g-CN-K>g-CN-Na>g-CN-Mg>g-CN-Ca>g-CN. This was attributed by the decreased band gap of doped g-C\(_3\)N\(_4\) from 2.57 to 2.29–2.46 eV as a result of a red shift caused by the doped metal resulting to an extended visible light response and high-charge carrier separation of the as-prepared photocatalytic semiconductor, hence increasing the production of -OH reactive species [34]. In the study done by Xu et al., it was also evident that doping Fe on the surface-alkalinized g-C\(_3\)N\(_4\) reduced the recombination of photo-generated charge carriers (electrons and holes) and the band energy of which lead to high photocatalytic activity of the doped g-C\(_3\)N\(_4\) on the degradation of tetracycline under visible light (\(\lambda \geq 420\)) irradiation [35]. Jiang et al. [36] synthesized the nitrogen (N) self-doped g-C\(_3\)N\(_4\) nanosheets with tunable band structures for enhanced photocatalytic tetracycline degradation in the visible light irradiation. It was evidently proved that doping nitrogen (N) on g-C\(_3\)N\(_4\) nanosheets increased the semiconductor photocatalytic activity as a result of reduced charge recombination as proved by the photoluminescence (PL) emission spectra study [36]. Ling et al. [37] reported the study of the synergistic effect of non-metal (sulphur) doping on the photocatalytic property of g-C\(_3\)N\(_4\) using the first-principle calculations. The obtained results indicated narrowing of the band gap and increased visible light response on S-doped g-C\(_3\)N\(_4\) photocatalyst [37]. The effect of metal or non-metal doping on g-C\(_3\)N\(_4\) was also revealed in studies done by Guo et al. who used potassium (K) and iron (Fe) [38], Fan et al. who used manganese (Mn) [39], Xie et al., Zhu et al., and Wu et al. who used cobalt (Co) [40–42]. Shu et al. using sodium (Na) synthesized doped mesoporous g-C\(_3\)N\(_4\) nanosheets for photocatalytic hydrogen production of which the results showed that the doped nanosheets exhibited lower recombination of photogenerated charge carrier (electron–hole pairs) than bulk g-C\(_3\)N\(_4\), hence resulting to excellent visible light photocatalytic hydrogen evolution efficiency up to about 13 times that of bulk g-C\(_3\)N\(_4\) [43]. All these prove that doping g-C3N4 with metal ion or non-metal has a significant improvement on the photocatalytic efficiency in the visible light irradiation.

### Modification with Other Carbonaceous Materials
Carbonaceous materials have a wide range of physical and chemical properties derived from the spatial organization of carbon atoms and their chemical covalent bonds [44]. Carbonaceous materials such as carbon nanotubes (CNTs), multiwalled carbon nanotubes (MWCNTs), carbon dots (CDs), graphene, and reduced graphene oxide have been widely incorporated in modifying different photocatalyst semiconductors in order to enhance their photocatalytic activity. Ma et al. [45] reported the synthesis of an artificial Z-scheme visible light photocatalytic system using the reduced graphene oxide as an electron mediator. In their report, results showed that g-C\(_3\)N\(_4\)/RGO/Bi\(_2\)MoO\(_6\) exhibited high photocatalytic activity (\(k = 0.055 \) min\(^{-1}\)) over degradation of rhodamine B dye as one of the common pollutant [45]. Also, in 2017, Ma and coworkers reported the synthesis of Bi\(_2\)MoO\(_6\)/CNTs/g-C\(_3\)N\(_4\) with enhanced de-romination of 2, 4-dibromophenol under visible light. The composite resulted into higher photocatalytic activity (\(k = 0.0078 \text{min}^{-1}\)) which was 3.61 times of g-C\(_3\)N\(_4\) (\(k = 0.00216 \text{min}^{-1}\)) [46]. Xie et al. [47] reported the construction of carbon dot-modified MoO\(_3\)/g-C\(_3\)N\(_4\) Z-scheme photocatalyst with enhanced visible light photocatalytic activity for the degradation of tetracycline as one of the common antibiotic pollutant found in waste water. In their work, it was observed and proved that the composite exhibited higher photocatalytic activity where 88.4% of tetracycline was removed compared to only 5.3% removal of g-C\(_3\)N\(_4\) [47].

### Heterostructure Graphitic Carbon Nitride Composite
The heterojunctions that are formed between the host semiconductors provide an internal electric field that facilitates separation of the electron–hole pairs and induces faster carrier migration [2]. It involve the combination of two semiconductors to form the heterojunction semiconductors.[48]. Several researches have proven that the heterojunction formation is the promising strategy to the improvement of the g-C3N4 photocatalytic activity. According to the band gap and electronic energy level of the semiconductors, the heterojunction semiconductor can be primarily divided into three different cases: straddling alignment (type I), staggered alignment (type II), and Z-scheme system. The band gap, the electron affinity (lowest potential of CB), and the work function (highest potential of VB) of the combined semiconductors determine the dynamics of the electron and hole in the semiconductor heterojunctions [32]

(a) Type I heterojunction semiconductor

In type-I heterojunction semiconductor, both VB and CB edges of semiconductor 2 are localized within the
energy gap of semiconductor 1, forming straddling band alignment (Fig. 1). The VB and CB alignment play a significant role in the determination of the physical properties of the generated charges and the photocatalytic performance. This kind of heterojunction does not improve photocatalytic activity of the prepared photocatalyst because of the accumulation of both charge carriers on one semiconductor [49]. From Fig. 1, the photogenerated electrons (e\(^{-}\)) are expected to move from the SrZrO\(_3\) conduction band (CB) to SrTiO\(_3\) conduction band (CB) due to reduction potential differences. Also, the photogenerated holes (h\(^{+}\)) generated in the valence band (VB) of SrZrO\(_3\) will migrate to the valence band of SrTiO\(_3\) due to the difference in their oxidation potentials. Hence, both electrons and holes will accumulate in SrTiO\(_3\) semiconductor causing high recombination to take place.

(b) Type II heterojunction semiconductor

In type-II heterojunction semiconductor, both VB and CB of semiconductor 1 are higher than that of semiconductor 2 (Fig. 2). Electrons from semiconductor 1 migrate to semiconductor 2 while the holes move from semiconductor 2 to semiconductor 1. If both semiconductors have sufficient intimate contacts, an efficient charge separation will occur during light illumination. Consequently, charge recombination is decreased, and so charge carriers have a longer lifetime, which results in higher photocatalyst activity [32]. Type II heterojunction semiconductor suffer from steric hindrance of charge transfer. When electron in the CB of semiconductor 1 migrates to the CB of semiconductor 2, there is a repulsion force created between coming electrons and existing electrons. Same applies when holes from the VB of semiconductor 2 migrates to the VB of semiconductor 1. In the steric hindrance created, there can be a small amount reduction in the expected photocatalytic activity of the as-prepared type II heterojunction photocatalyst.

(c) Z-Scheme heterojunction semiconductor

In the course of development and modifications of visible light-driven photocatalytic systems, Z-scheme was originally introduced by Bard in 1979 [32]. The Z-scheme heterojunction was developed to solve the steric hindrance exerted in type II heterojunction. Currently, there are three generations of the Z-scheme photocatalytic system (Fig. 3).

(i). First-generation Z-scheme heterojunction

It is also known as liquid-phase z-scheme photocatalytic system. It is built by combining two different semiconductors with a shuttle redox mediator (viz. an electron acceptor/donor (A/D) pair) as seen in Fig. 4a. It was first proposed by Bard et al in 1979. In 1997, Abe et
al. synthesized the liquid-phase Z-scheme semiconductor using $I^-/IO_3^-$, before Sayama et al. synthesised the liquid-phase Z-scheme using $Fe^{2+}/Fe^{3+}$ in 2001 [3]. Liquid-phase Z-scheme photocatalytic system can only be used for liquids. It also suffers from the backward reaction that is caused by the use of redox mediators such as $I^-/IO_3^-$ and $Fe^{2+}/Fe^{3+}$ [32].

(ii). Second-generation Z-scheme heterojunction semiconductor

It is also known as all-solid-state (ASS) Z-scheme system. In order to overcome the obvious problems identified in the first generation, Tada et al. in 2006 synthesised the all-solid-state CdS/Au/TiO$_2$ Z-scheme [32]. An ASS Z-scheme photocatalytic system is composed of two different semiconductors and a noble-metal nanoparticle (NP) as the electron mediator as seen in Fig. 4b. The use of the noble metal solves the backward reaction that was happening in the first generation (liquid-phase Z-scheme). Noble metals are expensive and very rare to obtain causing their wide application to be limited. Also, noble metals have high ability to absorb light. This affects the light absorbance of photocatalytic semiconductors, and their photocatalytic activities are also affected. In solving the light absorbance problem, Wang et al. in 2009 synthesised the mediator-free ASS Z-scheme [3].

(iii). Third-generation Z-scheme heterojunction semiconductor

It is commonly known as direct Z-scheme semiconductor. A direct Z-scheme photocatalyst consists of only two semiconductors that have a direct contact at their interface [32]. All the advantaged features in the previous two generation are inherited in direct Z-scheme photocatalyst. Unlike a type II semiconductor, electrons in the CB of semiconductor B migrate to recombine with the holes generated in the VB of semiconductor A forming a Z-transfer as shown in Fig. 5. In order to facilitate the easy Z-transfer of charge carriers, the participating semiconductors must have a close band energy level with perfect CB and VB alignment [50]. Currently, this is the known and suitable heterojunction system with high charge carrier (electron and holes) separation efficiency.

The Fundamental Mechanism of the Photocatalytic Semiconductor

When the incident light photon with equal or large energy than the band gap energy strike the semiconductor, the electrons in the valence band (VB) are photoexcited and move to the conduction band (CB), leaving equal number of the holes in the valence band (VB) [21]. The photoexcited electron ($e^-$) and holes ($h^+$) in the CB and VB, respectively, moves to the surface of the semiconductor [51]. It is at the surface of the photocatalyst semiconductor where reduction and oxidation of the electron acceptor and electron donor, respectively, take place as seen in Fig. 6.

The photocatalytic mechanism is summarised by the following Eqs. 1, 2 and 3

$$\text{Semiconductor} + h\nu \rightarrow e^-_{\text{CB}} + h^+_{\text{VB}} \quad (1)$$

$$e^-_{\text{CB}} + A \rightarrow A^- \quad (2)$$

$$h^+_{\text{VB}} + D \rightarrow \cdot D^+ \quad (3)$$

The doping effect, surface modification, and heterojunction formation have the direct effect on the movement of the generated charge carriers (electron and holes) of the synthesized photocatalyst. When the electron mediator atom is introduced in the semiconductor,
the movement of charge carrier depends on whether the mediator is an electron donor or acceptor. The dopant not only controls the charge recombination, but it also assists in band gap engineering of some wide band gap semiconductors. In heterojunction composite photocatalyst, the charge carrier transfer depends on the nature and properties of the participating semiconductors. In type II heterojunction semiconductor reduction and oxidation, reactions occur for semiconductor with a lower reduction potential and semiconductor with a lower oxidation potential, respectively. Due to electrostatic repulsion between electron–electron and hole–hole, the charge carrier transfer in type II heterojunction is restricted hence reducing photocatalytic activity of the synthesized photocatalyst. In the Z-scheme heterojunction, the movement of the charge carrier follows the Z-pattern where electrons remain on the semiconductor with the higher reduction potential while holes remain on semiconductor with the higher oxidation potential.

This paper place special emphasis on recently researched heterostructure graphitic carbon nitride (g-C3N4) looking at their characterizations and their applications in ambient conditions.

Characterization Methods for Heterostructure g-C3N4

Morphology

The morphological structure of the synthesized photocatalyst plays a significant role in its photocatalytic activity [52]. SEM, TEM, and XRD are used to study the morphology of the as-prepared photocatalyst [53, 54]. XRD shows different peaks that confirms that the formed structures are in agreement with the standard cards [10]. SEM and TEM shows the morphology of the as-prepared photocatalyst [55]. Figure 7A shows the XRD spectra of g-C3N4 (h), Bi2MoO6 (a), and the g-C3N4/Bi2MoO6 composites (b–g). As seen, the peaks at 27.40° and 13.04° are corresponding to the (002) and (100) planes of g-C3N4 [56] while the peaks at 28.3°, 32.6°, 47.7°, and 55.4° are in agreement with (131), (002), (060), and (331) planes of Bi2MoO6, respectively [12] which shows the perfect formation of the g-C3N4/Bi2MoO6 composite. The existence of a uniform fringe interval (0.336 nm) in the TEM images (Fig. 7B) is in agreement with the (002) lattice plane of g-C3N4 while that of 0.249 nm is in agreement to the (151) lattice plane of Bi2MoO6. In the same shape (Fig. 7C) ascribed by the elemental mapping of C-K, N-K indicates the existence of g-C3N4 while the mapping of Bi-M, Mo-L, and O-K shows the existence of Bi2MoO6 in the as-prepared heterojunction. This proves that there were the perfect formation of the heterojunction between g-C3N4 and Bi2MoO6.

X-Ray Photoelectron Spectroscopy (XPS) Characterization

The surface chemistry of the as-prepared composite has the greatest impact on its photocatalytic activity. X-ray
photoelectron spectroscopy (XPS) characterization has been extensively used to determine the surface chemistry of materials [57] by studying the changes in the electronic density on the different surfaces of a photocatalyst through investigating the shift in the binding energies [58]. A shift in the binding energy of a specific element of the semiconductor is caused by the introduction of the foreign materials which affects the electron migration on its surface [25, 31].

For instance, Longjun Song and coworkers confirmed the hydrothermal synthesis of novel g-C₃N₄/BiOCl heterostructure nanodiscs for efficient visible light photodegradation of rhodamine B using XPS characterization. In this study, all XPS spectra were calibrated using the C 1s

![Fig. 7](image)

**Fig. 7** (A) XRD of (b–g) g-C₃N₄/Bi₂MoO₆ composites with different g-C₃N₄ content (a) Bi₂MoO₆ (b) g-C₃N₄ (B) TEM images of (a) g-C₃N₄ (b) Bi₂MoO₆ (c) g-C₃N₄/Bi₂MoO₆ composite (C) SEM image of (a) g-C₃N₄/Bi₂MoO₆ showing corresponding elemental (C, N, Bi, Mo, and O) mapping. Reproduced with permission [35]. Copyright 2014 Royal Society of Chemistry

![Fig. 8](image)

**Fig. 8** a, b RhB degradation over various photocatalysts and c corresponding rate constants (k). Reproduced with permission [23]. Copyright 2014 Elservier B.V
signal at 284.8 eV [59]. The sp²-bonded carbon in N-containing aromatic rings (N=C=N) (Fig. 8b) were ascribed to the C 1s signals at 288.2 eV [60] while sp²-hybridized aromatic nitrogen bonded to carbon atoms (C=N) in triazine rings was attributed to 398.8 eV. This confirms the presence of sp²-bonded graphitic carbon nitride [60]. The existence of peaks at 159.4 and 164.5 eV is caused by Bi³+ in BiOCl while the peak at 530.2 eV is attributed to the Bi–O bonds in (BiO)²⁺ of the BiOCl. The weak peak at 404 eV is caused by the fact that g-C₃N₄ is coupled with BiOCl through the p-electrons of CN heterocycles. This confirms the coexistence of g-C₃N₄/BiOCl composite.

Photocatalytic-Reduction Test

Not all the photogenerated electrons reaching the surface of the photocatalyst have the ability to carry the photocatalytic-reduction reaction. Only the photogenerated electrons with sufficient reduction potentials participate fully in the reduction reaction. Equations 4, 5, 6, 7 and 8 summarize the standard redox potentials for various photocatalytic-reduction reactions.

\[
2H^+ + 2e^- \rightarrow H_2, \quad E_0 = -0.41 \text{V vs NHE} \quad \text{at pH} = 7 \tag{4}
\]

\[
CO_2 + 2H^+ + 2e^- \rightarrow HCOOH, \quad E_0 = -0.61 \text{V vs NHE} \quad \text{at pH} = 7 \tag{5}
\]

\[
CO_2 + 2H^+ + 2e^- \rightarrow CO + H_2O, \quad E_0 = -0.53 \text{V vs NHE} \quad \text{at pH} = 7 \tag{6}
\]

\[
CO_2 + 4H^+ + 4e^- \rightarrow HCHO + H_2O, \quad E_0 = -0.48 \text{V vs NHE} \quad \text{at pH} = 7 \tag{7}
\]

\[
CO_2 + 6H^+ + 6e^- \rightarrow CH_3OH + H_2O, \quad E_0 = -0.38 \text{V vs NHE} \quad \text{at pH} = 7 \tag{8}
\]

\[
CO_2 + 8H^+ + 8e^- \rightarrow CH_4 + 2H_2O, \quad E_0 = -0.24 \text{V vs NHE} \quad \text{at pH} = 7 \tag{9}
\]

The final products of the photocatalytic-reduction reaction can be the viable test to confirm that the heterojunction photocatalyst was successfully formed.

For example, Chao et al. [61] reported the photocatalytic reduction of CO₂ under BiO/g-C₃N₄. In their report, photoreduction of CO₂ to CO and CH₄ was possible due to high electronegativity of the CB of the as-prepared composite, CO₂/CO (−0.53 V) and CO₂/CH₄ (−0.24 V). But the photoreduction of CO₂ to CH₄ needs more illumination time to generate more electrons and increase the electron density on CB of BiO.

**Photocatalytic Applications of Heterostructure g-C₃N₄**

**Pollutant Degradation**

The change of human life style is causing thousands of both organic and inorganic pollutants enter the air, water, and soil. Pollutants such as pesticides, industrial chemicals, pharmaceutical chemicals, and heavy metals are common pollutants in the environment [62–68]. These pollutants can be detrimental to the environment and human health [69]. To eliminate these pollutants, different technologies have been employed/involved. These technologies include biological degradation, physical adsorption, filtration, and photocatalytic degradation [70]. Due to its ability to utilize sustainable solar energy for degradation of organic pollutants without causing any side effects to the environment, semiconductor-based photocatalytic degradation has captured the substantial attention [71]. Several semiconductors have been synthesized for the degradation of organic pollutants [7]. For decades, TiO₂ has emerged as the most common researched semiconductor for several organic pollutant degradation due to its photocatalytic properties, hydrophilicity, high reactivity, reduced toxicity, chemical stability, and lower costs [72]. Recently, graphitic carbon nitride has been the most scientific researched semiconductor due to its narrow band gap of 2.7 eV which permits it to absorb visible light directly without modification. Graphitic carbon nitride (g-C₃N₄) exhibits high thermal and chemical stability, owing to its tris-triazine ring structure and high degree of condensation [24]. Although various graphitic carbon nitride semiconductors have been studied for photocatalytic degradation of pollutants, their photocatalytic performance remains unsatisfactory suffering highly from charge (electron–hole) recombination. To overcome the electron–hole recombination in a single g-C₃N₄ semiconductor, different researchers have made enormous efforts toward developing novel photocatalytic systems with high photocatalytic activities [73]. The development of heterostructured graphitic carbon nitride photocatalysts semiconductors has proven to be potential for use in enhancing the efficiency of photocatalytic pollutant degradation through the promotion of the separation of photogenerated electron–hole pairs and maximizing the redox potential of the photocatalytic system [59].

For instance, Haiping Li and coworkers reported the solvothermal synthesis of g-C₃N₄/Bi₂MoO₆ heterostructure with enhanced visible light photocatalytic activity for degradation of rhodamine B (RhB) pollutants in aqueous solution using 1.829 g of as-prepared g-C₃N₄ which was added to 0.3234 g of Bi(NO₃)₃·5H₂O in 10 mL of ethylene glycol followed by sonication for 30 min before the addition of 0.0806 g of Na₂MoO₄·2H₂O and stirred for 1 h. Using ethylenediamine, the pH was
maintained to 7.0 throughout the reaction. The dispersion was heated in the polytetrafluoroethylene-lined stainless autoclave at 160 °C for 6 h and then allowed to cool to room temperature. The solid product was collected by filtration, washed thoroughly with water and ethanol, and dried at 80 °C before it undergone calcination at 400 °C for 1 h to eliminate remained organic species [26].

In their findings, they reported that the photocatalytic activity of g-C3N4/Bi2MoO6 (A8) was higher than those of g-C3N4 and Bi2MoO6, where about 98% of RhB was removed by g-C3N4/Bi2MoO6 composite, while less than 60% was removed by pure g-C3N4 (A0) or Bi2MoO6 as seen in Fig. 8a, b. When the experimental data were fitted in a pseudo-first order model (−ln(C/C0) = kt) to quantify the reaction kinetic of photocatalytic RhB degradation, the heterojunction g-C3N4/Bi2MoO6 (A8) exhibited the maximum k value (0.046 min−1) which was three times more than those of g-C3N4 (A0) or Bi2MoO6 (A100). This still proves that the heterojunction g-C3N4/Bi2MoO6 has high ability to degrade dye pollutants in aqueous than g-C3N4 and Bi2MoO6.

Furthermore, Lingjun Song and coworkers reported the facile hydrothermal synthesis of novel g-C3N4/BiOCl heterostructure nanodiscs for efficient visible light photodegradation of rhodamine B. In the heterostructure composite synthesis, a well-dispersed suspension of protonated g-C3N4 was prepared by dissolving a portion of the as-prepared g-C3N4 in 6.5 mL of hydrochloric acid under magnetic stirring followed by subsequently addition of 5 mmol of Bi(NO3)3·5H2O, KCl, and deionized (DI) water (15 mL). The pH of the mixture was subsequently adjusted to 6 with dilute NaOH solution. The white suspension obtained after continuous vigorous stirring for 2 h was heated at 140 °C for 12 h and allowed to cool to room temperature. The precipitates were collected by centrifugation, thoroughly washed with DI water and dried at 80 °C in air to furnish the target sample [76]. The effective separation of photogenerated electron–hole pairs, due to the charge transfer at the interface between two types of semiconductors in the composite, increased the photocatalytic activity of g-C3N4/BiOCl (95%) than that of individual g-C3N4 (30%) and BiOCl (52%).

Yan Gong and coworkers reported the synthesis of the novel metal organic framework (ZIF-8)-derived nitrogen-doped carbon (ZIF-NC) modified g-C3N4 heterostructured composite by the facile thermal treatment method where an appropriate amount of ZIF-CN in a methanol solution was firstly placed in an ultrasonic bath for 30 min to completely disperse the ZIF-NC before g-C3N4 powder was added and stirred for 24 h. After volatilization of the methanol in water bath at 60°C, the obtained powder was heated to 300°C for 2 h under atmosphere (Fig. 9). In their report, photocatalytic activity of ZIF-NC/g-C3N4 for the degradation of bisphenol A (BPA) in aqueous solution reached the removal rate of 97% after 60 min of irradiation with 0.5% ZIF-NC content. Excessive addition of the ZIN-NC to 1% over g-C3N4 surfaces hinder the light adsorption of g-C3N4 which results in low generation of electron–hole pairs on g-C3N4, hence resulting to decreased photocatalytic activity [58].

Xuli Miao and coworkers synthesized g-C3N4/AgBr nanocomposite decorated with carbon dots as a highly efficient visible light-driven photocatalyst by introduction of carbon dots (CDs) onto the surface of g-C3N4, followed by in-situ growth of AgBr nanoparticles on CD-modified g-C3N4 nanosheets (Fig. 10). After the evaluation of as-prepared samples for the degradation of RhB under visible light irradiation, they found that the ternary composites of g-C3N4/CDs/AgBr show higher photocatalytic activity than single AgBr, g-C3N4 with the RhB degradation rate reaching 96% after 40 min of irradiation [105].

Jiajia Wang and his coworkers reported the synthesis of Atomic scale g-C3N4/Bi2WO6 2D/2D heterojunction with enhanced photocatalytic degradation of ibuprofen (IBF) under visible light irradiation. As reported, as-prepared atomic scale g-C3N4 showed high photocatalytic activity (~96.1%) compared to that of pure g-C3N4 (38.2%) and of pure m-B2WO6 (67.3%) under the same experimental conditions. This also proves that there was high separation of photogenerated charge carriers in atomic scale g-C3N4/Bi2WO6 2D/2D heterojunction thus enhancing photocatalytic degradation efficiency of IBF.

Several other researches on the photocatalytic activities of the g-C3N4 heterojunction performances have been conducted by different researchers on different pollutants as summarised in Table 1.

**Photocatalytic Hydrogen Gas (H2) Production**

Depletion of the fossil fuel energy has made the production of hydrogen gas (H2) which has high heat energy value to receive much research attention recently [106]. Solar energy convention remains to be the promising technology for water splitting mechanism to generate H2 because of its simplicity and clean reactions [107–109]. Different photocatalysts has been studied on the water splitting for the H2 production (see Table 2).

For example, She and coworkers reported the synthesis of 2D α-Fe2O3/g-C3N4 Z-scheme catalysts. As reported, H2 evolution activity was further enhanced in the hybrids with α-Fe2O3 nanostructures, reaching 31400 μmol g−1 h−1 for α-Fe2O3/2D g-C3N4 (α-Fe2O3 loading 3.8 wt.%). Photocurrent experiments also confirmed the higher activity of α-Fe2O3/2D g-C3N4 (3.8 wt.% in comparison with samples containing ML g-
C$_3$N$_4$ and $\alpha$-Fe$_2$O$_3$ [113]. With these results, it is evident that heterostructured carbon nitride semiconductors have high photocatalytic efficiency on hydrogen production [109]. The photocatalytic hydrogen production by other studies of g-C$_3$N$_4$ heterojunctions are summarized in Table 2.

The photocatalytic hydrogen (H$_2$) production is hampered by the difficulty of separating the hydrogen and oxygen-containing products (hydrogen storage mechanism) which is caused by very close distance between reduction-oxidation sites. This in turn result into difficulties to separately deliver photogenerated electron and holes to the reduction and oxidation site, respectively, in the designed photocatalyst which might cause reverse reaction of hydrogen- and oxygen-containing products or even damages by explosion. In overcoming this challenge, studies have been made on how to feasibly separate produced hydrogen from oxygen-containing products while maintaining the close distance between reduction-oxidation site which is very essential photogenerated charge transfer. In 2017, Li Yang and co-workers synthesised sandwich structures of graphene with combined photocatalytic hydrogen production and storage ability [114]. In their study, the synthesized sandwiched graphene allows the penetration of only proton to the reduction site to produce hydrogen inside the sandwich. This not only to prevent the reverse reaction but also to facilitate the safe storage of the generated hydrogen reaching the storage rate of 5.2 wt% which is very close to the US Department of Energy standards.

Fig. 9 Schematic illustration of the formation of ZIF-NC/g-C$_3$N$_4$ composite. Reproduced with permission [24]. Copyright 2018 Elsevier BV

Fig. 10 Schematic illustration of preparation process of the g-C$_3$N$_4$/CDs/AgBr nanocomposite. Reproduced with permission [86]. Copyright 2017 Elsevier BV
| Photocatalyst          | Light source                        | Application                          | Performance | Ref.   |
|-----------------------|-------------------------------------|--------------------------------------|-------------|--------|
| g-C3N4/Bi2MoO6        | 300-W Xenon lamp (λ > 420-nm cut-off filter) | RhB degradation                      | \( k = 6.484 \times 10^{-2} \min^{-1} \) | [74]   |
| g-C3N4/Bi2MoO6        | 50-W 410-nm LED light               | Methylene blue (MB) degradation       | \( k = 6.88 \times 10^{-2} \min^{-1} \) | [75]   |
| g-C3N4/RGO/Bi2MoO6    | 500-W Xenon lamp (λ > 420-nm cut-off filter) | RhB degradation                      | \( k = 5.5 \times 10^{-2} \min^{-1} \) | [45]   |
| Bi2MoO6/CNTs/g-C3N4   | 500-W Xenon lamp (λ > 420-nm cut-off filter) | 2,4-Dibromophenol debromination and degradation | \( k = 7.8 \times 10^{-3} \min^{-1} \) | [46]   |
| g-C3N4/BiOCl          | 300-W Xenon arc lamp (λ ≥ 400-nm cut-off filter) | RhB degradation                      | \( k = 1.99 \times 10^{-1} \min^{-1} \) | [76]   |
| Bi2O3/g-C3N4          | 300-W Xenon lamp (λ > 420-nm cut-off filter) | Phenol degradation                    | \( k = 2.47 \times 10^{-3} \min^{-1} \) | [77]   |
| Bi2O3/g-C3N4          | 500-W Xenon lamp (λ > 400-nm cut-off filter) | Methylene blue degradation            | \( k = 2.53 \times 10^{-2} \min^{-1} \) | [78]   |
| Bi2O3/g-C3N4          | 35-W Xenon lamp                      | Amido black 1B degradation            | \( k = 1.722 \times 10^{-2} \min^{-1} \) | [80]   |
| Bi2O3/g-C3N4          | 300-W Xenon lamp (λ > 420nm cut-off filter) | Methylene blue degradation            | \( k = 6.3 \times 10^{-1} \min^{-1} \) | [81]   |
| WO3/g-C3N4            | 500-W Xenon lamp (λ > 400nm cut-off filter) | Methylene blue degradation            | \( k = 2.38 \times 10^{-2} \min^{-1} \) | [82]   |
| 500-W Xenon lamp      | 500-W Xenon lamp                     | RhB degradation                      | \( k = 1.08 \times 10^{-2} \min^{-1} \) | [83]   |
| WO3/g-C3N4            | 300-W Xenon lamp (λ > 400-nm cut-off) | Methylene blue degradation            | \( k = 1.393 \text{h}^{-1} \) | [84]   |
| g-C3N4/MoO3           | 300-W Xenon lamp (λ > 400nm)         | Methylene blue degradation            | \( k = 8.837 \times 10^{-1} \text{h}^{-1} \) | [85]   |
| Bi2O3/g-C3N4          | 150-W Xenon lamp (420-nm cut-off filter) | Methylene blue degradation            | \( k = 1.727 \times 10^{-2} \min^{-1} \) | [86]   |
| g-C3N4/Bi3WO6         | 300-W Xenon lamp (350–780-nm cut-off filter) | 2,4-dichlorophenol dechlorination (2,4-DCP) | \( k = 1.13 \text{h}^{-1} \) | [87]   |
| Ag3PO4/g-C3N4         | 300-W Xenon arc lamp (420-nm cut-off filter) | Tetracycline degradation             | \( k = 1.158 \times 10^{-1} \text{min}^{-1} \) | [88]   |
| MoO3/g-C3N4           | 350-W Xenon lamp (420-nm cut-off filter) | Tetracycline degradation             | \( k = 2.31 \times 10^{-2} \text{min}^{-1} \) | [47]   |
| BiVO4/g-C3N4          | 500-W Xenon lamp (λ > 420-nm cut-off filter) | RhB degradation                      | \( k = 3.42 \times 10^{-1} \text{h}^{-1} \) | [89]   |
| WO3/g-C3N4            | 300-W Xenon lamp (420-nm cut-off filter) | Ceftriaxur sodium (CFS) degradation   | \( k = 1.64 \times 10^{-2} \text{min}^{-1} \) | [90]   |
| g-C3N4/TiO2           | 15 W, 365-nm UV lamp                 | Formaldehyde (HCHO) degradation       | \( k = 7.36 \times 10^{-2} \text{min}^{-1} \) | [91]   |
| Bi2O3/g-C3N4          | 300-W Xenon lamp (λ > 420nm)         | RhB degradation                      | \( k = 7.46 \times 10^{-2} \text{min}^{-1} \) | [92]   |
| g-C3N4/TiO2           | 3-W 365-nm UV lamp                   | Brilliant red X3B degradation         | \( k = 5.1 \times 10^{-2} \text{min}^{-1} \) | [93]   |
| Bi2O3/g-C3N4          | 500-W Xenon arc lamp (400-nm cut-off filter) | RhB degradation                      | \( k = 1.01 \times 10^{-2} \text{min}^{-1} \) | [78]   |
| g-C3N4/Ag2CO3         | 300-W Xenon arc lamp (400-nm cut-off filter) | RhB degradation                      | \( k = 1.36 \times 10^{-1} \text{min}^{-1} \) | [94]   |
| g-C3N4/Bi2O3          | 300-W Xenon lamp (λ > 420-nm cut-off filter) | RhB degradation                      | \( k = 1.97 \times 10^{-1} \text{min}^{-1} \) | [95]   |
Also, Xijun Wang and coworkers synthesized the carbon–quantum-dot/carbon nitride hybrid with high ability of isolating hydrogen from oxygen in the photocatalytic water splitting using the first-principles calculation [115]. In this study, it was found that only protons were allowed to penetrate the inner layer of graphene to produce H₂. The produced hydrogen gas was then capsuled in the inner layer of the synthesised photocatalyst. This also prevents the reverse reaction and makes the availability of the produced hydrogen (H₂).

**CO₂ Reduction**

The population growth and industrialization has been detrimental the environment including the atmosphere [116]. CO₂ increase recently has remained to be the crucial agenda in the universe [117, 118]. CO₂ produced from burning of fuel from domestic to industrial level has contributed much on the atmospheric air pollution hence resulting into the current global warming the world is suffering today [119–121]. Different strategies have been developed to cut down the production of CO₂. The SDG 7 pinpoint for the clean and renewable energy as one way of reducing the production of CO₂ in the atmosphere [122, 123]. But increasing demand of fuel and productions in the industries still make the contribution of CO₂ to be high (Table 3). Technologies have been developed to degrade the produced CO₂. Among others, photocatalytic reactions have promised to be one of the best technologies for the CO₂ reduction.

Sheng Zhou and coworkers reported the facile in situ synthesis of graphitic carbon nitride (g-C₃N₄)-N-TiO₂ heterojunction as an efficient photocatalyst for the selective photoreduction of CO₂ to CO. The composites of graphitic carbon nitride and nitrogen-doped titanium dioxide composites (g-C₃N₄-N-TiO₂) were in situ synthesized by thermal treatment of the well-mixed urea and Ti(OH)₄ in an alumina crucible with a cover at different

| Table 1 | Studies of g-C₃N₄ heterojunctions for various pollutants degradations (Continued) |
|---------|-----------------------------------------------------------------------------------|
| Photocatalyst | Light source | Application | Performance | Ref. |
| g-C₃N₄/Bi₂WO₆ | 300-W Xenon lamp | Ibuprofen degradation | k = 5.2 × 10⁻² min⁻¹ | [60] |
| V₂O₅/g-C₃N₄ | 250-W Xenon lamp (420-nm cut-off filter) | RhB degradation | k = 4.91 × 10⁻² min⁻¹ | [96] |
| Al₂O₃/g-C₃N₄ | 350W Xenon lamp (400-nm cut-off filter) | RhB degradation | k = 2.57 × 10⁻² min⁻¹ | [97] |
| MoS₂/g-C₃N₄ | 300-W Xenon lamp (λ > 420-nm cut-off filter) | RhB degradation | k = 1.52 × 10⁻¹ min⁻¹ | [98] |
| CuO/g-C₃N₄ | 300-W Xenon lamp (λ > 420-nm cut-off filter) | Salicylic acid degradation | 94% degradation | [99] |
| g-C₃N₄-Cu₂O | LED lamp | Methyl orange degradation | 84% degradation | [100] |
| g-C₃N₄/BiO₁ | Visible light | RhB degradation | k = 3.99 × 10⁻² min⁻¹ | [101] |
| g-C₃N₄/TiO₂ | 30-W visible light lamp | Orange II degradation | k = 3.11 × 10⁻² min⁻¹ | [102] |
| Bi₂MoO₆/g-C₃N₄ | 300-W Xenon lamp (λ > 420-nm cut-off filter) | Bacterial disinfection (E.Coli DH5α) | k = 1.269h⁻¹ | [103] |
| g-C₃N₄/CeO₂ | 50-W compact fluorescent lamp (λ > 400-nm cut-off filter) | Methylene blue degradation | k = 2.46 × 10⁻¹h⁻¹ | [104] |

| Table 2 | Hydrogen production study by different g-C3N4 heterostructures |
|---------|-------------------------------------------------------------------|
| Photocatalyst | Source of light | Application | Performance | Ref. |
| g-C₃N₄/Au/CdS | 300-W Xenon lamp (420-nm cut-off filter) | Hydrogen production | 530 μmol after 5 h | [110] |
| WO₃/g-C₃N₄ | Artificial solar light | Hydrogen production | 110 μmol h⁻¹g⁻¹ | [107] |
| C₃N-TiO₂/g-C₃N₄ | 300-W Xenon arc lamp (400-nm cut-off filter) | Hydrogen production | 39.18 mmol h⁻¹g⁻¹ | [111] |
| WO₃/g-C₃N₄ | 300-W Xenon lamp (λ > 420-nm cut-off filter) | Hydrogen production | 1853 μmol h⁻¹g⁻¹ | [106] |
| g-C₃N₄/WS₂ | 300-W Xenon arc lamp (λ ≥ 420-nm cut-off filter) | Hydrogen production | 101 μmol h⁻¹g⁻¹ | [112] |
| Bi₂MoO₆/g-C₃N₄ | 300-W Xenon lamp (λ > 420-nm cut-off filter) | Hydrogen production | 563.4 μmol h⁻¹g⁻¹ | [103] |
mass ratios. The mixture was heated to 550°C for 3 h and then 580°C for 3 h at a heating rate of 5°C min\(^{-1}\) to obtain the product. The product was washed with nitric acid (0.1 M) and distilled water for several times to remove residual alkaline and sulfate species (e.g., ammonia and \(\text{SO}_4^{2-}\)) adsorbed on the sample, and then dried at 80°C overnight to get the final product.

In their report, photocatalytic of CO\(_2\) reduction was carried out in a gas-closed circulation system operated under simulated light irradiation with photocatalyst, CO\(_2\), and water vapor sealed in the system. The heterojunction between g-C\(_3\)N\(_4\) and nitrogen-doped TiO\(_2\) demonstrated enhanced catalytic performance reaching the highest CO evolution amount (14.73 \(\mu\)mol) during light irradiation compared with P25 (3.19 \(\mu\)mol) and g-C\(_3\)N\(_4\) (4.20 \(\mu\)mol) samples. The heterojunction between g-C\(_3\)N\(_4\) and nitrogen-doped TiO\(_2\) showed the high activity because it promotes the separation of light-induced electrons and holes. These results prove that the here-tostructured carbon nitride semiconductor has high photocatalytic CO\(_2\) reduction as compared to their precursors [126]. More studies on the heterojunctions of g-C\(_3\)N\(_4\) for photocatalytic reduction of CO\(_2\) are summarized in Table 3.

### Photocatalyst Stability

The stability of photocatalysts is crucial for their practical application [59]. It shows how the photocatalysts can be reused without or with little loss in their activities [21]. In order to know the reusability of the photocatalyst, the degradation of the pollutant by the same composite for several times/cycles are performed [127].

The as-synthesized g-C\(_3\)N\(_4\)/Bi\(_2\)MoO\(_6\) heterojunction photocatalyst exhibited excellent stability in the visible light photochemical degradation reactions. Figure 11 shows that after six consecutive runs, no apparent deactivation of the composite g-C\(_3\)N\(_4\)/Bi\(_2\)MoO\(_6\) (A8) is observed, and the RhB degradation efficiency declines by <1%.

Wang and coworkers [115] then designed a hybrid structure of carbon-quantum-dots (CQDs) attaching to a single-layered carbon nitride (C\(_3\)N\(_4\)) material. These scientists showed that the hybrid can harvest visible and infrared light for water splitting. Also, Darkwah and Ao also discussed how stable the carbon nitride can work more efficiently in degradation of both organic and inorganic compounds for wastewater treatment and related applications [22, 128, 129].

### Future Viewpoint of Heterostructure g-C\(_3\)N\(_4\)

The future research of heterostructure g-C\(_3\)N\(_4\) nano-based photocatalyst may focus on the design and synthesis of more effective nanostructures, which are responsive to morphology monitoring, evaluating the photocatalysis practicality, and the degradation behavior and mechanism of more types of pollutants, especially for non-dyed pollutants and then exploring the applications of diverse g-C\(_3\)N\(_4\) nano-based particles in treating wastewater, its effective application in solar energy utilization, sensing applications by fully assessing their photocatalytic ability, cost, energy consumption, and reusability.

One of the key areas to consider for future studies should mainly focus on employing new technologies or combination of the existing techniques of increasing the settling velocity of g-C\(_3\)N\(_4\) to upturn the run-off rate that could be used to improve the material for improving photocatalytic activities.

### Conclusion

Although photocatalytic degradation is an ideal strategy for cleaning environmental pollution, it remains challenging to construct a highly efficient photocatalytic system by steering the charge flow in a precise manner. Different researches have proven the high photocatalytic

**Table 3** Studies of g-C\(_3\)N\(_4\) heterojunctions on Carbon dioxide (CO\(_2\)) reduction

| Photocatalyst | Source of light | Application | Performance | Ref. |
|--------------|----------------|-------------|-------------|-----|
| g-C\(_3\)N\(_4\)/ZnO | 300-W Xenon arc lamp | CO\(_2\) reduction | 0.6 \(\mu\)mol h\(^{-1}\)g\(^{-1}\) CH\(_3\)OH | [124] |
| SnO\(_2\)/g-C\(_3\)N\(_4\) | 500-W Xenon lamp | CO\(_2\) reduction | 22.7 \(\mu\)mol h\(^{-1}\)g\(^{-1}\) CO, CH\(_3\)OH, CH\(_4\) | [125] |
| BiO\(_2\)/g-C\(_3\)N\(_4\) | 300-W Xenon arc lamp (\(\lambda\) > 400-nm cut-off filter) | CO\(_2\) reduction | 17.9 \(\mu\)mol g\(^{-1}\) CO | [61] |

Fig. 11 Cycling runs for photocatalytic degradation of RhB over g-C\(_3\)N\(_4\)/Bi\(_2\)MoO\(_6\) composite A8 under visible light irradiation. Reproduced with permission [23]. Copyright 2014 Elsevier B.V.
activity of the heterostructured semiconductors over pollutants degradation, hydrogen gas evolution, and carbon dioxide reduction. Among others, heterostructured carbon nitride (CN) semiconductors in recent decades have shown the anonymous photocatalytic activity towards organic pollutants, hydrogen production, and carbon dioxide. Reasonably, g-\( \text{C}_3\text{N}_4 \) has revealed to be one of the best candidates suitable for developing and assembling state-of-the-art composite photocatalysts. Therefore, there is slight doubt that the considerable advancement of g-\( \text{C}_3\text{N}_4 \) nano-based particle will endure to develop in the near future. Hence, more researches should consider its modification structures, mechanisms, and the degradative abilities of this candidate.

**Abbreviations**

\( g-\text{C}_3\text{N}_4 \): Graphite carbon nitride; TiO\(_2\): Titanium oxide; ZnO: Zinc oxide

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