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Review

Carbon-Doped Boron Nitride: A Metal-Free Catalyst for Superior Photocatalysis and Precision Adsorption

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Abstract

Boron nitride (BN) doped with carbon atoms is a new metal-free nanoparticle that has various applications, including photocatalysis and as an adsorbent in adsorption processes. Regarding application as a photocatalyst, in fact, the band gap energy of BN is roughly 5.2 eV, which is very high if compared with metal-based photocatalysts such as TiO_2, ZnO, etc. However, composite and doped BN give excellent activity in photodegradation with gap energy ranging between 1.5 and 2.5 eV. As it is a porous material, it gives extra efficiency to photocatalysis, which provides a larger surface area. With respect to adsorption, the addition of functional groups to BN edges makes the BN nanoparticle selective, which provides porosity, increase active sites and a large surface area, which varies from 100 to 950 $m^2\ g^{-1}$. Additionally, carbon-doped boron nitride can be used in electrocatalysis processes like carbon dioxide reduction and ammonia synthesis. All in all, carbon-doped boron nitride (BN) shows potential environmental remediation catalyst. Its enhanced photocatalytic activity, large surface area and improved visible light absorption enable BN to degrade pollutants in water medium for environmental clean-up applications. The preparation condition marginally effects the structural, optical and electronic more specifically band edges position of carbon doped BN.

Keywords: Boron nitride (BN); carbon doped BN; photocatalyst; adsorbent; electrocatalysis.

Introduction

Because of its exceptional physical and chemical properties, boron nitride (BN) is widely used in chemical applications. The high thermal conductivity, negatively charged , and robust chemical stability of hexagonal boron nitride (BN) nanoparticles, distinguished by their large specific surface area, prove to be quite advantageous for energy storage and wastewater cleanup [1–5] Hexagonal boron nitride (h-BN) was one two-dimensional material made of metal-free sources with a structure similar to graphite. It shares several characteristic properties of graphite,, including anisotropy, high hardness, thermal conductivity, moderate lubricity, and a perpendicular base plane orientation [6,7]. BN mirror image of carbon BN with an atomic ratio of two: one has three crystalline modifications, reminiscent to that carbon (allotropes): wurtzite BN or w-BN; cubic BN or c-BN (analogous to diamond), and hexagonal BN or h-BN (similar to graphite). Among these, h-BN has been shown to be the most stable phase under normal conditions [8].

The structural characteristics and the partially ionic nature of the B-N covalent bonds indicate their polarity [6]. In hexagonal boron nitride (h-BN), the nitrogen atoms hold onto their electrons more tightly than in graphite, where the

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electrons are evenly spread out along the carbon-carbon bonds. This is because nitrogen is much more electro-negative than boron, which means that it pulls the shared electrons in the B-N bonds closer to it. As a result, the lone pair of electrons in nitrogen's pz orbital doesn't fully delocalize with boron's pz orbital, making the bonding in h-BN more localized and polarized compared to graphite's uniform electron cloud [6]. Like graphite, h-BN has a layered structure with a perpendicular basal plane orientation, exhibits anisotropy (direction-dependent behavior), and offers excellent thermal conductivity. It's also remarkably hard and provides solid lubrication just like graphite. These shared traits make h-BN a close cousin to graphite in terms of structure and performance [6,9,10]. Although similar to graphite, in many respects h-BN has very different chemical, electrical and optical characteristics. Unlike graphite's conductive carbon layers, h-BN partially delocalized electrons create a wide band gap, making it an excellent electrical insulator and giving it a transparent, colorless appearance. This combination of traits makes h-BN incredibly versatile. It used in everything from UV optics and cosmetic products to heat-conductive yet electrically insulating fillers in electronics [10].

Like other carbon-based nanomaterials, boron nitride (BN) nanomaterials have been made in a number of different shapes and sizes. Scientists have successfully developed one-dimensional (1D) BN nanoribbons and nanotubes that resemble carbon nanotubes in geometry but with distinct BN properties. Similar to graphene, two-dimensional (2D) BN nanosheets provide remarkable chemical and thermal stability. Researchers have also engineered three-dimensional (3D) porous BN architectures and zero-dimensional (0D) BN fullerenes, which are the geometric equivalents of carbon buckyballs. This structural versatility allows BN nanomaterials to be precisely tailored for specific applications, from advanced thermal management systems to cutting-edge electronic devices, while leveraging the material's inherent advantages like high thermal conductivity and electrical insulation. The ability to create BN in these varied nanoscale forms significantly expands its potential uses across multiple high-tech industries [9]. Hexagonal boron nitride (h-BN) nanoparticles exhibit unique surface characteristics and active structural sites that can be enhanced through physical modifications, potentially introducing new physicochemical functionalities. These engineered nanomaterials belong to the class of low-dimensional BN structures, which are confined in at least one dimension to the nanoscale whether as ultra-thin 2D sheets, slender 1D nanotubes, or other nanoscale configurations. At this reduced scale, the material's high surface-to-volume ratio and exposed edges create more reactive sites compared to bulk h-BN, unlocking enhanced properties and broader applications in fields ranging from advanced composites to nanoscale electronics. The nanoconfinement effect fundamentally alters h-BN's behavior, making these low-dimensional forms particularly valuable for cutting-edge technological applications [6]. The surface characteristics of h-BN materials can be tailored to create porous structures that can be used for drug delivery, heterogeneous catalytic supports, pollutant control, and H_2 storage, among other applications [6]. Recent progress in template-free synthesis techniques have facilitated the creation of porous boron nitride (BN) materials with exceptionally high specific surface areas (SSAs). These materials typically exhibit SSAs ranging from 100 to 950 $m^2\ g^{-1}$, though cutting-edge developments have pushed this limit even further, achieving record surface areas approaching 1900 $m^2\ g^{-1}$. This substantial improvement in SSA values represents a major breakthrough in porous BN material synthesis, significantly enhancing their potential for applications requiring high surface area materials [11,12]. In hexagonal boron nitride (h-BN), the polarity of B-N bonds produces special chemical reactivity sites. while nitrogen atoms function as electron-rich (δ-) sites, boron atoms act as slightly electron-deficient (δ+) centers. The resulting charge polarization makes these atomic sites particularly responsive to various chemical functionalization approaches [6]. This unique electronic structure makes boron atoms natural targets for nucleophilic attack while nitrogen atoms readily react with electrophilic species. Essentially, the electron-deficient boron centers attract electron-rich molecules, and the electron-rich nitrogen sites are prone to attack by electron-seeking groups. This complementary reactivity allows for precise, site-selective chemical modifications of h-BN - boron atoms can be functionalized by nucleophiles while nitrogen react with electrophiles, enabling sophisticated control over the material's chemical properties. A number of functional groups including, hydroxyl (–OH) [13], amino ($–NH_2$) [14], ether (–OR) [15], amine (–NHR) [14], arcyl (–COR) [16] , alkyl (–R) [17], and halogen (–X) [16] groups, and also some heteroatoms (C and O), were added chemically to BN skeletons in an experiment. Boron nitride has large band gap, which is normally between 3.98 and 6 eV, is a major drawback, though, as it can only absorb high energy UV light with wavelengths shorter than 310 nm. The area of the electromagnetic spectrum that BN can efficiently use for optoelectronic applications is significantly reduced by this limitation [8,18]. Modified boron nitride exhibits enhanced photocatalytic activity when combined with other materials, as even slight structural changes can promote efficient Z-scheme charge transfer or create negatively charged active sites. By preventing rapid recombination and enhancing electron-hole pair mobility and separation under light irradiation, these modifications greatly increase photocatalytic

efficiency. This makes engineered BN composites particularly valuable for advanced light-driven applications [1]. It has recently been demonstrated that carbon-doped BN nanosheets and BN hetero-configurations are beneficial for photocatalytic H2 evolution and water pollutant elimination [6]. Huang and Wang pioneered a breakthrough by developing carbon-doped BCN nanosheets, effectively narrowing the band gap to 2.1 eV through strategic carbon incorporation. This clever modification enabled the photocatalyst to harness visible light (λ > 420 nm), achieving a notable 0.54% absorption coefficient at 405 nm wavelength. The engineered material not only boosted hydrogen production under visible light but also demonstrated remarkable versatility by efficiently driving photocatalytic CO_2 reduction - showcasing its dual functionality for sustainable energy applications [19]. Numerous investigations have shown that BCN nanoparticles are extremely effective, metal-free catalysts for the oxygen evolution reaction (OER), a basic process essential to the functioning of fuel cells, sensors, Li-O_2 batteries, and other electrochemical applications [20,21]. This review examines the performance of carbon-doped boron nitride (BN) in photocatalysis, adsorption, and electrocatalytic applications, with the aim of elucidating how carbon doping modulates the optical, electrical, and structural properties of BN. By emphasizing structure–property–performance relationships, this critical mini-review highlights the roles of B–N–C moieties, carbon-induced mid-gap states, vacancies, and edge defects in band gap narrowing, visible-light absorption, and interfacial charge transfer, thereby providing a perspective that clearly distinguishes it from existing BN/BCN reviews.

2. Carbon Doped Boron Nitride

By carefully adding carbon atoms, scientists have created a novel method of altering boron nitride. Carbon pairs function as alloying elements in these carbon-doped BN structures (also known as BCN), creating patterns resembling aromatic rings inside the BN lattice structure. The doping process involves carefully replacing adjacent boron-nitrogen atom pairs in single-layer BN sheets with carbon atom couples during early synthesis stages. Researchers achieve this through a clever carbon-displacement reaction technique, which allows precise control over the doping level while maintaining the material's structural integrity; this approach creates hybrid materials that combine the best properties of carbon and boron nitride, opening new possibilities for advanced applications which can be seen in Figure 1 [6,22]. These couples of C2 atoms could be separated or combined together to form C6 aromatic like ring structures [22]. As carbon doping increases, the aromatic carbon rings grow and eventually interconnect. Interestingly, even at 50% doping levels in BC_2N monolayers, computational models reveal that the most stable structure forms an intriguing pattern alternating parallel chains of BN and carbon zigzagging across the material's plane [23,24]. Different fixed isomer through each Carbon atom bonded with one Boron, Carbon and Nitrogen atom is supposed to be similar stability Because of the releasing of structural stress, that is to say the structure I that can be seen in Figure 1.

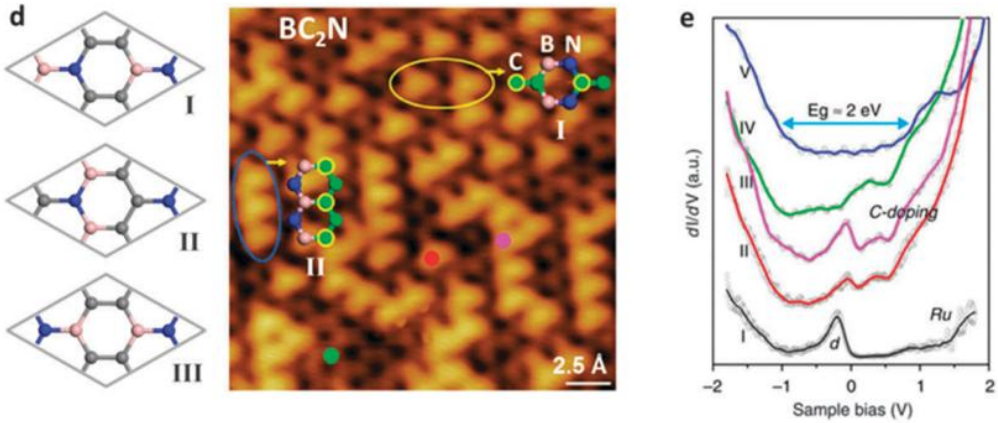

Figure 1. (d) Three theoretical calculations BC2N configurations and STM atomic picture of the BC2N fabricated on [Ru 0001] layer show the two very-stable BC2N isomers. (e) illustrates an band gap energy of 2 eV. [6,22].

A thorough grasp of the chemical environment and bonding properties of a carbon-doped boron nitride (C-doped BN) structure is necessary for analysis. Key bonds like B-C and N-C sp2 hybridized bonds can be found using advanced spectroscopy techniques like XPS (X-ray photoelectron spectroscopy), XANES (X-ray absorption near-edge structure), solid-state NMR, EELS (electron energy loss spectroscopy), and IR (infrared) spectroscopy [6,22].

2.1. Carbon-Doped Boron Nitride for Electro Catalytic Application

Electrocatalytic conversion of nitrogen gas to ammonia was performed by [25] team, a cathode catalyst, C-BN reaches an NH_3 output rate of 36.7 μg h^{-1} mg cat^{-1} at −0.55 V compared to a reversible hydrogen electrode (RHE), and is far greater than even the Nano plates of synthetic and exfoliated BN. The template method was utilized to synthesis carbon doped BN; here is the brief of experimental part. In a standard experimental trial, 1.13 g of 1-Butyl-3-methylimidazolium hexafluorophosphate [Bmim] BF4 was put in a beaker containing in 40 mL of ultrapure water and stirred until dissolving. After that, boric acid was mixed with urea the mole ratio is equal to 1:23 and then added to [Bmim] solution until homogeneous solution obtained. The water was evaporated at eighty Celsius by means of water bath, the white solid was got and then put in furnace at 900 °C for six hours in an oxygen free atmosphere (N_2 atmosphere). Cleaning stage was performed using 0.1M HCl in ultrapure water and ethanol for three times. Next, the obtained powder was put in an oven sixty Celsius until dried (24 hours) [25,26]. Figure 2 illustrates the synthetic approach of C doped Boron Nitride (BN). From the figure it is clear that nanosheets of boron nitride (BNNSs) consider a substance that resembles graphene but is composed of nitrogen (N) and boron (B) atoms organized in a thin, two-dimensional sheet rather than just carbon atoms. These nanosheets feature intriguing electrical properties and a large surface area, among other special qualities. Doping with carbon can change the BNNSs' surface chemistry and electrical structure, which could improve their catalytic performance. It is notable that for ammonia preparation, a potentially more environmentally friendly and sustainable option that can be used in milder conditions and, preferably, with renewable electricity is electrocatalysis.

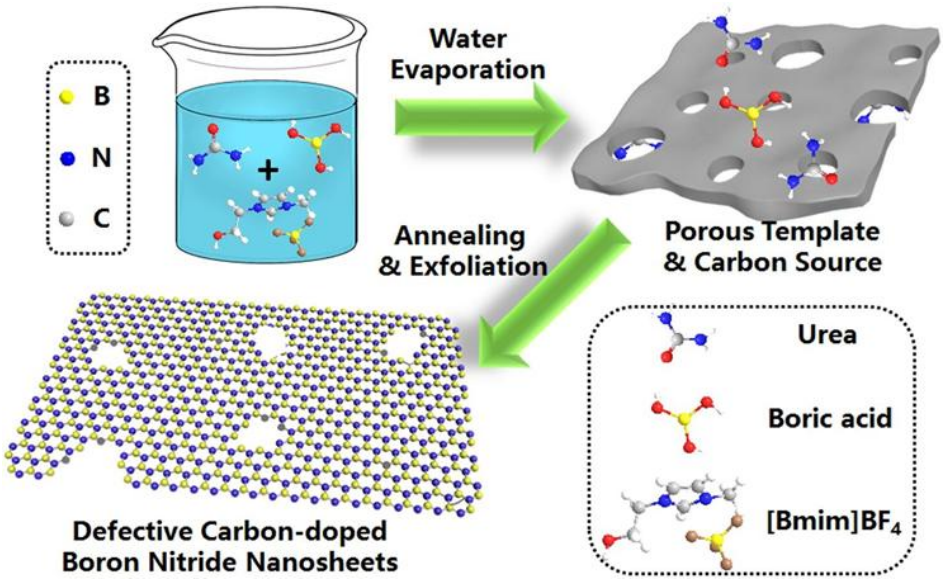

Figure 2. Block diagram for the synthesis of C doped BN nanosheets steps by step [25].

With respect to activity measurement, the procedure as illustrated by Liu *et al.* [25] was performed, the brief of experiment is as following. 100 mg of prepared C doped BN put in 50mL of ethanol and ultrasonic cell disruptor was utilized exfoliate it for two hours. Fifteen-minute centrifugation at rate about 300 rpm, next 5 weight percent 40 μL of sulfonated tetrafluoroethylene-based fluoropolymer-copolymer (Nafion) was added to the above solution of C-BN and then sonicated for one hour in order to get a homogeneous ink like solution. 100μL of the ink like solution was accumulated on a carbon paper electrode in one-to-one cm^2 area and kept at ambient temperature (25 ^oC), the deposited C-BN was 0.1mg thickness. The electrode was called C-BN/CP. Regarding electro-catalytic procedure, Ag/AgCl electrode (saturated KCl electrolyte) was used as reference electrode, and a graphite rod is used as counter electrode all against C-BN/CP working electrode. Figure 3 shows illustration of the characterization of C doped BN.

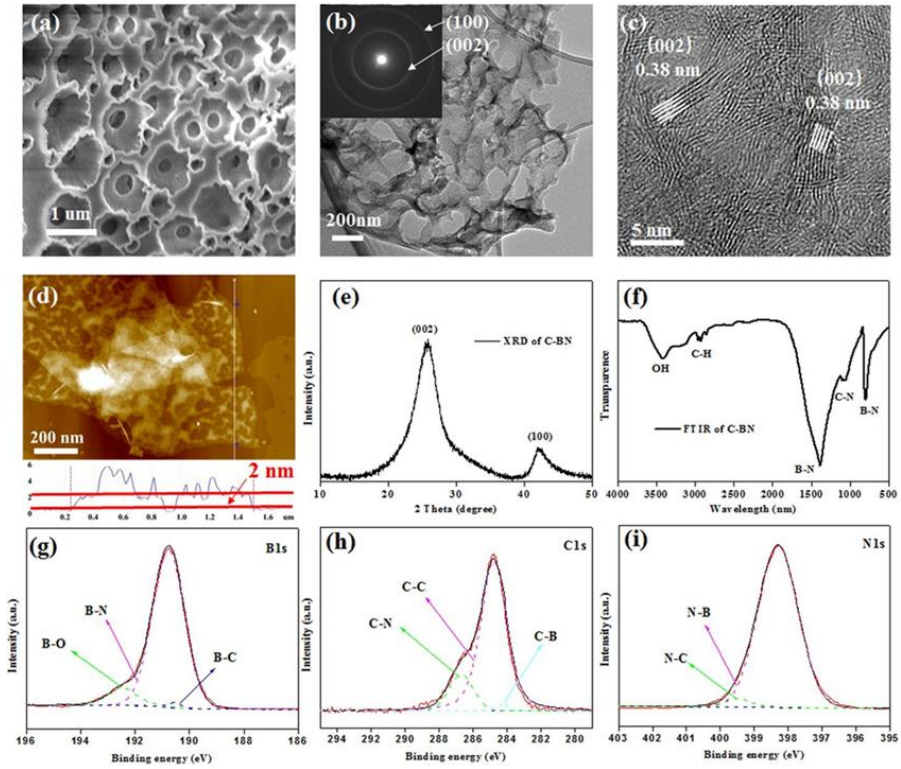

Figure 3. (A) SEM image, (B) TEM image, and (C) HRTEM images of Carbon doped boron nitride. (D) shows the AFM image. (E) shows XRD, (F) illustrate FTIR, and (G) XPS spectra of Boron 1s, (H) Carbon 1s, and (I) Nitrogen 1s [25]**.**

2.2. Carbon Doped Boron Nitride for Production of H_2 Gas from Water

The development of photo catalytic hydrogen generation from water is a hopeful technique for the efficient application of sunlight into chemical energy, and is seen as a long-term and viable solution for addressing global energy and environmental problems. In a research that conducted by Chen *et al.* [27] team, Carbon doped boron nitride (BCN) has been created as metal-free photo catalysts utilizing solid-gas interaction and boron core molecular design technique. The carbon-doped Boron Nitride was synthesized from four various materials, such as: melamine phosphate borate (MPB), melamine borate (MB), boric acid (BA) and boron oxide (BO). It has been found that the morphology of C-BN changes with changing the starting Martials (precursors) or even photo catalytic activity is different as well. Especially in comparison with those of bulk C-BN, the BCN-MPB Nano sheets gives much higher specific surface area, longer life time of exciton charge, and greater electron transfer capacity. Therefore, during light irradiation, BCN-MPB Nano sheets reveal markedly increased photo catalytic hydrogen production activity to those of C-B bulk [12].

Here is the brief of synthesis regarding BCN-MPB nanosheets: The stepwise method was applied to synthesize BCN-MPB; the precursors were melamine ($C_3H_6N_6$), boric acid (H_3BO_3), and phosphoric acid (H_3PO_4, 85%). Melamine was added to a homogeneous phosphoric acid solution at 50°C and under constant stirring for up to two hours. The solution was equilibrated to room temperature and then filtered and washed with distilled water and dried at 80°C. From this step, melamine phosphate (MP) adducts were obtained. he synthesis of MPB adducts involved mixing boric acid with MP under continuous stirring, followed by heating at 80°C in a water bath for three hours, equilibration to room temperature, filtration, washing with distilled water, and drying at 70°C overnight. For BCN-MPB, glucose, MPB adducts, and urea were ground together and heated at 1050°C for five hours in an ammonia atmosphere (5°C/min heating rate), with the final product washed in 0.1M HCl. Bulk BCN-MB was prepared similarly but without phosphoric acid and with drying at 90°C. BCN-BA was synthesized by grinding glucose, boric acid, and urea before furnace treatment under the same conditions, followed by HCl washing. Similarly, BCN-BO was produced using boron oxide instead of boric acid, with identical heating and washing steps [12]. The band gap may be reduced by altering the electronic band structure of BN by adding carbon atoms. This makes it possible for the substance to absorb more visible light and other parts of the solar spectrum, which increases the number of electron-hole pairs and improves light-harvesting efficiency [20,27,28] The BN lattice may develop vacancies or defects as a result of carbon doping. Figures 4, 5, and 6 shows the characterization of synthesized BCN nanoparticles and Figure 7 shows its photo electronic properties.

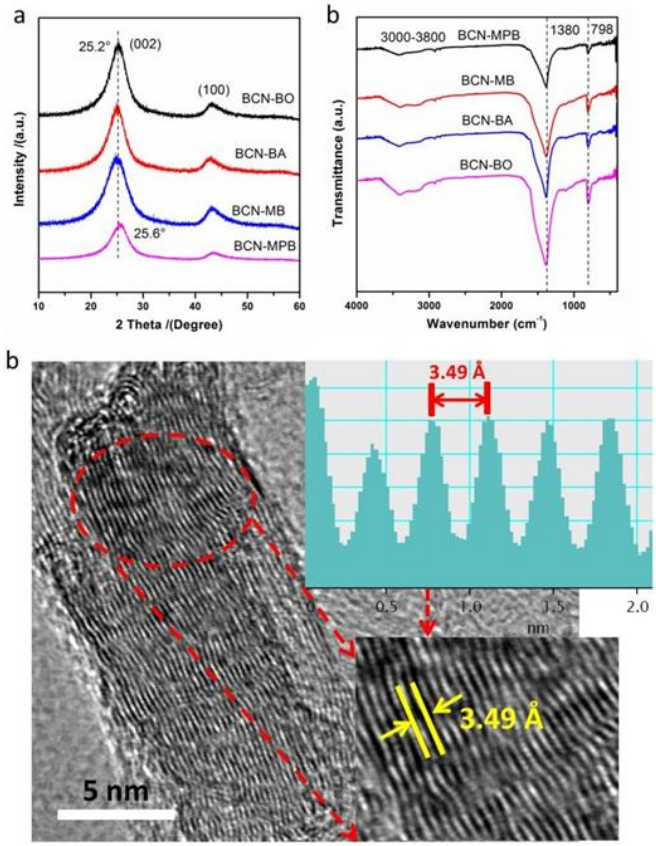

Figure 4. (a) X-ray diffraction (XRD) patterns of BCN-MPB, BCN-MB, BCN-BA, and BCN-BO samples; (b) High-resolution transmission electron microscopy (HRTEM) image of the BCN-MPB composite; (c) Fourier-transform infrared (FTIR) spectra of BCN-BO, BCN-BA, BCN-MB, and BCN-MPB.

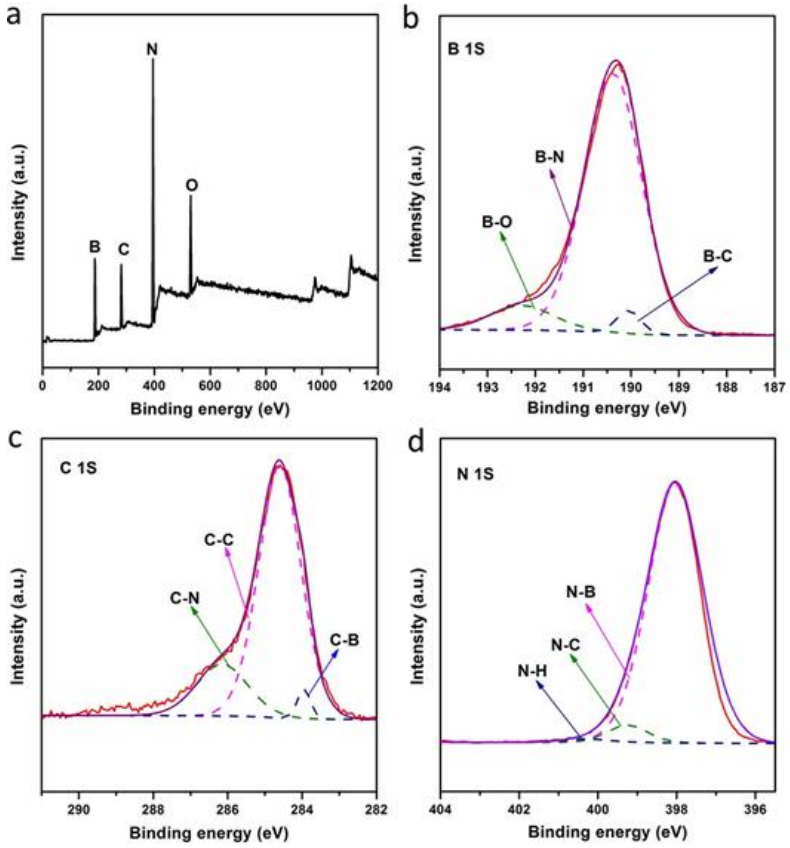

Figure 5. XPS survey spectrum and high-resolution core-level spectra of the BCN-MPB sample.

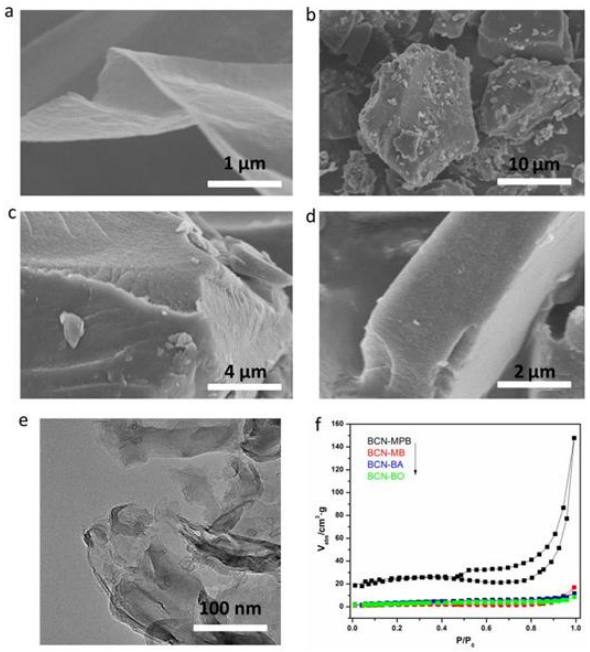

Figure 6. (a–d) SEM images of BCN-MPB, BCN-MB, BCN-BA, and BCN-BO, respectively; (e) TEM image of the BCN-MPB sample; (f) Nitrogen adsorption–desorption isotherms of BCN-MPB, BCN-MB, BCN-BO, and BCN-BA.

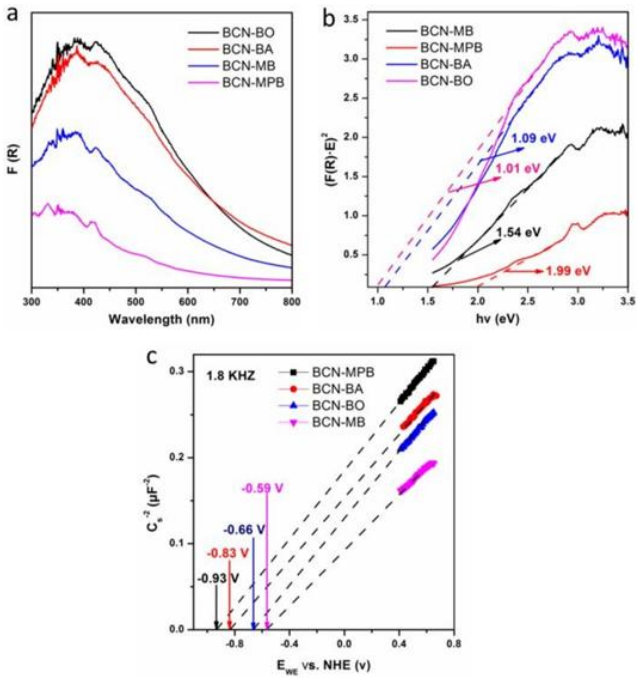

Figure 7. (a) UV–Vis absorption spectra of BCN-MPB, BCN-MB, BCN-BA, and BCN-BO; (b) Tauc plots for estimating the optical band gaps of the BCN samples as a function of photon energy; (c) Mott–Schottky plots used to determine the conduction band minima of BCN-MPB, BCN-MB, BCN-BA, and BCN-BO, measured in 0.2 M Na_2SO_4 solution at 1.8 kHz under dark conditions.

Here is another research for water splitting and carbon dioxide reduction that has been done by Huang et al.[19] team, The productivity of hydrogen was estimated to be 6.0 μmol h^{-1}. The noticeable quantum efficiency of BCN-30 was determined to be 0.54 percent at 405nm wavelength. Here is a brief procedure of this work: different amount of glucose as a source of Carbon was mixed with urea and boron oxide, the mixture was put in a furnace for 5 hours at 1,250 °C in oxygen free atmosphere (ammonium atmosphere). After preparation, the sample is referred to as BN-x, where x is the weight percentage of boron oxide and glucose. The following figure 8 shows characterization and opto-electronic properties of prepared photo-catalyst.

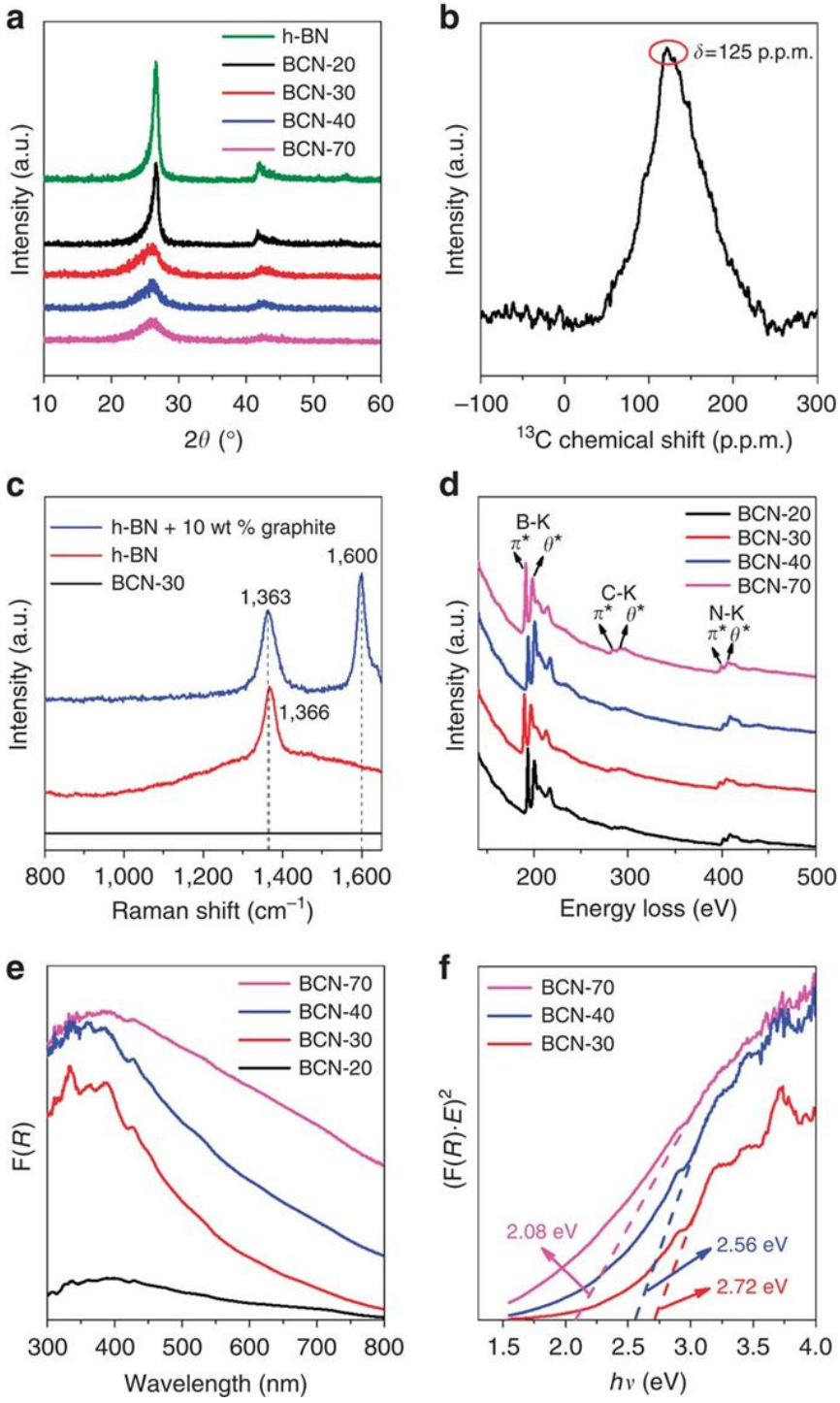

Figure 8. Characterization and structural analysis of carbon-doped boron nitride (BN): (a) XRD patterns of h-BCN synthesized with varying glucose ratios; (b) Solid-state 13C NMR spectrum of the BCN sample with x = 30; (c) Raman spectra; (d) Electron energy loss spectroscopy (EELS) spectra of the BCN-x sample; (e) UV–Vis diffuse reflectance spectra (DRS); (f) Band gap estimation of BCN-x samples based on Tauc plot analysis.

2.3. Carbon Doped Boron Nitride for Photodegradation

The Chen et al. team [1], carried out another study in which g-carbon nitride (CMBN) was used to modify boron nitride and use it as a photocatalyst. The band gap calculation and photocatalytic activity of CMBN are displayed in Figures 9 and 10. The breakdown of Enrofloxacin, in contaminated water can be efficiently photocatalyzed by carbon-doped boron nitride due to its improved absorption of visible light and other advantageous characteristics.

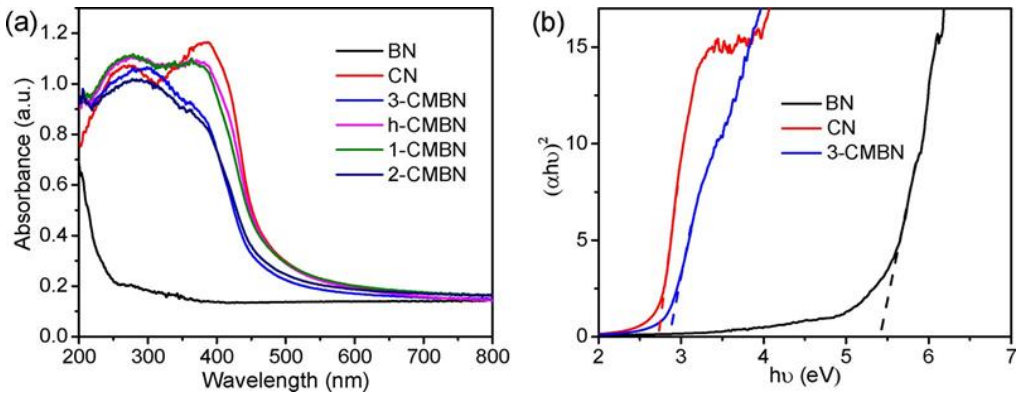

Figure 9. (a) DRS spectra of BN, CN, and 3-CMBN photocatalysts; (b) Tauc plots for estimating the optical band gaps of the samples.

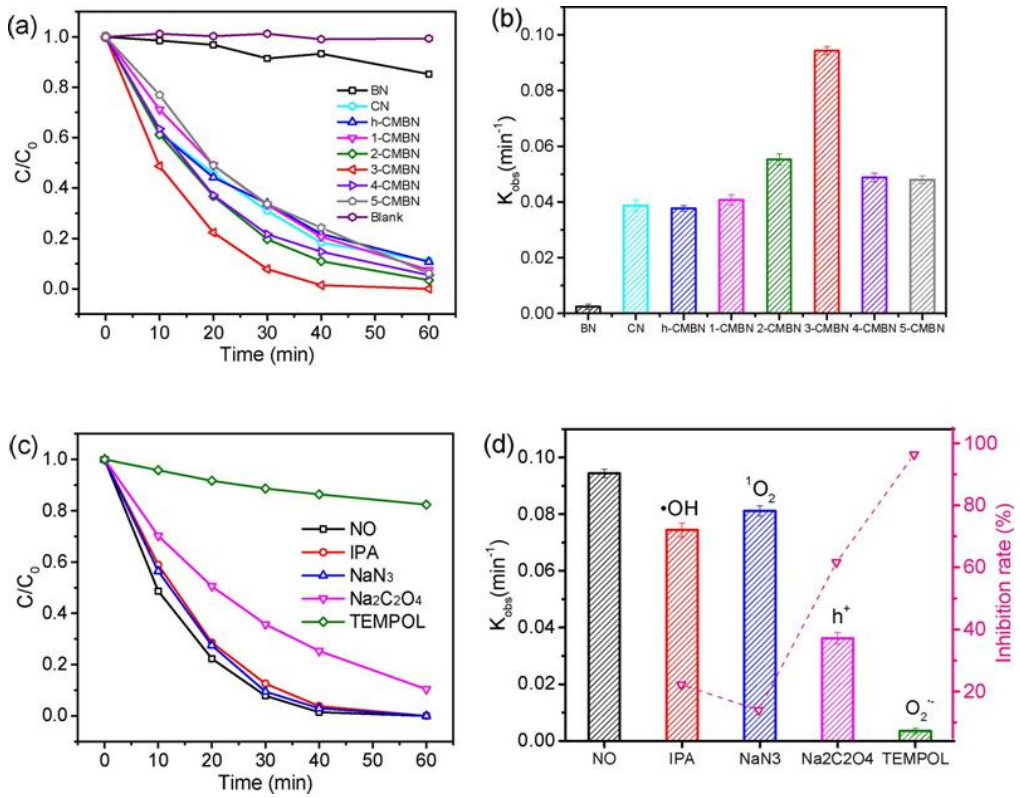

Figure 10. (a) Photocatalytic degradation of ENFX under blue LED light; (b) Kinetic rate constants for ENFX degradation with different photocatalysts; (c) scavengers trapping test using the 3-CMBN photocatalyst; (d) Kinetic rate constants of ENFX degradation (bars, left y-axis) alongside the reactive species inhibition rates (pink curve, right y-axis).

As regards to preparation of CMBN, here is the abstract of work: hydrothermal followed by calcination synthetic method was used to prepare CMBN, here is the brief of experimental procedure, three grams of melamine was mixed and dissolved with different quantity of BN (0.5, 1, 2, 3, 4, 5 g) in water then 40mL of ethanol was added. The solvent was vaporized at 80 oC and ultrasonicated for ten minutes. After being calcined for four hours at 550 °C at a rate of 3 °C per minute in an alumina crucible, the resulting powder was ground using an agate mortar [1].

A research have been done by Idrees et al. [3] on photodegradation of aqueous pollutants. In this research phosphorous and carbon co-doped boron nitride. The band gab has been reduced from 5.2 eV of BN to 3.8 eV Ag@CP-BNQDs, but still the research is UV active photocatalyst. The synthetic rout used for this preparation was hydrothermal. The efficiency was ordinary, therefore another research have been performed the same team [3] and silver atoms was loaded on phosphorous and carbon co-doped boron nitride. The obtained photocatalyst were very efficient and plasmonic. The following Figure 11 shows band edges obtained from aqueous solution and effect of different factors.

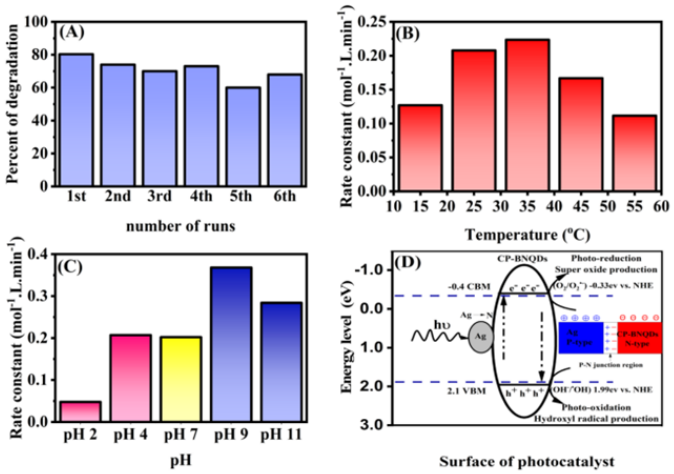

Figure 11. (A) efficiency cycles of tetracycline over Ag@CP-BNQDs across multiple uses; (B) Influence of temperature ; (C) Effect of initial pH; (D) Schematic illustration depicting the primary photocatalytic mechanism of Ag@CP-BNQDs [3].

2.4. Carbon Doped Boron Nitride for CO_2 Reduction

Another research were conducted by Lu et al team [29], the synthetic methods used in this research involve preparing precursors through recrystallization from homogeneous solutions containing boric acid and glucose. These precursors are then pyrolyzed at various temperatures under a nitrogen atmosphere to produce porous carbon doped BN photocatalysts. This work was used to convert carbon dioxide (CO_2) into useful hydrocarbons like carbon monoxide (CO) and methane (CH_4) through photocatalysis. This process can be utilized for renewable energy production, greenhouse gas reduction, and environmental remediation by converting CO_2 into fuels or chemical feedstocks under solar irradiation. The band gap obtained is approximately 2.97 eV and the band edges were -1.65 eV for conduction band and 1.32 eV for valance band as in the following Figure 12. 2.97 eV.

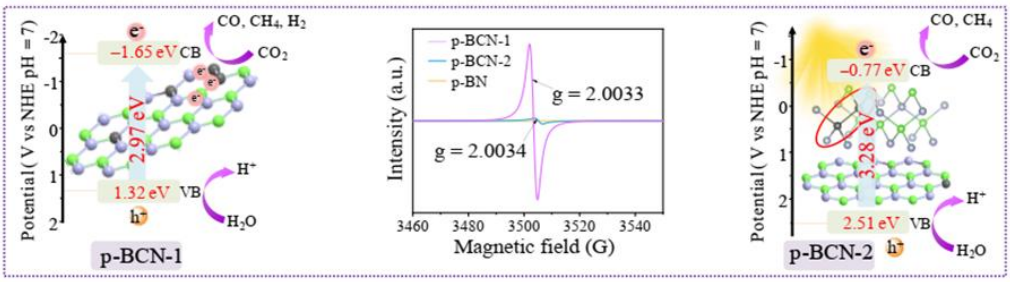

Figure 12. The possible scheme of carbon doped BN for photoreduction of CO_2 under simulated solar irradiation[29].

Where p-BCN-1 and p-BCN-2 is a sample prepared through a specific synthesis process. Sample P1 and P2 are different in recrystallization procedures; P1 was obtained by the prompt recrystallization from the homogeneous solution in an ice bath and P2 was obtained by recrystallization from the homogeneous solution via natural cooling to room temperature.

2.5. Carbon Doped Boron Nitride for Catalytic Degradation

In a research conducted by Shentu et al. [30] Carbon doped boron nitride was fabricated through a simple one-step pyrolysis method. The resulted nanostructure was then used to produce super oxide ($O_2^{-\bullet}$) species from peroxymonosulfate activation, then applied in catalytic water purification. The C-BN catalyst effectively activates peroxymonosulfate (PMS) with a low activation energy of 14.95 kJ/mol, demonstrating high efficiency in bisphenol A removal even at 0 °C. Figure 13 shows the summary of this research.

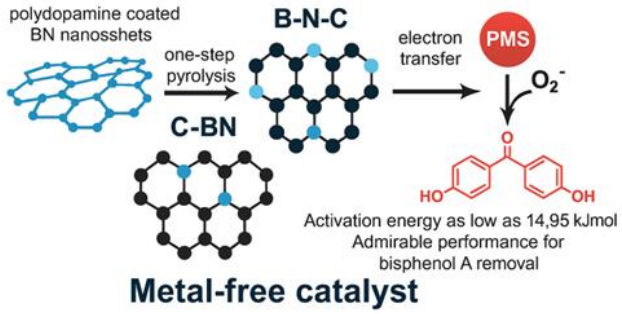

Figure 13. Summary of catalytic activity of carbon doped BN

2.6. Carbon Doped Boron Nitride as Adsorbent

Using 1-butyl-3-methylimidazolium tetrafluoroborate ([Bmim]BF_4) as a soft template and carbon source through calcination in a N_2 atmosphere, a novel carbon-doped porous boron nitride (C-BN) was successfully created. In comparison to pristine BN, the metal-free porous C-BN demonstrated significantly improved adsorption of dibenzothiophene (DBT), reaching one of the highest adsorption capacities reported to date: 35.2 mg S g^{-1} for 500 ppm sulfur model oil and 49.75 mg S g^{-1} according to the Langmuir isotherm model. The capacity dropped from 35.2 to 27.2 mg S g^- after three cycles of adsorption and desorption. The superior performance of porous C-BN was attributed to the increased exposure of atoms along pore edges and the stronger Lewis acid–base interactions between DBT and the carbon-doped BN framework. Additionally, by changing the cation or anion of the ionic liquid, this method offers a flexible way to modify the structure and composition of BN, enabling the addition of additional heteroatoms and accurate pore size control [26].

Sun et al. described a one-step oxygen-limited process was used to create carbon-doped boron nitride (BCN), which was then assessed for its ability to adsorb sulfamethoxazole (SMX). With fast adsorption taking place during the first ten minutes and reaching about half of the equilibrium adsorption capacity, the results showed that BCN had a better removal effectiveness at lower temperatures. The adsorption of SMX followed a pseudo-second-order model, according to kinetic analysis, suggesting a chemisorption-dominated mechanism. With a maximal adsorption capacity of 28.75 mg g^{-1} at 10 °C, adsorption isotherm fitting demonstrated good agreement with the Langmuir model. Thermodynamic studies provided additional evidence that the adsorption process was spontaneous. A mixture of hydrogen bonding, π–π interactions, and electrostatic interactions was identified as the adsorption mechanism [31].

Duan et al. reported that different contents of carbon-doped boron nitride (BCN) adsorbents were created. Under light irradiation, the BCN demonstrated an increasing CO_2 adsorption capacity, suggesting that sunlight could play a significant role in the low-cost CO_2 collection process. Following UV light irradiation at 0.15 and 1 bar CO_2 pressure, respectively, the best-performing sample BCN (1:3) demonstrated increases in CO_2 adsorption capacity of 32% and 28%. Numerous tests and studies, including the Hall effect test, DFT computation, and EPR, have been carried out to explain this intriguing occurrence. The findings demonstrated that the photoelectric effects of producing more free electrons, which increased the Lewis alkalinity of BCN adsorbents and hence improved their CO_2 adsorption capabilities, are responsible for the improved CO_2 absorption properties. This work opens a new avenue for the design and study of CO_2 capture materials by using the photoelectric effect for the first time to boost the effective capture capacity of CO_2 [32].

3. Conclusions

In conclusion, boron nitride has desirable properties like high specific surface area, superior thermal conductivity, and exceptional chemical stability; however, its wide band gap significantly restricts its direct use in photocatalysis. By altering the electronic structure of BN, which results in band gap narrowing, increased visible-light absorption, and improved charge carrier dynamics, carbon doping has emerged as a successful tactic to get around this restriction. The photocatalytic and adsorptive capabilities of carbon-doped BN in processes like water splitting, ammonia synthesis,

and pollutant removal are greatly improved by these structural and optical changes. Notwithstanding these developments, issues with accurate dopant control, long-term stability, and scalable synthesis still exist, underscoring the necessity of more thorough research to fully realize the environmental and photocatalytic potential of carbon-doped BN materials. Future research should focus on advanced characterization techniques, theoretical modeling to elucidate structure–electronic–activity relationships, life-cycle assessment, and the development of scalable and sustainable synthesis routes.

Conflicts of Interest: The authors declare that they have no conflicts of interest to disclose.

Abbreviations

The following abbreviations are used in this manuscript:

BN	**Boron Nitride**
h-BN	**hexagonal boron nitride**
w-BN	**wurtzite Boron Nitride**
c-BN	**cubic Boron Nitride**
BCN	**Carbon-doped Boron Nitride**

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