Contents lists available at *Dergipark*

International Journal of Boron Science and Nanotechnology

journal homepage: *https://dergipark.org.tr/tr/pub*

Number 5, April 2026

REVIEW ARTICLE

Receive Date:6 April 2026 Accepted Date:29 April 2026

Boron Based Nanomaterials for Environmental Sustainability: Applications, Opportunities, and Risks

Hussein Elaibi[a, b]*, Farah Mutlag[a], Ebru Halvacı[a], Halit Demir[c], Ismet Meydan[d], Tugba Gur[d], Fatih Sen[a]*

[a] *Sen Research Group, Department of Biochemistry, Dumlupinar University, Kutahya 43000, Türkiye.*
[b] *Department of Pharmacy, Al Safwa University College, Karbala 56001, Iraq.*
[c] *Department of Biochemistry, Faculty of Science, Van Yuzuncu Yil University, Türkiye.*
[d] *Van Vocational School of Health Services, Van Yuzuncu Yil University, Zeve Campus, Van, Türkiye.*

Abstract

Among the major threats to environmental sustainability are water pollution, air contamination, soil degradation due to erosion and nutrient depletion, climate change and inefficient waste management that create a pressing need for advanced sustainable remediation technologies. Notably, boron-based nanomaterials have increasingly attracted interest due to their unique physicochemical properties such as high chemical and thermal stability, tunable surface chemistry, structural versatility and multifunctional performance. In this article, we review the major boron-based nanomaterials with hexagonal boron nitride, porous boron nitride, boron carbon nitride, boron doped carbons and Boron-doped diamond electrodes in environmental applications. The topics include water purification, heavy metal extraction, the removal and capture of organic and inorganic pollutants, air treatment, capture of CO_2, waste recycling and treatment as well as smart fertilizers and controlled release pesticides for agricultural uses. This review further summarizes the predominant mechanisms involved including adsorption, membrane separation, photocatalysis, electrochemical oxidation, sensing and controlled release. Also, environmental risks and toxicological considerations are addressed, with an emphasis on ecotoxicity, exposure pathways, and safe-and-sustainable-by-design principles. While boron-based nanotechnology holds great potential for next generation environmental solutions, continued research efforts towards scaling up such materials as well as understanding long-term safety, life-cycle performance and ease of real-world use are necessary to facilitate broad deployment.

Click here and insert your abstract text.

Keywords: boron-based nanomaterials; boron nitride; environmental sustainability; water treatment; pollutant removal; carbon capture; toxicological assessment.

1. Introduction

Environmental sustainability is increasingly a matter of interconnected pressures linked to air pollution, water scarcity and contamination, inadequate wastewater treatment, soil degradation, and climate change. Air pollution is among the top environmental threats to public health. Ambient and household air pollution contributes to collectively approximately 6.7–7 million premature deaths each year, as per the WHO, emphasizing the interlinkage between environmental quality with human well-being [1], [2], [3], [4].

Data from WHO/UNICEF Joint Monitoring Programme indicate that in 2024, 2.1 billion people still lacked safely managed drinking-water services. Wastewater management, too, is still an enormous problem: we can easily read in the older UN assessments that over 80% of global a large proportion of wastewater is discharged into aquatic environments without adequate treatment; while according to the most recent update from UN-Water, household wastewater discharge was unsafe for 42% in 2022, proving again how much pressure insufficient treatment puts on aquatic environments [1], [2], [3], [4].

At the same time, FAO and UNEP noted that soil pollution endangers food safety, ecosystem services, water quality, biodiversity and human health solving it is essential for sustainable development. These pressures are exacerbated by climate change. UNEP's Emissions Gap Report 2025 warns that while commitments were higher than the previous year, these are still not falling within the range of what it would take to meet the Paris goals and require faster, deeper emissions cuts with a likely overshoot of 1.5°C without accelerated mitigation [5], [6], [7].

In this context, nanotechnology represents a great opportunity in environmental application as nanomaterials can offer high surface area and adjustable surface chemistry with improved reactivity and separational/catalytic properties. These boron-based nanomaterials and boron-doped functional materials in various nanoforms have gained momentum due to their chemical stability, thermal and corrosion resistance, low density and specific applicability in areas like adsorption, membrane engineering as well as anti-pollution/aggressive degradation. Due to these traits, boron-based nanomaterials have recently been highlighted as of high relevance toward both water purification and wider environmental remediation technologies [8], [9].

This article reviews boron-based nanomaterials, including boron nitride nanomaterials and boron-doped functional systems, in environmental remediation and sustainable resource management as emerging materials for environmental remediation and sustainable resource management. The article focuses on their roles in water treatment, heavy-metal removal, pollutant capture and degradation, air purification, carbon capture, waste management, recycling, and sustainable agriculture.

2. Methodology

2.1. Review Design

We present a state-of-the-art overview of these applications using a comprehensive literature search methodology in this article. The aim of the review was to compile, summarize and systematically assess peer-reviewed evidence on applications for boron nitride (BN) nanomaterials and boron-doped functional materials in drinking water treatment, pollutants removal, air cleaning, carbon capture, waste recycling, waste management, and sustainable agriculture.

2.2. Literature Search Strategy

We searched the literature from 2015 to March 2026 in order to find both underpinning studies and recent progress in environmental application of boron-based nanotechnology. The literature search was conducted across major academic databases and publishers, including ScienceDirect, Springer, Wiley Online Library, and Taylor & Francis

Online, with supplementary searches performed where necessary to improve coverage.
The search process used combinations of material-related and application-related keywords. Material-focused terms included boron nanomaterials, boron nitride nanosheets, hexagonal boron nitride, porous boron nitride, and boron-doped nanomaterials. Application-focused terms included water treatment, adsorption, membrane separation, heavy metal removal, pollutant degradation, air purification, carbon capture, wastewater treatment, recycling, smart fertilizers, nano-enabled pesticides, toxicity, and risk assessment.

2.3. Sources and Study Selection

We focused on peer reviewed review articles, highly cited original research articles and recent application-oriented studies that presented clear information on the synthesis of materials, including physicochemical properties, environmental mechanisms, treatment performance/regeneration potential and comparative advantages to conventional materials. Further, institutional and intergovernmental authoritative reports were used to provide context on the wider environmental burden and sustainability landscape, specifically with regard to air pollution, drinking water access, wastewater treatment, soil contamination as well as climate mitigation.
Studies were included when they met one or more of the following criteria: focused on environmentally relevant boron-based nanomaterials; demonstrated remediation or sustainability-related applications experimentally; explained the mechanisms of pollutant capture, degradation, or separation; or addressed ecotoxicity, exposure pathways, safe by design, or regulatory implications.

2.4. Data Organization and Thematic Analysis

The final synthesis followed a structured thematic review rather than a full systematic review protocol. The selected literature was organized into thematic areas corresponding to the structure of the article. Topics addressed included environmental issues and nanotechnology's contribution to them; how boron nanomaterials can be beneficial due to their unique characteristics; how to treat and desalinate water; how to remove heavy metals and other contaminants from water; how to clean the air and remove CO_2; how to manage and recycle wastes; how to apply these technologies in agriculture; and how to assess the potential risks associated with using these materials in the environment. Each topic also included an analysis of the relationship between different properties of materials and their performance. These included surface area, defect engineering, adsorption; the function of membranes; catalytic or photocatalytic activity; and stability. Additionally, comparative studies were included, which compared boron-based materials with their traditional counterparts as sorbents, catalysts, and membranes.

2.5. Reporting Framework

This review is not presented as a full systematic review or meta-analysis. Instead, PRISMA 2020 principles were used as a reporting guide to improve transparency in the literature search, study selection, and organization of evidence. Accordingly, the manuscript adopts a structured and reproducible review approach, while not claiming full compliance with all PRISMA requirements.

2.6. Scope and Limitations of the Method

The focus for this review is on qualitative synthesis as opposed to a meta-analysis of quantitative attributes. Consequently, the results will not include a statistical summary or categorisation of the data; instead, they will give a comprehensive view of important themes within the literature, as well as how some of these theme’s impact on sustainability and/or function but will not provide a direct comparison of all performance measures reported in the literature. The rapidly changing nature of this area has also caused several potential application areas to have limited or emerging research evidence.

2.7. Sustainability-Oriented Analytical Perspective

The application of a final interpretive layer to this research sought to create a bridge between the materials-science literature and the larger context of sustainability. In this regard, the literature reviewed was interpreted based on technical performance as well as environmental benefits and feasibility, toxicity, safe-by-design considerations, and long-term relevance for sustainability. This process allowed the paper to produce a cohesive narrative of material properties, methods of application, and risk-governance.

3. Environmental Problems and the Role of Nanotechnology

The environmental problem space most relevant to boron-based nanotechnology can be organized around three dominant exposure domains: water, soil, and air.

3.1. Major Environmental Challenges: Water, Air, and Soil Pollution

The discharge of inadequately treated domestic sewage into aquatic environments continues to place nutrients, pathogens, heavy metals, dyes, pharmaceuticals, and other persistent contaminants in rivers, lakes and coastal seas. In 2022, recent global monitoring showed that 42% of the household wastewater produced was discharged without proper treatment, which confirms that wastewater pollution is still a major direct cause of both ecosystem deterioration and downstream public health problems. Heavy metals such as mercury, lead, and cadmium are of particular concern because they are toxic and persistent. They are released through a wide variety of human activities into the environment [2], [10].

Pollution of the soil risks food safety, biodiversity, atmospheric and water quality, ecosystem services, and human health according to recent FAO and UNEP assessments. Plus, a Lindh et al., 2025 estimate based on surveys worldwide in science suggested that toxic metal pollution affects 14–17% of cropland globally with between 0.9 and 1.4 billion people living in affected regions. In the air domain, particulate matter and reactive gases maintain a high incidence of primary diseases: WHO indicates that combined ambient and household air pollution causes an estimated 6.7 million premature deaths every year, highlighting the magnitude of air pollution as an environmental as well as public-health threat [5], [11], [12].

3.2. Nanotechnology Offers Advanced Environmental Solutions

Nanotechnology is considered to be a powerful platform for advanced remediation of contaminants due to nanoscale materials having relatively high specific surface area, tunable surface chemistry, abundant reactive sites and improved interfacial activity. These properties allow several large classes of applications, such as nano-adsorbents for capturing contaminants, nano-enabled membranes for selective separation processes, catalytic and photocatalytic systems for breakdown of hardly degradable pollutants (for example heavy metals), and nanosensors or nanobiosensors for environmental monitoring and process control. While most systems are still under laboratory research, recent reviews indicate that nanomaterial-based optimized systems are also in development for the detection and removal of heavy metals, airborne pollutants, pesticides, pathogens and greenhouse gas emissions. Boron-based nanomaterials, particularly boron nitride and boron-doped functional materials, have been identified as relevant candidates for environmental remediation within this broader field (adsorption and membrane-related applications) [9], [13], [14].

However, the environmental promise of nanotechnology does not resolve concerns regarding scalability, cost, release, persistence, transformation and long-term safety. There is increasing push in reviews of engineered nanomaterials to transition away from proof-of-concept performance towards safe-by-design or safe-and-sustainable-by-design approaches where hazard, exposure, life cycle thinking and functionality is considered during early development phases. Associated research on environmental release and fate suggests that nanomaterials can enter technical systems and environmental compartments during manufacture, use, and disposal during manufacture, use, and end-of-life management; hence green synthesis, life-cycle assessment, and risk-governed design are coming to the forefront as responsible deployment considerations [15], [16], [17], [18].

4. Environmental Advantages of Boron-Based Nanomaterials

4.1. Unique Physicochemical Properties of Boron Nanomaterials

It is worth mentioning that boron-based nanomaterials represent a broader materials platform, but the environmental literature is mostly dominated by studies on boron nitride (BN) and its derivatives either in the form of h-BN or porous BN architecture as well as BCN systems. Boron-doped adsorbents the wider boron-based family also includes boron-doped carbons/biochars and boron doped diamond (BDD) electrodes, which are widely researched for adsorption, catalysis, electrochemical oxidation, sensing, and resource-recovery applications. Similarly boron carbide (B_4C) nanostructures have also gained attention; however, they seem to be less dominant in the review literature on environmental implications than BN-based systems [9], [19], [20], [21].

Among them, h-BN is particularly attractive for environmental technologies on account of its combination of high chemical stability, thermal resistance, corrosion resistance, mechanical robustness and low density with a lamellar two-dimensional structure whose elemental layers can be processed as nanosheets, composites and membrane-forming additives. BN-based remediation achieves such general applicability because adsorption and separation scalability are inherently dependent on surface area, morphology control, defect tuning, heteroatom doping and surface functionalization to optimize the material properties for target pollutants and process conditions; thus BN is not only chemically stable but also highly tunable [21], [22].

In membrane-related applications, h-BN is often described as a 2D additive material or active layered material with angstrom scale interlayer spacing and high structural stability under chemically demanding conditions. This is advantageous for selective transport under oxidative, saline, and chemically demanding conditions in complex waters, this combination is advantageous for treating these types of water. Mesoporous BN offers this advantage even more, providing high surface area and chemically tunable adsorption sites, and BCN materials introduce beneficial optical and electrical properties for photocatalytic applications as well as degradation of pollutants [23], [24], [25].

A study by Zhang et al. showed that this material not only has a high specific surface area, but also removes Cu^{2+} ions from water with an extraordinarily large uptake of 819 mg/g, with the authors demonstrating that microscopic properties such as the porous structure and pore accessibility contribute greatly to Hexagonal Boron Nitride:adsorption behavior; thus showing how native physicochemical properties in boron-based nanomaterials are able to correlate directly with their environmental remediation power [26].

4.2. Comparative Environmental Benefits over Conventional Materials

Compared to many traditional sorbents and membrane additives, boron-based nanomaterials represent an important trade-offer an important combination of stability, structural tunability and multifunctionality. Recent investigations into the adsorption capabilities of BN-based adsorbents reveal that they may also be competitive (if not even beneficial) when compared against both established and upstart adsorbent materials, such as activated carbon, bentonite, zeolites, graphene oxide, metal-organic frameworks and MXenes; particularly in cases where structural imperfections/engineered defects oxygen- or amino-containing groups [45] along with custom porous structures can enhance adsorption mechanisms. This has environmental implications since selective capture allows reduction of material usage and therefore, a greater potential for regeneration [23], [27], [28].

BN-based membranes have been associated with improved water flux and antifouling properties in ultrafiltration-, nanofiltration-and reverse-osmosis related systems. However, because fouling and flux decline (which is used to calculate) are key drivers of operating cost, cleaning frequency, and chemical demand on water treatment applications these properties actually provide a true sustainability benefit rather than simply lab-scale. Such evaluations and some newly developed membrane studies have been shown that incorporation of BN nanosheets or the use of modifiers derived from BN not only can be advantageous to address permeability performance, however it does not need to involve a loss in separation performance, whilst also introducing resistance to fouling in liquid purification systems [24], [29], [30].

Another benefit of boron-based systems is their design freedom. By means of functionalization, defect engineering, heteroatom doping and composite formation, these materials can be tailored in the direction of adsorptive capture or toward catalytic/photocatalytic transformation of contaminants. BCN-derived materials show exceptionally high potential for photocatalytic pollutant decomposition, and boron-doped carbons and biochars are growing in prominence as multi-functional pollutants adsorbers and catalysts. Electrochemical remediation is an important application area, especially BDD electrodes are desirable in terms of chemical stability, resistance to biofouling or anodic corrosion and good environmental–electrochemistry performance which have made it attractive for advanced oxidation and monitoring applications. Collectively, these attributes indicate that boron-based nanomaterials have the potential to decrease chemical dosing while enhancing longevity and minimizing secondary waste when correctly designed and implemented [20], [21], [31].

García Doménech et al. two-dimensional boron nitride nanofiltration membranes and their application in dye molecule water purification. Researchers reported retention values excellent for the representative dye's methyl orange, methylene blue and Evans blue were all 100% across membranes developed herein, surpassing those memorably published but generally poor; and BN membranes produced via organic-solvent exfoliation methodologies. By demonstrating that the BN-based membranes can balance both high separation efficiency and a relatively green and affordable fabrication route by water exfoliation, this study adds experimental evidence for their superior environmental performance.

Table 1 illustrates the main classes of boron-based nanomaterials used in environmental applications, highlighting their key physicochemical properties, principal environmental advantages, major limitations or challenges, typical application areas, and supporting references.

Table 1. Physicochemical Characteristics, Environmental Advantages, Limitations, and Applications of Major Boron-Based Nanomaterials.

Material	Key physicochemical characteristics	Main environmental advantages	Main limitation / challenge	Typical environmental applications	Ref
Hexagonal boron nitride (h-BN)	Two-dimensional layered structure; high chemical and thermal stability; mechanical robustness; corrosion resistance; defect- and surface-dependent behavior	Suitable for adsorption and membrane systems under harsh conditions; supports selective separation and stable performance in complex water matrices	Pristine h-BN is chemically inert, so performance often depends on defect engineering, functionalization, or composite formation; the mechanistic understanding of membrane-scale performance still requires further study	Water purification, membrane modification, adsorption, pollutant separation	[8], [9]
Porous boron nitride (porous BN)	High specific surface area; tunable pore architecture; abundant accessible	Strong sorption potential for oils, solvents, dyes, organics, and gas molecules; attractive as an	Hydrolytic/moisture stability can be a concern for some porous BN materials, so structure and surface chemistry often need	Water treatment, oil/solvent cleanup, dye adsorption, gas capture, carbon	[32], [33]

	adsorption sites; chemically and thermally stable porous framework	advanced adsorbent for water cleaning and CO_2 capture	optimization for wet environmental conditions	capture	
Boron carbon nitride (BCN)	Hybrid B–C–N framework; tunable electronic structure; defect-sensitive surface chemistry; improved optical/light-response compared with pristine BN	More suitable than pristine BN for photocatalytic and photo-assisted pollutant degradation because carbon incorporation can improve light absorption and charge separation	Synthesis control, phase/composition uniformity, and reproducibility remain important challenges; many systems still need performance optimization for real environmental matrices	Photocatalytic degradation of organic pollutants, water and wastewater treatment, environmental catalysis	[34], [35]
Boron carbide (B_4C) nanostructures	Boron-rich ceramic structure; high hardness; chemical resistance; thermal stability; nanostructured forms can provide catalytic surface activity	Durable and potentially recyclable photocatalytic material for wastewater treatment under demanding conditions	Environmental-remediation evidence is still more limited than for BN-based materials; the field remains comparatively less mature and less extensively reviewed	Dye degradation, photocatalytic wastewater treatment, emerging remediation systems	[19]
Boron-doped carbons / boron-doped biochars	Porous carbon matrix modified by boron; altered surface polarity/acidity; tunable pore structure; active boron-containing surface groups	Boron doping can enhance adsorption affinity and broaden functionality toward antibiotics, dyes, phenolics, and sometimes CO_2 capture	Large-scale production routes and cost-effective, reproducible synthesis remain important practical challenges; performance depends strongly on doping level and pore architecture	Adsorption of dyes and organics, antibiotic removal, multifunctional sorbents, carbon capture	[31], [36], [37]
Boron-doped diamond (BDD) electrodes	Very wide electrochemical potential window; exceptional chemical stability; strong resistance to corrosion and fouling; robust electrochemical surface	Particularly powerful for advanced oxidation and electrochemical pollutant destruction in harsh wastewaters; long operational durability and usefulness in sensing/monitoring	High cost and electrode fabrication/infrastructure requirements can restrict broader deployment despite strong performance	Electrochemical wastewater treatment, advanced oxidation processes, sensing and monitoring	[38], [39], [40]

5. Boron-based nanomaterials for Water Treatment and Contaminant Removal

5.1. Adsorption and Membrane-Based Treatment Technologies

One of the most important roles of boron nitride (BN) in environmental literature is its function as a high-performance adsorbent for inorganic and organic pollutants. Nanoforms of boron nitride (BN), such as BN nanosheets, nanotubes, porous BN and composites containing these materials have been tested for their ability to remove heavy metals, dyes, pharmaceuticals or other hazardous organic materials. This performance is attributed to defect sites, surface functional groups, and high surface area as well as polar B–N bonding that invigorates pollutant–surface interactions. In addition, the review also highlights that regeneration and reusability of BN adsorbents could be among practical criteria, that enhance the sustainability profile of water-treatment systems [8], [27].

Many studies have demonstrated the applications of BN-based materials as active layered materials or membrane additives in RO, NF and UF systems in membrane engineering. BN incorporation has been shown to enhance transport, separation performance, membrane flux and fouling resistance, rendering BN-containing membranes promising in sustainable water purification according to a recent review. These trends are also supported by primary studies: for instance, a BN-modified PES nanofiltration membrane demonstrated a 2-fold increase of water permeation compared to the bare membrane with comparable protein and dye rejection, whereas retention values as high as 100% were reported for representative dyes across particular water-exfoliated BN nanofiltration membranes [24], [41].

García Doménech et al. water-exfoliated 2D BN nanofiltration membranes and their application in water purification. The membranes demonstrated near-total rejection of methyl orange, methylene blue, and Evans blue and outperformed similar BN membranes made via organic-solvent exfoliation methods. This study is significant, as it correlates high separation performance with a relatively greener membrane-fabrication approach [30].

5.2 Boron-based nanomaterials in Desalination and Wastewater Treatment

There is growing interest in the use of nanomaterial-enabled membranes for water treatment due to water scarcity and increased needs for desalination, but sustainability of these materials depends on separation efficiency, but also energy demand, durability and fouling/cleaning burden. Accordingly, BN-enabled membranes are increasingly being considered for this purpose given that BN provides chemical stability, structural robustness and tunable surface properties while independent membrane literature highlights the inclusion of specifically BN-based systems in desalination, RO, NF commercialization and first steps towards UF applications. The review literature further reports that additional mechanistic and scale-up work is required before the complete environmental value of BN membranes can be determined [24].

Because of the complexity of wastewater streams, boron-based treatment extends beyond filtration alone. In particular, boron-doped diamond electrodes have been extensively studied as a robust anode material for electrochemical advanced oxidation, and compared to other methods, they possess significant capability in not only degrading but also mineralizing recalcitrant organics realistically present in wastewater streams. Meanwhile, it is environmentally significant for advanced oxidation to be able to reach contaminants that are adsorbed only with difficulty, even though operational energy consumption remains a significant consideration of design. In a study from 2024 on actual textile wastewater, BDD turned in the best overall performance of anode materials tested, achieving complete color removal and nearly 61% COD removal [42], [43].

For the electrochemical oxidation of real textile wastewater, a study by Afonso et al. compared BDD with several Ti/MMO anodes. The BDD electrode provided the best overall treatment outcome, reaching complete color strength removal and substantial COD reduction at a competitive specific energy consumption level. That boron-assisted water electrochemical systems can fill an important gap in membrane - based treatment-especially when the wastewater contains recalcitrant organic pollutants [42].

6. Applications for Heavy Metal and Pollutant Removal

6.1. Removal of Heavy Metals from Contaminated Water

This is the reason heavy-metal removal remains important; metals like Cu, Cr, Zn, Ni, Pb, Hg, Cd and as are persistent in water where local systems can be difficult to remediate once they have entered water systems. Several studies have evaluated the adsorption capacity of boron nitride directly. Although a universally applicable real-world evaluation method is still lacking, the modification of structures and treatment processes using such basic information might well improve metal-laden sewage disposal technology through relatively simple practical means. Such forums also point out what little real use these numbers have in universal comparisons. Performance assessments depend on system type and perhaps change with pH, temperature or other chemicals in the environment. This is why researchers should be very cautious about comparing results from different studies [27], [44], [45] .

More sophisticated architectures than the simple BN powders mentioned previously have been developed to improve metal uptake and promote recovery. One typical case is a hybrid porous h-BN-based magnetic aerogel fabricated to achieve high adsorption capacity as well as structural porosity and magnetic recoverability. These systems mirror the greater drive within this research field: to utilize BN not simply as a passive sorbent, but rather as a tunable platform for selective and reusable heavy-metal remediation [46].

A study by Kumar et al. Novel fabricated poly(ethyleneimine)-modified h-BN nanosheet-based magnetic hybrid aerogels for effective removal of metals and dyes from water. The high uptake of methylene blue and acid orange was also recorded, with the material presenting maximum adsorption capacities of 833 mg g^{-1} for Cr (VI) and 426 mg g^{-1} for As (V). These findings show that hierarchically structured BN-based composites represent multifunctional, high-capacity contaminant removal materials for use in aqueous systems [46].

6.2. Degradation or Capture of Organic and Inorganic Pollutants

In addition to their simple contaminant-capture role, boron-based nanomaterials are being employed and studied as catalytic and photocatalytic platforms toward the degradation of dyes, pharmaceuticals, endocrine-disrupting compounds (EDCs), and other recalcitrant water pollutants. However, for high-performance degradation, pure BN is seldom used alone; most reports have shown that after coupling with photoactive phases or forming heterojunctions to reduce its wide band gap and tune its electronic structure through doping and compositing, thereby improving activity. These strategies enhance light harvesting, charge separation, and production of reactive oxygen species over BN-based systems and thus are more effective for pollutant degradation than sorption alone [9], [47].

Besides photocatalysis, boron materials have also been used as Fenton-like systems in advanced oxidation. Recently, a very interesting work found that boron-doped porous carbon (BPC) could act as an efficient cocatalyst to accelerate the Fe (III)/Fe (II) redox cycle and strengthen hydroxyl-radical-driven oxidation in the Fe (III)/H_2O_2 system. It was reported in the study that BPC at low dosage (0.04 g L^{-1}) could effectively degrade pollutants, along with BPS configured as a membrane component this arrangement also performs reasonably for micro-polluted water purification via continuous flow (i.e. through-holes). These observations are significant, as they demonstrate that inclusion of boron can be beneficial for oxidation kinetics and reinforce reactor-relevant treatment design.[48].

The catalytic potential of boron-based materials also extends beyond BN itself. Boron carbide (B_4C) nanostructures have been reported as recyclable, visible-light-active photocatalysts for wastewater treatment, reinforcing that “boron-based” remediation materials include a broader family of boron-containing solids. More recent work has also shown that B_4C can promote broad-spectrum degradation in oxidant-assisted systems, including phenols, dyes, antibiotics, endocrine disruptors, and pesticides, indicating that boron carbide can function both as a photocatalytic material and as a promoter in oxidation-based remediation [49].

A study by Singh et al., evaluated nanostructured B_4C as a recyclable photocatalyst for wastewater treatment and reported degradation efficiencies of 91.09% for Synazol Yellow and 76.04% for methylene blue at a catalyst loading of 0.5 g L^{-1}. The same study also reported good reusability and described the material as biocompatible up to approximately 800 ppm, highlighting its potential as a comparatively stable and reusable boron-based photocatalyst for industrial dye remediation [19].

Table 2 illustrates representative boron-based nanomaterials, removal mechanisms, target contaminants, and experimental examples discussed in Section 6, highlighting their role in heavy metal adsorption and degradation/capture of organic and inorganic pollutants.

Table 2. Boron-based nanomaterials for heavy metal and pollutant removal from water.

Boron-based material	**Main mechanism**	**Target contaminant(s)**	**Representative example**	**Key result**	**Environmental significance**
Porous h-BN nanosheets	Adsorption via defect sites, surface functional groups, and electrostatic/coordination interactions	Cu^{2+}	Porous h-BN nanosheets used for Cu^{2+} adsorption	High adsorption capacity for Cu^{2+}	Demonstrates the suitability of BN as a stable and tunable adsorbent for toxic metal removal
PEI-modified h-BN magnetic hybrid aerogel	Enhanced adsorption through amine-rich functional groups and porous recoverable structure	Cr (VI), As (V)	Magnetic hybrid aerogel based on modified h-BN	High-capacity removal of Cr(VI) and As(V) with easy separation after treatment	Combines strong metal uptake with structural recoverability and multifunctionality
BN-based photocatalyst / BN composite photocatalyst	Photocatalytic degradation through heterojunction-assisted charge separation and reactive oxygen species generation	Dyes, pharmaceuticals, refractory organics	BN-coupled photocatalytic systems for dye degradation	High degradation efficiency under light irradiation	Supports pollutant destruction rather than simple capture, reducing persistence of organics
Boron-doped porous carbon	Fenton-like catalytic enhancement through accelerated electron transfer and Fe(III)/Fe(II) cycling	Organic pollutants in micro-polluted water	Boron-doped porous carbon used as cocatalyst in oxidation system	Enhanced oxidation capacity and improved pollutant degradation	Highlights boron-enabled advanced oxidation as a complementary treatment to adsorption
Boron carbide (B_4C) nanostructures	Recyclable photocatalytic degradation	Synthetic dyes and organic wastewater pollutants	Nanostructured B_4C applied in wastewater treatment	Efficient dye degradation with	Shows that boron-based remediation extends beyond BN to other

				reusability	catalytically active boron solids

7. Air Purification and Carbon Capture Technologies

7.1. Boron-Based Nanomaterials for Air Pollutant Removal

There is a growing interest in the application of nanomaterials to counteract air pollution via mechanisms such as adsorption, catalytic oxidation, enhancement in filtration and sensing/monitoring. A seminal review on nanomaterials in the context of air remediation can act as nanoadsorbents, 'nanocatalysts', 'nanofilters', and 'nanosensors' but also highlights that practical use must consider potential nanoparticle release, transformation, and environmental consequences. In this broader context, boron-based nanomaterials in particular h-BN and porous BN have sparked interest for air purification of both indoor and industrial environments thanks to the chemical and thermal stability of their polar B–N framework combined with a tunable surface interaction [50], [51].

Notably, h-BN was identified as an attractive element in adsorptive and hybrid air-purification devices, including recently proposed multi-pollutant capture designs. The co-adsorption of formaldehyde (HCHO) and CO_2 on modified h-BN was studied in 2024, revealing that HCHO adsorption can be enhanced on doped h-BN surfaces while favorable surface interactions drive cooperative HCHO/CO_2 capture. Since this work was based on density functional theory, it should be considered as mechanistic and predictive rather than direct device-level validation, but nevertheless supports the idea that BN-based surfaces could be engineered for whole-surface indoor-air purification concepts [52].

A practical sustainability note: air purification also requires measurement and control, not just removal. BN nanostructures are currently being investigated as gas-sensing materials, frequently through defect engineering, heteroatom doping, or metal decoration to adjust adsorption energies and electrical properties. A review from 2024 dedicated to BN-based gas sensors highlights that while this field has grown to include theoretical modeling, synthesis of materials, and application-relevant sensor design, many systems still remain in the phases between calculation and proof-of-concept toward robust real-world success [51], [53].

A study by Bläker et al. investigated porous boron nitrides and commercial activated carbons for gas-phase purification via trace-level adsorption of hydrocarbons. When expressed per micropore surface area, the BN materials had up to 50% greater loadings of polar and aromatic adsorptives than activated carbons, and they also had oxidation temperatures >900 °C—about 400 °C higher than those of the carbons studied. The same study noted that BN was not yet mass-for-mass competitive with all VOC due to lower microporosity but provides substantial experimental support that a unique combination of surface polarity and thermal stability for selective air-pollutant capture is available in many different forms of BN [50].

7.2. Applications in CO_2 Capture and Climate Mitigation

Climate mitigation is increasingly in need of not just rapid emission reductions, but also effective carbon management technologies, from capture and use to storage and, in some cases, carbon removal pathways. Within this context, boron-based nanomaterials are being investigated for their utilization as solid adsorbents in CO_2 capture, especially since porous-derived BN architectures can combine high surface area to volume ratios, defect-rich chemistry, and polar functional species on the surface that may be preferred for interaction with CO_2. Recent efforts have started moving away from simple powder-adsorption measurements toward forms that are more applicable to realistic adsorption beds and dynamic gas-separation systems [54].

A significant recent advance is the development of porous BN granules used for dynamic CO_2 adsorption. A binder free route of simple amide granulation reported in 2025 yielded BN granules with a specific surface area as high as 1503.2 $m^2\ g^{-1}$ and CO_2 adsorption capacity of 3.83 $mmol\ g^{-1}$ at 0 °C and pressure 1 bar. Importantly, the same study also tested dynamic adsorption and gave values of 4.95 mmol g⁻¹ at 10 bar and 5 °C; this is significant because dynamic conditions provide a better approximation to industrial operation than static equilibrium tests alone can. This line of work makes a stronger case for porous BN as a carbon-capture material that could be commercially viable [54].

A study. Jiao et al. developed porous BN granules specifically for dynamic CO_2 adsorption, addressing a practical limitation of many powder-form sorbents. The resulting granules combined high surface area, good mechanical properties, and strong CO_2 uptake under both static and dynamic conditions, including 3.83 mmol g^{-1} at 0 °C and 1 bar and 4.95 mmol g^{-1} at 10 bar and 5 C. This study is especially important because it moves porous BN closer to engineering-relevant carbon-capture applications, rather than remaining only a laboratory powder adsorbent [54].

Table 3 illustrates Main boron-based nanomaterials, operating mechanisms, and representative environmental functions discussed in Section 7, with emphasis on air pollutant removal, gas sensing, and carbon capture applications.

Table 3. Boron-based nanomaterials for air purification and CO_2 capture.

Boron-based material	**Main mechanism**	**Target pollutant / gas**	**Representative example**	**Key result / functional advantage**	**Environmental significance**
h-BN / modified h-BN	Adsorption through surface interactions and polar B–N bonding	VOCs, formaldehyde	Modified h-BN surfaces studied for HCHO capture	Strong adsorption potential and possible multi-pollutant capture behavior	Promising for indoor air purification and hybrid adsorption systems
Porous BN	Gas-phase adsorption using porous surface and selective interaction sites	Hydrocarbons, polar/aromatic vapors	Porous BN compared with activated carbon in trace adsorption	Higher normalized uptake for some polar/aromatic adsorbates and high thermal stability	Suggests value for selective gas purification under harsh conditions
BN-based gas-sensing nanostructures	Tunable adsorption energies and electronic response through doping/defect engineering	SO_2, CO, and other environmentally relevant gases	BN nanostructures investigated as gas sensors	Sensitive detection potential for hazardous gases	Supports monitoring, ventilation control, leak detection, and smart purification systems
Porous BN granules / porous BN frameworks	CO_2 adsorption promoted by surface polarity, defects, and high surface area	CO_2	Porous BN granules designed for dynamic CO_2 adsorption	Strong static and dynamic CO_2 uptake with improved handling properties	Advances BN toward practical carbon-capture systems
Boron-doped	Enhanced CO_2 affinity via	CO_2	Boron-doped porous carbon	Improved CO_2 capture relative	Demonstrates the role of

porous carbons	boron-induced polar/basic surface functionalities		adsorbents	to undoped carbon materials	heteroatom chemistry in increasing carbon-capture performance
Carbon-doped boron nitride (BCN/BN-derived adsorbents)	Photo-enhanced or energy-assisted adsorption	CO_2	Light-responsive boron-based CO_2 adsorbent systems	Increased adsorption after irradiation	Conceptually promising for lowering regeneration energy in future capture technologies

8. Boron in Waste Management and Recycling Processes

8.1. Boron Nanotechnology in Waste Monitoring and Treatment

Waste-management systems generate both pollution risks and treatment opportunities. ...depends not only on pollutant removal but also on timely monitoring of gaseous emissions and contaminated liquid streams. Within this context, boron-based nanomaterials, especially sensing materials. A DFT study on B24N24 fullerene reported selective recognition of SO_2 and CS_2 with short recovery times, illustrating the potential of BN-derived platforms for hazardous gas monitoring, although much of this evidence remains at the predictive or proof-of-concept stage rather than full facility deployment [55], [56].

For treatment, the most mature boron-enabled platform is the boron-doped diamond (BDD) electrode, which is widely reviewed as a robust anode for electrochemical oxidation of refractory contaminants in wastewater and leachates. A recent opinion review highlights the expanding role of BDD electrodes in wastewater treatment and disinfection, while a 2025 pilot-scale study on landfill leachate reported that BDD electrochemical oxidation removed more than 80% of COD, 70% of TOC, and 70% of NH_4^+-N within 80 minutes during batch operation. In the same study, a 30-day pilot run at 200 L h^{-1} maintained COD and NH_4^+-N removals above 50% and 40%, respectively, supporting the relevance of BDD systems for difficult waste streams when energy use and by-product formation are properly managed [57], [58].

BN-based photocatalytic materials also align with waste-treatment goals because they can transform persistent organics rather than merely capture them. For example, a $BiVO_4$/h-BN nanocomposite study reported visible-light degradation of 93.3% Rhodamine B, 92.9% Congo red, 94.1% amoxicillin, and 90.1% cephalexin in 60 minutes, together with reduced phytotoxicity after treatment. This supports the view that BN-containing composites may contribute to oxidative treatment trains for contaminated wastewater and industrial residual streams [47], [59].

A study by Liu et al. evaluated a pilot-scale BDD electrochemical oxidation process for landfill leachate treatment and showed strong removal of organic matter and ammonium under realistic operating conditions, with relatively low disinfection by-product formation. This study is especially useful for Section 8 because it links boron-enabled treatment directly to a real waste-management stream, rather than to simplified laboratory water matrices [58].

8.2. Resource Recovery and Recycling Applications

A key sustainability advantage of boron-based nanomaterials is their potential to support waste-to-resource conversion, especially when they function as reusable catalysts or when boron-containing waste itself is converted into useful materials. In plastic recycling, BN nanosheets decorated with Fe_3O_4 nanoparticles have been reported as a magnetic bifunctional catalyst for post-consumer PET recycling. The reported BHET yield ranged from 77% to 100%, depending on catalyst configuration, and the catalyst could be recovered magnetically for repeated use. This illustrates a practical circular-economy pathway in which boron-based nanomaterials can improve catalytic depolymerization while simplifying catalyst separation.

Another option for circularity that boron can help with is the valorization of industrial waste containing boron. A previous study utilized boron waste to synthesize mesoporous silica (MCM-41), while a subsequent review stated that the synthesis afforded an adsorption capacity of 351.7 mg g^{-1} for methylene blue and retained performance over four cycling/regeneration runs. And this is significant as it turns boron waste, which had been a disposal issue, into a feedstock for functional environmental materials.

More broadly, the World Bank treats wastewater as a resource rather than a liability, pointing out that energy (biofuels), clean water (treated effluent), fertilizers and nutrients can be recovered from it in circular-economy wastewater systems. That framing is broadly compatible with recovery-oriented treatment trains that utilize boron-based catalysts, electrodes, and sorbents given their life-cycle impacts and safety fall within technical performance considerations.

A study by Nabid et al. demonstrated that Fe_3O_4-decorated BN nanosheets can act as a magnetically recoverable catalyst for post-consumer PET recycling, with high BHET yields and easy catalyst separation. This makes it one of the clearest examples of a boron-based nanomaterial contributing directly to **recycling and resource recovery**, rather than to pollutant removal alone.

9. Use of nanotechnology in agriculture

Nanotechnology is increasingly discussed in sustainable agriculture because it can improve nutrient-use efficiency, controlled delivery, crop protection, and input management, while potentially reducing leaching, volatilization, repeated application, and off-target losses. Nano-enabled fertilizers and pesticides as promising tools for precision farming, but they also stress that agronomic benefit must be balanced against questions of soil fate, food-chain transfer, ecotoxicity, and regulatory oversight.

9.1. Boron-based smart fertilizers for sustainable agriculture

Within the broader field of nanofertilizers, boron-based systems are being investigated as smart micronutrient-delivery platforms for crops that suffer from boron deficiency. The most direct evidence to date derives from nanoscale boron nitride, which has been evaluated as a potential boron source because of its nanoscale structure, high surface area and biocompatibility that may provide an advantage for the availability of nutrients while reducing toxicity risk than standard ionic boron inputs. Nano-fertilizers more broadly are reported to support more efficient nutrient uptake, lower nutrient losses and controlled release through nanostructured formulations, the conceptual basis for classifying boron-based nanoformulation [56], [60], [61].

One recent primary study provides compelling support for this application. In a greenhouse cucumber experiment, for example, the application of nano-BN at 10 mg kg^{-1} soil homogeneously significantly improved seedling fresh weight by 15.8% as compared to untreated control (the authors claimed that the nano-BN supplied the required micronutrients without any toxicity responses observed accompanying ionic boron applications). Increases in rhizosphere dissolved organic matter, soil enzyme activity and the gene abundances for microbes harboring nitrogen-fixing genes have also been reported following this nano-BN application; This observation points out that apart from its position as a micronutrient provider, nano-BN might serve as a functional input to modulate rhizosphere processes required to perform carbon and nitrogen cycles [61].

Boron-based smart fertilization can also overlap with plant-protection strategies. For example, ionic-liquid-assisted boron nitride nanosheets conjugated with ammonium dimolybdate (BNNS–IL–ADM) were developed as a seed-dressing platform that combined micronutrient delivery with sustained release of active components. In that study, the BN-based carrier showed high loading capacity (509.0 mg g^{-1}) for volatile active ingredients, promoted seed germination and plant growth, and improved colloidal dispersibility and seed-surface adhesion, illustrating how boron-

based nanomaterials, can be engineered as multifunctional agro-inputs rather than simple nutrient powders [56].
A study by Xu et al. demonstrated that soil-applied nano-BN can act as a boron-based smart fertilizer in cucumber, increasing biomass and improving rhizosphere biochemical and microbial functions without the visible toxicity seen for the ionic boron control. This study is especially valuable because it links boron nanomaterials to both crop growth and soil-function indicators, which are central to sustainable agriculture claims [61].

9.2. Nano-enabled pesticides and controlled-release systems

Nano-enabled pesticide systems are being developed to improve loading capacity, controlled release, adhesion, UV stability, rainfastness, and target-zone retention, thereby reducing repeated spraying and limiting off-target losses. Review articles on nanocarrier-based agrochemicals describe controlled-release systems as one of the most promising directions in smart agriculture because they can respond to pH, temperature, light, or other environmental triggers while maintaining pesticide efficacy. These reviews also emphasize that the environmental case for nanopesticides depends on whether improved delivery actually translates into lower residues and lower overall exposure in realistic agricultural settings [60], [62], [63].

Boron-based nanomaterials have already been used as pesticide carriers in several primary studies. A study developed functionalized boron nitride nanoplatelet composite nanocarriers for avermectin delivery and reported a high pesticide loading capacity of 181.9 ± 5.2 mg g^{-1}. The carrier also provided pH-responsive release, with about a two- to three-fold increase in release rate when pH increased from 7 to 11, and it reduced avermectin photodegradation under UV irradiation by about 30%. These results are important because they show that boron nitride can contribute not only to pesticide loading but also to stability and on-demand release behavior [64].

More recent work has pushed this concept further toward field-relevant disease management. In 2025, h-BN-reinforced supramolecular gels were developed for precision delivery of tebuconazole against soil-borne fungal disease. According to the study, h-BN narrowed the pore-size distribution, enhanced mechanical stability, and helped restrict fungicide diffusion, producing dual pH- and temperature-responsive sustained release. The formulation increased fungicide retention time to 940 min, which was 14.69 times longer than free tebuconazole, raised root-zone retention to 41.45% compared with 13.48% for the commercial formulation, reduced EC_{50} by 54.10%, and achieved complete mycelial suppression in pot trials while also reducing phytotoxicity [64] .

A related 2023 study also showed that BNNS–IL–ADM seed-dressing formulations improved antibacterial performance against Ralstonia solanacearum by 92.86% and 92.50% relative to ADM and a commercial formulation, while enhancing adhesion and coating uniformity on seeds. Together, these studies indicate that boron-based nanomaterials can act as carriers, stabilizers, and release regulators in next-generation pesticide systems [65], [66].

A study by Hao et al. showed that h-BN-reinforced supramolecular fungicide gels can substantially improve adhesion, sustained release, soil retention, and disease-control performance compared with conventional formulations. This makes the study one of the clearest demonstrations that boron-based nanomaterials can support controlled-release pesticide delivery in a way that is directly relevant to sustainable crop protection [65], [66].

10. Environmental Risks and Toxicological Assessment

10.1. Ecotoxicity and Human Health Concerns

Although boron-based nanomaterials are widely promoted for environmental remediation, their depends not only on performance but also on hazard potential toward aquatic organisms, terrestrial biota, and humans. The available evidence suggests that toxicity is material-specific and morphology-dependent, rather than uniformly high or uniformly negligible. In particular, recent studies indicate that particle size, aspect ratio, surface chemistry, aggregation behavior, and the surrounding medium can strongly influence biological responses [67], [68].

For aquatic ecotoxicity, one of the clearest recent studies showed that hexagonal boron nitride (h-BN) nanosheets can adversely affect freshwater primary producers at relatively low exposure levels. Zou et al. reported that 0.1–1 μg mL^{-1}

h-BN nanosheets suppressed the growth of Chlorella vulgaris by up to 45.3% and linked this response to extraction of phospholipids from cell membranes, membrane permeabilization, oxidative stress, and inhibition of CO_2 fixation. This is important because it shows that even when h-BN is chemically stable, it can still trigger biologically significant membrane-level and metabolic effects in environmentally relevant organisms [67].

A study by Zou et al. demonstrated that low-dose h-BN nanosheets could inhibit freshwater algal growth through membrane damage and metabolic disruption. This study is particularly useful for this subsection because it directly connects boron-based nanomaterials to ecotoxicological endpoints, rather than only to mammalian biocompatibility or technical performance [67].

10.2. Risk Assessment, Exposure Pathways, and Safe Design

Risk assessment for boron-based nanomaterials must consider not only intrinsic hazard, but also where, when, and in what form exposure occurs. Current evidence indicates that the most relevant occupational pathways are inhalation and skin contact, especially during production, handling, composite abrasion, and other powder-generating operations [69].

Environmental exposure pathways extend beyond manufacturing. Release can occur during use, weathering, washing, abrasion, wastewater discharge, and end-of-life disposal, and the resulting risks depend heavily on transformation and medium effects. For example, an aquatic-toxicology study showed that boron nitride nanosheets were highly unstable and prone to aggregation/precipitation in mineral water but became more stable in the presence of natural organic matter (NOM). The same study found that ...caused no acute immobilization in *Daphnia magna*, even at 100 mg L^{-1}, yet when combined with cadmium they produced a “Trojan horse” effect, increasing metal toxicity at 1 mg L^{-1} boron nitride nanotubes ; NOM partially mitigated this combined effect. These results show why realistic risk assessment must include mixture effects, colloidal behavior, and water chemistry, not only single-material toxicity tests [70].

A further complication is that boron-based nanomaterials can undergo biological or environmental transformation, which may alter both persistence and hazard. A review on degradation of two-dimensional materials notes that h-BN may degrade through B–O bond formation under oxidative enzymatic conditions, ultimately yielding boric acid as an end product. This is a useful reminder that “stable” does not necessarily mean “unchanging,” and that transformation products should be considered in long-term safety evaluations [71].

For this reason, the emerging consensus is to apply safe-by-design and increasingly safe-and-sustainable-by-design (SSbD) principles from the earliest stages of material development. The current European SSbD guidance frames assessment iteratively and includes hazard, worker exposure during production, consumer and environmental exposure during use, and life-cycle considerations, while broader roadmap work emphasizes the need to integrate exposure assessment, life cycle thinking, circularity, and sustainability metrics throughout innovation. Earlier EU-oriented work on smart nanomaterials also stressed that agreed terminology, criteria, and assessment tools are needed to move from proof-of-concept nanomaterials toward responsibly governed applications. For boron-based nanomaterials, this means designing for lower hazard, lower release potential, controlled degradation, recyclability, and realistic exposure monitoring, rather than optimizing remediation performance alone [72], [73], [74].

A study by Visani de Luna et al. showed that pulmonary toxicity of boron nitride nanomaterials is aspect-ratio dependent, with h-BN nanosheets showing much better lung clearance and lower inflammatory effects than boron nitride nanotubes. This study is especially important for Section 10.2 because it provides a direct basis for safe design choices, indicating that morphology control can reduce inhalation-related risk [68].

Table 4 illustrates representative boron-based nanomaterials, major ecotoxicological and human-health concerns, relevant exposure pathways, and safe-design implications discussed in Section 10, with emphasis on morphology-dependent toxicity, mixture effects, occupational exposure, and life-cycle-aware risk management.

Table 4. Environmental risks, toxicological concerns, and safe-design considerations for boron-based nanomaterials.

Boron-based material /	**Main risk or assessment**	**Representative evidence**	**Key finding**	**Implication for safe design / risk**

context	**focus**			**management**
h-BN nanosheets in aquatic systems	Ecotoxicity toward primary producers	Freshwater alga *Chlorella vulgaris* exposed to h-BN nanosheets	Low doses (0.1–1 μg mL^{-1}) inhibited algal growth by up to 45.3%, linked to membrane damage and disruption of carbon assimilation	Avoid assuming inertness of h-BN in aquatic environments; evaluate dose, dispersion state, and species sensitivity in environmental applications
h-BN nanosheets vs BN nanotubes	Morphology-dependent pulmonary toxicity	Mouse aspiration study comparing 2D h-BN with high-aspect-ratio BNNTs	h-BN showed much better lung clearance and lower inflammatory response, whereas BNNTs were more persistent and associated with chronic inflammatory/fibrotic effects	Prefer lower-aspect-ratio or sheet-like forms when functionally possible; morphology control is a key safety lever
h-BN and TPU–hBN composites	Human-cell hazard across product life cycle	Human skin keratinocytes and bronchial epithelial cells exposed to h-BN, abraded composites, and degraded products	Under tested conditions, no marked acute cytotoxicity or broad omics disruption was observed despite cellular uptake	Composite form may reduce immediate hazard in some cases, but life-cycle testing remains necessary because exposure form changes with abrasion/weathering
BN nanosheets in water with co-pollutants	Mixture effects, colloidal behavior, and aquatic exposure pathways	*Daphnia magna* exposed to BNNS alone and with Cd in the presence/absence of natural organic matter (NOM)	BNNS alone showed no acute immobilization even at 100 mg L^{-1}, but at 1 mg L^{-1} they enhanced cadmium toxicity; NOM partly mitigated this effect	Risk assessment should include co-contaminants, natural organic matter, aggregation behavior, and realistic water chemistry rather than single-material tests alone
BNNT manufacturing / occupational handling	Worker exposure via inhalation and skin contact	Workplace exposure assessment summarized in BNNT toxicity review	Personal breathing-zone boron concentrations ranged from non-detectable to 0.95 μg m^{-3}, showing occupational exposure is measurable even when relatively low	Use engineering controls, dust management, and exposure monitoring in production and handling stages
Boron-based nanomaterials across the life	Safe-and-sustainable-by-design	European Commission methodological	Current guidance recommends tiered, early-stage assessment	Design for lower release potential, controlled degradation, reduced

cycle	(SSbD)	guidance and roadmap work	integrating hazard, exposure, and sustainability considerations across the material life cycle	hazard, recyclability, and application-specific exposure control from the start

Conclusion and Future Perspectives

Boron-based nanomaterials exhibit great promise for environmental sustainability owing to their excellent stability, tunable surface chemistry and multifunctional performances. Due to these favorable properties, materials such as h-BN, porous BN, boron carbon nitride, boron-doped carbons and boron-doped diamond electrodes have shown relevant applications in the field of water treatment, including heavy metal removal and pollutant degradation; air purification; carbon capture; waste management; and sustainable agriculture (air cleaning and vapor capture), carbon sequestration; waste management; and sustainable agriculture. They could have environmentally applicable value due to their unique performances on various types of remediation mechanisms, such as adsorption, membrane separation, catalysis, electrochemical oxidation, sensing and controlled release.

However, treatment efficiency is not the sole measure of their practical sustainability. Issues of scalability, cost, regeneration, long-term stability, and environmental and human-health safety are still major questions. The existing evidence indicates that the risks arising from boron-based nanomaterials are highly dependent on material form, surface properties, exposure pathway and environment conditions and reveals a need for detailed evaluation of their potential hazard prior to large scale application.

Future studies should thus target pilot-scale validation, real-environment testing, life-cycle assessment and safe-and-sustainable-by-design strategies. Material recovery and recyclability also demand more attention as well as both low cost and green synthesis routes. Boron-based nanotechnology is an attractive platform for next-generation environmental solutions, though practical implementation and safety concerns will ultimately determine their long-term sustainability and practical success.

References

[1] W. W. A. P. (United Nations), *The United Nations World Water Development Report*. UNESCO Pub., 2017.

[2] W. H. Organization, *Progress on the proportion of domestic and industrial wastewater flows safely treated–Mid-term status of SDG Indicator 6.3. 1 and acceleration needs, with a special focus on climate change, wastewater reuse and health*. World Health Organization, 2024.

[3] S. de Wit *et al.*, “Water, sanitation and hygiene (WASH): the evolution of a global health and development sector,” *BMJ Glob. Heal.*, vol. 9, no. 10, 2024.

[4] WHO/UNICEF Joint Monitoring Programme Team, *Progress on household drinking water, sanitation and hygiene 2000-2025: special focus on inequalities*. World Health Organization, 2025.

[5] D. Hou *et al.*, “Global soil pollution by toxic metals threatens agriculture and human health.,” *Science*, vol. 388, no. 6744, pp. 316–321, Apr. 2025, doi: 10.1126/science.adr5214.

[6] UNEP, “Emissions Gap Report 2025,” United Nations Environment Programme, Mar. 2025.

[7] F. A. O. and UNEP, “Global assessment of soil pollution: Report,” FAO and UNEP, Mar. 2021.

[8] I. Ihsanullah, “Boron nitride-based materials for water purification: Progress and outlook.,” *Chemosphere*, vol. 263, p. 127970, Jan. 2021, doi: 10.1016/j.chemosphere.2020.127970.

[9] V. Gadore, S. R. Mishra, A. K. Singh, and M. Ahmaruzzaman, “Advances in boron nitride-based nanomaterials for environmental remediation and water splitting: a review,” *RSC Adv.*, vol. 14, no. 5, pp. 3447–3472, 2024, doi: 10.1039/d3ra08323c.

[10] UN-Water, “Progress on Wastewater Treatment - 2024 Update,” UN-Water, Mar. 2024.

[11] W. H. Organization, “Ambient (outdoor) air pollution,” Mar. 2024, *World Health Organization*.

[12] W. H. Organization, “Air pollution data portal,” Mar. 2026, *World Health Organization*.

[13] M. Sharma *et al.*, “Next-generation nanomaterials-based biosensors: Real-time biosensing devices for detecting emerging environmental pollutants,” *Mater. Today Sustain.*, vol. 29, p. 101068, 2025, doi: https://doi.org/10.1016/j.mtsust.2024.101068.

[14] C. Jiang, S. Liu, T. Phenrat, and Q. Sui, “Nanomaterial-Enabled Environmental Remediation and Removal of Emerging Pollutants,” 2025. doi: 10.3390/toxics13100810.

[15] E. Abbate *et al.*, “Operationalization of the safe and sustainable by design framework for chemicals and materials: challenges and proposed actions.,” *Integr. Environ. Assess. Manag.*, vol. 21, no. 2, pp. 245–262, Mar. 2025, doi: 10.1093/inteam/vjae031.

[16] M. M. Abady, D. M. Mohammed, T. N. Soliman, R. A. Shalaby, and F. A. Sakr, “Sustainable synthesis of nanomaterials using different renewable sources,” *Bull. Natl. Res. Cent.*, vol. 49, no. 1, p. 24, 2025, doi: 10.1186/s42269-025-01316-4.

[17] B. D. Trump *et al.*, “Safety-by-design and engineered nanomaterials: the need to move from theory to practice,” *Environ. Syst. Decis.*, vol. 44, no. 1, pp. 177–188, 2024, doi: 10.1007/s10669-023-09927-w.

[18] B. Giese *et al.*, “Risks, Release and Concentrations of Engineered Nanomaterial in the Environment,” *Sci. Rep.*, vol. 8, no. 1, p. 1565, 2018, doi: 10.1038/s41598-018-19275-4.

[19] P. Singh *et al.*, “Nanostructured boron carbide (B4C): A bio-compatible and recyclable photo-catalyst for efficient wastewater treatment,” *Materialia*, vol. 1, pp. 258–264, 2018, doi: https://doi.org/10.1016/j.mtla.2018.08.001.

[20] C. Trellu, S. Chakraborty, P. V Nidheesh, and M. A. Oturan, “Environmental Applications of Boron-Doped Diamond Electrodes: 2. Soil Remediation and Sensing Applications,” *ChemElectroChem*, vol. 6, no. 8, pp. 2143–2156, Apr. 2019, doi: https://doi.org/10.1002/celc.201801877.

[21] H. H. P. Quang, P. K. T. Nguyen, P. Singh, P. Raizada, and V.-H. Nguyen, “Engineered boron-doped biochar for sustainable environmental remediation and circular energy systems: A review,” *J. Environ. Chem. Eng.*, vol. 13, no. 5, p. 118194, 2025, doi: https://doi.org/10.1016/j.jece.2025.118194.

[22] H. Elaibi, F. Mutlag, and F. Sen, “BioGreen Boron: Plant-mediated Boron-containing Nanomaterials for Medical and Environmental Applications–A PRISMA-guided Structured Review,” *Chem. Africa*, vol. 9, no. 3, p. 117, 2026.

[23] I. Itskou, A. L’Hermitte, S. Marchesini, T. Tian, and C. Petit, “How to Tailor Porous Boron Nitride Properties for Applications in Interfacial Processes.,” *Accounts Mater. Res.*, vol. 4, no. 2, pp. 143–155, Feb. 2023, doi: 10.1021/accountsmr.2c00148.

[24] S.-N. Nam *et al.*, “Review of boron nitride-based membranes in liquid purification/separation applications,” *Chem. Eng. J.*, vol. 453, p. 139740, 2023, doi: https://doi.org/10.1016/j.cej.2022.139740.

[25] S. Avasarala and S. Bose, “2D nanochannels and huge specific surface area offer unique ways for water remediation and adsorption: assessing the strengths of hexagonal boron nitride in separation technology,” *Funct. Compos. Mater.*, vol. 4, no. 1, p. 5, 2023, doi: 10.1186/s42252-023-00042-2.

[26] J. Zhang, H. Zhang, P. Zhou, P. Qing, H. Xu, and Y. Zhang, “Porous hexagonal boron nitride nanosheets with large adsorption capacity for Cu2+ synthesized through a two-step roasting process,” *Mater. Lett.*, vol. 213, pp. 211–213, 2018, doi: https://doi.org/10.1016/j.matlet.2017.11.075.

[27] Y.-G. Park *et al.*, “Boron nitride-based nanomaterials as adsorbents in water: A review,” *Sep. Purif. Technol.*, vol. 288, p. 120637, 2022, doi: https://doi.org/10.1016/j.seppur.2022.120637.

[28] T. Jähnichen, “Is porous boron nitride suited for water treatment?–a critical perspective on the materials water stability,” *Mater. Adv.*, 2026.

[29] V. Vatanpour, M. Mehrabi, M. Masteri-Farahani, and S. Amiri, “Improvement of permeability and antifouling properties of polyamide thin-film nanocomposite nanofiltration membranes using boron nitride quantum dots,” *Ind. Eng. Chem. Res.*, vol. 63, no. 12, pp. 5237–5248, 2024.

[30] N. García Doménech *et al.*, “High-Performance Boron Nitride-Based Membranes for Water Purification,” 2022. doi: 10.3390/nano12030473.

[31] X. Chen *et al.*, “Elevated efficiency in tartrazine removal from wastewater through boron-doped biochar:

enhanced adsorption and persulfate activation," *Biochar*, vol. 6, no. 1, p. 79, 2024, doi: 10.1007/s42773-024-00377-4.

[32] A. L'Hermitte *et al.*, "Effect of surface functionalization on the moisture stability and sorption properties of porous boron nitride," *Microporous Mesoporous Mater.*, vol. 352, p. 112478, 2023, doi: https://doi.org/10.1016/j.micromeso.2023.112478.

[33] S. Marchesini, X. Wang, and C. Petit, "Porous Boron Nitride Materials: Influence of Structure, Chemistry and Stability on the Adsorption of Organics," *Front. Chem.*, vol. Volume 7-, 2019, doi: 10.3389/fchem.2019.00160.

[34] P. Sharma *et al.*, "Recent advances and perspective in Boron Carbon Nitride and Boron Nitride based materials for photocatalytic energy and environmental applications," *J. Water Process Eng.*, vol. 70, p. 106896, 2025, doi: https://doi.org/10.1016/j.jwpe.2024.106896.

[35] Y. K. Recepoglu, A. Y. Goren, V. Vatanpour, Y. Yoon, and A. Khataee, "Boron carbon nitride nanosheets in water and wastewater treatment: A critical review," *Desalination*, vol. 533, p. 115782, 2022, doi: https://doi.org/10.1016/j.desal.2022.115782.

[36] H. H. Kim, K.-H. An, and B.-J. Kim, "Preparation of Mesoporous Boron-Doped Porous Carbon Derived from Coffee Grounds via Hybrid Activation for Carbon Capture and Storage," 2025. doi: 10.3390/batteries11040158.

[37] L. Xu *et al.*, "Facile synthesis of boron-doped porous biochar as a metal-free adsorbent for efficient removal of aqueous tetracycline antibiotics," *J. Environ. Sci.*, vol. 152, pp. 235–247, 2025, doi: https://doi.org/10.1016/j.jes.2024.04.044.

[38] A. Mijajlović, V. Stanković, T. Mutić, S. Djurdjić, F. Vlahović, and D. Stanković, "Boron-Doped Diamond Electrodes for Toxins Sensing in Environmental Samples—A Review," 2025. doi: 10.3390/s25072339.

[39] L. Chen *et al.*, "Boron-doped diamond electrodes for environmental applications: From structure-property relationships to electrochemical remediation and sensing," *J. Environ. Chem. Eng.*, vol. 14, no. 2, p. 121837, 2026, doi: https://doi.org/10.1016/j.jece.2026.121837.

[40] P. V Nidheesh, G. Divyapriya, N. Oturan, C. Trellu, and M. A. Oturan, "Environmental applications of boron-doped diamond electrodes: 1. Applications in water and wastewater treatment," *ChemElectroChem*, vol. 6, no. 8, pp. 2124–2142, 2019.

[41] V. Vatanpour *et al.*, "Anti-fouling polyethersulfone nanofiltration membranes aided by amine-functionalized boron nitride nanosheets with improved separation performance," *J. Environ. Chem. Eng.*, vol. 8, no. 6, p. 104454, 2020, doi: https://doi.org/10.1016/j.jece.2020.104454.

[42] C. Afonso, C. Y. Sousa, D. M. Farinon, A. Lopes, and A. Fernandes, "Electrochemical Oxidation of Pollutants in Textile Wastewaters Using BDD and Ti-Based Anode Materials," 2024. doi: 10.3390/textiles4040030.

[43] A. V Karim, P. V. Nidheesh, and M. A. Oturan, "Boron-doped diamond electrodes for the mineralization of organic pollutants in the real wastewater," *Curr. Opin. Electrochem.*, vol. 30, p. 100855, 2021, doi: https://doi.org/10.1016/j.coelec.2021.100855.

[44] F. Han, Y. Zong, D. Jassby, J. Wang, and J. Tian, "The interactions and adsorption mechanisms of ternary heavy metals on boron nitride," *Environ. Res.*, vol. 183, p. 109240, 2020.

[45] J. P. Vareda, A. J. M. Valente, and L. Durães, "Assessment of heavy metal pollution from anthropogenic activities and remediation strategies: A review," *J. Environ. Manage.*, vol. 246, pp. 101–118, 2019.

[46] A. S. Krishna Kumar, J. Warchol, J. Matusik, W.-L. Tseng, N. Rajesh, and T. Bajda, "Heavy metal and organic dye removal via a hybrid porous hexagonal boron nitride-based magnetic aerogel," *npj Clean Water*, vol. 5, no. 1, p. 24, 2022, doi: 10.1038/s41545-022-00175-0.

[47] E. J. Sohn *et al.*, "Photocatalytic boron nitride-based nanomaterials for the removal of selected organic and inorganic contaminants in aqueous solution: A review.," *Chemosphere*, vol. 349, p. 140800, Feb. 2024, doi: 10.1016/j.chemosphere.2023.140800.

[48] H. Zhang *et al.*, "Boron-doped porous carbon boosts electron transport efficiency for enhancing Fenton-like oxidation capacity: High-speed driving of Fe(III) reduction," *Appl. Catal. B Environ.*, vol. 343, p. 123535, 2024, doi: https://doi.org/10.1016/j.apcatb.2023.123535.

[49] Y. Zhang *et al.*, "Nano boron carbide effectively boost Fenton-like performance of hematite mediated systems: Roles of hematite exposed facets and synergistic catalysis between Fe and B.," *Environ. Pollut.*, vol. 363, no. Pt 1, p. 125050, Dec. 2024, doi: 10.1016/j.envpol.2024.125050.

[50] C. Bläker *et al.*, "Adsorbent Properties of Porous Boron Nitride and Activated Carbon: A Comparative Study.," *ACS omega*, vol. 9, no. 42, pp. 42721–42733, Oct. 2024, doi: 10.1021/acsomega.4c02625.

[51] H. Saleem, S. J. Zaidi, A. F. Ismail, and P. S. Goh, "Advances of nanomaterials for air pollution remediation and their impacts on the environment," *Chemosphere*, vol. 287, p. 132083, 2022, doi: https://doi.org/10.1016/j.chemosphere.2021.132083.

[52] Y. Nan, C. Feng, Y. Zhuo, and P. Hu, "Co-adsorption enhancement of formaldehyde/carbon dioxide over modified hexagonal boron nitride for whole-surface capture purification.," *J. Environ. Manage.*, vol. 356, p. 120586, Apr. 2024, doi: 10.1016/j.jenvman.2024.120586.

[53] Y. Zhang, Y. Wang, C. Qin, and J. Cao, "Synthesis and modification of boron nitride nanomaterials for gas sensors: from theory to application," *Phys. Chem. Chem. Phys.*, vol. 26, no. 45, pp. 28307–28331, 2024.

[54] X. Jiao *et al.*, "Constructing of porous boron nitride granules for dynamic adsorption of CO2," *Sep. Purif. Technol.*, vol. 362, p. 131727, 2025, doi: https://doi.org/10.1016/j.seppur.2025.131727.

[55] S. Ding and W. Gu, "Evaluate the potential utilization of B24N24 fullerene in the recognition of COS, H2S, SO2, and CS2 gases (environmental pollution)," *J. Mol. Liq.*, vol. 345, p. 117041, 2022, doi: https://doi.org/10.1016/j.molliq.2021.117041.

[56] R. Kushwah, S. G. Alamir, S. Al-Sulaimi, A. Al-Harrasi, and A. E. Ibrahim, "Multifaceted boron nitride nanomaterials: a comprehensive review of synthesis, property engineering and multidisciplinary applications," *RSC Adv.*, vol. 16, no. 9, pp. 7777–7802, 2026.

[57] K. S. G. C. Oliveira, E. V. dos Santos, L. D. Loor-Urgilés, A. Shabanloo, and C. A. Martínez-Huitle, "The world impact of boron doped diamond electrodes and low-cost strategies for novel production systems for sustainable wastewater treatment," *Curr. Opin. Electrochem.*, vol. 50, p. 101648, 2025, doi: https://doi.org/10.1016/j.coelec.2025.101648.

[58] W. Liu *et al.*, "An evaluation of a pilot-scale EO process based on BDD anode for leachate treatment: Performance, DOM degradation behavior and DBPs formation," *J. Water Process Eng.*, vol. 76, p. 108243, 2025, doi: https://doi.org/10.1016/j.jwpe.2025.108243.

[59] S. Sankeetha *et al.*, "Interaction of BiVO4 anchored 2D hexagonal boron nitride nanocomposite for photocatalytic water pollutants degradation and phytotoxicity assessment," *Colloids Surfaces A Physicochem. Eng. Asp.*, vol. 675, p. 132024, 2023, doi: https://doi.org/10.1016/j.colsurfa.2023.132024.

[60] P. Fincheira *et al.*, "Eco-Efficient Systems Based on Nanocarriers for the Controlled Release of Fertilizers and Pesticides: Toward Smart Agriculture," 2023. doi: 10.3390/nano13131978.

[61] X. Xu *et al.*, "Nanoscale-boron nitride positively alters rhizosphere microbial communities and subsequent cucumber (Cucumis sativa) growth: A metagenomic analysis," *Sci. Total Environ.*, vol. 958, p. 178115, 2025, doi: https://doi.org/10.1016/j.scitotenv.2024.178115.

[62] V. Forest, J. Pourchez, and E. Flahaut, "Efficiency and safety of nanopesticides, it takes two to tango. An overview of the lack of data on possible effects on human health," *Sci. Total Environ.*, vol. 973, p. 179156, 2025, doi: https://doi.org/10.1016/j.scitotenv.2025.179156.

[63] H. Zhang *et al.*, "Controlled release system of nanopesticides based on noncovalent interactions," *ACS Agric. Sci. Technol.*, vol. 4, no. 9, pp. 851–871, 2024.

[64] L. Hao *et al.*, "Composite pesticide nanocarriers involving functionalized boron nitride nanoplatelets for pH-responsive release and enhanced UV stability," *Chem. Eng. J.*, vol. 396, p. 125233, 2020, doi: https://doi.org/10.1016/j.cej.2020.125233.

[65] L. Hao *et al.*, "Boron Nitride Reinforced Supramolecular Gels Nano-Assembled with Fungicides toward Soil-Borne Fungal Disease Management.," *Adv. Sci. (Weinheim, Baden-Wurttemberg, Ger.*, vol. 13, no. 7, p. e15855, Feb. 2026, doi: 10.1002/advs.202515855.

[66] L. Hao *et al.*, "Functionalized boron nitride nanosheets conjugated with plant micronutrients as seed dressing agents towards control of bacterial wilt disease," *Environ. Sci. Nano*, vol. 10, no. 9, pp. 2343–2358, 2023, doi:

10.1039/D3EN00173C.

[67] W. Zou, Y. Huo, X. Zhang, C. Jin, X. Li, and Z. Cao, “Toxicity of hexagonal boron nitride nanosheets to freshwater algae: Phospholipid membrane damage and carbon assimilation inhibition,” *J. Hazard. Mater.*, vol. 465, p. 133204, 2024, doi: https://doi.org/10.1016/j.jhazmat.2023.133204.

[68] L. A. Visani de Luna *et al.*, “Pulmonary Toxicity of Boron Nitride Nanomaterials Is Aspect Ratio Dependent.,” *ACS Nano*, vol. 17, no. 24, pp. 24919–24935, Dec. 2023, doi: 10.1021/acsnano.3c06599.

[69] M. Carlin *et al.*, “Hazard assessment of hexagonal boron nitride and hexagonal boron nitride reinforced thermoplastic polyurethane composites using human skin and lung cells,” *J. Hazard. Mater.*, vol. 473, p. 134686, 2024, doi: https://doi.org/10.1016/j.jhazmat.2024.134686.

[70] G. H. da Silva, J. Ji, M. T. Maia, D. Mattia, and D. S. T. Martinez, “Exploring the combined toxicity of boron nitride nanosheets, cadmium and natural organic matter on Daphnia magna,” *Aquat. Toxicol.*, vol. 279, p. 107198, 2025, doi: https://doi.org/10.1016/j.aquatox.2024.107198.

[71] S. Vranic, R. Kurapati, K. Kostarelos, and A. Bianco, “Biological and environmental degradation of two-dimensional materials,” *Nat. Rev. Chem.*, vol. 9, no. 3, pp. 173–184, 2025.

[72] A. Mech *et al.*, “Safe- and sustainable-by-design: The case of Smart Nanomaterials. A perspective based on a European workshop,” *Regul. Toxicol. Pharmacol.*, vol. 128, p. 105093, 2022, doi: https://doi.org/10.1016/j.yrtph.2021.105093.

[73] F. R. Cassee *et al.*, “Roadmap towards safe and sustainable advanced and innovative materials. (Outlook for 2024-2030).,” *Comput. Struct. Biotechnol. J.*, vol. 25, pp. 105–126, Dec. 2024, doi: 10.1016/j.csbj.2024.05.018.

[74] C. Apel *et al.*, “Safe-and-sustainable-by-design: State of the art approaches and lessons learned from value chain perspectives,” *Curr. Opin. Green Sustain. Chem.*, vol. 45, p. 100876, 2024.