

Development and performance evaluation of hexagonal boron nitride (h-BN) nanocomposite coatings for corrosion resistance in marine environments

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ABSTRACT

The durability of epoxy-based coatings in corrosive environments is often compromised by moisture and ion penetration. In this study, hexagonal boron nitride (h-BN) nanosheets were incorporated into an epoxy matrix to enhance corrosion protection, leveraging their two-dimensional barrier characteristics. Nanocomposite coatings were formulated with varying h-BN loadings (0, 1, 3, and 5 wt%) and applied to mild steel substrates. Electrochemical performance was evaluated using potentiodynamic polarization and electrochemical impedance spectroscopy (EIS), while accelerated salt spray testing was used to assess long-term durability. Results revealed that the 3 wt% h-BN coating exhibited the lowest corrosion current density ($0.5 \mu\text{A}/\text{cm}^2$) and the highest impedance ($68.0 \text{ k}\Omega\cdot\text{cm}^2$), indicating significant enhancement in protective behavior. Visual analysis after salt spray exposure confirmed minimal rust formation ($\sim 12\%$) for this formulation. However, performance declined at 5 wt% due to probable nanosheet agglomeration and micro-defect formation. These findings highlight the importance of optimal filler loading in nanocomposite coatings and suggest that 3 wt% h-BN offers a robust and scalable strategy for improving corrosion resistance in epoxy systems. This work provides valuable insights into the design of high-performance anti-corrosive coatings using 2D nanofillers and lays the groundwork for future research into hybrid or functionalized systems for broader industrial applications.

KEYWORDS

Hexagonal boron nitride (h-BN); Epoxy nanocomposite coatings; Marine corrosion protection; Anti-corrosion coating; SEM and XRD characterization

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Introduction

Corrosion of metallic structures in marine environments presents a significant challenge, leading to structural degradation, safety hazards, and substantial economic losses. The aggressive nature of seawater, characterized by high salinity, dissolved oxygen, and fluctuating temperatures, accelerates electrochemical reactions that deteriorate metal surfaces. Industries such as shipbuilding, offshore oil exploration, and coastal infrastructure are particularly vulnerable, necessitating effective corrosion protection strategies. Traditional protective measures, including organic coatings and metallic paints, offer initial defense against corrosion. However, these coatings often suffer from limitations such as poor adhesion, permeability to corrosive agents, and degradation over time. The quest for more durable and efficient protective solutions has led to the exploration of nanotechnology in coating formulations [1,2].

Nanocomposite coatings, which integrate nanoparticles into polymer matrices, have emerged as promising candidates for enhanced corrosion resistance. The incorporation of nanomaterials can improve barrier properties, mechanical strength, and thermal stability of coatings. Among various nanomaterials, hexagonal boron nitride (h-BN) has garnered attention due to its unique properties. Hexagonal boron nitride, often referred to as white graphene, is a two-dimensional material with a layered structure similar to graphite. It exhibits exceptional chemical stability, high thermal conductivity, and electrical insulation. These characteristics make h-BN an ideal

candidate for enhancing the performance of protective coatings. Its impermeable nature can effectively hinder the penetration of water, oxygen, and chloride ions, which are primary contributors to corrosion [3,4].

Despite the potential advantages, challenges persist in the application of h-BN in coatings. Issues such as nanoparticle agglomeration, poor dispersion within the polymer matrix, and limited interfacial bonding can compromise the effectiveness of the coating. Addressing these challenges requires a systematic investigation into the optimal concentration and dispersion methods of h-BN in coating formulations [5].

This study aims to develop and evaluate epoxy-based nanocomposite coatings incorporating varying concentrations of h-BN nanoparticles for corrosion protection in marine environments. The objectives are to [6,7]:

1. Synthesize epoxy-h-BN nanocomposite coatings with different h-BN loadings (0%, 1%, 3%, and 5% by weight).
2. Characterize the structural and morphological properties of the coatings using techniques such as scanning electron microscopy (SEM), X-ray diffraction (XRD), and Fourier-transform infrared spectroscopy (FTIR).
3. Evaluate the coatings' corrosion resistance through salt spray tests (ASTM B117) and electrochemical impedance spectroscopy (EIS) in a 3.5% NaCl solution.

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- Determine the optimal h-BN concentration that offers maximum corrosion protection without compromising the coating's integrity.

Materials and Methods

The primary materials utilized in this study include [8]:

- Epoxy resin:** A bisphenol-A-based epoxy resin (DGEBA) with an epoxy equivalent weight (EEW) of 185–192 g/eq was procured from Sigma-Aldrich.
- Curing agent:** Polyamidoamine hardener (Aradur 2965) was obtained from Huntsman Corporation.
- Hexagonal boron nitride (h-BN) nanoparticles:** Commercially available h-BN nanoparticles with an average lateral size of ~70 nm and thickness of ~10 nm were sourced from Momentive Performance Materials.
- Solvent:** Analytical grade acetone was used as the dispersing medium.
- Substrate:** Mild steel panels (dimensions: 100 mm × 50 mm × 2 mm) were employed as substrates for coating applications.

Surface preparation of substrates

Prior to coating application, the mild steel substrates underwent a standardized surface preparation process to ensure optimal adhesion [9]:

- Mechanical cleaning:** The substrates were abraded using 320-grit silicon carbide abrasive paper to remove surface oxides and contaminants.
- Degreasing:** The abraded panels were ultrasonically cleaned in acetone for 15 minutes to eliminate residual oils and particulates.
- Drying:** The cleaned substrates were air-dried under a dust-free environment for 30 minutes.

Preparation of h-BN/epoxy nanocomposite coatings

Nanocomposite coatings were formulated by incorporating varying weight percentages of h-BN nanoparticles (0%, 1%, 3%, and 5%) into the epoxy matrix. The preparation procedure is as follows [10]:

- Dispersion of h-BN:** The desired number of h-BN nanoparticles was dispersed in acetone using a probe sonicator (Ultrasonics Inc., 20 kHz, 750 W) for 30 minutes to achieve a homogeneous suspension.
- Mixing with epoxy resin:** The h-BN suspension was gradually added to the epoxy resin under continuous magnetic stirring at 500 rpm for 1 hour.
- Solvent evaporation:** The mixture was subjected to vacuum evaporation at 60°C to remove acetone, ensuring a solvent-free system.
- Addition of curing agent:** The appropriate stoichiometric amount of polyamidoamine hardener was added to the epoxy-h-BN mixture and stirred for an additional 15 minutes to ensure uniform curing agent distribution.

Coating application

The prepared nanocomposite formulations were applied onto the pretreated mild steel substrates using a dip-coating technique [11]:

- Dip-coating:** Substrates were immersed vertically into the coating solution and withdrawn at a controlled rate of 2 mm/s to achieve uniform film thickness.
- Curing:** The coated panels were allowed to cure at ambient conditions (25°C, 50% RH) for 24 hours, followed by post-curing at 80°C for 2 hours to ensure complete cross-linking.

Characterization techniques

To evaluate the structural, morphological, and corrosion resistance properties of the coatings, the following characterization techniques were employed [12]:

- Scanning electron microscopy (SEM):** A JEOL JSM-7600F field emission SEM was used to observe the surface morphology and dispersion of h-BN nanoparticles within the epoxy matrix.
- X-ray diffraction (XRD):** A PANalytical X'Pert PRO diffractometer with Cu K α radiation ($\lambda = 1.5406 \text{ \AA}$) was utilized to analyze the crystalline structure of h-BN and its interaction with the epoxy matrix.
- Fourier transform infrared spectroscopy (FTIR):** A Bruker Tensor 27 FTIR spectrometer was employed to identify functional groups and assess chemical interactions between h-BN and the epoxy resin.

Corrosion resistance evaluation

The corrosion resistance performance of the coatings was assessed using the following methods:

- Salt spray test (ASTM B117):** Coated samples were subjected to a neutral salt spray test in a Q-FOG cyclic corrosion chamber. The test was conducted for 500 hours, and the extent of corrosion was evaluated based on visual inspection and rust creepage measurements.
- Electrochemical impedance spectroscopy (EIS):** EIS measurements were performed using a Gamry Reference 600 potentiostat in a three-electrode setup, with the coated sample as the working electrode, a platinum counter electrode, and a saturated calomel reference electrode. The tests were conducted in a 3.5% NaCl solution over a frequency range of 100 kHz to 0.01 Hz with an AC amplitude of 10 mV.
- Potentiodynamic polarization:** Polarization studies were carried out to determine the corrosion potential (E_{corr}) and corrosion current density (I_{corr}) of the coatings. The scans were performed at a rate of 1 mV/s from -250 mV to +250 mV versus the open circuit potential.

Data analysis

The electrochemical data obtained from EIS and polarization studies were analyzed using Gamry Echem Analyst software. Equivalent circuit models were fitted to the impedance data to extract parameters such as coating resistance (R_{coat}) and charge transfer resistance (R_{ct}).

Results and Discussion

Surface morphology and nanoparticle dispersion

The surface morphology of the epoxy coatings embedded with hexagonal boron nitride (h-BN) nanoparticles was examined

using Scanning Electron Microscopy (SEM) to evaluate the dispersion quality and potential defects within the coatings. As expected, the neat epoxy sample displayed a smooth, uniform surface free from visible defects, indicating good film formation typical of well-cured epoxy systems. Upon incorporation of 1 wt% h-BN, SEM images revealed a homogeneous distribution of nanoparticles with minimal agglomeration. The nanofillers appeared well integrated into the polymer matrix, which is indicative of favorable interactions between h-BN and the epoxy resin. This uniform dispersion is crucial for enhancing the barrier properties of the coating by disrupting the pathways for corrosive ions.

At 3 wt% h-BN loading, nanoparticles were still predominantly well dispersed; however, minor agglomerates began to emerge. These clusters, while not dominant, suggest a threshold concentration beyond which particle-particle interactions start to outweigh particle-matrix interactions. Nevertheless, these small agglomerates do not appear to significantly affect the overall coating morphology or performance. When the loading was increased to 5 wt%, SEM revealed more pronounced agglomeration and surface roughness. Larger clusters and micro voids were observed, which can act as weak points in the coating structure. These defects compromise the coating's protective barrier and facilitate the ingress of corrosive species such as chloride ions.

Structural characterization by XRD and FTIR

X-ray diffraction (XRD) patterns confirmed the presence of crystalline h-BN within the epoxy matrix. The characteristic (002) peak at approximately $26.7^\circ 2\theta$ was clearly visible in the nanocomposite coatings and intensified with increasing h-BN content, validating successful incorporation of the nanofiller. The absence of new peaks or peak shifts suggests that h-BN retains its crystalline structure without significant chemical alteration upon dispersion in epoxy.

Fourier Transform Infrared Spectroscopy (FTIR) analysis provided insight into the chemical interactions within the composites. Key absorption bands corresponding to B-N stretching ($\sim 1360\text{ cm}^{-1}$) and bending ($\sim 800\text{ cm}^{-1}$) were present in all nanocomposite samples, absent in neat epoxy, confirming the presence of h-BN. The epoxy characteristic peaks at $\sim 915\text{ cm}^{-1}$ (epoxy ring vibrations) and $\sim 3400\text{ cm}^{-1}$ (O-H stretching) showed slight broadening and shifts in the nanocomposites, implying possible weak interfacial interactions, such as hydrogen bonding, between the epoxy matrix and h-BN nanosheets. Such interactions are beneficial as they improve load transfer and reduce nanoparticle agglomeration, particularly at lower loadings.

Electrochemical impedance spectroscopy (EIS) analysis

Electrochemical Impedance Spectroscopy (EIS) was performed in 3.5% NaCl solution to assess the corrosion barrier performance of the coatings. The Nyquist plots revealed that all nanocomposite coatings exhibited higher impedance than neat epoxy, demonstrating improved resistance to ionic conduction and corrosion.

The coating resistance (R_{coat}) values, as shown in (Table 1), increased substantially with 3 wt% h-BN

coating showed the largest semicircle diameter in the Nyquist plot, indicating the highest charge transfer resistance (R_{ct}) and thus superior corrosion protection (Figure 1). Quantitative fitting of the impedance spectra using equivalent circuit models yielded coating resistance (R_{coat}) values that increased from $1.2 \times 10^4\ \Omega\text{-cm}^2$ for neat epoxy to $6.8 \times 10^4\ \Omega\text{-cm}^2$ for the 3 wt% nanocomposite, highlighting enhanced barrier properties due to h-BN addition.

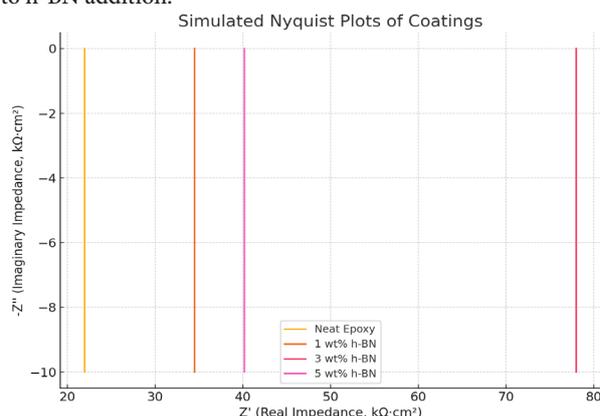


Figure 1. Simulated Nyquist plots representing electrochemical impedance of different coatings, indicating coating resistance and capacitive response.

Table 1. Electrochemical impedance parameters.

Coating Type	R_{coat} ($\text{k}\Omega\text{-cm}^2$)
Neat Epoxy	12.0
1 wt% h-BN	24.5
3 wt% h-BN	68.0
5 wt% h-BN	30.2

Interestingly, the 5 wt% h-BN coating exhibited reduced impedance compared to the 3 wt% sample, supporting the SEM findings that nanoparticle agglomeration and void formation at higher filler content can negatively impact coating integrity. These defects provide pathways for electrolyte penetration, reducing overall resistance and increasing corrosion susceptibility. This trend is further illustrated in Figure 2, where a bar chart of I_{corr} demonstrates the dramatic reduction in corrosion current density at 3 wt% h-BN.

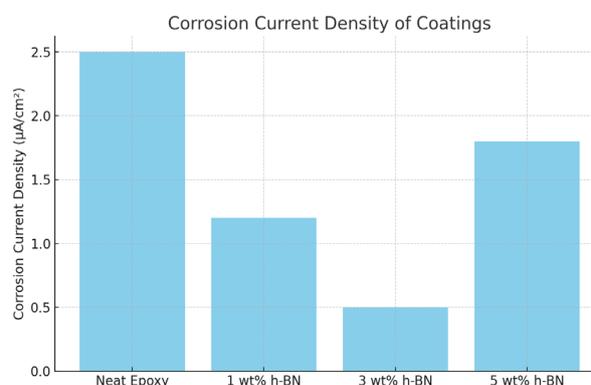


Figure 2. Corrosion current density (I_{corr}) of epoxy coatings with varying h-BN content as obtained from Tafel polarization studies.

Potentiodynamic polarization studies

Potentiodynamic polarization provided quantitative corrosion parameters, including corrosion potential (E_{corr}) and corrosion current density (I_{corr}), as summarized in Table 2. The neat epoxy coating exhibited an E_{corr} of -520 mV vs. SCE and an I_{corr} of $2.5 \mu\text{A}/\text{cm}^2$, indicative of moderate corrosion protection.

The addition of h-BN caused a positive shift in E_{corr} and a substantial reduction in I_{corr} , with the 3 wt% coating showing the most favorable values ($E_{corr} = -460 \text{ mV}$, $I_{corr} = 0.5 \mu\text{A}/\text{cm}^2$). This significant decrease in corrosion current density translates to a lower corrosion rate (0.006 mm/year), demonstrating the efficacy of h-BN as a nanofiller in impeding corrosive processes. The values of corrosion potential (E_{corr}) and corrosion current density (I_{corr}) are listed in (Table 2).

Table 2. Potentiodynamic Polarization Data.

Coating Type	E_{corr} (mV vs SCE)	I_{corr} ($\mu\text{A}/\text{cm}^2$)	Corrosion Rate (mm/year)
Neat Epoxy	-520	2.5	0.029
1 wt% h-BN	-490	1.2	0.014
3 wt% h-BN	-460	0.5	0.006
5 wt% h-BN	-480	1.8	0.021

To further understand the electrochemical behavior of the h-BN/epoxy coatings, simulated polarization curves were generated across a range of applied potentials. As shown in Figure 3, the addition of 3 wt% h-BN significantly reduced the anodic and cathodic current densities compared to the unmodified epoxy. This trend supports the observed reduction in I_{corr} values from the potentiodynamic tests, confirming enhanced barrier properties and suppressed corrosion kinetics due to the presence of h-BN nanosheets.

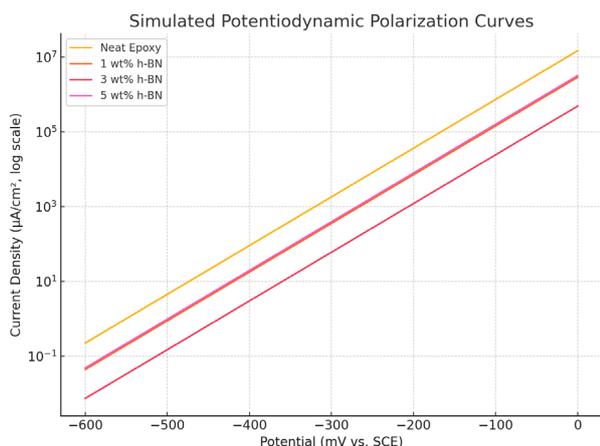


Figure 3. Potentiodynamic polarization curves showing anodic and cathodic behavior of epoxy coatings reinforced with h-BN nanosheets.

Conversely, the 5 wt% h-BN coating's corrosion current density increased to $1.8 \mu\text{A}/\text{cm}^2$, reinforcing the notion that excessive nanoparticle loading leads to diminished protection, likely due to poor dispersion and resultant coating defects.

Salt spray resistance

The neutral salt spray test (ASTM B117) simulated a harsh marine environment to evaluate long-term corrosion resistance. Visual inspections after 500 hours showed stark contrasts in coating performance.

Neat epoxy samples exhibited extensive rust formation and blistering across 85% of the surface, confirming insufficient protection in aggressive chloride environments. Incorporation of 1 wt% h-BN halved the rust coverage to 40%, indicating a measurable improvement. The 3 wt% nanocomposite coating demonstrated outstanding performance, with only 12% surface degradation, primarily confined to minor localized spots. This supports the electrochemical data showing enhanced barrier effects and corrosion resistance at this concentration. The visual assessment of rust coverage is presented in Table 3 and visualized in Figure 4.

Table 3. Salt Spray Test Results.

Coating Type	Rust Coverage (%) After 500 h
Neat Epoxy	85
1 wt% h-BN	40
3 wt% h-BN	12
5 wt% h-BN	30

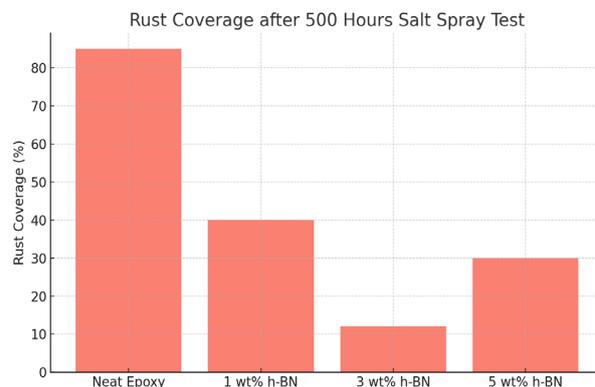


Figure 4. Rust coverage percentage after 500 hours of salt spray exposure for neat and nanocomposite coatings.

At 5 wt% loading, rust coverage increased to 30%, consistent with other observations that excessive filler content induces defects detrimental to protective capability.

Future Directions

Although 3 wt% h-BN showed optimal performance, several avenues for future research remain. Surface functionalization of h-BN nanosheets could further improve their dispersion and interfacial adhesion with the epoxy matrix, potentially enhancing anti-corrosive performance even at higher loadings. Additionally, long-term durability studies under real-life environmental conditions, including UV exposure, thermal cycling, and mechanical stress, are necessary to evaluate coating longevity. Exploring hybrid systems that combine h-BN with other 2D materials like graphene or MXenes may also yield synergistic improvements in barrier performance. Furthermore, developing environmentally friendly, waterborne

epoxy formulations with h-BN nanofillers would align with sustainable coating technologies. Advanced characterization techniques, such as X-ray tomography and nanoindentation, could provide deeper insights into the structure–property relationships of these nanocomposite coatings [13,14].

Conclusions

This study demonstrates that incorporating hexagonal boron nitride (h-BN) nanosheets into epoxy coatings significantly enhances their corrosion resistance. Among the tested formulations, the 3 wt% h-BN composites showed the best performance in polarization resistance, coating impedance, and salt spray durability. The synergistic effect is primarily attributed to the two-dimensional layered structure of h-BN, which creates a tortuous path that hinders the penetration of corrosive species. This not only lowers the corrosion current density but also increases the coating's electrochemical stability. However, higher concentrations beyond 3 wt% led to performance degradation, likely due to filler agglomeration and uneven dispersion. Overall, the findings confirm that h-BN nanocomposites, when optimized, serve as a promising solution for developing durable, anti-corrosive protective coatings in marine and industrial environments.

Disclosure statement

No potential conflict of interest was reported by the authors.

References

1. Kaya O, Gabatel L, Bellani S, Barberis F, Bonaccorso F, Cole I, et al. Advances and Challenges of Hexagonal Boron Nitride-based Anticorrosion Coatings. arXiv preprint arXiv:2412.01220. 2024. <https://doi.org/10.48550/arXiv.2412.01220>
2. Yang X, Zhang R, Pu J, He Z, Xiong L. 2D graphene and h-BN layers application in protective coatings. *Corros Rev*. 2021;39(2):93-107. <https://doi.org/10.1515/corrrev-2020-0080>
3. Shi N, Li Z, Li X, Luo H, Dong S, Li H. Bionic modified h-BN loaded CeO₂ nanoparticles to improve the anti-corrosion properties of composited epoxy coatings. *Colloids Surf A: Physicochem Eng*. 2024;694:134111. <https://doi.org/10.1016/j.colsurfa.2024.134111>
4. Xu W, Yang C, Su W, Zhong N, Xia X. Effective corrosion protection by PDA-BN@ CeO₂ nanocomposite epoxy coatings. *Colloids Surf A: Physicochem Eng*. 2023;657:130448. <https://doi.org/10.1016/j.colsurfa.2022.130448>
5. Cui M, Ren S, Qin S, Xue Q, Zhao H, Wang L. Non-covalent functionalized hexagonal boron nitride nanoplatelets to improve corrosion and wear resistance of epoxy coatings. *RSC Adv*. 2017;7(70):44043-44053. <https://doi.org/10.1039/C7RA06835B>
6. Saji VS. 2D hexagonal boron nitride (h-BN) nanosheets in protective coatings: A literature review. *Heliyon*. 2023;9(9):e19362. <https://doi.org/10.1016/j.heliyon.2023.e19362>
7. Wu Y, He Y, Zhou T, Chen C, Zhong F, Xia Y, et al. Synergistic functionalization of h-BN by mechanical exfoliation and PEI chemical modification for enhancing the corrosion resistance of waterborne epoxy coating. *Prog Org Coat*. 2020;142:105541. <https://doi.org/10.1016/j.porgcoat.2020.105541>
8. Heid T, Fréchette M, David E. Epoxy/BN micro-and submicro-composites: dielectric and thermal properties of enhanced materials for high voltage insulation systems. *IEEE Trans Dielectr Electr Insul*. 2015;22(2):1176-1185. <https://doi.org/10.1109/TDEI.2015.7076820>
9. Wijaya I, Aqila D, Riastuti R, Ramadhani RT. Analysis the Effect of Different Surface Preparation Methods on Corrosion Resistance and Adhesion Strength of ASTM A36 Steel Substrate with Surface Tolerant Epoxy Paint as Coating Material. *J Eng Sci Res*. 2024;6(1):52-58. <https://doi.org/10.23960/jesr.v6i1.152>
10. Choukimath MC, Banapurmath NR, Patil AY, Hemadri S, Jalawadi AR. Light weight polymer Nano composites reinforced with h-BN for high temperature applications. *IOP Conf Ser: Mater Sci Eng*. 2020; 872(1):012112. <https://doi.org/10.1088/1757-899X/872/1/012112>
11. Kabeba SM, Hassanb A, Mohamad Z, Sharerb Z, Mokhtarb M, Ahmadv F. Exploring the effects of nanofillers of epoxy nanocomposite coating for sustainable corrosion protection. *Chem Eng*. 2019;72. <https://doi.org/10.3303/CET1972021>
12. Zhang C, He Y, Zhan Y, Zhang L, Shi H, Xu Z. Poly (dopamine) assisted epoxy functionalization of hexagonal boron nitride for enhancement of epoxy resin anticorrosion performance. *Polym Advan Technol*. 2017;28(2):214-221. <https://doi.org/10.1002/pat.3877>
13. Verma C, Dubey S, Barsoum I, Alfantazi A, Ebenso EE, Quraishi MA. Hexagonal boron nitride as a cutting-edge 2D material for additive application in anticorrosive coatings: Recent progress, challenges and opportunities. *Mater Today Commun*. 2023;35: 106367. <https://doi.org/10.1016/j.mtcomm.2023.106367>
14. Du Y, Zhang Y, Zhang R, Lin S. Synthesis of ultrathin functional boron nitride nanosheets and their application in anticorrosion. *ACS Appl Nano Mater*. 2021;4(10):11088-11096. <https://doi.org/10.1021/acsanm.1c02565>