Contents lists available at *Dergipark*

International Journal of Boron Science and Nanotechnology

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

Number 1, December 2024

REVIEW ARTICLE

Received Date: 21.12.2024 Accepted Date: 31.12.2024

The role of boron in new generation technologies and sustainable future

Ebru Halvaci[1], Damla Ikballi[1], Alper Ozengul[1], Berk Sevimli[1], Afnan Ashour Tumeh[1],Zeynep Guzel[1], Mehmet Selcuk Erdogan[1], Guray Kaya[2*], Onder Uysal[3*], Fatih Sen[1*]

[1]*Kütahya Dumlupinar University, Sen Research Group, Department of Biochemistry, Dumlupinar University, 43100, Kutahya, Türkiye*,
[2]*Kütahya Dumlupinar University, Department of Metallurgical and Materials Engineering, 43100, Kutahya, Türkiye,*
[3]*Kütahya Dumlupinar University, Department of Mining Engineering, 43100, Kutahya, Türkiye,*

Abstract

Boron, one of the cornerstones of chemistry and materials science, offers a wide range of uses in the historical and modern world. This element, which is found in nature as borate and boric acid salts, has traditionally been used in glass, ceramic and antiseptic products. But in the modern era, boron is becoming a strategic material in many fields, from energy technologies to nanotechnology. In addition, the role of boron in the energy sector, especially in renewable energy systems and battery technologies, is very prominent. In solar energy systems, boron stands out as a component that increases the energy density and lifespan of lithium-ion batteries, while increasing the efficiency of photovoltaic cells. While the importance of boron hydrides is increasing in the field of hydrogen storage and release, boron carbide increases safety by providing neutron control in nuclear energy reactors. In addition, boron is used in the production of lightweight and durable materials in the defense and aerospace industries. In the field of nanotechnology, boron nanotubes and nanomaterials enable groundbreaking applications in energy storage, industrial catalysts and sensor technologies. In addition, boron-based compounds attract attention in the biomedical field with their anti-cancer properties and effects that support wound healing. The boron element also contributes to sustainable agricultural practices as the main component of fertilizers that support plant growth and increase productivity in agriculture. The versatile use of boron makes it an indispensable component in the energy, materials and biotechnology fields of the future.

Keywords: Boric acid; Borates; Chemical structure; Metalloid

---

* Corresponding author.
E-mail address: fatih.sen@dpu.edu.tr; guray.kaya@dpu.edu.tr; onder.uysal@dpu.edu.tr

1. Introduction

The element boron has played an important role in various fields of science and technology in historical and modern times. Boron is an element of both historical and modern importance in the chemical world. independently discovered by Sir Humphry Davy, Joseph Louis Gay-Lussac and Louis Jacques Thénard in 1808, boron was first synthesized in pure form by Ezekiel Weintraub in 1909 [1]. Boron has been used for many years in glass and ceramics making, and its durability and shape retention ability make it an indispensable material for these sectors [2]. At the same time, its antiseptic and preservative nature allows it to be used in various applications, including textile dyeing, agricultural chemicals, etc. [3]. Thanks to energy technologies and advanced material sciences, boron is continuously gaining importance today. In innovative applications such as hydrogen storage, lithium ion batteries and solar panels, boron compounds are all obtained [4]. Similar research is being conducted to show how boron hydrides play an integral role in hydrogen storage and how boron-grounded electrolytes also increase the energy density and lifetime of batteries. Properties such as high hardness and low density provide weight-broken boron-based materials that can serve as a lighter and more robust alternative to steel in the aerospace and defence industries [5]. For ballistic armour and metal matrix composites, compounds such as boron carbide and boron nitride are generally preferred [6]. In addition, the use of boron in the biomedical field also constitutes its remarkable properties. It has anticancer properties and promotes healing similar to that of boron. In particular, Boron Neutron Capture Therapy (BNCT) is becoming an emerging treatment modality that specifically targets diseased cells. BNCT is expected to damage the tumour, but not the surrounding healthy tissues. Due to their antiseptic properties, boron compounds are also widely used in numerous wound healing processes [7]. Boron plays a role in many new technologies in the field of nanotechnology, including boron nanotubes and boron nanospheres. These nanomaterials have various applications, including energy storage devices and industrial catalysts. Boron nanotubes can provide significant weight and cost reduction in aerospace and automotive industries due to their low density as well as high mechanical strength and chemical stability[8]. Furthermore, boron-derived nanomaterials are equally applicable in green technologies, including the removal of environmental pollutants and sustainable energy solutions. The role of boron in the energy field is becoming increasingly important. It helps to strengthen composite materials used in wind turbines and makes solar panels more efficient. From an energy point of view, the neutron-absorbing property of boron carbide is highly relevant to nuclear energy, as it affects the safety and efficiency of reactors. Lithium-boron-based batteries have high energy density and their stable nature makes them suitable energy sources for portable devices and electric vehicles. Boron also plays a very important role in agriculture. Boron is an essential element for processes such as plant growth, photosynthesis and cell wall formation. Boron is an essential micronutrient and its deficiency in soil can directly affect plant health and lead to yield loss. Boron-based fertilisers improve crop quality and soil structure. Especially in crops of economic importance, eliminating boron deficiency directly increases productivity. Furthermore, the use of boron in combination with pesticides offers a solution that promotes sustainability in agricultural production. In conclusion, although boron has historically been used in traditional industries such as glass, ceramics and textiles, in the modern era it continues to play a vital role in many fields such as high-tech applications, the energy sector, biomedical innovations and nanotechnology [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21], [22], [23], [24], [25], [26], [27], [28], [29]. With its wide range of applications and versatile properties, boron continues to be a shaping factor in the future of energy, materials and biotechnology. Better understanding and utilizing the potential of boron is critical for sustainable development and technological progress. This review comprehensively covers the characterization of boron, its role in the historical and modern world, its versatile use in nanomaterials and its importance in the country's reserves, and provides an important framework for possible future uses [30], [31], [2], [4], [32], [33], [6], [34], [8].

2. Characteristics of boron

2.1. *Physical properties*

Boron has been found as many allotopes with wide range of physicochemical properties. Boron is a black, brittle, metallic lustre crystalline solid or a brown powder in amorphous forms. The metal has high melting (2.076 °C) and boiling (3.927 °C) points, which demonstrate a thermal stability enabling positioning of boron as crucial in bodies designed for high-temperature conditions. This low density combined with considerable hardness has made the element a popular choice for lightweight, yet durable materials. Moreover, boron has a high neutron absorption power, so it is useful in nuclear applications. Sulfur is also used during the design of innovative protective nuclear shielding materials, to ensure the safety and efficiency of nuclear reactors. Boron has continuing research on its physical properties in order to optimize an even wider array of applications for the technology of the future. Recent developments in materials science are likely to create more uses for boron-based composites, particularly in the aerospace and automotive industries [35], [36], [37].

2.2. *Chemical properties*

Boron is known for its strong tendency to form covalent bonds. Its compounds mainly show +3 oxidation state. Boron-containing compounds like borates and borides are known for thermal resilience and chemical corrosion resistance. These properties make boron well-suited for high temperature and chemically harsh environments. Moreover, boron's coordination and the formation of stable complexes with organic or inorganic molecules have moved boron into the spotlight for potential applications in catalysis, pharmaceuticals, and materials science. A cluster compound is a type of complex formed by chemical bonds and new studies are now studying boron for its potential to form available cluster compounds for nanotechnology and medical purposes. By harnessing the idiosyncratic chemical properties native to boron, researchers hope to effect paradigm shifts in fields ranging from energy storage to drug delivery. Its transformative potential highlights exploring the role of boron in developing catalysts for renewable energy production [8], [38], [39], [40], [41].

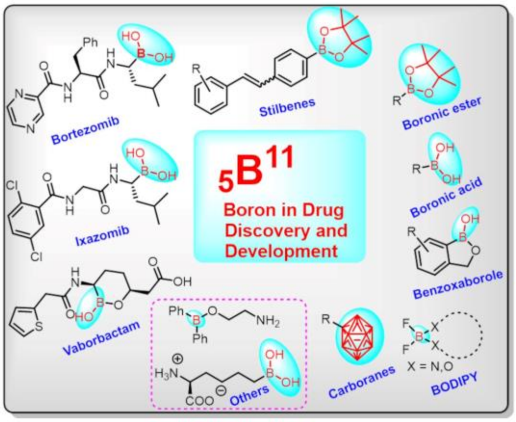

Fig 1. Boron in drug discovery and development [31] , reprinted with permission of MDPI.

3. The role of boron in nanomaterials

Boron Is an Element with High Functionality for the Modern World Boron is a binary element located between metals and nonmetals in the periodic table with a rich, multidimensional chemical structure that allows it to interact with both metals and nonmetals. Boron is used in many industrial and scientific fields due to these properties, and it is becoming an integral part of advanced technological applications such as nanotechnology. Nanomaterials are individual materials which can be manipulated at nanoscale level. The combination of boron with nanomaterials is a brand new chapter for materials science. "Because of its chemical properties, boron endows nanomaterials with outstanding characteristics, such as chemical stability, hardness, thermal stability, and uniqueness in electronic properties. In consequence, boron-doped nanomaterials are additionally incorporated efficiently in numerous jobs including electrical power storage units as well as bio-technological applications. This review aims to cover the mechanical, thermal, electrical and the chemical property enhancement that boron incorporation imparts to the nanomaterials. It is also highlighted the significance and potential of boron nanomaterials in biotechnology. Boron seems timely for advances in materials science and nanotechnology and this study aims to make this issue salient.

3.1. Mechanical properties and hardness

Boron offers extremely high hardness and durability, especially in compounds such as boron carbide (B_4C). Studies in the literature reveal that B_4C is effective in improving wear resistance and is often preferred in advanced industrial applications. Incorporating these compounds into nanomaterials not only improves mechanical strength, but also supports sustainability by leading to less material loss in manufacturing processes. Boron carbide-based nanocomposites offer a wide range of applications from cutting tools to ballistic armour [42], [43].

3.2. Thermal properties

It provides nanomaterials with high thermal stability and conductivity, so that these materials can be used for a variety of applications. The largest established application of boron is in the glass industry, and the properties of boron are highly beneficial in modern electronic devices and in extreme temperature applications where heat management is critical.

3.2.1. High thermal conductivity

Boron-based nanomaterials have very good thermal conductivity, which contributes to the design of high temperature resistant materials. Boron nitride (BN) is a remarkable example in this field. BN, which can be stable at high temperature, is widely used in heat dissipation of electronic devices. While various synthesis methods are reported in the literature to increase the thermal conductivity potential of BN, nanometre-sized configurations provide significant performance improvements. This makes BN an important paradigm for high power laser system and micro light device temperature control [44].

3.2.2. Role in electronic applications

Furthermore, the use of semiconductor compounds such as boron nitride optimises electronics outside the nanotechnology paradigm. Boron is important for piezoelectric applications as well as for conducted charge regulation. Furthermore, the simultaneous electrical conductivity and thermal stability of boron-based materials support the development of energy-saving electronic devices. For example, due to the reliable high temperature performance of boron, BN-based transistors and capacitors can be incorporated into next generation electronic systems [45].

3.3. Chemical resistance and corrosion resistance

Boron is an extremely chemically stable element and thanks to this character it greatly prevents corrosion when applied to nanomaterials. Compounds such as boron carbide (B_4C) and boron nitride (BN) are important for making durable materials with exceptional resistance to harsh environments. In the literature, they are shown to be resistant to oxidation and other chemical degradation. These properties make boron-doped nanomaterials suitable for application under extremely harsh conditions such as submarine structures, aircraft parts and nuclear reactor coatings. In addition, the low weight and chemical resistance of boron-based nanomaterials are expected to provide a significant advantage in the creation of energy efficient materials [41]. Boron nanomaterials with chemical stability can significantly improve corrosion resistance. Boron-containing compounds such as boron carbide and boron nitride are best known for their resistance to oxidation and extreme environmental conditions. These properties make it possible to design long-lasting materials [46].

3.4. Optical properties

Boron-based nanomaterials are important for both optical and optoelectronic applications. The unique light absorption properties of boron compounds enable their use in high performance devices such as lasers, photodetectors and optical waveguides. Materials such as boron nitride (BN) are becoming popular in low-loss optical communication systems due to their high purity in light transmission. In addition, it has been confirmed in the literature that boron is suitable for ultraviolet light emitting diodes (UV-LED) and photonic crystal structures. Thanks to the precise atomic level bonding of boron, the optical properties of the presented nanomaterials can be tuned, leading to a fundamental advance towards a new generation of optical devices. Recent studies show that the optical properties of boron are also used in energy storage applications. As mentioned, boron doped materials have been shown to improve the functioning of photovoltaic systems and provide superior performance in solar energy applications [46], [47].

3.5. Biotechnology applications

Boron is becoming more and more important in biotechnological applications and is driving innovations in this field. Including the integration of nanomaterials into biotechnology, especially with the use of boron-based nanostructures, it offers the potential for a wide range of applications from drug delivery systems to biosensors [48].

3.5.1. Drug delivery and targeted therapy

Boron nanostructures are used in drug delivery systems that are particularly effective in cancer treatment. Boron nitride nanotubes (BNNT) and boron nanoparticles help protect healthy cells by delivering drug molecules to targeted sites [49].

*3.5.2. Bi*osensors

AdvertisementImproving the sensitivity and functionality of biosensors with boron-based nanomaterials. Materials with particularly interesting chemistry and physical properties are boron carbide and boron nitride nanotubes. Because of their perfect interaction with biomolecules, they can be used for the specific and high-sensitivity detection of certain biomarkers. This makes them highly applicable in medical diagnostics, particularly for early disease detection. Researchers will be able to develop efficient and reliable tools for detecting changes in biomolecules and make significant contributions to the development of early diagnostic systems by utilizing boron-based nanomaterials in biosensor design [50].

3.5.3. Cancer treatment

Boron neutron capture therapy (BNCT) is based on the principle that boron binds specifically to cancer cells and kills them by neutron bombardment. This method is an important innovation in cancer treatment. The role of boron in nanomaterials has groundbreaking potential for improving mechanical, thermal, electrical and chemical properties. These properties increase the applicability of boron-doped nanomaterials, especially in various fields such as electronics, optoelectronics, energy storage and biotechnology. The integration of boron into nanotechnology plays a central role in future materials science designs, offering innovative solutions at both industrial and academic levels [51], [52].

4. Use of boron in solar energy, battery technologies and hydrogen production

Boron is a versatile element with great potential, especially in the fields of hydrogen energy and energy storage. With the developing nanotechnology, boron-based nanomaterials are making significant contributions to energy systems and remarkable progress is being made, especially in areas such as hydrogen production, storage and transportation. [53]. Due to these unique properties, boron-based nanomaterials have great prospect for energy-saving, environmental protection and renewable energy utilization. The target is boron and the applications are in solar energy, battery technologies and studies of hydrogen energy. Boron has particular relevance in agriculture science and applications [34] and renewable energy [54]. For example, boron is applied in solar panels, specifically in the boron doping the process of adding the elemental boron or boron-containing graphics to the target material to improve it of silicon photovoltaic (PV) cells to increase the amount of current flowing through these cells and improve the structural, mechanical, and electrical properties of solar cells for higher energy conversion. [55]. At the same time, boron glass extends the lifetime of solar panels and improves their environmental durability. However, boron compounds also play an important role in concentrated solar energy systems, improving the thermal efficiency of these systems. Boron-based materials can also be used as electrolyte stabilizers in lithium ion and sodium ion batteries. [56], [57]. These materials increase the energy density and lifetime of the battery, while providing better stability in charge and discharge cycles [57]. Solid cell formats also enable next-generation energy storage platforms, such as boron carbide composed of boron-containing materials [58]. Reportedly, boron ranks as one of the best additives when it comes to hydrogen production, storage and the subsequent transport of the fuel [59]. We can create sodium borate solid that can generate hydrogen gas efficiently and in a green way. Also, these compounds provide a variety of advantages in fuel cells [60]. Hydrogen systems are generally accepted to play a significant role to achieve zero emission targets especially in transportation and mobility sectors. On energy systems zero emission energy system with a land crisid carbon impact energy systems [61]. Boron applies to energy storage as well as green fuels technologies in every of those systems in addition to entire integration of renewable energy, since it's one of the few materials can be used in those schemes The role of boron can be employed in methods of energy storage systems in the continuous use of renewable energy resource [54]. In batteries, boron allows for improved energy storage from intermittent sources like wind and solar. It can also serve as a catalyst, which can promote hydrogen production from renewable resources of energy [62]. Hydrogen is also important for zero emission energy systems. “Boron is one of the building blocks of this economy as compounds that allow the clean and low-cost production of hydrogen.” In addition, this boron-based storage device is a lighter and safe storage method than conventional storage systems [59]. Produced with one of the most abundant elements on earth, the hydrogen economy significantly facilitates the decarbonisation of generating electricity and heat, which contributes to reducing carbon emissions in power generation and transport systems. In particular boron hydride nanomaterials (e.g., sodium borohydride, $LiBH_4$) is vital for safe and efficient hydrogen storage and transportation [63], [54]. And these materials can store hydrogen in a way that is more energy-dense and portable.

4.1. Boron nanotubes and hydrogen storage

Another boron-based nanomaterial that is of interest in hydrogen storage is the boron nanotubes. The novel structures of the nanotubes have the potential to improve effectively the hydrogen adsorption capacity. This will increase the surface area and, consequently, allow hydrogen to be stored more efficiently in its boron form. The mechanical strength of the boron nanotubes is outstanding, with high thermal conductivity, hence being extremely useful for energy systems [34].

4.2. Boron carbide nanotubes and solid cell energy storage systems

These boron carbide nanotubes offer B_4C's next generation energy storage solution in solid cell technologies. Solid electrolytes are known to enable good and safe energy storage compared to liquid ones. Boron carbide is thus basically able to solve the problems of storage and transport of hydrogen simultaneously [64].

4.3. Sustainable boron utilization and environment impacts

Although the potential of boron in energy technologies is enormous, it also has sustainable use and environmental impacts. This requires a careful analysis of the situation. If not done properly, the extraction and processing of boron minerals causes serious environmental impacts. Problems such as contamination of groundwater resources, soil contamination and habitat loss are among the potential environmental impacts of boron mining [65], [66], [67]. Therefore, it is important to adopt mining methods that comply with environmental standards. Furthermore, the use of innovative technologies in the mining process can reduce environmental impacts [68]. Recycling of boron-containing materials is emerging as part of sustainable energy technologies. The recovery of boron compounds provides great advantages both economically and environmentally [69]. At this point, effective waste management, long-term viability of boron-based technologies, waste management strategies, minimizing the harm of boron compounds are aimed [69], [70].

5. Natural occurring and reserves

5.1. *Abundance in earth crust*

Boron is classified as a comparatively scarce element, comprising roughly 0.001% of the Earth's crust. It does not occur in its elemental form but is found as borates or borosilicates. These compounds are mainly created through geological processes such as volcanic activity and evaporation. Trace amounts of boron are soluble in seawater. The role of elemental boron in sedimentary rocks and volcanic deposits has drawn attention to its geochemical significance relative to how elements are distributed across Earth. The importance of geological conditions required for the formation of boron further emphasizes on the rarity and commercial significance of boron as mineral resource. Continue researching the distribution mechanisms of boron in nature to explore new reserves and improve extraction methods. Expanding our understanding of boron occurrences in nature will be facilitated by advances in remote sensing, and geochemical analyses, which are expected to develop in the coming years. To facilitate this, boron-rich territories are being mapped in detail to assist in mining methods, optimizing the use of these limited resources [71], [72].

5.2. *Major boron deposits*

Major boron deposits are found in Turkey, the United States, Argentina, Russia and China. Of these, Turkey is estimated to hold around 72% of the world boron reserves, including colmanite and tincal. Taking proper advantage of these reserves is important in order to supply the growing world demand. Researchers are working toward green mining processes that allow for resource extraction without damaging the environment. Boron reserves are critical in determining the trade dynamics and economic strategies on the global stage. Nations holding substantial boron reserves hold a strategic position to export boron internationally, making their role indispensable in the global boron market. But as demand for boron grows, exploration of previously untapped reserves and recycling initiatives will help buttress natural deposits. A lot of work is being done to establish a fairer system for cooperation in the boron trade [56],[73], [5], [74].

6. Extraction and processing

6.1. *Mining techniques*

Boron is mined from borate minerals such as borax (sodium borate), colemanite and kernite. Depending on boron deposits' depth and concentration, the mining methods, which can be used, include open pit and underground mining. They used these techniques to produce boron-bearing minerals efficiently. Innovative Sensor-Based sorting and Automation technologies are being incorporated into mining processes to enhance efficiency and minimize environmental damage. Humans are learning to use artificial intelligence and machine learning in its daily operations. In addition, environmental consciousness is rising, with companies installing water recycling systems and land rehabilitation programs. There are efforts to incorporate renewable energy sources and to reduce the carbon emissions from boron extraction in mining [72], [38], [75], [60].

6.2. *Refinement processes*

A boron ore mineral with requirements for chemical processing and purification of boron that classify it as boron ore and serve as a precursor for boric acid or boron oxide. Several further processes including dissolution, crystallization and heat treatment are applied in order to obtain boron compounds with the desired high purity. For the sustainability of boron production, some efforts have been made to develop advanced chemical processing methods, like solvent extraction and membrane separation, to reduce energy input and waste output. This line field is because of the more significant industrial options for the extraction of boron auxiliary sources, which require additional interest in fewer environmental costs. This will, thus, greatly contribute to the economic feasibility and environmental sustainability of boron production when coupled with novel catalysts and energy-conserving separation processes. Research partnerships between academia and industry encourage innovation in plasmonic Technologies [4], [32], [76].

7. Applications of boron

7.1. Agricultural uses

Boron is considered an essential micronutrient for plants. Its function in cell wall formation, carbohydrate metabolism and nutrient transport is critical for plant growth and development. Soil boron deficiency adversely affects the yield and quality of various crops as a result boron is added as a fertilizer. Newer forms of boron fertilizers, such as slow-release and nano fertilizers, are being formulated to overcome these limitations as they offer higher bioavailability with enhanced nutrient use efficiency and lower environmental effects. In addition, studies on boron involvement in the augmentation of abiotic stress response and drought response in plants are being extensively studied. Precision Agriculture: Researchers are working on boron integrated systems to enable precision agriculture and minimize excess nutrient usage. Analysis of such data through IoT improves boron use and contributes to sustainable agricultural production. Smallholders are also now receiving better information about the agricultural advantages of boron using public-private partnerships for information dissemination and boron adoption on a global level. The Figure 2, below is an example of this information [3], [77], [78], [4], [8].

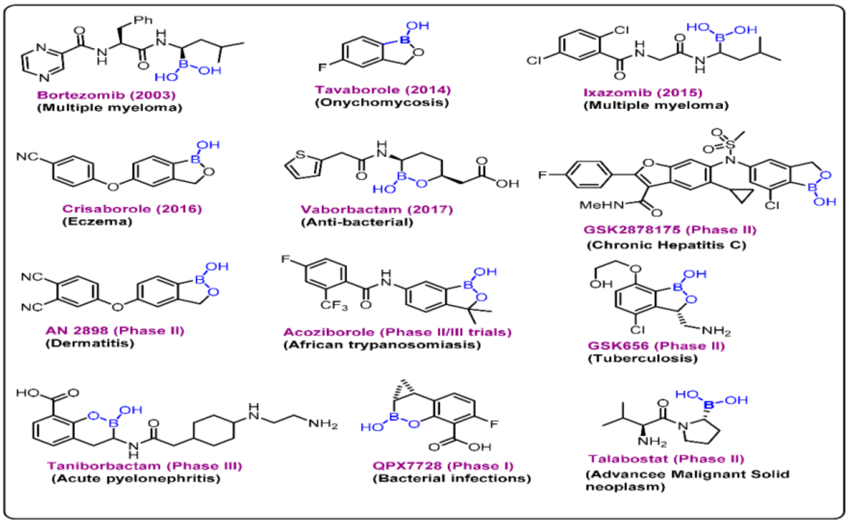

Fig 2. Chemistry of boron [79] reprinted with permission of MDPI.

7.2. *Industrial applications*

7.2.1. *Glass and ceramics*

Specialized boron compounds are ideal as a source of boron for borosilicate glass with high thermal resistance and successful durability. Boron serves a similar purpose in ceramic glazes where it contributes to appearance and performance enhancements. Borosilicate is voluminous in nature, being used in photovoltaic panels and laboratory utensils, assisting in renewable energy and scientific technologies, respectively. New borosilicate formulations are under development for high-performance optics and for space exploration applications [80], [81].

7.2.2. *Detergents and cleaning products*

Detergents contain borax and other boron compounds for their role as emulsifying and water softening agents. These characteristics are used for increasing cleaning success and product stability to enhance cleaning efficacy and product stability. To adhere to worldwide sustainability objectives, studies are being carried out to produce eco friendly detergents from boron that are not only biodegradable but also non-toxic. Researchers are exploring the potential of adding boron nanoparticles to cleaning products and substances to enhance their cleaning power against resilient stains and disease-causing organisms [82].

7.2.3. *Metallurgy*

Boron is used as an alloy to enhance steel and aluminum to increase hardness, wear resistance and corrosion resistance. These strengthened properties make boron-containing alloys popular with the automotive and construction sectors. Their strategic importance is evident in the fact that boron is being investigated for use in superalloys that go into aerospace and defense applications. These ongoing studies will help assess the long-term performance of boron-reinforced materials under harsh conditions, as well as their reliability for critical applications [83], [84].

7.3. *Technological applications*

7.3.1. *Electronics*

Semiconductors are materials essential to the functioning of electronic devices, and boron works as a dopant, which are substances that change the electronic properties of a material. For example, Boron-doped silicon is used in transistor and photovoltaic cell production which have helped with larger scale advances like electronics. The significance of boron in the progressive domains, inclusive of quantum computers, bendable electronics and subsequent degree sensor technologies is an energetic subject of examination. After finding that boron can be used to make these next-generation electronics more powerful and energy-efficient, collaborative research projects now look into specific applications of boron [36], [85], [86].

7.3.2. *Energy*

Research is being carried out on boron-based energy storage materials for next-generation batteries and hydrogen storage systems to address the energy needs of the world. Energy storage systems are based on these boron based compounds including boron hydrides and borophene which are believed to have better energy densities and efficiencies. Expected to accelerate the transition towards a sustainable energy future boron-based energy technology commercialisation [85], [87], [88], [89].

8. Challenges in the boron industry

8.1. *Environmental concerns*

Boron extractions and processing have included habitat destruction and water pollution. Sustainable practices, along with technological innovation, are necessary to mitigate these negative impacts. To that end, environmental regulations and cleaner production technologies have been developed to mitigate these problems. Collaboration with stakeholders throughout the boron value chain is recognised as vital to embedding the promotion of environmental sustainability in everything they do [72].

8.2. *Economic factors*

Various factors influence the boron market; these include but are not limited to: demand, which changes over time; trade policies; and the competition between the main producers. This also deemed as one of the factors that is vital of the growth of boron sector which is stable supply chain. To mitigate the impact, strategic partnerships and investments in R&D are being explored to promote market resilience system wide. To correct the disparities inherent in this resource, it is suggested that international frameworks be established for fair trade and equitable resource distribution [75].

9. Future perspectives and research

9.1. *Advanced materials*

Studies are being conducted on boron-based nanomaterials, such as boron nitride nanotubes and borophene. These materials possess extraordinary mechanical, thermal and electronic properties. Sought potential uses in aerospace, medicine and quantum computing. Production of boron nanomaterials on a scale is recognized to be one of the important research. Encouragement of international collaborations to sculpt the progress and deployment of the advanced boron-based materials [59], [54], [59].

9.2. *Sustainable agriculture*

Mitigating the adverse effect of boron on plant physiology requires the development and implementation of boron fertilisers that impart acceptable amounts of the element into biological systems whilst limiting its discharge into non-target environments. At the same time, precision agriculture is used to improve boron application efficiency. Other micronutrients are integrated with boron in smart delivery models for improved agricultural productivity too. The seed trials for the boron-rich fertilizers are being conducted in various agro-climatic regions in the country to validate its effectiveness [90], [58], [90], [91].

9.3. *Renewable energy*

However, compounds of boron have been of much interest due to their possible application in the field of renewable energy technologies such as fuel cells, polymer solar cells, and thermoelectric material. These developments are expected to significantly contribute to the aspiration of a sustainable energy future. Efficient waste heat recovery utilizing boron-based thermoelectric materials through the innovation of processes. Collaborative work between academia and industry is driving the use of boron in renewable energy solutions [63], [92], [54], [93].

9.4. *Boron in medicine*

Research on boron-based compounds explores their bioactivity, as well as their application in cancer treatment and drug delivery. Boron Neutron Capture Therapy (BNCT) may be an ideal targeting method for cancer treatment. Boron clusters are also potentially applicable in drug design and molecular imaging which is an emerging area of research. Clinical trials currently evaluate boron treatments' safety and efficacy, whereby they enter mainstream medicine [78], [40], [33], [94], [39].

10. Conclusion

The superior physical and chemical properties of the element boron have made it an indispensable material in strategic areas such as energy, electronics, healthcare and agriculture. Especially its innovative applications in nanotechnology carry the versatile structure of boron further. The high durability, thermal stability and electrical properties of boron nanotubes and boron nitride-based materials have positioned them as an important component in new generation technologies. In addition, boron-based neutron capture therapies (BNC Oct) for the treatment of cancer are breaking new ground in the field of medicine and demonstrate the biomedical potential of boron. The importance of boron in renewable energy and sustainable technologies is increasing gradually. The use of boron compounds in energy systems such as solar panels, lithium ion batteries and hydrogen production contributes to reducing environmental impacts while increasing energy efficiency. In particular, boron nanotubes and boron hydride compounds play a critical role in hydrogen storage and transportation, providing an important solution for achieving zero emission targets. However, it is necessary to adopt careful management strategies regarding the sustainable use of boron and its environmental impacts. Reducing the environmental impacts of boron mining and innovative approaches to the recycling of boron compounds support long-term sustainability in this field. In addition, its contributions to sustainable energy production and storage show that boron will play a critical role for a future independent of fossil fuels. Boron-based materials, especially in hydrogen storage and solar energy technologies, are revolutionizing the energy sector. In the future, the discovery of new application areas of boron and its integration with existing technologies indicate that it is a candidate to become the focal point of scientific research. With the development of innovative methods, it is expected that the full potential of boron in high-performance materials and green technologies will be revealed. In this context, investments and research made on boron element are of great importance both in terms of economic and environmental sustainability.

References

[1] Y. Zhu, J. Cai, N. S. Hosmane, and Y. Zhang, “Introduction: basic concept of boron and its physical and chemical properties,” in *Fundamentals and Applications of Boron Chemistry*, Elsevier, 2022, pp. 1–57. doi: 10.1016/B978-0-12-822127-3.00003-X.

[2] “Bor Dergisi » Makale » Thermal decomposition behaviors, kinetics and thermodynamics of colemanite.” Accessed: Dec. 21, 2024. [Online]. Available: https://dergipark.org.tr/tr/pub/boron/issue/87444/1452576

[3] J. Poater, M. Solà, C. Viñas, and F. Teixidor, “π Aromaticity and Three-Dimensional Aromaticity: Two sides of the Same Coin,” *Angew. Chemie - Int. Ed.*, vol. 53, no. 45, pp. 12191–12195, Nov. 2014, doi: 10.1002/ANIE.201407359.

[4] S. Kutuk, “Morphology, Crystal Structure and Thermal Properties of Nano-Sized Amorphous Colemanite Synthesis,” *Arab. J. Sci. Eng.*, vol. 49, no. 8, pp. 11699–11716, Aug. 2024, doi: 10.1007/S13369-024-08801-4.

[5] S. Sumitani and Y. Nagasaki, “Boron neutron capture therapy assisted by boron-conjugated nanoparticles,” *Polym. J.*, vol. 44, no. 6, pp. 522–530, Jun. 2012, doi: 10.1038/PJ.2012.30.

[6] A. G. Celik and G. O. Cakal, “Characterization of espey colemanite and variation of its physical properties with temperature,” *Physicochem. Probl. Miner. Process.*, vol. 52, no. 1, pp. 66–76, 2016, doi: 10.5277/PPMP160106.

[7] R. Tiwari, K. Mahasenan, R. Pavlovicz, C. Li, and W. Tjarks, “Carborane clusters in computational drug design: A comparative docking evaluation using AutoDock, FlexX, Glide, and Surflex,” *J. Chem. Inf. Model.*, vol. 49, no. 6, pp. 1581–1589, Jun. 2009, doi: 10.1021/CI900031Y.

[8] B. Kiraly *et al.*, “Borophene Synthesis on Au(111),” *ACS Nano*, vol. 13, no. 4, pp. 3816–3822, Apr. 2019, doi: 10.1021/ACSNANO.8B09339.

[9] F. A. Unal, S. Ok, M. Unal, S. Topal, K. Cellat, and F. Şen, “Synthesis, characterization, and application of transition metals (Ni, Zr, and Fe) doped TiO2 photoelectrodes for dye-sensitized solar cells,” *J. Mol. Liq.*, vol. 299, p. 112177, Feb. 2020, doi: 10.1016/j.molliq.2019.112177.

[10] P. Taslimi *et al.*, “Pyrazole[3,4-d]pyridazine derivatives: Molecular docking and explore of acetylcholinesterase and carbonic anhydrase enzymes inhibitors as anticholinergics potentials,” *Bioorg. Chem.*, vol. 92, Nov. 2019, doi: 10.1016/J.BIOORG.2019.103213.

[11] R. N. E. Tiri, F. Gulbagca, A. Aygun, A. Cherif, and F. Sen, “Biosynthesis of Ag–Pt bimetallic nanoparticles using propolis extract: Antibacterial effects and catalytic activity on NaBH4 hydrolysis,” *Environ. Res.*, vol. 206, p. 112622, Apr. 2022, doi: 10.1016/j.envres.2021.112622.

[12] R. Ayranci, G. Başkaya, M. Güzel, S. Bozkurt, F. Şen, and M. Ak, “Carbon Based Nanomaterials for High Performance Optoelectrochemical Systems,” *ChemistrySelect*, vol. 2, no. 4, pp. 1548–1555, Feb. 2017, doi:

10.1002/slct.201601632.

[13] R. Ayranci *et al.*, “Enhanced optical and electrical properties of PEDOT via nanostructured carbon materials: A comparative investigation,” *Nano-Structures & Nano-Objects*, vol. 11, pp. 13–19, Jul. 2017, doi: 10.1016/j.nanoso.2017.05.008.

[14] F. Sen, A. A. Boghossian, S. Sen, Z. W. Ulissi, J. Zhang, and M. S. Strano, “Observation of oscillatory surface reactions of riboflavin, trolox, and singlet oxygen using single carbon nanotube fluorescence spectroscopy,” *ACS Nano*, vol. 6, no. 12, pp. 10632–10645, Dec. 2012, doi: 10.1021/nn303716n.

[15] N. Lolak, E. Kuyuldar, H. Burhan, H. Goksu, S. Akocak, and F. Sen, “Composites of Palladium-Nickel Alloy Nanoparticles and Graphene Oxide for the Knoevenagel Condensation of Aldehydes with Malononitrile,” *ACS Omega*, vol. 4, no. 4, pp. 6848–6853, Apr. 2019, doi: 10.1021/acsomega.9b00485.

[16] B. Sen, B. Demirkan, A. Şavk, S. Karahan Gülbay, and F. Sen, “Trimetallic PdRuNi nanocomposites decorated on graphene oxide: A superior catalyst for the hydrogen evolution reaction,” *Int. J. Hydrogen Energy*, vol. 43, no. 38, pp. 17984–17992, Sep. 2018, doi: 10.1016/j.ijhydene.2018.07.122.

[17] F. Şen, G. Gökağaç, and S. Şen, “High performance Pt nanoparticles prepared by new surfactants for C 1 to C3 alcohol oxidation reactions,” *J. Nanoparticle Res.*, vol. 15, no. 10, Oct. 2013, doi: 10.1007/S11051-013-1979-5.

[18] F. Gulbagca, A. Aygün, M. Gülcan, S. Ozdemir, S. Gonca, and F. Şen, “Green synthesis of palladium nanoparticles: Preparation, characterization, and investigation of antioxidant, antimicrobial, anticancer, and DNA cleavage activities,” *Appl. Organomet. Chem.*, vol. 35, no. 8, Aug. 2021, doi: 10.1002/aoc.6272.

[19] F. Şen and G. Gökağaç, “Pt nanoparticles synthesized with new surfactants: Improvement in C 1-C3 alcohol oxidation catalytic activity,” *J. Appl. Electrochem.*, vol. 44, no. 1, pp. 199–207, Jan. 2014, doi: 10.1007/S10800-013-0631-5.

[20] F. Şen and G. Gökağaç, “Improving catalytic efficiency in the methanol oxidation reaction by inserting Ru in face-centered cubic Pt nanoparticles prepared by a new surfactant, tert-octanethiol,” *Energy and Fuels*, vol. 22, no. 3, pp. 1858–1864, May 2008, doi: 10.1021/EF700575T.

[21] S. Ertan, F. Şen, S. Şen, and G. Gökağaç, “Platinum nanocatalysts prepared with different surfactants for C1-C3 alcohol oxidations and their surface morphologies by AFM,” *J. Nanoparticle Res.*, vol. 14, no. 6, Jun. 2012, doi: 10.1007/s11051-012-0922-5.

[22] B. Demirkan *et al.*, “Composites of Bimetallic Platinum-Cobalt Alloy Nanoparticles and Reduced Graphene Oxide for Electrochemical Determination of Ascorbic Acid, Dopamine, and Uric Acid,” *Sci. Rep.*, vol. 9, no. 1, p. 12258, Aug. 2019, doi: 10.1038/s41598-019-48802-0.

[23] B. Demirkan *et al.*, “Palladium supported on polypyrrole/reduced graphene oxide nanoparticles for simultaneous biosensing application of ascorbic acid, dopamine, and uric acid,” *Sci. Rep.*, vol. 10, no. 1, Dec. 2020, doi: 10.1038/S41598-020-59935-Y.

[24] B. Şen, A. Aygün, T. O. Okyay, A. Şavk, R. Kartop, and F. Şen, “Monodisperse palladium nanoparticles assembled on graphene oxide with the high catalytic activity and reusability in the dehydrogenation of dimethylamine-borane,” *Int. J. Hydrogen Energy*, vol. 43, no. 44, pp. 20176–20182, Nov. 2018, doi: 10.1016/J.IJHYDENE.2018.03.175.

[25] B. Şen, A. Aygün, A. Şavk, S. Akocak, and F. Şen, “Bimetallic Palladium–İridium Alloy Nanoparticles as Highly Efficient and Stable Catalyst for The Hydrogen Evolution Reaction,” *Int. J. Hydrogen Energy*, vol. 43, no. 44, pp. 20183–20191, Nov. 2018, doi: 10.1016/j.ijhydene.2018.07.081.

[26] N. Korkmaz *et al.*, “Biogenic silver nanoparticles synthesized via Mimusops elengi fruit extract, a study on antibiofilm, antibacterial, and anticancer activities,” *J. Drug Deliv. Sci. Technol.*, vol. 59, Oct. 2020, doi: 10.1016/J.JDDST.2020.101864.

[27] Z. Ozturk, F. Sen, S. Sen, and G. Gokagac, “The preparation and characterization of nano-sized Pt-Pd/C catalysts and comparison of their superior catalytic activities for methanol and ethanol oxidation,” *J. Mater. Sci.*, vol. 47, no. 23, pp. 8134–8144, 2012, doi: 10.1007/s10853-012-6709-3.

[28] E. Erken, Y. Yildiz, B. Kilbaş, and F. Şen, “Synthesis and characterization of nearly monodisperse Pt

nanoparticles for C1 to C3 alcohol oxidation and dehydrogenation of dimethylamine-borane (DMAB)," *J. Nanosci. Nanotechnol.*, vol. 16, no. 6, pp. 5944–5950, Jun. 2016, doi: 10.1166/JNN.2016.11683.

[29] M. B. Askari, P. Salarizadeh, A. Di Bartolomeo, and F. Şen, "Enhanced electrochemical performance of MnNi2O4/rGO nanocomposite as pseudocapacitor electrode material and methanol electro-oxidation catalyst," *Nanotechnology*, vol. 32, no. 32, Aug. 2021, doi: 10.1088/1361-6528/ABFDED.

[30] D. Kuru, "Amorf borun elektrokimyasal eksfoliasyonuyla bor nanotabakalarının sentezi ve karakterizasyonu," *Bor Derg.*, vol. 9, no. 3, pp. 111–119, Sep. 2024, doi: 10.30728/BORON.1483030.

[31] "Bor Dergisi » Makale » Amorf borun elektrokimyasal eksfoliasyonuyla bor nanotabakalarının sentezi ve karakterizasyonu." Accessed: Dec. 21, 2024. [Online]. Available: https://dergipark.org.tr/tr/pub/boron/issue/87444/1483030

[32] P. Lotti *et al.*, "Thermal stability and high-temperature behavior of the natural borate colemanite: An aggregate in radiation-shielding concretes," *Constr. Build. Mater.*, vol. 203, pp. 679–686, Apr. 2019, doi: 10.1016/J.CONBUILDMAT.2019.01.123.

[33] I. B. Sivaev, V. I. Bregadze, and N. T. Kuznetsov, "Derivatives of the closo-dodecaborate anion and their application in medicine," *Russ. Chem. Bull.*, vol. 51, no. 8, pp. 1362–1374, 2002, doi: 10.1023/A:1020942418765.

[34] M. Zhao, C. Casiraghi, and K. Parvez, "Electrochemical exfoliation of 2D materials beyond graphene," *Chem. Soc. Rev.*, vol. 53, no. 6, pp. 3036–3064, Feb. 2024, doi: 10.1039/D3CS00815K.

[35] R. Lo, J. Fanfrlík, M. Lepšík, and P. Hobza, "The properties of substituted 3D-aromatic neutral carboranes: The potential for σ-hole bonding," *Phys. Chem. Chem. Phys.*, vol. 17, no. 32, pp. 20814–20821, Aug. 2015, doi: 10.1039/C5CP03617H.

[36] X. He, S. Joo, H. Xiao, and H. Liang, "Boron-Based Nanoparticles for Chemical-Mechanical Polishing of Copper Films," *ECS J. Solid State Sci. Technol.*, vol. 2, no. 1, pp. P20–P25, 2013, doi: 10.1149/2.021301JSS.

[37] B. C. Das *et al.*, "Boron chemicals in diagnosis and therapeutics," *Future Med. Chem.*, vol. 5, no. 6, pp. 653–676, Apr. 2013, doi: 10.4155/FMC.13.38.

[38] W. D. Loomis and R. W. Durst, "Chemistry and biology of boron.," *Biofactors*, vol. 3, no. 4, pp. 229–239, Apr. 1992, Accessed: Dec. 21, 2024. [Online]. Available: https://europepmc.org/article/med/1605832

[39] E. Hey-Hawkins, "Boron-based compounds : potential and emerging applications in medicine," p. 470, 2018, Accessed: Dec. 21, 2024. [Online]. Available: https://books.google.com/books/about/Boron_Based_Compounds.html?hl=tr&id=235aDwAAQBAJ

[40] I. B. Sivaev and V. V. Bregadze, "Polyhedral boranes for medical applications: Current status and perspectives," *Eur. J. Inorg. Chem.*, no. 11, pp. 1433–1450, 2009, doi: 10.1002/EJIC.200900003.

[41] Z. Q. Wang, T. Y. Lü, H. Q. Wang, Y. P. Feng, and J. C. Zheng, "Review of borophene and its potential applications," *Front. Phys.*, vol. 14, no. 3, Jun. 2019, doi: 10.1007/S11467-019-0884-5.

[42] M. Antadze *et al.*, "Metal-ceramics based on nanostructured boron carbide," *Solid State Sci.*, vol. 14, no. 11–12, pp. 1725–1728, Nov. 2012, doi: 10.1016/j.solidstatesciences.2012.08.004.

[43] Z. V. Eremeeva, S. Kamali, A. I. Lizunov, and V. A. Ovchinnikov, "Production of Nanostructured Boron Carbide Ceramics for Industrial Applications," *Key Eng. Mater.*, vol. 910, pp. 1075–1080, Feb. 2022, doi: 10.4028/p-dd4bb5.

[44] T. Lo Wong, C. Vallés, A. Nasser, and C. Abeykoon, "Effects of boron-nitride-based nanomaterials on the thermal properties of composite organic phase change materials: A state-of-the-art review," *Renew. Sustain. Energy Rev.*, vol. 187, p. 113730, Nov. 2023, doi: 10.1016/j.rser.2023.113730.

[45] J. H. Kim, T. V. Pham, J. H. Hwang, C. S. Kim, and M. J. Kim, "Boron nitride nanotubes: synthesis and applications," *Nano Converg.*, vol. 5, no. 1, p. 17, Dec. 2018, doi: 10.1186/s40580-018-0149-y.

[46] R. Y. Tay *et al.*, "Advanced nano boron nitride architectures: Synthesis, properties and emerging applications," *Nano Today*, vol. 53, p. 102011, Dec. 2023, doi: 10.1016/j.nantod.2023.102011.

[47] T. Xu *et al.*, "Advances in synthesis and applications of boron nitride nanotubes: A review," *Chem. Eng. J.*, vol. 431, p. 134118, Mar. 2022, doi: 10.1016/j.cej.2021.134118.

[48] F. Ali, N. S Hosmane, and Y. Zhu, “Boron Chemistry for Medical Applications,” *Molecules*, vol. 25, no. 4, p. 828, Feb. 2020, doi: 10.3390/molecules25040828.
[49] X. Li *et al.*, “Multimodal luminescent-magnetic boron nitride nanotubes@NaGdF 4 :Eu structures for cancer therapy,” *Chem. Commun.*, vol. 50, no. 33, pp. 4371–4374, 2014, doi: 10.1039/C4CC00990H.
[50] H. Zhu *et al.*, “Ni-doped boron nitride nanotubes as promising gas sensing material for dissolved gases in transformer oil,” *Mater. Today Commun.*, vol. 33, p. 104845, Dec. 2022, doi: 10.1016/j.mtcomm.2022.104845.
[51] E. Cebeci, B. Yüksel, and F. Şahin, “Anti-cancer effect of boron derivatives on small-cell lung cancer,” *J. Trace Elem. Med. Biol.*, vol. 70, p. 126923, Mar. 2022, doi: 10.1016/j.jtemb.2022.126923.
[52] E. E. Mohammed, N. Türkel, U. M. Yigit, A. B. Dalan, and F. Sahin, “Boron Derivatives Inhibit the Proliferation of Breast Cancer Cells and Affect Tumor-Specific T Cell Activity In Vitro by Distinct Mechanisms,” *Biol. Trace Elem. Res.*, vol. 201, no. 12, pp. 5692–5707, Dec. 2023, doi: 10.1007/s12011-023-03632-0.
[53] Z. Huang, S. Wang, R. D. Dewhurst, N. V. Ignat’ev, M. Finze, and H. Braunschweig, “Boron: Its Role in Energy-Related Processes and Applications,” *Angew. Chemie Int. Ed.*, vol. 59, no. 23, pp. 8800–8816, Jun. 2020, doi: 10.1002/anie.201911108.
[54] P. Ranjan, J. M. Lee, P. Kumar, and A. Vinu, “Borophene: New Sensation in Flatland,” *Adv. Mater.*, vol. 32, no. 34, Aug. 2020, doi: 10.1002/ADMA.202000531.
[55] J. Ma *et al.*, “Improvement of solar cells performance by boron doped amorphous silicon carbide/nanocrystalline silicon hybrid window layers,” *Sol. Energy Mater. Sol. Cells*, vol. 114, pp. 9–14, Jul. 2013, doi: 10.1016/j.solmat.2013.02.013.
[56] Y. Zhu, S. Gao, and N. S. Hosmane, “Boron-enriched advanced energy materials,” *Inorganica Chim. Acta*, vol. 471, pp. 577–586, Feb. 2018, doi: 10.1016/j.ica.2017.11.037.
[57] C. (Allen) Zheng, “Examining the Benefits of Using Boron Compounds in Lithium Batteries: A Comprehensive Review of Literature,” *Batteries*, vol. 8, no. 10, p. 187, Oct. 2022, doi: 10.3390/batteries8100187.
[58] A. Budak and M. Gönen, “Extraction of boric acid from colemanite mineral by supercritical carbon dioxide,” *J. Supercrit. Fluids*, vol. 92, pp. 183–189, 2014, doi: 10.1016/J.SUPFLU.2014.05.016.
[59] P. Rohani, S. Kim, and M. T. Swihart, “Boron Nanoparticles for Room-Temperature Hydrogen Generation from Water,” *Adv. Energy Mater.*, vol. 6, no. 12, Jun. 2016, doi: 10.1002/AENM.201502550.
[60] P. Argust, “Distribution of Boron in the environment,” *Biol. Trace Elem. Res.*, vol. 66, no. 1–3, pp. 131–143, 1998, doi: 10.1007/BF02783133.
[61] Y. Zhu, S. Gao, and N. S. Hosmane, “Boron-enriched advanced energy materials,” *Inorganica Chim. Acta*, vol. 471, pp. 577–586, Feb. 2018, doi: 10.1016/J.ICA.2017.11.037.
[62] E. Serrano, G. Rus, and J. García-Martínez, “Nanotechnology for sustainable energy,” *Renew. Sustain. Energy Rev.*, vol. 13, no. 9, pp. 2373–2384, Dec. 2009, doi: 10.1016/J.RSER.2009.06.003.
[63] S. H. Farjana, N. Huda, M. A. P. Mahmud, and C. Lang, “Comparative life-cycle assessment of uranium extraction processes,” *J. Clean. Prod.*, vol. 202, pp. 666–683, Nov. 2018, doi: 10.1016/J.JCLEPRO.2018.08.105.
[64] C. Guo and C. Wang, “Strategies for enhancing hydrogen storage capacity of carbon-based sandwich material by boron doping: Exploring the optimal doping ratio,” *J. Energy Storage*, vol. 97, p. 112915, Sep. 2024, doi: 10.1016/j.est.2024.112915.
[65] S. Bolan *et al.*, “Boron contamination and its risk management in terrestrial and aquatic environmental settings,” *Sci. Total Environ.*, vol. 894, p. 164744, Oct. 2023, doi: 10.1016/j.scitotenv.2023.164744.
[66] F. ARLI, “The Critical Significance of Boron Mine in Future Energy Technologies,” *J. Soft Comput. Artif. Intell.*, vol. 3, no. 2, pp. 83–92, Dec. 2022, doi: 10.55195/jscai.1216892.
[67] A. Mott *et al.*, “Boron in geothermal energy: Sources, environmental impacts, and management in geothermal fluid,” *Renew. Sustain. Energy Rev.*, vol. 167, p. 112825, Oct. 2022, doi: 10.1016/j.rser.2022.112825.
[68] M. Onifade *et al.*, “Advancing toward sustainability: The emergence of green mining technologies and practices,” *Green Smart Min. Eng.*, vol. 1, no. 2, pp. 157–174, Jun. 2024, doi: 10.1016/j.gsme.2024.05.005.
[69] E. H. Ezechi, M. H. Isa, S. R. Kutty, and N. B. Sapari, “Boron recovery, application and economic

significance: A review," in *2011 National Postgraduate Conference*, IEEE, Sep. 2011, pp. 1–6. doi: 10.1109/NatPC.2011.6136374.

[70] Ç. Sevim and M. Kara, "Boron and Boron-Containing Compounds Toxicity," in *The Toxicity of Environmental Pollutants*, IntechOpen, 2022. doi: 10.5772/intechopen.103179.

[71] E. J. Reardon, "Dissociation constants for alkali earth and sodium borate ion pairs from 10 to 50°C," *Chem. Geol.*, vol. 18, no. 4, pp. 309–325, 1976, doi: 10.1016/0009-2541(76)90013-9.

[72] P. D. Howe, "A review of boron effects in the environment.," *Biol. Trace Elem. Res.*, vol. 66, no. 1–3, pp. 153–166, Jan. 1998, doi: 10.1007/BF02783135.

[73] K. R. Pulagam *et al.*, "Gold nanoparticles as boron carriers for boron neutron capture therapy: Synthesis, radiolabelling and in vivo evaluation," *Molecules*, vol. 24, no. 19, Oct. 2019, doi: 10.3390/MOLECULES24193609.

[74] L. Li *et al.*, "On-Demand Biodegradable Boron Nitride Nanoparticles for Treating Triple Negative Breast Cancer with Boron Neutron Capture Therapy," *ACS Nano*, vol. 13, no. 12, pp. 13843–13852, Dec. 2019, doi: 10.1021/ACSNANO.9B04303.

[75] A. Azapagic, "Life cycle assessment and its application to process selection, design and optimisation," *Chem. Eng. J.*, vol. 73, no. 1, pp. 1–21, 1999, doi: 10.1016/S1385-8947(99)00042-X.

[76] T. Türkbay, B. Laratte, A. Çolak, S. Çoruh, and B. Elevli, "Life Cycle Assessment of Boron Industry from Mining to Refined Products," *Sustain.*, vol. 14, no. 3, p. 1787, Feb. 2022, doi: 10.3390/SU14031787/S1.

[77] M. Calvaresi and F. Zerbetto, "In silico carborane docking to proteins and potential drug targets," *J. Chem. Inf. Model.*, vol. 51, no. 8, pp. 1882–1896, Aug. 2011, doi: 10.1021/CI200216Z.

[78] R. Núñez, M. Tarrés, A. Ferrer-Ugalde, F. F. De Biani, and F. Teixidor, "Electrochemistry and Photoluminescence of Icosahedral Carboranes, Boranes, Metallacarboranes, and Their Derivatives," *Chem. Rev.*, vol. 116, no. 23, pp. 14307–14378, Dec. 2016, doi: 10.1021/ACS.CHEMREV.6B00198.

[79] B. C. Das *et al.*, "Boron Chemicals in Drug Discovery and Development: Synthesis and Medicinal Perspective," *Molecules*, vol. 27, no. 9, p. 2615, Apr. 2022, doi: 10.3390/molecules27092615.

[80] I. Waclawska, "Thermal behaviour of mechanically amorphized colemanite: II. Internal structure reconstitution processes of ground colemanite," *J. Therm. Anal.*, vol. 48, no. 1, pp. 155–161, 1997, doi: 10.1007/BF01978975.

[81] Ö. Yildiz, "The effect of heat treatment on colemanite processing: A ceramics application," *Powder Technol.*, vol. 142, no. 1, pp. 7–12, Apr. 2004, doi: 10.1016/J.POWTEC.2004.03.006.

[82] T. Schaffran, J. Li, G. Karlsson, K. Edwards, M. Winterhalter, and D. Gabel, "Interaction of N,N,N-trialkylammonioundecahydro-closo-dodecaborates with dipalmitoyl phosphatidylcholine liposomes," *Chem. Phys. Lipids*, vol. 163, no. 1, pp. 64–73, Jan. 2010, doi: 10.1016/J.CHEMPHYSLIP.2009.09.004.

[83] S. Biyik, F. Arslan, and M. Aydin, "Arc-Erosion Behavior of Boric Oxide-Reinforced Silver-Based Electrical Contact Materials Produced by Mechanical Alloying," *J. Electron. Mater.*, vol. 44, no. 1, pp. 457–466, Jan. 2015, doi: 10.1007/S11664-014-3399-4.

[84] M. Kizilca and M. Copur, "Thermal dehydration of colemanite: kinetics and mechanism determined using the master plots method," *Can. Metall. Q.*, vol. 56, no. 3, pp. 259–271, Jul. 2017, doi: 10.1080/00084433.2017.1349023.

[85] J. T. Abrahamson *et al.*, "Excess thermopower and the theory of thermopower waves," *ACS Nano*, vol. 7, no. 8, pp. 6533–6544, Aug. 2013, doi: 10.1021/NN402411K.

[86] W. Kaim, N. S. Hosmane, S. Záliš, J. A. Maguire, and W. N. Lipscomb, "Boron atoms as spin carriers in two- and three-dimensional systems," *Angew. Chemie - Int. Ed.*, vol. 48, no. 28, pp. 5082–5091, Jun. 2009, doi: 10.1002/ANIE.200803493.

[87] M. J. Starink, "A new method for the derivation of activation energies from experiments performed at constant heating rate," *Thermochim. Acta*, vol. 288, no. 1–2, pp. 97–104, 1996, doi: 10.1016/S0040-6031(96)03053-5.

[88] S. Günbatar, A. Aygun, Y. Karataş, M. Gülcan, and F. Şen, "Carbon-nanotube-based rhodium

nanoparticles as highly-active catalyst for hydrolytic dehydrogenation of dimethylamineborane at room temperature," *J. Colloid Interface Sci.*, vol. 530, pp. 321–327, Nov. 2018, doi: 10.1016/J.JCIS.2018.06.100.

[89] M. A. Chowdhury, M. M. K. Uddin, M. B. A. Shuvho, M. Rana, and N. Hossain, "A novel temperature dependent method for borophene synthesis," *Appl. Surf. Sci. Adv.*, vol. 11, Oct. 2022, doi: 10.1016/J.APSADV.2022.100308.

[90] J. Wu, B. Li, and J. Lu, "Life cycle assessment on boron production: is boric acid extraction from salt-lake brine environmentally friendly?," *Clean Technol. Environ. Policy*, vol. 23, no. 7, pp. 1981–1991, Sep. 2021, doi: 10.1007/S10098-021-02092-1.

[91] A. Sivakami, R. Sarankumar, and S. Vinodha, "Introduction to nanobiotechnology: Novel and smart applications," *Bio-manufactured Nanomater. Perspect. Promot.*, pp. 1–22, Jun. 2021, doi: 10.1007/978-3-030-67223-2_1.

[92] S. H. Farjana, N. Huda, M. A. Parvez Mahmud, and R. Saidur, "A review on the impact of mining and mineral processing industries through life cycle assessment," *J. Clean. Prod.*, vol. 231, pp. 1200–1217, Sep. 2019, doi: 10.1016/J.JCLEPRO.2019.05.264.

[93] S. H. Farjana, N. Huda, M. A. P. Mahmud, and C. Lang, "A global life cycle assessment of manganese mining processes based on EcoInvent database," *Sci. Total Environ.*, vol. 688, pp. 1102–1111, Oct. 2019, doi: 10.1016/J.SCITOTENV.2019.06.184.

[94] M. F. Hawthorne, "New horizons for therapy based on the boron neutron capture reaction," *Mol. Med. Today*, vol. 4, no. 4, pp. 174–181, Apr. 1998, doi: 10.1016/S1357-4310(98)01226-X.