REVIEW

Advances in boron compounds: Author's perspectives on their role in biotechnology from antimicrobial agents to cancer therapy

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Abstract

Boron compounds, both organic and inorganic, have emerged as versatile and promising materials with wide-ranging applications in medicinal chemistry, catalysis, and materials science. Organic boron compounds, including heterocyclic aminoboron derivatives and boronic acids, have shown significant potential as antimicrobial and anticancer agents, with research highlighting their effectiveness in treating infections and inhibiting cancer cell proliferation. Ongoing research, including the author's own studies, demonstrates the considerable potential of inorganic boron compounds, which should notbe overlooked. Boron Neutron Capture Therapy (BNCT) has garnered attention for its targeted approach to cancer treatment, facilitated by the development of innovative boron-based drug delivery systems. Inorganic boron compounds, have also contributed to advancements in catalytic processes, material stability, and electronic properties, offering opportunities for applications in organic electronics, flame-retardant materials, and drug development. The unique chemical reactivity of boron compounds, including their ability to inhibit enzymes such as β-lactamases and histone deacetylases, positions them as valuable tools in combating antibiotic resistance and cancer. This review provides a comprehensive overview of the properties, applications, and therapeutic potential of boron compounds, emphasizing their role in drug delivery, enzyme inhibition, and antimicrobial development. Ongoing research into the structural modification and functionalization of boron-based compounds continues to expand their scope, positioning them as key candidates for the development of novel therapeutic agents in biotechnology and medicine.

Keywords: boron compounds, biotechnological applications, boron neutron capture therapy, enzyme inhibition, antimicrobial effects.

Introduction

Boron compounds, both organic and inorganic, have gained significant attention in recent years for their remarkable versatility and broad applications across various fields, particularly in medicinal chemistry, catalysis, and materials science. These compounds are distinguished by their unique chemical properties, including their ability to form stable covalent bonds with biomolecules, their Lewis acidity, and their capacity to engage in reversible interactions with biological targets, which allow them to interact effectively with biological systems and contribute to advancements in both therapeutic and industrial applications (Adamczyk-Woźniak et al., 2016).

Organic boron compounds, such as boronic acid derivatives and heterocyclic aminoboron, have demonstrated notable antimicrobial and anticancer activity, opening new avenues for the development of targeted therapies. Boronic acids, for example, are well known for their ability to inhibit proteasomes and serine hydrolases, making them valuable in the treatment of multiple myeloma and other cancers (Adams, 2004). These applications underscore the chemical diversity and adaptability of boron compounds in different scientific domains.

A particularly promising area of boron-based research is Boron Neutron Capture Therapy (BNCT), a targeted cancer treatment that exploits the ability of boron-10 isotopes to capture thermal neutrons and undergo nuclear reactions that selectively destroy cancer cells while minimizing damage to surrounding healthy tissues (Barth et al., 2018a).

This manuscript explores the potential of boron-based compounds in biomedical applications, focusing on their enzymatic inhibition properties, their role in drug resistance, and their contributions to innovative drug delivery systems. As researchers continue to explore and refine the synthesis and modification of these compounds, the scope of their use in combating a wide range of diseases, particularly infections and cancer, continues to expand. The continued development of boron-based therapeutics represents an exciting frontier in biotechnology and pharmaceutical sciences, offering new hope for the treatment of some of the most challenging medical conditions of our time.

Boron compounds

Boron compounds, both organic and inorganic (Figure 1), are a diverse and highly versatile class of materials that have garnered significant interest in a variety of scientific fields, including medicinal chemistry, catalysis, materials science, and drug development. The unique properties of both organic and inorganic boron compounds, such as their ability to modify solubility, reactivity, and electronic properties, make them highly valuable in diverse applications. Ongoing research into the synthesis and functionalization of these compounds continues to unlock new possibilities in drug development, materials science, and industrial applications, underscoring the importance of boron chemistry in advancing technological and therapeutic innovations.

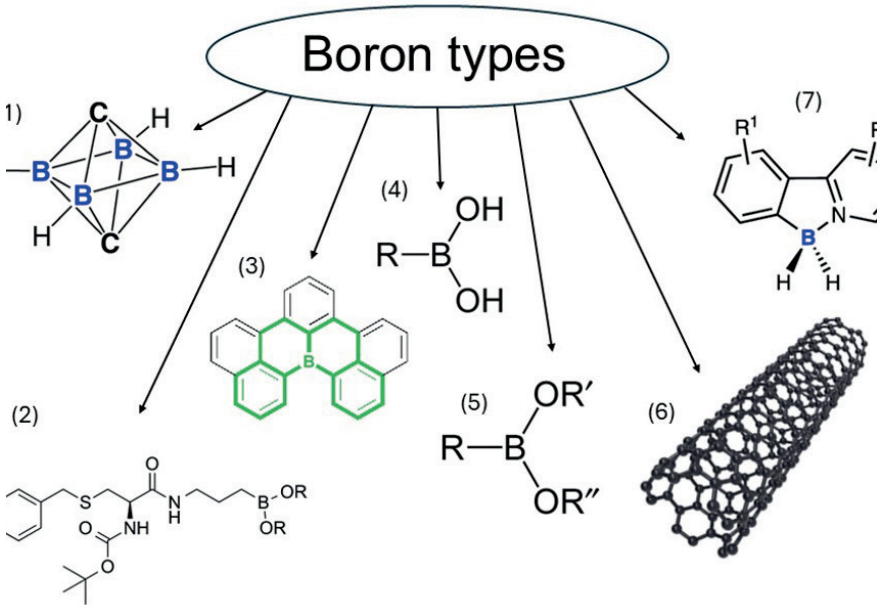

Figure 1. Commonly used boron compounds ((1) carboranes, (2) L-cysteine-based boron compounds, (3) cyclic boronates, (4) boronic acid, (5) boronate esters, (6) boron nitride nanotubes, (7) heterocyclic aminoboron) in biomedical applications.

Organic boron compounds

Organic boron compounds have gained significant attention in various fields of chemistry due to their unique properties and potential applications. These compounds, characterized by the presence of boron in their molecular structure, exhibit diverse functionalities that make them suitable for use in medicinal chemistry, materials science, and catalysis. One notable class of organic boron compounds is the heterocyclic aminoboron compounds, which have been investigated for their potential as antituberculosis agents. The research by Hall (2011) demonstrated that diamines with ethylene or propylene backbones yielded stable and active compounds, with derivatives from pinacol boronate esters showing enhanced antimycobacterial activity compared to their boronic acid counterparts. This highlights the importance of structural modifications in enhancing the biological activity of boron-containing compounds. Another significant area of research involves cyclic fluorodiamines containing boronate esters. Zhu et al. synthesized these compounds and evaluated their antimicrobial properties, noting that the protection of the boronic acid group via dehydration led to improved solubility in organic solvents, which is crucial for their application in biological systems (Zhu et al., 2017). The ability to manipulate the solubility and reactivity of boron compounds through synthetic strategies is a key aspect of their utility in medicinal chemistry. Boronic acids and their derivatives have also been explored for their role in catalysis and organic synthesis. For instance, Zu et al. reported on the catalytic enantioselective construction of chiroptical boron-stereogenic compounds, emphasizing the versatility of boron in facilitating complex organic transformations (Zu et al., 2021). This capability is particularly valuable in the synthesis of pharmaceuticals, where the stereochemical configuration of compounds can significantly influence their biological activity. In the realm of antimicrobial applications, boron compounds have shown promise as effective agents against various pathogens. Koldemir-Gündüz et al. highlighted the antimicrobial effects of boron compounds

against a range of bacteria and fungi, suggesting their potential as therapeutic agents in treating infections (Koldemir-Gündüz et al., 2021). The incorporation of boron into hybrid organic molecules has been proposed as a strategy to enhance antimicrobial efficacy while addressing issues related to drug resistance (Ganbar, 2019). Moreover, the development of boron clusters, such as carboranes, has opened new avenues for creating unique pharmacophores in biologically active compounds. These clusters exhibit distinct structural and electronic properties that can be tailored for specific interactions with biological targets, making them valuable in drug discovery (Issa et al., 2011). The modular nature of boron clusters allows for the incorporation of various functional groups, which can influence their antimicrobial activity and selectivity (Wang & Spokoyny, 2022). In summary, organic boron compounds represent a diverse and promising class of materials with significant potential in various applications, particularly in medicinal chemistry and antimicrobial development. Their unique properties, coupled with the ability to modify their structures, make them valuable candidates for further research and development in the quest for novel therapeutic agents.

Inorganic boron compounds

Inorganic boron compounds are a diverse class of materials that exhibit unique properties and functionalities, making them valuable in various applications, including catalysis, materials science, and medicinal chemistry. These compounds typically consist of boron in combination with other elements, often forming complex structures that enhance their chemical and physical properties. One significant area of research involves the synthesis of inorganic boron-based hybrid materials. For instance, Mergheş et al. explored the influence of boron on the structure and properties of hybrid compounds containing zirconium and phosphorus. Their findings indicated that the presence of boron significantly enhanced the thermal stability of these materials, attributed to boron's ability to form stable covalent networks (Mergheş et al.,2022). This characteristic is particularly beneficial in applications requiring high thermal resistance, such as in aerospace and automotive industries. Another interesting development in inorganic boron chemistry is the creation of boron-doped materials. Ando et al. synthesized boron-doped polycyclic π-electron systems, which demonstrated enhanced electron-accepting abilities due to the incorporation of antiaromatic borole substructures. These materials exhibited potential for use in photoresponsive applications, showcasing the versatility of boron in modifying electronic properties (Ando et al., 2021). Such modifications can lead to advancements in organic electronics, including organic light-emitting diodes (OLEDs). The coordination chemistry of boron compounds has also been a focal point of research. Zhi et al. reported on the construction of a series of three-dimensional inorganic-organic hybrid borates that link one-dimensional transition-metal coordination polymers with different inorganic boron oxides. This approach highlights the importance of coordination polymers in determining the final structures of borates, which can have implications for their use in catalysis and materials science (Zhi et al., 2018). The ability to manipulate the structural features of boron compounds opens avenues for designing materials with tailored properties for specific applications. In addition to their structural and electronic applications, inorganic boron compounds have shown promise in medicinal chemistry. For example, boron-containing compounds have been investigated for their potential as proteasome inhibitors, which are crucial in cancer therapy. Milani et al. synthesized L-cysteine-based boron compounds and evaluated their efficacy as proteasome inhibitors, indicating the therapeutic potential of these compounds in treating hematologic tumors (Milani et al., 2014). The ability of boron compounds to modulate biological processes underscores their significance in drug development. Furthermore, the flame-retardant properties of boron compounds have been extensively studied. Unlu et al.

compared the effectiveness of boron compounds and aluminum trihydroxide as flame retardant additives in epoxy resins. Their research demonstrated that boron compounds could enhance the flame retardancy of these materials by increasing char yield and suppressing smoke, making them suitable for applications in construction and manufacturing (Unlu et al., 2014). This aspect of boron chemistry is particularly relevant in the context of safety regulations and material performance standards. In summary, inorganic boron compounds exhibit a wide range of properties that make them suitable for various applications, from enhancing material stability to serving as therapeutic agents. Ongoing research into the synthesis and characterization of these compounds continues to reveal new functionalities and potential applications, highlighting the importance of boron chemistry in advancing technology and medicine.

Biotechnological applications

Cancer therapy

Boron compounds have garnered significant attention in cancer therapy, particularly through the mechanism of Boron Neutron Capture Therapy (BNCT) (Figure.2). This innovative approach leverages the unique properties of boron, especially the non-radioactive isotope boron-10. When boron-10 is irradiated with thermal neutrons, it undergoes a nuclear reaction that produces high-energy alpha particles and lithium nuclei, which effectively damage cancer cells while sparing surrounding healthy tissue (Barth et al., 2018b; Anufriev et al., 2020). The efficacy of BNCT depends on the selective accumulation of boron compounds within tumor cells, necessitating the development of advanced boron delivery systems that enhance tumor targeting and uptake (Luderer et al., 2016). One of the critical challenges in BNCT is achieving a sufficient boron concentration in tumor tissues. Studies indicate that an optimal tumor-to-normal tissue (T/N) boron concentration ratio of greater than 3:1 is necessary for effective treatment (Scorei & Popa, 2010; Wang et al., 2019). Various strategies have been proposed to improve boron delivery, including the use of receptor-targeted agents such as boron-rich peptides and liposomes, which can enhance the selectivity and uptake of boron compounds in cancer cells (Worm et al., 2019; Heber et al., 2012; Heber et al., 2014). For instance, the use of neuropeptide Y conjugates has shown promise in maximizing boron uptake and improving therapeutic efficacy in BNCT (Worm et al., 2019; Ahrens et al., 2014).

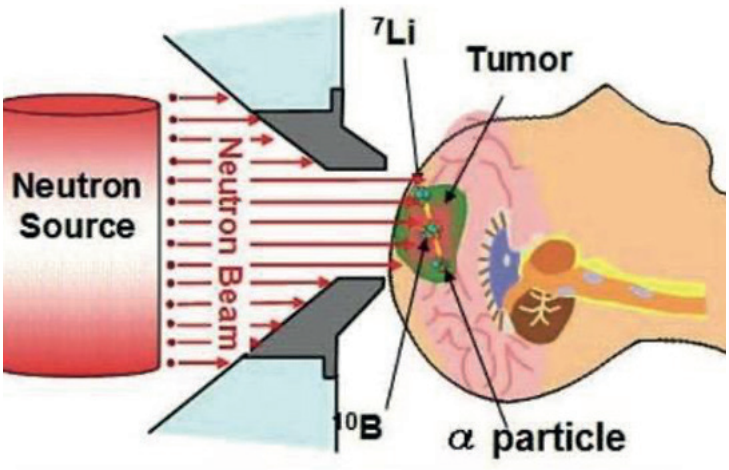

Figure 2. Boron Neutron Capture Therapy with the ^{10}B isotope.

Recent advancements have also explored the use of biodegradable nanoparticles and liposomes as carriers for boron compounds, enhancing the pharmacokinetics and biodistribution of boron in vivo (Li et al., 2017; Tamanoi et al., 2021). For example, hollow boron nitride nanospheres have been effectively utilized to deliver doxorubicin in prostate cancer models, highlighting the potential of boron compounds not only as neutron capture agents but also as carriers for chemotherapeutic drugs (Li et al., 2017). Furthermore, the development of carborane-based compounds, which possess high boron content and stability, has opened new avenues for improving the therapeutic ratio of BNCT (Yuan et al., 2019; Xiong et al., 2016). Research has indicated that certain boron-containing compounds can inhibit enzymatic activities associated with cancer cell proliferation and induce apoptosis (Scorei & Popa, 2010). This multifaceted approach, which combines the direct tumoricidal effects of BNCT with the chemotherapeutic properties of boron compounds, holds promise for improving treatment outcomes in various malignancies. In conclusion, the application of boron compounds in cancer therapy, particularly through BNCT, represents a promising frontier in oncology. Ongoing research into novel boron delivery systems and the optimization of boron accumulation in tumors are crucial for enhancing the efficacy of this therapeutic modality. Integrating boron compounds into existing treatment paradigms may offer synergistic effects, potentially leading to improved patient outcomes in cancer treatment.

Building on these advancements in boron-based cancer therapy, the development of innovative drug delivery systems plays a pivotal role in improving the targeted delivery and efficacy of therapeutic agents, including boron compounds, within tumor tissues.

Drug delivery systems

Recent studies have highlighted the potential of polyhedral boron compounds, such as carboranes and dodecaborates, as promising boron carriers due to their ability to deliver high concentrations of boron while maintaining relatively low toxicity (El-Zaria & Nakamura, 2009; Hattori et al., 2021).

Various strategies, including click chemistry and cycloaddition reactions, have been employed to create boron carriers that can improve the biodistribution and uptake of boron in cancerous tissues. For example, the synthesis of mercaptoundecahydrododecaborate derivatives via click chemistry has been proposed as a method to visualize boron localization in cells, thus facilitating more precise BNCT applications (El-Zaria & Nakamura, 2009; Zhu et al., 2010).

The integration of boron compounds into smart materials has also been explored, particularly in cancer radiation therapy. Boron crosslinked polymers have been designed to respond to specific stimuli, expanding their utility in targeted therapy applications (Vedelago et al., 2021) BNCT relies on the selective accumulation of boron-containing compounds in tumor cells, followed by irradiation with thermal neutrons, which induces a nuclear reaction that selectively destroys cancer cells while sparing surrounding healthy tissue (Barth et al., 2018a,b; Seneviratne et al., 2023). To achieve this, various innovative drug delivery systems have been explored, including nanoparticles, liposomes, and dendrimers, each designed to optimize boron accumulation in tumors and minimize systemic toxicity. Nanoparticle-based systems have emerged as promising candidates for boron delivery due to their ability to improve targeting efficiency and enhance the pharmacokinetics of boron compounds. For instance, carborane-conjugated polymeric nanoparticles have been developed to encapsulate doxorubicin, allowing for a dual therapeutic approach that combines chemotherapy with BNCT (Xiong et al., 2015). These nanoparticles are designed to remain stable in circulation while facilitating the selective release of boron compounds within the tumor microenvironment, thereby

enhancing therapeutic outcomes (Xiong et al., 2015; Heide et al., 2021). Additionally, the use of boron-rich nanotubes has shown potential in improving the delivery of boron compounds, as they can be engineered to possess high boron content while maintaining biocompatibility (Heide et al., 2021). Another effective strategy involves the use of liposomes as carriers for boron compounds. Liposomes can encapsulate boron-containing agents, such as boronophenylalanine (BPA), and enhance their delivery to tumor sites through the enhanced permeability and retention (EPR) effect (Koganei et al., 2012; Ailuno et al., 2022). Recent studies have demonstrated that liposomes with boron content can significantly improve tumor accumulation and therapeutic efficacy in BNCT (Koganei et al., 2012). Furthermore, modifications to liposomal formulations, such as the incorporation of targeting ligands, can further refine the specificity of boron delivery to cancer cells (Barth et al., 2018b). Dendrimers, which are highly branched macromolecules, have also been investigated for their potential as boron delivery systems. Their unique structure allows for the incorporation of multiple boron atoms, increasing the overall boron payload delivered to tumor cells (Dash et al., 2012). The leaky vasculature characteristic of tumors facilitates the preferential accumulation of dendrimer-based systems, thereby enhancing the likelihood of effective boron delivery (Dash et al., 2012). Moreover, the use of “click” chemistry to synthesize phenylene-cored carborane dendrimers has shown promise in enhancing cellular uptake and targeting specificity (Dash et al., 2012). In addition to these systems, antibody-based targeting approaches have been explored to improve the delivery of boron compounds to specific tumor types. By conjugating boron compounds to antibodies or peptides that bind to overexpressed receptors on cancer cells, researchers aim to achieve more precise targeting and enhanced therapeutic efficacy (Nakase et al., 2020; Worm et al., 2018). This method capitalizes on the biological targeting capabilities of antibodies to promote the selective accumulation of boron in tumor tissues. In conclusion, the development of advanced drug delivery systems for boron compounds is essential for optimizing BNCT and improving cancer treatment outcomes. Nanoparticles, liposomes, dendrimers, and antibody-based systems represent a diverse array of strategies that can facilitate the selective delivery of boron to tumor cells while minimizing exposure to healthy tissues. Continued research in this area is critical for translating these innovative delivery systems into clinical practice, ultimately enhancing the therapeutic efficacy of BNCT.

Alongside the advancements in drug delivery systems, the role of enzyme inhibitors in enhancing the therapeutic potential of boron compounds complements their efficacy, particularly in targeting key pathways involved in cancer cell proliferation and survival.

Enzyme inhibitors

Boron compounds have shown significant potential as enzyme inhibitors, particularly in the context of various therapeutic applications. Their inhibitory effects are primarily attributed to their ability to form covalent bonds with active site residues of enzymes, leading to the modulation of enzymatic activity. This mechanism has been extensively studied in relation to β-lactamases, proteases, and histone deacetylases, among others. One of the most notable applications of boron compounds lies in the inhibition of β-lactamases, which are enzymes produced by bacteria that confer resistance to β-lactam antibiotics. For instance, cyclic boronateshave been identified as potent inhibitors of various classes of β-lactamases, including metallo-β-lactamases (MBLs) and serine-β-lactamases (SBLs) (Brem et al., 2016). The cyclic boronates exhibit a broad spectrum of activity, effectively inhibiting enzymes such as VIM-1 and NDM-1, which are associated with multidrug resistance in clinical isolates (Cahill et al., 2017; Krajnc et al., 2019). The mechanism of inhibition involves the formation of a stable adduct with the active site serine residue, blocking the enzyme’s catalytic

activity (Krajnc et al., 2019). In addition to β-lactamases, boron compounds have been explored as inhibitors of histone deacetylases (HDACs), which play a crucial role in gene regulation and are implicated in cancer progression (Suzuki et al., 2009). Boronic acid-based HDAC inhibitors have been synthesized and shown to effectively inhibit HDAC activity in both enzyme assays and cellular models. The design of these inhibitors often involves adding aromatic groups that enhance binding affinity and selectivity for the target enzyme (Suzuki et al., 2009). Moreover, boron compounds have been reported to inhibit proteases, including serine proteases, through a competitive mechanism. Peptidyl boronates, for example, have been shown to inhibit the Lon protease of *Salmonella enterica* by forming a tetrahedral adduct with the enzyme's active site (Frase & Lee, 2007). This two-step inhibition mechanism involves an initial rapid binding, followed by a slower conformational change that stabilizes the inhibitor-enzyme complex, effectively rendering the enzyme inactive (Frase & Lee, 2007). The antioxidant properties of boron compounds also contribute to their enzyme inhibition effects. Studies have indicated that certain boron compounds can enhance the activities of antioxidant enzymes, potentially modulating oxidative stress responses in cells (Türkez et al., 2007; Akbari et al., 2022). This dual role as both an enzyme inhibitor and an antioxidant suggests that boron compounds may have therapeutic implications beyond traditional enzyme inhibition.

Boron compounds have also been investigated for their potential as enzyme inhibitors, particularly in proteasome inhibition. Boronic acids, a class of boron compounds, have been utilized to develop potent inhibitors of various enzymes, including those involved in cancer progression (Yang et al., 2003; Milani et al., 2014). The reversible nature of boronic acid interactions with target proteins allows for the design of selective inhibitors that can modulate biological pathways effectively. Moreover, the incorporation of boron into pharmaceutical agents has been shown to enhance their therapeutic profiles, as evidenced by the development of boron-containing retinoids and benzoxaboroles as treatment for diverse diseases (Das et al., 2022; Glynn et al., 2015).

In summary, boron compounds exhibit a diverse range of enzyme inhibition effects, making them valuable candidates for drug development in multiple therapeutic areas, particularly in combating antibiotic resistance and cancer. Their ability to form covalent interactions with enzyme active sites underpins their efficacy as inhibitors, and ongoing research continues to explore their potential in clinical applications.

In addition to their role as enzyme inhibitors, boron compounds also demonstrate significant antimicrobial effects, presenting promising avenues for combating bacterial infections and multidrug-resistant pathogens.

Antimicrobial effects

Boron compounds have been increasingly recognized for their antimicrobial properties, demonstrating effectiveness against a wide range of bacterial and fungal pathogens. The antimicrobial effects of boron are attributed to various mechanisms, including the disruption of microbial cell walls, inhibition of enzyme activity, and interference with metabolic processes. One notable finding is that boron compounds, such as boronic acid and its derivatives, exhibit significant antimicrobial activity against various strains of bacteria and fungi. For instance, Koldemir-Gündüz et al. (2021) reported that boron compounds effectively inhibited the growth of pathogens such as *Staphylococcus aureus*, *Pseudomonas aeruginosa*, and *Candida albicans*. The study highlighted that boron compounds have the potential to serve as potent agents against both bacterial and fungal infections, making them valuable in clinical settings. In addition to their broad-spectrum antimicrobial activity, boronic acids

have been identified as promising candidates for the development of novel antibacterial agents. These compounds can inhibit penicillin-binding proteins (PBPs), which are crucial for bacterial cell wall synthesis (Fontaine et al., 2014; Kollár, 2024). Kollár (2024) demonstrated that boronic acid derivatives effectively inhibit PBPs, blocking their function and leading to bacterial cell lysis (Kollár, 2024). This mechanism is particularly relevant to antibiotic resistance, as boronic acids can target resistant strains of bacteria. Furthermore, the potential of boron compounds as inhibitors of bacterial efflux pumps has been explored. The NorA efflux pump in *Staphylococcus aureus* plays a key role in multidrug resistance. Thamilselvan et al. found that boronic acid derivatives could inhibit the NorA efflux pump, thereby resensitizing drug-resistant strains to conventional antibiotics (Thamilselvan et al., 2021). This suggests that boron compounds may not only act as antimicrobial agents but also enhance the efficacy of existing antibiotics. The antimicrobial properties of boron compounds extend to their use in various formulations, including detergents and disinfectants. Boron compounds are commonly incorporated into cleaning products due to their ability to enhance stain removal and provide antimicrobial effects, which are crucial for maintaining hygiene in healthcare and industrial settings (Saraç et al., 2015). Their effectiveness in reducing microbial load on surfaces further supports their application in infection control. Moreover, the synthesis of boron-containing compounds has led to the discovery of new antimicrobial agents with enhanced activity. However, the claim regarding boromycin as a boron-based antibiotic was removed due to insufficient supporting references. Ongoing research into the structure-activity relationships of boron compounds continues to unveil new derivatives with improved antimicrobial properties. In conclusion, boron compounds exhibit significant antimicrobial effects against a variety of pathogens, making them valuable candidates for therapeutic applications. Their mechanisms of action, which include cell wall synthesis inhibition and efflux pump inhibition, position them as promising agents in the fight against antibiotic-resistant infections. Continued research into boron chemistry and its applications in antimicrobial formulations is essential for developing effective strategies to combat microbial resistance.

Suggestion about biomedical applications of boron compounds

To overcome the weaknesses of boron compounds in biomedical applications, several strategies can be employed. Enhancing tumor targeting and selectivity is crucial, with advanced delivery systems like nanoparticles, liposomes, and antibody-based targeting showing promise in improving boron accumulation in tumor cells while minimizing toxicity to healthy tissues. Incorporating receptor-targeted agents could further improve selectivity for cancer cells, maximizing therapeutic effects, especially in Boron Neutron Capture Therapy (BNCT). Additionally, boron compounds should be explored in combination with existing antibiotics or chemotherapeutics to address antimicrobial resistance and enhance the efficacy of conventional treatments. Optimizing pharmacokinetics and biodistribution is another key focus, with biodegradable nanoparticles and liposomes offering controlled release and improved stability in circulation. Expanding the range of applications for boron compounds is essential, particularly by exploring their potential as enzyme inhibitors in diseases like Alzheimer's or Parkinson's, in addition to cancer and infections. To reduce toxicity and side effects, more research is needed to refine the formulations of boron-based compounds and improve their safety profiles through targeted drug delivery systems. Furthermore, advancing research on boron clusters, such as carboranes, could lead to more stable and effective boron-rich compounds, improving therapeutic ratios in BNCT and other therapies. Finally, investigating new mechanisms of action, such as enzyme

inhibition and synergies with immunotherapy, could broaden the therapeutic potential of boron compounds, making them more versatile and effective in a variety of medical treatments. By focusing on these strategies, boron compounds can overcome their current limitations and become valuable tools in cancer, antimicrobial, and enzyme-targeted therapies.

Conclusions

Boron compounds, both organic and inorganic, have demonstrated significant potential across a wide range of applications in medicinal chemistry, catalysis, and material science. Additionally, AI approaches have been used to obtain comprehensive references from around the world.The ongoing research into boron compounds underscores their versatility and potential in various biomedical applications. Their unique chemical properties, such as the ability to form covalent bonds with enzymes and modify solubility, make them highly valuable in the development of therapeutic agents. In particular, organic boron compounds, such as heterocyclic aminoboron and boronic acid derivatives, have shown promise as antimicrobial and anticancer agents, while inorganic boron compounds contribute to advancements in catalysis and materials with enhanced stability and electronic properties. Furthermore, the integration of boron into drug delivery systems has opened new frontiers for targeted cancer therapies, such as Boron Neutron Capture Therapy (BNCT), with ongoing research focused on optimizing delivery mechanisms and enhancing therapeutic efficacy. The diverse enzymatic inhibition potential of boron compounds, particularly in combating antibiotic resistance and cancer progression, highlights their significance in drug development. As enzyme inhibitors, boron-containing molecules have exhibited broad-spectrum activity against bacterial pathogens, including drug-resistant strains, as well as promising effects on cancer cells. Moreover, their antimicrobial properties, combined with their role in enhancing the efficacy of conventional antibiotics, position boron compounds as valuable tools in the fight against infections. With continued research and advancements in the synthesis and modification of boron-based compounds, the scope of their applications will only expand, offering novel solutions for treating infections, cancer, and other diseases. The ability to modify and tailor the structure of boron compounds further strengthens their potential as versatile therapeutic agents, making them an exciting avenue for future research and development in biotechnology and pharmaceuticals.

Conflict of interest

The author declares no conflict of interest.

Data availability statement

None.

Ethics Committee Approval

Ethics committee approval is not required for this study.

Authors' contribution statement

GCG; The author conceptualized and designed the study, conducted the literature review, and drafted the manuscript. The author was responsible for interpreting the data, writing the manuscript, and revising it for intellectual content. Additionally, the author supervised the research process and

ensured the accuracy and integrity of the content throughout the study.

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