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Biological Evaluation and Industrial Applications of Group 13 Element Complexes with Nitrogen and Sulfur Donor Ligands: A Comprehensive Review

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Abstract
This comprehensive review delves into the synthesis, structural characterization, biological evaluation, and industrial applications of Group 13 element complexes with nitrogen and sulfur donor ligands. The study synthesizes insights from 20 selected research papers to highlight significant advancements in the stability, reactivity, and functional properties of these complexes. Key findings demonstrate the remarkable antimicrobial, anticancer, and enzyme inhibitory activities of these complexes, alongside their practical applications in catalysis and agriculture. The review underscores the importance of ligand design in developing metal complexes with tailored properties and identifies promising directions for future research, including optimizing synthetic methods, exploring new ligand frameworks, and conducting detailed mechanistic studies to enhance their applicability in various fields.
Keywords: *Group 13 Elements, Nitrogen Donor Ligands, Sulfur Donor Ligands, and Metal Complexes*

I. Introduction

Group 13 elements, also known as the boron group, include boron (B), aluminum (Al), gallium (Ga), indium (In), and thallium (Tl). These elements are characterized by having three electrons in their outermost shell, which contributes to their unique chemical properties. Boron, the lightest member of the group, is a metalloid with distinct non-metallic characteristics, whereas the heavier members, aluminum through thallium, exhibit metallic properties. The chemistry of Group 13 elements is rich and varied, encompassing a wide range of oxidation states, predominantly +3, but also including +1 for thallium and occasionally for other heavier elements. The diverse chemistry of these elements makes them of significant interest in various scientific and industrial applications.

Boron, in particular, is essential in the formation of borates and boranes, which are crucial in material science and organic synthesis. Aluminum is well-known for its applications in materials due to its lightweight and corrosion-resistant properties, making it invaluable in the aerospace, transportation, and packaging industries. Gallium, indium, and thallium have specialized uses in electronics and photonics. For instance, gallium arsenide (GaAs) is a critical component in semiconductor technology, while indium tin oxide (ITO) is used in transparent conductive coatings for touchscreens and solar cells. Thallium, although less commonly used due to its toxicity, finds applications in specialized areas such as high-density materials and certain electronic devices.

Overview of Nitrogen and Sulfur Donor Ligands

Nitrogen and sulfur donor ligands are pivotal in the coordination chemistry of Group 13 elements. These ligands can donate electrons from their lone pairs to the metal center, forming stable complexes with various metals. Nitrogen donor ligands, such as amines, imines, and nitriles, are widely used due to their ability to form strong coordinate bonds with metal centers. Sulfur donor ligands, including thiols, thioethers, and thiocarbamates, are also significant because they can provide additional stability and unique reactivity to metal complexes due to the soft donor nature of sulfur.

The combination of nitrogen and sulfur donor ligands in a single complex can lead to enhanced stability and reactivity, making these ligands particularly useful in the synthesis of novel metal complexes. Mixed nitrogen-sulfur donor ligands are of great interest as they can form chelate rings, which enhance the stability of the complexes and can introduce unique electronic properties. These ligands are particularly useful in catalysis, where the stability and electronic properties of the catalyst can significantly influence its activity and selectivity.

Significance of Group 13 Element Complexes

The complexes of Group 13 elements with nitrogen and sulfur donor ligands have garnered considerable attention due to their wide range of applications. These complexes are not only interesting from a theoretical perspective, providing insights into metal-ligand interactions and coordination chemistry, but also have practical applications in various fields. For instance, the catalytic properties of these complexes are of particular interest in organic synthesis, where they can facilitate a variety of chemical transformations. The ability to tailor the electronic properties of these complexes through the choice of ligands makes them versatile catalysts for different reactions.

Additionally, the biological activity of these complexes is an area of growing interest. Complexes of Group 13 elements with nitrogen and sulfur donor ligands have shown promising results in antimicrobial, anticancer, and enzyme inhibitory activities. This makes them potential candidates for the development of new therapeutic agents. The structural flexibility and tunable properties of these complexes allow for the design of compounds with specific biological targets, enhancing their effectiveness and selectivity.

Objectives and Scope of the Review

The primary objective of this review is to systematically synthesize and structurally characterize complexes of Group 13 elements (boron, aluminum, gallium, indium, and thallium) with nitrogen and sulfur donor ligands, employing various synthetic and characterization techniques. The review aims to evaluate the thermal and hydrolytic stability of these complexes and their biological activities, including antimicrobial, anticancer, and enzyme inhibitory properties. Additionally, the review will explore the practical applications of these complexes in agriculture and industry, focusing on their roles as catalysts and in enhancing crop yield and pest control. The scope includes a thorough analysis of Schiff's bases, semicarbazones, and thiosemicarbazones as ligands, highlighting their synthesis, properties, and biological activities to identify key factors influencing their effectiveness and potential future research directions.

II. Methodology

This study is based on secondary data, collected from a diverse range of sources including books, international journals, research papers, and online databases. The selection process involved identifying and reviewing 20 research papers that focus on the synthesis, characterization, and applications of Group 13 element complexes with nitrogen and sulfur donor ligands. These sources provide comprehensive insights into the thermal and hydrolytic stability, biological activities, and industrial applications of these complexes. The collected data were meticulously analyzed to compile a thorough review that highlights significant advancements and identifies key factors influencing the effectiveness of these complexes, thereby guiding future research directions in this field.

An analysis and Review of research papers

Author(s) and Year	**Title**	**Importance or Significance of the Study**	**Objectives of the Study**	**Materials and Methods Used**	**Findings and Conclusion**	**Research Gap**	**Direction for Further Research**
Venkatachalam, T.K., Stimson, D.H.R., Bhalla, R., Mardon, K., Bernhardt, P.V., & Reutens, D.C. (2019)	Synthesis of 18F-radiolabeled diphenyl gallium dithiosemicarbazone using a novel halogen exchange method and in vivo biodistribution	Highlights the novel synthesis method for radiolabeling gallium complexes, which can potentially be used for in vivo imaging.	To develop a facile method for the synthesis of 18F-radiolabeled diphenyl gallium dithiosemicarbazone and study its biodistribution in mice.	Used [18F] fluoride exchange of a nitrato anion under mild conditions. Biodistribution studied in mice using PET. Chemicals from Sigma Aldrich were used without further purification. Anhydrous methanol and DMSO were stored under	Developed a novel method for synthesizing 18F-radiolabeled diphenyl gallium dithiosemicarbazone. The tracer showed potential for in vivo imaging.	Limited information on long-term stability and detailed pharmacokinetics in larger biological models.	Further studies on long-term stability, detailed pharmacokinetics, and potential therapeutic applications in larger biological models. Exploration of other Group 13 elements with similar synthesis methods.

				nitrogen. Sodium methoxide was kept and transferred under nitrogen atmosphere.			

Jinxu Qi, Taichen Liu, Wei Zhao, Xinhua Zheng, Yihong Wang (2020)	Synthesis, crystal structure and antiproliferative mechanisms of gallium(III) complexes with benzoylpyridine thiosemicarbazones	This study highlights the potential of Ga(III) complexes as anti-tumor drugs with higher efficacy compared to platinum-based drugs.	1. Synthesize six thiosemicarbazone ligands and their corresponding Ga(III) complexes. 2. Study the structure and activity relationships of these compounds. 3. Investigate the mechanism behind gallium complexes promoted apoptosis. 4. Examine expression of cell cycle-associated proteins related to apoptosis.	Synthesis of six thiosemicarbazone ligands and their Ga(III) complexes. Characterization by X-ray single crystal diffraction. Biological assays to assess antiproliferative mechanisms.	Ga(III) complex (C6) showed the highest anticancer activity against HepG-2 cells. It promotes cell cycle arrest in G1 phase, induces apoptosis by enhancing ROS, activating caspase-3/9, and increasing cytochrome and apaf-1 expression.	The precise mechanism of how Ga(III) complexes enhance bioavailability and activity in vivo remains unclear.	Further research should explore in vivo studies to validate the efficacy and safety of Ga(III) complexes, and investigate the detailed molecular mechanisms of their anticancer activities.

Jawad, Q. A., Zinad, D. S., Salim, R. D., Al-Amiery, A. A., Gaaz, T. S., Takri, M. S., Kadhum, A. A. H.	Synthesis, Characterization, and Corrosion Inhibition Potential of Novel Thiosemicarbazone on Mild Steel in Sulfuric Acid Environment	Study addresses corrosion inhibition in industrial settings, particularly in sulfuric acid	Synthesize and characterize novel thiosemicarbazone, evaluate its corrosion inhibition properties	NMR, FT-IR spectroscopy, CHN analyses, electrochemical impedance spectroscopy (EIS), weight loss method, scanning electron microscopy (SEM)	Thiosemicarbazone showed high inhibition efficiency against mild steel corrosion in 1N H2SO4. Mechanism verified through various analytical methods.	Temperature impact on inhibition efficiency needs further exploration.	Investigate long-term stability and practical application of thiosemicarbazone in diverse acidic environments.

Altıntop et al., 2016	Synthesis and evaluation of new benzodioxole-based thiosemicarbazone...	Investigates new thiosemicarbazone derivatives for potential anticancer properties due to their specificity and reduced toxicity.	Synthesize new derivatives, evaluate cytotoxic effects on cancer and normal cells, assess inhibitory effects on cholinesterases, explore mechanisms of action.	Synthesis of benzodioxole-based thiosemicarbazone derivatives, cell culture studies (A549, C6, NIH/3T3), enzymatic assays (AChE, BuChE), apoptosis and mitochondrial studies, docking on SIRT1.	Identified compound 5 as promising anticancer agent with apoptotic effects and mitochondrial disturbance. No correlation found between anticancer activity and cholinesterase inhibition.	Lack of understanding on mechanistic links between specific compound structures and biological activities. Need for more comprehensive studies on structure-activity relationships and specific molecular	Further investigate structure-activity relationships, explore additional biological pathways and targets, conduct in vivo studies for therapeutic efficacy and toxicity profiles.

						targets.	
Ahmed, M.F., & Almalki, A.H. (2021).	Design, synthesis, antiproliferative activity, and cell cycle analysis of new thiosemicarbazone...	Thiosemicarbazones as potential anticancer agents; development of new chemotherapeutic drugs.	Design and synthesize new thiosemicarbazone derivatives targeting ribonucleotide reductase; evaluate their antiproliferative activity and cell cycle effects.	In vitro screening in 60 cancer cell lines; enzyme inhibitory assays against ribonucleotide reductase; flow cytometric analysis for cell cycle and apoptosis; gene expression analysis (p53, BAX, caspase-3, Bcl-2).	Compounds IIIa, IIIe, and IIIh show potent inhibitory activity against ribonucleotide reductase; compound IIIa induces apoptosis and G2/M cell cycle arrest; upregulation of p53, BAX, and caspase-3; downregulation of Bcl-2.	Need for further studies on the long-term efficacy and safety; exploration of combination therapies; clinical trials for validation.	Investigate synergistic effects in combination with other anticancer agents; conduct preclinical and clinical trials; explore mechanistic pathways for enhanced therapeutic efficacy.
Alam, I. S., Arrowsmith, R. L., Cortezon-Tamarit, F., Twyman, F., Kociok-Köhn, G., Botchway, S. W., Dilworth, J. R., Carroll, L., Aboagye, E. O., & Pascu, S. I. (2013)	Microwave Gallium-68 radiochemistry for kinetically stable bis(thiosemicarbazone) complexes: Structural investigations and cellular uptake under hypoxia	This study is significant for developing gallium-68 complexes that exhibit hypoxia selectivity, crucial for imaging in cancer diagnosis and treatment.	To synthesize bis(thiosemicarbazone) complexes of gallium-68 using microwave synthesis, evaluate their stability and cellular uptake under hypoxia, and assess their potential for in vivo imaging.	Microwave synthesis, structural characterization, cellular uptake studies using laser scanning confocal microscopy, flow cytometry, radioactive cell retention assays under normoxia and hypoxia.	Gallium-68 complexes showed 34% higher retention in hypoxic cells compared to normoxic cells after 30 minutes, increasing to 53% at 120 minutes. Suitable for hypoxia-selective imaging. Rapid excretion in mice observed.	Further exploration needed on the long-term stability and biodistribution of these complexes in vivo.	Investigate different ligand designs to enhance hypoxia selectivity and improve in vivo imaging efficacy. Develop strategies to mitigate potential toxicity and optimize radiolabeling procedures.
Beckford, F. A., Brock, A., Gonzalez-Sarrías, A., & Seeram, N. P. (2016).	Cytotoxic gallium complexes containing thiosemicarbazones derived from 9-anthraldehyde: Molecular docking with biomolecules	The study investigates the cytotoxic activity of gallium complexes with thiosemicarbazones, exploring their potential as anticancer agents.	- Synthesis of gallium complexes with 9-anthraldehyde thiosemicarbazones - Assessment of anticancer activity - Investigation of biophysical reactivity	Synthesis of gallium complexes, cytotoxicity assays on human colon cancer cell lines (HCT-116 and Caco-2), binding studies with DNA and human serum albumin, molecular	The complexes exhibited cytotoxic activity against cancer cell lines, strong DNA binding, and chemical nuclease activity. Binding constants	The relationship between DNA binding strength and anticancer activity needs further clarification.	Further studies are needed to explore the specific mechanisms of cytotoxicity and optimize complex structures for enhanced therapeutic efficacy.

				docking studies	varied and did not directly correlate with anticancer efficacy.		
Blau et al., 2013	Design, synthesis and biological evaluation of new aryl thiosemicarbazone as antichagasic candidates	Addresses the need for new treatments for Chagas disease with minimal mutagenic profiles.	Synthesis, biological assay, and docking studies of aryl thiosemicarbazones targeting cruzain and trypanothione reductase.	Synthesis of 12 aryl thiosemicarbazones, biological assays against T. cruzi, and docking studies.	Three p-nitroaromatic thiosemicarbazones show potent activity against T. cruzi with no mutagenic effects observed.	Lack of correlation between cruzain inhibition and trypanocidal activity.	Further investigation into mechanisms of action and optimization of compounds for clinical trials.
Jessica Chan, Amber L. Thompson, Michael W. Jones, Josephine M. Peach (2009)	Synthesis and structural studies of gallium(III) and indium(III) complexes of 2-acetylpyridine thiosemicarbazones	Investigates the synthesis and structural characterization of gallium(III) and indium(III) complexes with potential biological applications	To prepare and characterize gallium and indium complexes using various spectroscopic and crystallographic techniques	Fluorescence, UV–Vis, IR, 1H and 13C NMR spectroscopy, mass spectrometry, X-ray crystallographic analysis	Stability studies indicate potential biological activity of [InL3Cl2MeOH] complex	Lack of extensive studies on indium(III) thiosemicarbazone complexes	Further biological evaluation of stable complexes, exploration of dual imaging-therapeutic agents using indium-111
Fernando Cortezon-Tamarit et al. (2016)	Applications of “Hot” and “Cold” Bis(thiosemicarbazonato) Metal Complexes in Multimodal Imaging	Investigates the use of bis(thiosemicarbazonato) metal complexes for multimodal imaging applications	To explore the potential of aromatic bis(thiosemicarbazonato) metal complexes for optical and PET/SPECT imaging applications	Synthesis techniques, spectroscopic characterization, imaging studies	Greater kinetic stability of acenaphthenequinone BTSC complexes; potential for hypoxia-selective imaging agents	Limited studies on gallium-based acenaphthenequinone BTSC complexes for in vivo applications	Further exploration of gallium-based BTSC complexes for in vivo imaging; development of dual imaging-therapeutic agents using various metallic species
Mouayed A. Hussein, Muhammad Adnan Iqbal, Muhammad Ihtisham Umar, Rosenani A. Haque, Teoh Siang Guan (2015)	Synthesis, structural elucidation and cytotoxicity of new thiosemicarbazone derivatives	Investigates the synthesis, characterization, and cytotoxicity of new thiosemicarbazone derivatives	To synthesize and characterize new thiosemicarbazone derivatives using NMR, CHN analysis, and X-ray crystallography	1H & 13C NMR, CHN analysis, single crystal X-ray crystallography	Compounds 2 and 4 exhibit significant cytotoxicity against cancer cell lines; potential for chemotherapeutic drug development	Lack of detailed mechanistic studies on cytotoxicity mechanisms of compounds; Limited exploration of structure-activity relationshi	Further exploration of cytotoxic mechanisms, structure-activity relationships for drug development

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Salman Ahmad Khan, Praveen Kumar, Rajkumar Joshi, Prince F. Iqbal, Kishwar Saleem (2008)	Synthesis and in vitro antibacterial activity of new steroidal thiosemicarbazone derivatives	Investigates the antibacterial activity of steroidal thiosemicarbazone derivatives against Gram-positive and Gram-negative bacteria	To synthesize steroidal thiosemicarbazone derivatives and evaluate their antibacterial activity in vitro	Elemental analyses, IR spectroscopy, 1H NMR spectroscopy, mass spectroscopy	Compounds inhibit growth of both Gram-positive and Gram-negative bacteria. Some derivatives show higher activity.	Lack of previous studies on steroidal thiosemicarbazone derivatives against bacteria	Further exploration of structure-activity relationships in steroidal thiosemicarbazone derivatives, investigation of mechanisms of antibacterial action

Christian R. Kowol, Roland Berger, Rene Eichinger, Alexander Roller, Michael A. Jakupec, Peter P. Schmidt, Vladimir B. Arion, Bernhard K. Keppler (2007)	Gallium(III) and Iron(III) Complexes of r-N-Heterocyclic Thiosemicarbazones: Synthesis, Characterization, Cytotoxicity, and Interaction with Ribonucleotide Reductase	Investigates the synthesis and characterization of gallium(III) and iron(III) complexes with potential anticancer properties, focusing on their interaction with ribonucleotide reductase and cytotoxic effects.	To synthesize and characterize gallium(III) and iron(III) complexes using various spectroscopic and crystallographic techniques, and assess their cytotoxicity and interaction with ribonucleotide reductase.	Elemental analysis, spectroscopic methods (NMR, IR, UV-vis), mass spectrometry, X-ray crystallography	Gallium(III) enhances cytotoxicity, while iron(III) weakens it; complexes interact with ribonucleotide reductase. Potential for dual imaging-therapeutic agents using gallium(III).	High general toxicity of thiosemicarbazones limits therapeutic index; additional modes of action and targets beyond ribonucleotide reductase inhibition need exploration.	Further exploration of dual imaging-therapeutic agents using gallium(III) and iron(III) complexes; investigation into reducing general toxicity of thiosemicarbazones for improved therapeutic outcomes.
Jinxu Qi, Qian Yao, Kun Qian, Liang Tian, Zhen Cheng, Yihong Wang (2018)	Gallium(III) complexes of α-N-heterocyclic piperidylthiosemicarbazones: Synthesis, structure-activity relationship, cellular uptake and activation of caspases-3/7/9	Investigates gallium(III) complexes with α-N-heterocyclic piperidylthiosemicarbazones for their potential in cancer therapy	To synthesize and characterize gallium(III) complexes, evaluate their antitumor activity, and explore their mechanism of action	X-ray single crystal diffraction, cellular uptake studies, caspase activation assays, iron depletion assays, spectroscopic techniques	Gallium complexes exhibit enhanced antitumor activity, induce apoptosis through caspase activation, and affect cellular iron metabolism	Preclinical development phase of gallium-thiosemicarbazone complexes, comparison with existing gallium compounds in clinical trials	Further clinical trials of gallium-thiosemicarbazone complexes, optimization of formulation to reduce hydrolysis and increase bioavailability

C. Saxena, N. C. Bhardwaj, D. Singh, R. V. Singh (1993)	Synthesis and Characterization of Aluminium(III) Complexes of Thiosemicarbazones	Investigates the synthesis and characterization of aluminium(III) complexes with thiosemicarbazones	To synthesize aluminium complexes with various thiosemicarbazones and characterize them using elemental analyses and spectral studies	Elemental analyses, electronic, IR, and 1H NMR spectral studies	Aluminum complexes exhibit bidentate chelating nature; different coordination environments confirmed	Lack of extensive studies on biological or industrial applications of these aluminium complexes	Further exploration of potential biological activities or industrial applications of aluminium(III) thiosemicarbazone complexes

R. V. Singh, Mukesh Kumar Biyala, Nighat Fahmi (2005)	Important Properties of Sulfur–Bonded Organoboron (III) Complexes with Biologically Potent Ligands	Investigates the properties of organoboron(III) complexes with sulfur and nitrogen donor ligands and their potential biologically significant activities	To synthesize and characterize organoboron(III) complexes using elemental analysis, molecular weight determination, and spectroscopic studies	Elemental analysis, molecular weight determinations, conductance measurements, UV, IR, and NMR (1H, 13C, 11B) spectral studies	Complexes exhibit significant antimicrobial properties; tetracoordinated geometry observed	Potential for further studies on broader biological applications and mechanism of antimicrobial action	Exploration of catalytic properties, environmental applications, and structural modifications of organoboron(III) complexes

Lakshmi Narayana Suvarapu & Sung-Ok Baek (2015)	Synthesis and Characterization of 4-Benzyloxybenzaldehyde-4-methyl-3-thiosemicarbazone and Its Cd(II) Complex	Investigates the synthesis and characterization of a new thiosemicarbazone ligand and its Cd(II) complex	To synthesize 4-benzyloxybenzaldehyde-4-methyl-3-thiosemicarbazone (BBMTSC) and its Cd(II) complex using various analytical techniques	Elemental analysis, UV-Vis absorption spectra, FT-IR, mass spectra, NMR, XRD, FESEM	BBMTSC forms a stable Cd(II) complex with unique structural properties	Potential gaps in the biological evaluation or industrial applications of BBMTSC and its Cd(II) complex	Further investigation into biological activities of BBMTSC-Cd(II) complex, applications in environmental analysis

Taracad K. Venkatachalam, Paul V. Bernhardt, Damion H. R. Stimson, Gregory K. Pierens, Rajiv Bhalla, David C. Reutens (2017)	A Novel Strategy to Introduce 18F, a Positron Emitting Radionuclide, into a Gallium Nitrate Complex: Synthesis, NMR, X-Ray Crystal Structure, and Preliminary Studies on Radiolabelling with 18F	Introduces a novel method to incorporate 18F into gallium nitrate complexes, potentially useful for imaging agents	To synthesize and characterize gallium complexes with thiosemicarbazones and explore 18F radiolabelling	Synthesis, NMR spectroscopy, X-ray crystallography, preliminary radiolabelling studies with 18F	Successful synthesis of 18F-gallium complexes; potential for new imaging agents	Focus on gallium-thiosemicarbazone complexes; limited exploration of other radiolabelling strategies	Further optimization of 18F radiolabelling conditions; evaluation of biological applications for new imaging agents

Sunita Yadav, R.V. Singh (2011)	Ferrocenyl-substituted Schiff base complexes of boron: Synthesis, structural, physico-chemical and biochemical aspects	Investigates the synthesis and characterization of boron complexes derived from ferrocenyl-substituted Schiff bases	To prepare boron complexes using specific ligands and evaluate their structural, physico-chemical, and biological properties	Microanalytical analysis, melting point, electronic, IR, 1H NMR, 13C NMR spectroscopy, cyclic voltammetry, X-ray powder diffraction	Boron complexes exhibit tetrahedral structures; show antimicrobial and plant growth regulating activities	Potential for further studies on the biological mechanisms and specific applications of these complexes	Exploration of boron complexes as potential agents in cancer therapy and other biomedical applications

Sunita Yadav, Suresh Chand Joshi, Ran Vir Singh	Studies on the synthesis, characterization and antimicrobial and antifertility aspects of sulfur donor ligands and their Al(III)	Investigates the synthesis, characterization, antimicrobial, and antifertility activities of aluminium(III) and gallium(III) complexes	To synthesize and characterize aluminium and gallium complexes with 1-acetylferrocenehydrazinecarbothioamide (L1H) and 1-acetylferrocenecarbodithioic acid (L2H); evaluate their antimicrobial and antifertility activities	Microanalytical analysis, melting point, electronic, IR, 1H NMR, 13C NMR spectroscopy, X-ray powder diffraction	Complexes showed higher antimicrobial activities than ligands; exhibited antiandrogenic properties in	Potential for further biological studies on broader spectrum of pathogens; detailed mechanism of antiandrogenic effects	Explore applications in other biological assays; optimize complexes for enhanced antimicrobial and antifertilit

(2013)	and Ga(III) complexes	with sulfur donor ligands			antifertility studies		y activities

III. Discussion

The synthesis and biological evaluation of Group 13 element complexes with nitrogen and sulfur donor ligands have garnered significant interest due to their diverse applications in medicine and industry. These complexes exhibit unique properties that make them promising candidates for various biological activities, including antimicrobial, antifungal, anticancer, and other therapeutic applications. The combination of Group 13 elements (boron, aluminum, gallium, indium, and thallium) with thiosemicarbazones and other ligands enhances their biological activity profiles, making them potential alternatives to conventional treatments.

The biological evaluation of these complexes often involves comprehensive studies to assess their efficacy and safety profiles. For instance, the antiproliferative activities of gallium(III) complexes with benzoylpyridine thiosemicarbazones were explored by Qi et al. (2020), highlighting their potential mechanisms against cancer cells (Qi et al., 2020). Such studies provide crucial insights into the molecular interactions and pathways targeted by these complexes, essential for further drug development and optimization.

Industrial applications of Group 13 element complexes extend beyond their biological activities to include materials science and catalysis. For example, the utilization of gallium(III) complexes in multimodal imaging by Cortezon-Tamarit et al. (2016) underscores their versatility in diagnostic technologies (Cortezon-Tamarit et al., 2016). These complexes exhibit favorable stability and selective targeting properties, enhancing their utility in medical diagnostics and therapeutic monitoring.

Moreover, the structural diversity and coordination modes of these complexes play pivotal roles in their biological and industrial applications. The synthesis and characterization of gallium(III) and indium(III) complexes with 2-acetylpyridine thiosemicarbazones by Chan et al. (2009) exemplify the importance of structural studies in elucidating their functional properties and optimizing their performance in specific applications (Chan et al., 2009). Understanding these structures facilitates the design of novel complexes with tailored properties for targeted applications.

Despite the progress made in exploring the biological and industrial potentials of Group 13 element complexes, several challenges and research gaps remain. One significant challenge is the need for enhanced understanding of their mechanisms of action at the molecular level. This includes elucidating their interactions with biological targets and their effects on cellular processes, which are essential for optimizing their therapeutic efficacy and minimizing side effects.

Furthermore, the development of sustainable synthetic routes and scalable production methods for these complexes is crucial for their commercial viability. Addressing these challenges requires interdisciplinary efforts integrating synthetic chemistry, molecular biology, and materials science to advance the field and translate laboratory findings into practical applications. Future research should focus on refining structure-activity relationships, exploring new ligand designs, and evaluating their performance in preclinical and clinical settings to realize the full potential of Group 13 element complexes in biomedicine and industry.

IV. Conclusion

In conclusion, the review highlights the diverse biological activities and industrial applications of Group 13 element complexes with nitrogen and sulfur donor ligands. These complexes have demonstrated significant potential in various biomedical fields, including antimicrobial, anticancer, and diagnostic imaging applications. The studies discussed underscore the importance of structural characterization and biological evaluation in optimizing the efficacy and safety profiles of these complexes. Moreover, their versatility in industrial applications, such as catalysis and materials science, further enhances their value in technological advancements. Despite the progress made, continued research efforts are essential to address existing challenges and fully exploit the therapeutic and industrial potentials of Group 13 element complexes.

V. Suggestions

Moving forward, it is crucial to focus on several key areas to advance the field of Group 13 element complexes. Firstly, further studies should aim to elucidate the detailed mechanisms of action of these complexes at the molecular level. This includes exploring their interactions with specific biological targets and understanding their impact on cellular pathways. Such insights are pivotal for rational drug design and optimization. Secondly, there is a need for the development of innovative synthetic methodologies that enable the efficient and sustainable production of these complexes. Scalable synthesis routes will facilitate their translation from laboratory settings to practical applications in medicine and industry. Lastly, interdisciplinary collaborations between chemists, biologists, and materials scientists are encouraged to foster synergistic research approaches that can accelerate discoveries and innovations in this promising field.

Directions for Further Studies

Future research directions should prioritize the exploration of novel ligand designs and their complexes with Group 13 elements. This includes investigating the potential of new ligands that exhibit enhanced biological activities or specific targeting capabilities. Additionally, comparative studies between different Group 13 elements (boron, aluminum, gallium, indium, and thallium) with various ligands could provide valuable insights into structure-activity relationships and optimize complex designs for specific applications. Furthermore, expanding the scope of applications to include emerging areas such as nanomedicine, environmental remediation, and bioimaging will broaden the impact of Group 13 element complexes in diverse fields. Overall, integrating fundamental research with applied studies will pave the way for transformative advancements in both biological evaluation and industrial applications of these unique complexes.

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