Recent Advances in Lithium Tetraborate ($Li_2B_4O_7$): Synthesis, Characterization, and Emerging Applications

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Abstract

Lithium tetraborate ($Li_2B_4O_7$, LTB) is an important borate material owing to its excellent thermoluminescent, optical, dielectric, piezoelectric, and radiation-sensitive properties [1–6]. Its effective atomic number (Z_eff ≈ 7.3), close to that of human tissue, makes it highly suitable for radiation dosimetry and medical applications [5–7]. LTB also possesses high thermal stability, low hygroscopicity, excellent chemical durability, and a wide optical band gap, making it useful for optical devices, neutron scintillation detectors, phosphors, and photonic applications [2–4,8–10]. Various synthesis methods, including solid-state reaction, sol–gel processing, hydrothermal synthesis, combustion synthesis,co-precipitation and high-energy ball milling, have been employed to produce lithium tetraborate nanoparticles with enhanced structural and optical properties [3,4,11–14]. In addition, rare-earth doping significantly improves its luminescence and thermoluminescence performance for radiation detection and sensing applications [11–15]. This review briefly discusses the properties, synthesis methods, characterization techniques, and emerging applications of lithium tetraborate while highlighting its future potential in advanced radiation dosimetry and multifunctional nanomaterials [1–4,15–20].

Keywords—Lithium tetraborate; $Li_2B_4O_7$; Borate materials; Thermoluminescence; Nanoparticles; Radiation dosimetry; Optical properties.

1. INTRODUCTION

Lithium tetraborate ($Li_2B_4O_7$) is one of the most important borate materials because of its excellent thermoluminescent, optical, dielectric, and radiation-sensitive properties [1–6]. It crystallizes in a tetragonal structure composed of BO_3 and BO_4 units, which provide high thermal stability, chemical durability, and optical transparency [2,3,18]. These characteristics make LTB an attractive material for radiation dosimetry, optical devices, piezoelectric sensors, and photonic technologies [2–5,8].

The unique crystal framework of lithium tetraborate consists of interconnected borate units that contribute significantly to its remarkable structural stability and multifunctional physical properties. The coexistence of BO_3 triangular groups and BO_4 tetrahedral units forms a rigid three-dimensional network that enhances thermal resistance and optical transparency. This stable crystal structure also facilitates the incorporation of various activator ions without causing significant lattice distortion, making lithium tetraborate an excellent host material for luminescent applications. Owing to its wide optical band gap and low phonon energy, the material exhibits excellent optical performance over a broad wavelength range. These characteristics have encouraged extensive research on lithium tetraborate for advanced photonic devices, laser host materials, optical waveguides, and scintillation detectors. In recent years, improvements in synthesis techniques have further enhanced its crystallinity and functional performance, making it an attractive material for both fundamental research and industrial applications.

A major advantage of lithium tetraborate is its effective atomic number (Z_eff ≈ 7.3), which closely matches that of human soft tissue, making it an excellent tissue-equivalent material for thermoluminescent dosimeters (TLDs) [5–7]. It exhibits good dose linearity, low fading, high reproducibility, and excellent radiation sensitivity, making it suitable for medical, industrial, and environmental radiation monitoring [5–7,11].

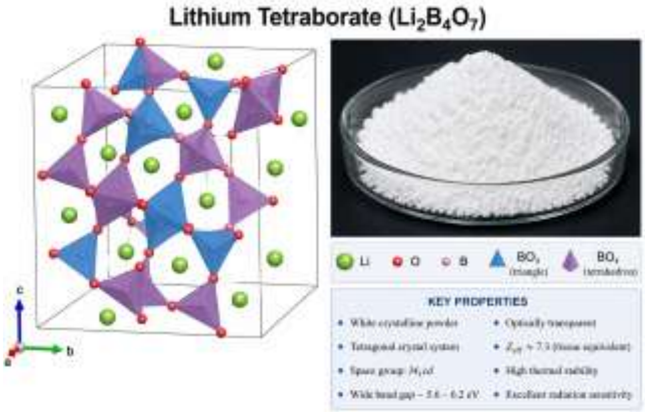

Figure 1. Crystal structure and key characteristics of lithium tetraborate ($Li_2B_4O_7$).

In Figure Lithium tetraborate crystallizes in a tetragonal crystal system consisting of interconnected BO_3 triangular and BO_4 tetrahedral structural units, with lithium ions occupying interstitial positions within the crystal lattice. This unique three-dimensional borate framework provides excellent thermal stability, chemical durability, optical transparency, and radiation sensitivity. Owing to its tissue-equivalent effective atomic number, wide optical band gap, and superior thermoluminescent properties,

$Li_2B_4O_7$ has become an important multifunctional material for radiation dosimetry, scintillation detectors, photonic devices, and advanced optical sensing applications.

Because its effective atomic number closely resembles that of biological soft tissue, lithium tetraborate provides highly accurate absorbed-dose measurements with minimal energy dependence during radiation exposure. This feature is particularly important in medical physics, where precise dosimetry is essential for radiotherapy treatment planning and radiation safety. Furthermore, lithium tetraborate exhibits excellent thermal stability, allowing repeated heating cycles without significant degradation of its thermoluminescent response. The material also demonstrates low hygroscopicity and high chemical durability, ensuring long-term stability during storage and repeated use. These advantages have established lithium tetraborate as one of the most reliable phosphor materials for personal, environmental, and clinical radiation monitoring systems.

Recent research has focused on lithium tetraborate nanoparticles because nanoscale materials exhibit improved crystallinity, larger surface area, enhanced luminescence, and superior radiation sensitivity [3,11–15,20]. Several synthesis techniques, including sol–gel processing, hydrothermal synthesis, combustion synthesis, and high-energy ball milling, have been developed to obtain nanoparticles with controlled morphology and improved functional properties [3,11–14,20].

The reduction of particle size into the nanometer range significantly modifies the structural and electronic characteristics of lithium tetraborate. Nanoparticles possess a much larger specific surface area, resulting in increased surface activity and enhanced interaction with incident radiation. Advances in nanotechnology have enabled precise control over particle size, morphology, crystallinity, and defect concentration through optimization of synthesis parameters. Such improvements have led to enhanced thermoluminescent sensitivity, better optical transparency, and improved photoluminescence efficiency compared with bulk materials. Modern synthesis techniques also allow the preparation of highly homogeneous nanoparticles suitable for advanced sensing, optoelectronic, and radiation detection applications.

Furthermore, rare-earth doping with Cu, Ag, Eu, Dy, Ce, Sm, and Mn ions enhances the thermoluminescent and photoluminescent performance of lithium tetraborate by introducing efficient trapping and luminescence centers [4,11–15]. Consequently, lithium tetraborate has emerged as a promising material for radiation detectors, neutron scintillators, phosphors, optical sensors, and multifunctional nanodevices [1,2,8,11–15].

The incorporation of suitable rare-earth ions creates additional trapping centers and modifies the electronic band structure, thereby improving charge storage capability and radiative recombination processes. As a result, doped lithium tetraborate exhibits stronger luminescence intensity, improved radiation sensitivity, and enhanced dosimetric performance. Recent studies have also investigated co-doping strategies to further optimize the trapping mechanisms and emission characteristics of lithium tetraborate. Beyond radiation dosimetry, these modified materials are being explored for applications in ultraviolet photodetectors, optical communication systems, biosensors, smart photonic devices, and next-generation scintillation detectors. Continuous advancements in defect engineering, nanocomposite fabrication, and computational materials design are expected to further expand the scientific and technological importance of lithium tetraborate in multifunctional materials research.

2. SYNTHESIS METHODS

Several synthesis methods have been employed to prepare lithium tetraborate ($Li_2B_4O_7$) with controlled particle size, morphology, crystallinity, and improved optical properties. The continuous advancement of nanotechnology has enabled the development of several efficient synthesis routes capable of producing lithium tetraborate nanoparticles with superior structural and functional characteristics. Different synthesis techniques offer distinct advantages in terms of particle-size control, crystallinity, chemical homogeneity, phase purity, and defect concentration. The optimization of synthesis parameters such as precursor composition, reaction temperature, pH, calcination time, and heating rate plays a crucial role in determining the quality of the synthesized material. Appropriate selection of the synthesis method not only improves crystallinity but also enhances the optical, dielectric, thermoluminescent, and luminescent properties of lithium tetraborate. Recent research has focused on developing low-cost, environmentally friendly, and energy-efficient synthesis techniques capable of producing highly uniform nanoparticles for advanced technological applications. Therefore, understanding the advantages and limitations of each synthesis route is essential for designing lithium tetraborate materials with improved performance for radiation dosimetry, optical sensing, photonic devices, and multifunctional nanotechnology applications. The selection of the synthesis route significantly influences the structural, morphological, and luminescent characteristics of the final material [3,4,11,12,19,20].

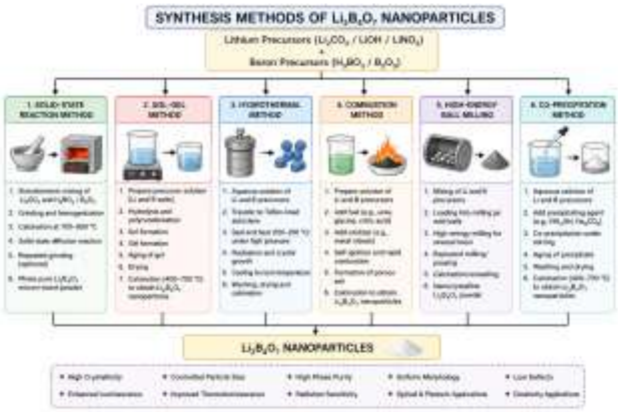

Figure 2. Schematic representation of the principal synthesis methods employed for the preparation of lithium tetraborate ($Li_2B_4O_7$) nanoparticles.

The figure illustrates the six commonly used synthesis routes—solid-state reaction, sol–gel, hydrothermal, combustion, high-energy ball milling, and co-precipitation—along with their major processing steps and the resulting nanomaterials exhibiting controlled particle size, high crystallinity, phase purity, enhanced luminescence, and improved thermoluminescent properties for radiation dosimetry, optical sensing, and photonic applications.

2.1 Solid-State Reaction

The solid-state reaction method is the conventional technique for synthesizing lithium tetraborate by heating lithium carbonate (Li_2CO_3) and boric acid (H_3BO_3) or boron oxide (B_2O_3) at temperatures between 700 and 900 °C [3,18,19]. In this method, stoichiometric quantities of the precursor materials are accurately weighed, thoroughly mixed, and finely ground to ensure homogeneous distribution before calcination. Proper mixing increases the contact area between reactant particles and facilitates efficient diffusion during high-temperature treatment. The reaction proceeds through solid-state diffusion, resulting in the gradual formation of crystalline lithium tetraborate. The heating schedule, calcination temperature, and holding time significantly influence crystallite growth, grain size, and phase purity. Slow heating generally promotes uniform crystal growth while minimizing thermal stresses within the material. Repeated grinding followed by intermediate calcination is often employed to improve reaction completeness and eliminate unreacted precursor phases. Although the synthesized particles are generally in the micrometre range, the method produces highly crystalline materials with excellent structural stability and reproducible properties. Because of its simplicity, low production cost, and suitability for bulk production, the solid-state reaction method continues to be extensively used for preparing lithium tetraborate ceramics, phosphors, and radiation-sensitive materials. Although this method is simple, economical, and suitable for large-scale production, it generally produces larger particle sizes and requires prolonged calcination due to limited diffusion between reactants [3,19].

2.2 Sol–Gel Method:

The sol–gel method is widely employed because it provides excellent chemical homogeneity, lower synthesis temperature, and better control over particle size and morphology [3,4,11,12]. The synthesis begins with the preparation of a homogeneous precursor solution containing lithium and boron compounds dissolved in an appropriate solvent. Controlled hydrolysis and polycondensation reactions lead to the formation of a stable colloidal sol, which gradually transforms into a three-dimensional gel network. The molecular-level mixing achieved during this process ensures excellent compositional uniformity and significantly reduces diffusion distances during crystallization. The ageing, drying, and calcination stages are carefully optimized to obtain highly crystalline lithium tetraborate nanoparticles with controlled particle size and morphology. Parameters such as precursor concentration, solution pH, solvent type, ageing duration, and calcination temperature strongly influence the structural and optical properties of the final product. The sol–gel technique also enables homogeneous incorporation of rare-earth dopants, thereby improving luminescence intensity, thermoluminescent response, and radiation sensitivity. Because of its excellent compositional control, high purity, and ability to produce uniform nanostructures, the sol–gel method has become one of the most preferred synthesis techniques for preparing lithium tetraborate nanoparticles for optical devices, radiation dosimetry, phosphors, and advanced photonic applications. Lithium tetraborate nanoparticles synthesized by this method exhibit improved crystallinity, enhanced luminescence, and superior thermoluminescent performance compared with conventionally prepared materials [4,11,19].

2.3 Hydrothermal Method

Hydrothermal synthesis involves crystallization of precursors in a sealed autoclave under elevated temperature and pressure [3,12,15]. In this synthesis route, aqueous solutions containing lithium and boron precursors are transferred into a Teflon-lined stainless-steel autoclave, where crystallization occurs under controlled hydrothermal conditions. The elevated pressure generated inside the autoclave promotes rapid nucleation and controlled crystal growth, resulting in highly uniform nanoparticles. The reaction temperature, pressure, precursor concentration, pH of the solution, and reaction duration are important parameters that determine the crystallinity, particle size, and morphology of the synthesized material. Unlike conventional high-temperature ceramic methods, hydrothermal synthesis enables the formation of crystalline lithium tetraborate at comparatively lower temperatures, thereby reducing energy consumption and minimizing undesirable grain growth. The closed reaction environment also minimizes contamination from external sources and improves the chemical purity of the final product. Furthermore, hydrothermal processing facilitates excellent control over nanoparticle morphology, allowing the synthesis of spherical, rod-like, and plate-like nanostructures depending on the experimental conditions. The synthesized nanoparticles generally exhibit excellent crystallinity, low defect density, high optical transparency, and improved luminescent performance. Because of these advantages, hydrothermally synthesized lithium tetraborate has attracted considerable attention for applications in radiation dosimetry, optical sensors, photonic devices, scintillation detectors, and advanced luminescent materials. This method produces highly crystalline nanoparticles with narrow particle-size distribution, controlled morphology, and fewer structural defects, making it suitable for optical and sensing applications [3,11,21].

2.4 Combustion Method

Combustion synthesis utilizes metal salts and suitable organic fuels to rapidly produce fine lithium tetraborate powders with high surface area and good crystallinity [4,11,12]. The combustion process involves mixing lithium and boron precursor salts with suitable fuels such as urea, glycine, citric acid, or hydrazine to obtain a homogeneous precursor solution. Upon heating, an exothermic redox reaction occurs between the oxidizing metal salts and the organic fuel, releasing a large amount of thermal energy within a very short time. This rapid heat generation promotes instantaneous nucleation and crystallization, producing fine lithium tetraborate powders with porous microstructure and high specific surface area. The nature of the fuel, fuel-to-oxidizer ratio, ignition temperature, and heating conditions strongly influence the crystallinity, particle size, and morphology of the synthesized nanoparticles. The large volume of gases evolved during combustion prevents excessive particle agglomeration and contributes to the formation of highly porous powders. Because the synthesis is completed within a few minutes, the combustion method offers significant advantages in terms of reduced processing time and energy consumption. The resulting powders generally exhibit excellent crystallinity and enhanced luminescent properties after suitable post-calcination treatment. Owing to its simplicity, rapid processing, low production cost, and scalability, combustion synthesis has become an attractive method for preparing lithium tetraborate phosphors and radiation-sensitive nanomaterials. The method is simple, energy-efficient, and suitable for preparing luminescent phosphor materials for radiation detection applications [4,11].

2.5 High-Energy Ball Milling

High-energy ball milling is a top-down approach in which bulk lithium tetraborate powder is mechanically reduced into nanocrystalline particles [19,20]. During the milling process, repeated impact, friction, deformation, and fracturing of powder particles occur due to collisions with rapidly rotating hardened steel or tungsten carbide balls inside the milling chamber. These continuous mechanical forces gradually reduce the particle size from the micrometre range to the nanometre scale while simultaneously increasing lattice strain and defect density. Milling parameters including rotational speed, milling duration, ball-to-powder ratio, milling atmosphere, and ball material significantly influence the structural, morphological, and optical characteristics of the final product. Careful optimization of these parameters is necessary to obtain uniform nanoparticles with minimum contamination and controlled crystallite size. The mechanically milled powders generally possess increased surface area and enhanced chemical reactivity, making them suitable for subsequent thermal treatment and densification. In many cases, post-annealing is carried out after milling to relieve internal lattice strain, improve crystallinity, and restore the optical and thermoluminescent properties of the material. High-energy ball milling is particularly advantageous because it is economical, scalable, easy to operate, and compatible with industrial production. Furthermore, it can be effectively combined with other synthesis techniques to fabricate advanced lithium tetraborate nanocomposites with improved functional performance. The technique is economical, scalable, and suitable for large-scale production; however, prolonged milling may introduce lattice strain and crystal defects that influence optical and thermoluminescent properties [19,20].

2.6 Co-Precipitation Method

The co-precipitation method is an effective wet-chemical synthesis technique used for the preparation of lithium tetraborate ($Li_2B_4O_7$) nanoparticles because it offers excellent compositional homogeneity, low processing temperature, and precise control over particle size and morphology [3,4,11,15,22]. In this method, aqueous solutions containing lithium and boron precursors are mixed under continuous stirring, and a suitable precipitating agent is added to promote the simultaneous precipitation of the constituent ions [3,11,22]. The resulting precipitate is thoroughly washed, dried, and calcined at an appropriate temperature to obtain highly crystalline lithium tetraborate nanoparticles with high phase purity [4,15,19]. The synthesis parameters, including precursor concentration, solution pH, precipitation rate, ageing time, and calcination temperature, significantly influence the crystallinity, particle-size distribution, morphology, and optical properties of the synthesized material [3,11,15,22]. Compared with conventional solid-state synthesis, the co-precipitation method provides better chemical uniformity, reduced particle agglomeration, and improved control over nanostructure formation [4,11,15]. Owing to these advantages, co-precipitation has become an attractive synthesis route for producing lithium tetraborate nanoparticles with enhanced thermoluminescent, photoluminescent, and radiation-sensitive properties for applications in radiation dosimetry, optical sensors, phosphors, and advanced photonic devices [4,11,15,22].

3. CHARACTERIZATION TECHNIQUES

Comprehensive characterization is essential to understand the structural, morphological, optical, and thermal properties of lithium tetraborate nanoparticles [3,4,11,16–20,21,23–25]. A combination of advanced characterization techniques is generally employed to establish the relationship between synthesis conditions and the resulting material properties. Detailed structural and spectroscopic investigations provide valuable information regarding crystallinity, phase composition, particle size, defect chemistry, elemental composition, and optical behavior of lithium tetraborate nanoparticles. These analytical techniques not only confirm the successful formation of the desired crystal phase but also help optimize synthesis parameters for improved functional performance. Accurate characterization is particularly important for radiation dosimetry applications, where crystal quality, defect concentration, and luminescence characteristics directly influence the sensitivity and reliability of the material. The combined use of structural, microscopic, thermal, and spectroscopic techniques provides a comprehensive understanding of the physicochemical properties of lithium tetraborate nanoparticles and supports their development for advanced technological applications.

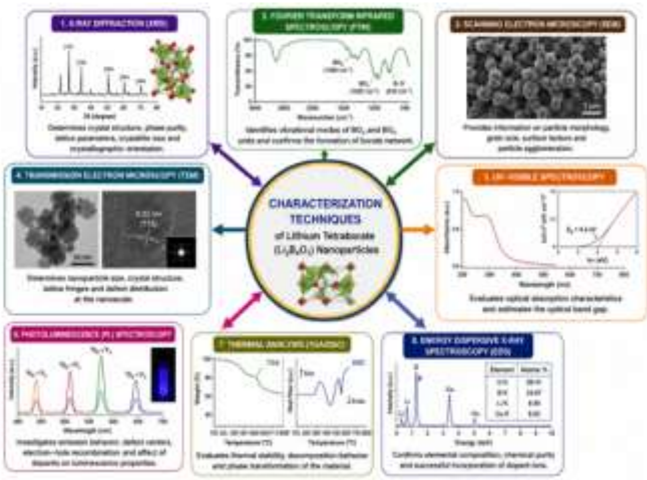

Figure 1. Characterization techniques employed for lithium tetraborate ($Li_2B_4O_7$) nanoparticles.

In figure Comprehensive characterization is essential for evaluating the structural, morphological, optical, thermal, and compositional properties of $Li_2B_4O_7$ nanoparticles. Techniques such as XRD, FTIR, SEM, TEM, UV–Visible spectroscopy, PL spectroscopy, TGA/DSC, and EDS provide valuable information regarding crystal structure, phase purity, particle morphology, optical band gap, luminescence behavior, thermal stability, and elemental composition. These analyses collectively establish the relationship between synthesis conditions and the functional performance of lithium tetraborate nanomaterials for radiation dosimetry and photonic applications [22-26].

3.1 X-ray Diffraction (XRD)

X-ray Diffraction (XRD) is used to determine crystal structure, phase purity, lattice parameters, crystallite size, and crystallographic orientation of lithium tetraborate nanoparticles [3,19,20]. XRD analysis provides direct evidence for the successful formation of the tetragonal lithium tetraborate phase by comparing the observed diffraction peaks with standard reference data. The average crystallite size can be estimated using the Debye–Scherrer equation, while peak broadening provides useful information regarding lattice strain and crystallite dimensions. Variations in diffraction peak intensity and position also indicate changes in crystal quality caused by different synthesis conditions or dopant incorporation. Therefore, XRD remains one of the most important techniques for evaluating the structural properties of lithium tetraborate nanomaterials.

3.2 Fourier Transform Infrared Spectroscopy (FTIR)

Fourier Transform Infrared Spectroscopy (FTIR) identifies the characteristic vibrational modes of BO_3 and BO_4 structural units and confirms the formation of the borate network [2,3,18,19]. The FTIR spectrum provides valuable information regarding the chemical bonding and molecular structure of lithium tetraborate. The characteristic absorption bands corresponding to B–O stretching and bending vibrations confirm the formation of interconnected borate units within the crystal lattice. Changes in band position or intensity may indicate structural modifications resulting from synthesis conditions, thermal treatment, or dopant incorporation. FTIR analysis also verifies the removal of residual organic species after calcination and confirms the successful formation of high-purity lithium tetraborate nanoparticles.

3.3 Scanning Electron Microscopy (SEM)

Scanning Electron Microscopy (SEM) provides information on particle morphology, grain size, surface texture, and particle agglomeration [11,19,20]. SEM images reveal the surface characteristics and microstructural features of synthesized nanoparticles with high spatial resolution. The technique is useful for evaluating particle distribution, porosity, grain connectivity, and surface uniformity. SEM observations help determine the influence of synthesis parameters on particle growth and agglomeration behaviour. The obtained micrographs also provide qualitative information regarding the effectiveness of different synthesis methods in producing homogeneous lithium tetraborate nanoparticles suitable for optical and radiation-related applications.

3.4 Transmission Electron Microscopy (TEM)

Transmission Electron Microscopy (TEM) is employed to determine nanoparticle size, crystal structure, lattice fringes, and defect distribution at the nanoscale [3,11,20]. TEM provides high-resolution images that enable direct observation of individual nanoparticles and their internal crystal structure. High-resolution TEM (HRTEM) further reveals lattice fringes, interplanar spacing, grain boundaries, and crystal defects with atomic-scale precision. Selected Area Electron Diffraction (SAED) patterns obtained during TEM analysis confirm the crystalline nature and phase purity of lithium tetraborate nanoparticles. The technique is particularly valuable for correlating nanoscale structural features with optical and thermoluminescent properties.

3.5 UV–Visible Spectroscopy

UV–Visible spectroscopy is used to evaluate optical absorption characteristics and estimate the optical band gap of lithium tetraborate nanoparticles [2,21,23]. The optical absorption spectrum provides important information regarding electronic transitions occurring within the material. The optical band gap is commonly calculated using Tauc's method, which helps evaluate the effect of particle size, crystallinity, and dopant concentration on the electronic structure. Variations in absorption behaviour also provide insight into defect formation and quantum confinement effects in nanostructured lithium tetraborate. These optical studies are essential for evaluating the suitability of the material for photonic and optoelectronic applications.

3.6 Photoluminescence (PL) Spectroscopy

Photoluminescence (PL) spectroscopy investigates emission behavior, defect centers, electron-hole recombination, and the influence of rare-earth dopants on luminescence properties [4,11,21]. PL spectra provide detailed information regarding radiative recombination processes, emission intensity, and defect-related energy levels within the material. The emission characteristics are strongly influenced by synthesis conditions, crystal quality, and dopant concentration. Analysis of PL spectra enables researchers to understand the role of intrinsic and extrinsic defects in determining luminescence efficiency. Enhanced photoluminescence intensity generally indicates improved crystallinity and efficient incorporation of activator ions into the lithium tetraborate lattice.

3.7 Thermal Analysis (TGA/DSC)

Thermogravimetric analysis (TGA) and differential scanning calorimetry (DSC) evaluate thermal stability, decomposition behavior, and phase transformation of lithium tetraborate materials [13,18,19]. TGA measures changes in sample weight with increasing temperature, thereby providing information regarding moisture removal, decomposition of precursor compounds, and thermal stability. DSC complements TGA by identifying endothermic and exothermic events associated with crystallization, phase transitions, and melting behaviour. These thermal analyses help determine optimum calcination temperatures required to obtain highly crystalline lithium tetraborate nanoparticles with improved structural stability and functional performance.

3.8 Energy Dispersive X-ray Spectroscopy (EDS)

Energy Dispersive X-ray Spectroscopy (EDS) confirms the elemental composition, chemical purity, and successful incorporation of dopant ions into lithium tetraborate nanoparticles [19,20]. EDS analysis provides qualitative and semi-quantitative elemental information by detecting the characteristic X-ray emissions from the sample. The technique verifies the presence of lithium, boron, oxygen, and intentionally introduced dopant elements while confirming the absence of undesirable impurities. Elemental mapping obtained through EDS further demonstrates the uniform distribution of constituent elements throughout the nanoparticles. The combined use of EDS with SEM or TEM provides comprehensive structural and compositional characterization, ensuring the successful synthesis of high-purity lithium tetraborate nanomaterials for advanced scientific and technological applications.

4. CONCLUSION

Lithium tetraborate is an important multifunctional borate material because of its excellent thermoluminescent, optical, dielectric, and radiation-sensitive properties [1–6]. Its unique combination of high thermal stability, wide optical band gap, low hygroscopicity, and excellent chemical durability has made it one of the most extensively investigated borate-based materials for scientific and technological applications. The versatility of lithium tetraborate enables its utilization in radiation detection, photonics, optoelectronics, laser technology, and advanced sensing systems. Continuous improvements in material design and nanotechnology have further strengthened its importance as a multifunctional material for both fundamental research and industrial applications. Recent advances in synthesis techniques, including solid-state reaction, sol–gel processing, hydrothermal synthesis, combustion synthesis, and high-energy ball milling, have enabled the preparation of highly crystalline nanoparticles with improved structural, optical, and luminescent properties [3,4,11,19,20–21,23–25]. The availability of multiple synthesis routes provides researchers with flexibility to tailor particle size, morphology, crystallinity, and defect concentration according to specific application requirements. Optimization of synthesis parameters has significantly enhanced the thermoluminescent sensitivity, optical transparency, and luminescence efficiency of lithium tetraborate nanoparticles. Furthermore, controlled incorporation of rare-earth and transition-metal dopants has expanded the functional capabilities of this material by improving charge trapping efficiency and emission characteristics. These developments have opened new opportunities for designing high-performance nanomaterials with superior radiation response and optical performance.

Characterization using XRD, FTIR, SEM, TEM, UV–Visible spectroscopy, photoluminescence, thermal analysis, and EDS provides comprehensive information regarding the structural and functional behavior of lithium tetraborate nanomaterials [2,3,11–14,16–18,20,21]. The combined application of these advanced characterization techniques enables detailed understanding of crystal structure, surface morphology, elemental composition, optical transitions, defect chemistry, and thermal stability. Such comprehensive investigations are essential for correlating synthesis conditions with material performance and for optimizing lithium tetraborate nanoparticles for specialized technological applications. Reliable characterization also contributes to quality control, reproducibility, and the development of high-performance materials suitable for commercial and industrial implementation.

Owing to its tissue-equivalent effective atomic number and excellent radiation response, lithium tetraborate continues to be a promising material for radiation dosimetry, neutron detection, scintillation detectors, phosphors, and advanced photonic devices [1,5,8,11,21]. Future research should focus on developing environmentally friendly synthesis methods, improving nanoparticle uniformity, engineering defect structures, and exploring novel rare-earth co-doping strategies to further enhance the functional performance of lithium tetraborate. In addition, integration of lithium tetraborate nanomaterials into smart sensors, wearable radiation monitoring systems, biomedical imaging devices, and next-generation optoelectronic components is expected to broaden its practical applications. With continuous progress in nanoscience, materials engineering, and radiation technology, lithium tetraborate is anticipated to remain an important multifunctional material for advanced healthcare, nuclear science, environmental monitoring, and photonic technologies.

5. FUTURE SCOPE

Future research should focus on developing environmentally friendly and low-temperature synthesis methods to produce lithium tetraborate nanoparticles with enhanced purity and controlled morphology [3,11,15]. The adoption of green chemistry approaches, energy-efficient processing techniques, and sustainable precursor materials will help reduce environmental impact while maintaining high product quality. Optimization of reaction parameters such as precursor concentration, pH, calcination temperature, and reaction time will further improve crystallinity, particle-size distribution, and morphological uniformity. The development of scalable synthesis techniques capable of producing high-quality nanoparticles with reproducible properties will also facilitate the commercial utilization of lithium tetraborate in various technological fields. Rare-earth co-doping and defect engineering are expected to improve thermoluminescence, photoluminescence, and radiation sensitivity for next-generation dosimetry applications [4,11,21]. Future investigations should explore the synergistic effects of multiple rare-earth dopants and transition-metal ions to optimize charge trapping mechanisms, emission intensity, and thermal stability. Advanced defect engineering strategies may also enable precise control over luminescence centers and electronic band structure, thereby significantly improving the sensitivity and reliability of lithium tetraborate-based radiation detectors. Furthermore, systematic investigations of the relationship between dopant concentration, defect chemistry, and luminescence characteristics will provide valuable insights for designing high-performance dosimetric materials.

The integration of lithium tetraborate nanoparticles into multifunctional nanocomposites, wearable radiation dosimeters, neutron scintillation detectors, optical sensors, and photonic devices represents an important future research direction [1,8,11,15]. The incorporation of lithium tetraborate nanoparticles into polymer matrices, ceramic composites, and hybrid nanostructures may enhance their mechanical strength, flexibility, and multifunctional performance. Such advanced nanocomposites could find applications in flexible electronic devices, smart healthcare systems, real-time radiation monitoring, aerospace technologies, and nuclear safety equipment. In addition, the miniaturization of lithium tetraborate-based sensing devices is expected to support the development of portable and wearable radiation monitoring systems for medical personnel, industrial workers, and environmental monitoring applications.

Furthermore, computational modeling, machine learning, and artificial intelligence can be employed to optimize synthesis parameters and predict material performance, accelerating the development of advanced lithium tetraborate-based materials for healthcare, nuclear technology, environmental monitoring, and optoelectronic applications [2–4,13,20,21]. The integration of computational materials science with experimental investigations can significantly reduce the time and cost associated with material development by predicting crystal structures, defect formation energies, optical properties, and radiation response before experimental synthesis. Machine learning algorithms can efficiently analyze large experimental datasets to identify optimum synthesis conditions and establish relationships between processing parameters and functional properties. Artificial intelligence-assisted materials design is also expected to accelerate the discovery of novel dopant combinations and multifunctional lithium tetraborate nanomaterials with enhanced performance. Future interdisciplinary research combining nanotechnology, computational modeling, advanced characterization, and intelligent data analysis will play a crucial role in expanding the practical applications of lithium tetraborate in healthcare, radiation protection, nuclear science, environmental monitoring, photonics, and next-generation optoelectronic technologies.

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