Technobius Physics, 2025, 3(3), 0035, DOI: https://doi.org/10.54355/tbusphys/3.3.2025.0035

Technobius Physics

https://technobiusphysics.kz/

e-ISSN 3007-0147

Review

Comprehensive Overview of X-Ray Diffraction: Principles, Techniques, and Applications in Material Science

Hersh F Mahmood[1,*], Soran Abdrahman Ahamd[2], Masood Abu-Bakr[1].

[1]Civil Engineering Department, University of Halabja, Halabja, Kurdistan Region, Iraq
[2]Civil Engineering Department, College of Engineering, University of Sulaimani, Sulaimani, Kurdistan Region, Iraq
*Corresponding author: hersh.faqe@uoh.edu.iq

Abstract. This paper provides an overview of XRD, including its principles, instrumentation, data analysis, and applications. While visual characteristics can aid in identifying certain minerals, powder XRD remains the most reliable and accurate method for phase identification and structural analysis. Beyond crystallography, XRD offers valuable insights into the short- and intermediate-range structures of amorphous materials such as glasses, revealing its broader relevance in emerging technologies. It is widely used for analyzing powders, solids, thin films, and nanomaterial. XRD is often combined with techniques like SEM, TEM, PCS, EBSD, SPM, DLS, ND, and SAED to enhance material characterization. The paper covers fundamental principles such as Bragg's Law and X-ray interaction with crystal lattices, as well as advancements in XRD instrumentation, including X-ray sources, diffractometer, and detectors, reflecting the rapid scientific progress in XRD technology.

Keywords: X-ray, diffraction, material science, non-destructive analysis, microstructure characterization.

1. Introduction

X-ray diffraction (XRD) is a powerful analytical technique used to determine the molecular structure of crystalline materials by measuring the diffraction of X-rays through a sample. The resulting interference patterns provide information about the lattice structure, allowing researchers to analyze parameters such as unit cell dimensions, crystal symmetry, strain, and defects. The discovery of X-rays by W.C. Röentgen in 1895 [1] marked the beginning of this field. In 1912, Max von Laue proposed that X-rays have wavelengths comparable to interatomic distances in crystals. Acting on his idea, Walter Friedrich and Paul Knipping conducted the first X-ray diffraction experiment on crystals [2]. In 1913, William Henry Bragg and his son William Lawrence Bragg discovered the crystal structure of sodium chloride (NaCl), laying the foundation for X-ray crystallography. The Braggs' work explained how cleavage faces of crystals reflect X-rays at specific angles—now described by Bragg's Law. Shortly after, in 1916, P. Debye and P. Scherrer developed methods to analyze polycrystalline materials [2]. XRD instruments have evolved since Karl Weissenberg introduced the Weissenberg camera in the 1920s, although the fundamental principles remain largely unchanged. Significant advancements have been made with the integration of minicomputers for instrument control, data acquisition, and processing [3].

This paper provides a comprehensive overview of XRD techniques, including their historical development, instrumentation, work procedures, sample preparation, and broad applications. Among various XRD techniques, powder X-ray diffraction (PXRD) is particularly notable for its ability to simultaneously characterize both precursor and final products, providing a complete qualitative assessment of microstructural behavior [4]. When the Bragg angle is unknown for a new crystalline

material, two primary techniques are used to generate diffraction patterns: the Laue method and the rotation method. The Laue method, developed by Max von Laue, involves exposing a stationary single crystal to a broad, white spectrum of X-rays. This allows for rapid determination of crystal symmetry and orientation by capturing a comprehensive snapshot of all diffraction directions. While useful for studying highly symmetric or complex structures, its diffraction patterns often contain overlapping spots, complicating interpretation. It is mainly used for qualitative analysis when the exact wavelength of the X-rays is not well known [5].

In contrast, the rotation method – also known as the oscillation or precession method – involves rotating the crystal in a monochromatic X-ray beam of known wavelength. This technique collects diffraction data across multiple angles and is used in both single-crystal and powder diffraction studies. For powdered samples, it is referred to as powder diffraction; for intact crystals, it is called single-crystal diffraction. Both methods rely on measuring the intensity of diffracted X-rays as the sample, tube, or detector moves to vary the diffraction angle (2θ), the angle between the incident and diffracted beams. These measurements are critical for structural characterization. The diffraction angle provides insights into the interplanar spacing (d-spacing) of the crystal lattice, essential for structural determination using Bragg's Law. By analyzing the positions, intensities, and shapes of diffraction peaks, researchers can derive key structural details such as crystallite size, chemical bonding, and lattice distortions – parameters that directly influence the physical properties and potential applications of materials in fields such as chemistry, materials science, and nanotechnology. The atomic arrangement within a crystal can also be determined by reconstructing the observed diffraction pattern. Symmetry, lattice constants, and defect structures can be identified with high precision. Tools like the Renninger diagram – which plots X-ray reflection intensity against the angle of incidence – further assist in structural analysis. For example, identifying a single forbidden reflection can help determine specific isomeric forms and subtle atomic configurations [6].

Modern XRD techniques have expanded these capabilities. Grazing Incidence XRD (GIXRD), a non-destructive method, is especially suited for thin films and coatings, allowing analysis without damaging the sample. It also enables direct assessment of film density through grazing incidence angle-dependent scattering intensity [7]. High-Resolution XRD (HRXRD) employs highly monochromatic beams and optics with extremely low angular divergence to achieve sub-angstrom resolution. It is particularly effective for measuring strain, composition, thickness, and crystalline quality in epitaxial films and heterostructures [8]. HRXRD has been used to confirm epitaxial growth and detect internal grain boundaries in crystals grown by various techniques using multicrystal diffractometer [9]. Accurate simulations of reciprocal space maps (RSMs), accounting for the effects of mirrors, monochromators, analyzers, and slits, have shown strong agreement with experimental data, as demonstrated with a perfect Si(110) crystal [10]. Furthermore, combined real and reciprocal space X-ray mapping techniques are now widely employed to investigate the epitaxial growth of semiconductors [11]. The versatility, precision, and non-destructive nature of XRD make it indispensable in both scientific research and industrial applications, including material development, quality control, and microstructure analysis. The technique continues to evolve, driving innovation across multiple fields. The XRD technique is widely used for microstructure measurement, testing, and in-depth research investigations. The instrument is shown in Figure 1.

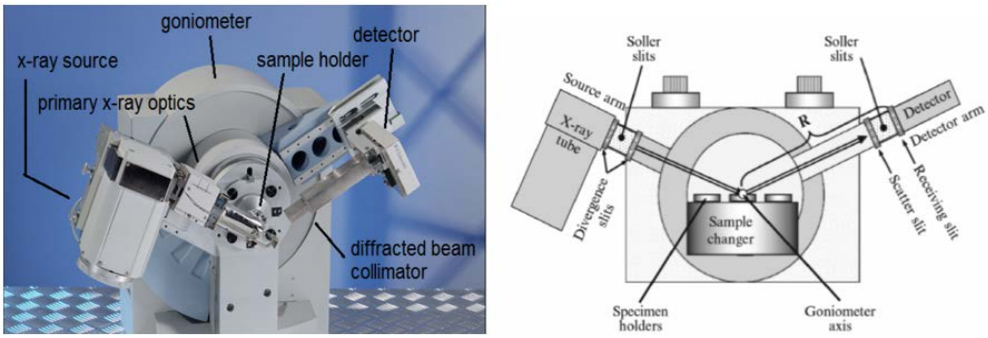

Figure 1 – XRD instrument for microstructural analysis and research applications

2. Methods

This review was conducted using a structured and systematic approach to ensure comprehensive coverage of the scientific literature related to XRD, its principles, instrumentation, and applications in material science. The methodology comprised three main stages: literature search, study selection, and data extraction and synthesis.

2.1 Literature Search Strategy

A comprehensive literature search was undertaken to identify relevant studies published between 2000 and 2025. The search was performed across several major scientific databases, including Scopus, Web of Science, ScienceDirect, SpringerLink, and IEEE Xplore, which are recognized for their extensive coverage of peer-reviewed publications in physics and materials science. To supplement this search, additional sources such as Google Scholar and ResearchGate were examined for grey literature and conference proceedings not indexed in the aforementioned databases.

The search strategy employed a combination of keywords and Boolean operators to maximize retrieval of relevant studies. Search terms included "X-ray diffraction" OR "XRD", "powder X-ray diffraction" AND "material characterization", "GIXRD" OR "HRXRD" AND "applications", and "X-ray diffraction" AND "crystal structure analysis". Filters were applied to restrict results to publications in the English language and peer-reviewed sources only. All identified records were exported to Mendeley reference management software, where duplicate entries were removed.

2.2 Inclusion and Exclusion criteria

Studies were screened based on predefined criteria to ensure that only high-quality and relevant literature was included in this review. The inclusion criteria were as follows:

– Articles published in peer-reviewed journals, conference proceedings, or authoritative book chapters focusing on XRD principles, methodology, or applications in materials science.

– Research presenting experimental or theoretical investigations, technological advancements, or combined analytical approaches involving XRD (e.g., integration with SEM, TEM, or synchrotron techniques).

– Studies providing sufficient detail regarding experimental setup, data acquisition, and analysis procedures.

Conversely, publications were excluded if they met one or more of the following conditions:

– Non-English language publications.

– Non-peer-reviewed articles, opinion pieces, or editorials lacking scientific rigor.

– Studies focusing exclusively on medical imaging or other X-ray-based methods unrelated to diffraction analysis.

– Duplicates or sources without methodological or analytical depth.

2.3 Data Extraction and Synthesis

Following the screening process, a total of 112 studies were selected for detailed review. Relevant information was extracted from each study using a structured template, capturing bibliographic details (authors, publication year, and journal source), type of XRD technique investigated (PXRD, GIXRD, HRXRD, or synchrotron-based methods), study objectives, experimental conditions, sample characteristics, and reported findings.

The extracted data were analyzed qualitatively to identify recurring themes, methodological advancements, and application trends in XRD research. Comparative evaluation was conducted to highlight similarities and differences among studies, particularly in relation to instrumentation design, data acquisition strategies, and interpretation of diffraction patterns. The findings were then synthesized into thematic categories representing the historical development, theoretical principles, technical progress, and modern applications of XRD. This approach ensured a coherent narrative that

reflects the current state of knowledge while identifying research gaps and directions for future investigations.

3-N. X-Ray Diffractometer: Components, Mechanism, and Applications

XRD is a fundamental analytical technique used to investigate the atomic and molecular structure of crystalline materials. This chapter provides an in-depth examination of the XRD device components, the principles underlying its operation, variations in experimental geometry, and its diverse applications. The information is synthesized from various studies [2], [3], [7], [8], [12], [13], [14], [15], [16], highlighting the current state of knowledge and identifying critical advancements in the field.

3.1 Components of the XRD Device

The standard X-ray diffractometer consists of three primary components: the X-ray source (tube), the sample holder, and the X-ray detector. Each element performs a distinct function that is essential to producing high-quality diffraction data.

The X-ray tube generates X-rays through thermionic emission. Electrons emitted from a heated tungsten filament are accelerated under high voltage toward a target material, typically copper or molybdenum. When the electron beam collides with the target, inner-shell electrons are ejected, creating vacancies filled by outer-shell electrons. The transition releases energy in the form of characteristic X-rays whose wavelengths are specific to the target element (Figure 2). These X-rays are directed toward the sample for analysis.

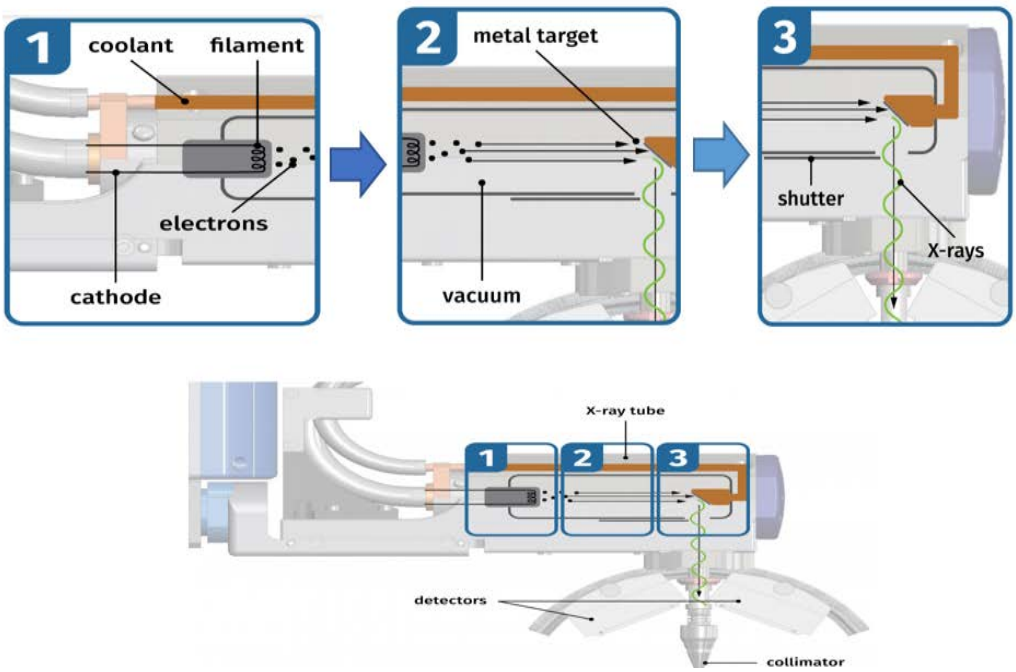

Figure 2 – Mechanism of X-ray generation

The sample holder positions the specimen within the beam path. Its design must minimize background scattering and ensure precise alignment, as even minor deviations can affect diffraction patterns. The detector collects the diffracted beams, converting X-ray intensity into electronic signals that are subsequently processed to generate a diffraction pattern. This pattern reveals information about crystal symmetry, atomic arrangement, and interplanar spacings [2], [4].

3.2 Experimental geometry and reflection mode

In a typical XRD experiment operating in reflection mode, the X-ray source remains fixed while the sample rotates relative to the incident beam. This rotation allows the beam to probe different crystallographic planes of the material. Simultaneously, the detector rotates at twice the angle of the sample (2θ geometry) to capture diffracted rays accurately. This configuration ensures reliable recording of diffraction peaks and facilitates calculation of interplanar spacing using Bragg's law [3], [7]:

$$n\lambda = 2d \sin\theta \quad (1)$$

Where n is an integer, λ is the X-ray wavelength, d is the interplanar spacing, and θ is the diffraction angle. The resulting diffraction peaks provide quantitative information on phase composition, crystallinity, and structural defects (Figure 3).

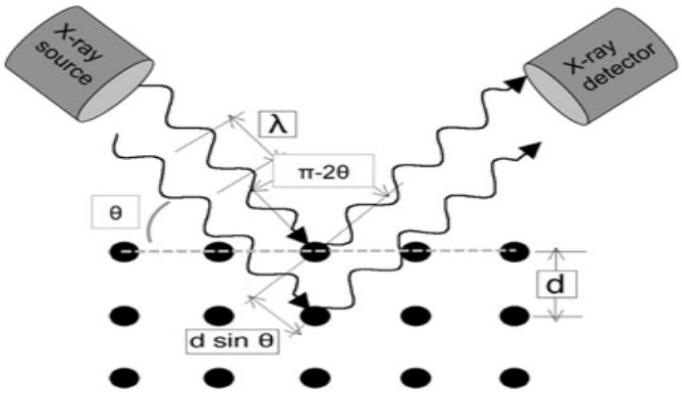

Figure 3 – Schematic illustration of the experimental geometry

Advanced geometries, including GIXRD and HRXRD, have been developed to enhance analytical sensitivity. GIXRD utilizes a shallow incident angle, improving the characterization of thin films and surface layers without damaging the sample [26]. HRXRD employs monochromatic beams and high-precision optics, enabling sub-arcsecond angular resolution crucial for studying epitaxial films and semiconductor interfaces [17] (Figures 4 and 5).

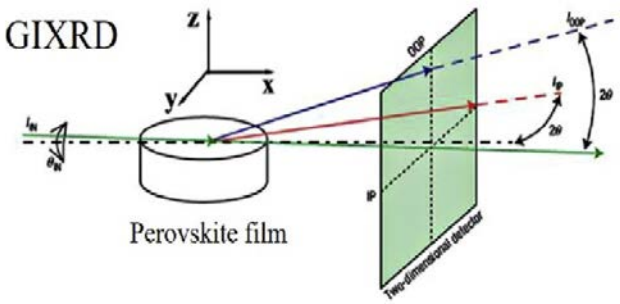

Figure 4 – GIXRD experimental setup [17]

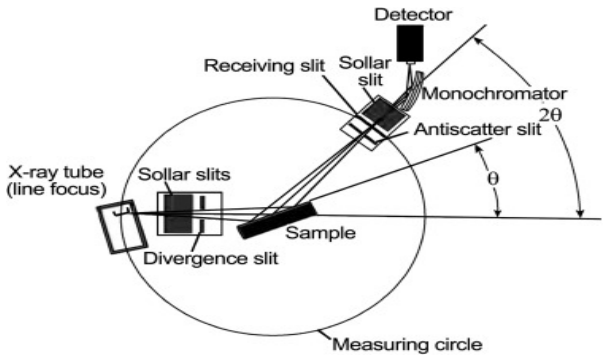

Figure 5 – Schematic diagram of HRXRD setup for eitaxial layer and interface analysis [17]

Table 1 summarizes the primary features and applications of PXRD, GIXRD, and HRXRD, illustrating their complementarity in material characterization.

Table 1 – Comparison of XRD techniques, their applications, and geometrical configurations

#	Technique	Purpose	Geometry Highlights
1	PXRD	Bulk crystal structure from powders	θ–2θ scan; random orientation
2	GIXRD	Thin film analysis	Small incident angle; surface-sensitive
3	HRXRD	High-resolution strain and defect mapping	Optics-enhanced; precise angular resolution

3.3 Mechanism of XRD analysis

The principle of XRD is based on constructive interference of monochromatic X-rays scattered by periodic crystal planes. Millions of crystallites within a powdered sample contribute simultaneously to the observed diffraction pattern, assuming a random orientation distribution. The resulting intensities depend on crystallite size, defects, and orientation [7].

Mineral identification using XRD typically involves two steps: (i) peak matching between the experimental pattern and reference databases, and (ii) comparison of observed diffraction angles (2θ) to standard values [8]. However, amorphous phases, preferred orientation, and sample imperfections can complicate data interpretation, requiring careful calibration and sometimes complementary analytical methods.

Recent studies demonstrate that instrument geometry and crystallite orientation strongly affect peak intensities. For example, Fewster [7] highlighted deviations in predicted intensity values when comparing kinematical and dynamical scattering theories, particularly for micrometer-sized crystallites. Additionally, thermal effects during X-ray generation can cause intensity variations exceeding 15% [16], emphasizing the importance of controlled experimental conditions.

3.4 Applications across scientific disciplines

XRD has become indispensable in materials research, pharmaceuticals, geology, and even planetary science. The CheMin XRD instrument aboard NASA's Mars Science Laboratory successfully identified clay minerals and amorphous phases on Mars' surface, demonstrating the technique's robustness in extraterrestrial environments [11], [12], [18].

In pharmaceutical studies, XRD provides critical insights into polymorphic forms of drug compounds, essential for drug stability and efficacy [13]. Industrially, fully automated XRD systems optimize production processes in mining, cement, and superconductor manufacturing by delivering rapid and reliable phase identification [14]. Furthermore, synchrotron-based high-resolution diffraction measurements offer unparalleled sensitivity in detecting strain states in advanced composite conductors [14], [4].

The growing interest in nanomaterials and hybrid polymers has expanded XRD applications. As reported in [15], [16], [17] temperature-dependent XRD spectra reveal changes in nanoparticle size and morphology, while combined XRD-SEM analyses elucidate structural modifications in graphene oxide-based composites, enhancing understanding of their electrical and mechanical properties.

3.5 Sample preparation and its influence on data quality

Proper sample preparation is critical for reliable diffraction data. Finely ground powders (<44 μm) ensure random crystallite orientation, improving peak sharpness and intensity. Coarse powders, in contrast, produce broader, less intense peaks, complicating structural interpretation (Figure 6). As demonstrated in [4], sample homogeneity, moisture content, and contamination can significantly degrade signal quality.

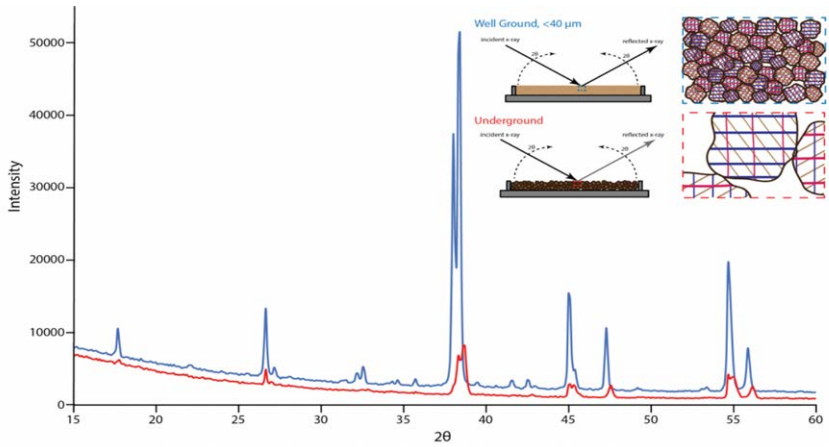

Figure 6 – Diffraction patterns of two samples with different grain sizes

Preferred orientation effects are particularly problematic in metals and polymers, where crystallites align due to manufacturing processes. Misalignment in the sample holder can suppress certain reflections, leading to incomplete data. Rotating the specimen by 90° during measurement, as recommended in [4], can mitigate these artifacts, producing a diffraction pattern representative of the bulk material (Figure 7).

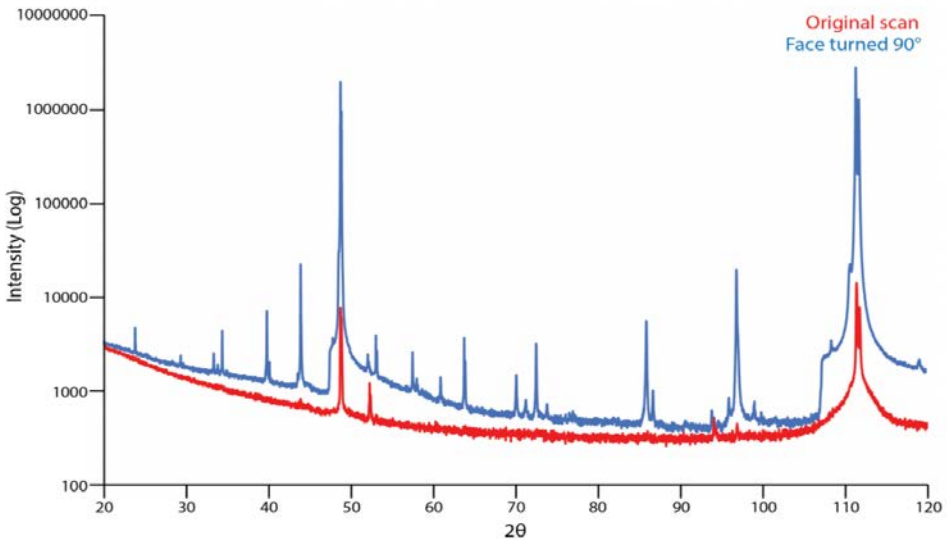

Figure 7 – Initial orientation showing many undetected peaks due to a 90° rotation of the sample surface

3.6 Synthesis of Findings

The reviewed studies collectively demonstrate that the accuracy and reliability of XRD measurements depend on multiple factors: instrument design, geometry configuration, and sample preparation techniques. Technological advances such as GIXRD, HRXRD, and synchrotron sources have expanded the resolution and sensitivity of XRD analyses, enabling nanoscale and in-situ studies across diverse scientific fields. However, achieving reproducible results still requires careful control of experimental conditions, meticulous sample handling, and standardized analytical protocols.

4. Discussion

The analysis of the reviewed literature confirms that XRD remains one of the most powerful and widely utilized analytical techniques for investigating the structural properties of crystalline materials. The reviewed studies consistently demonstrate that PXRD provides a highly reliable and reproducible approach for phase identification and structural characterization, surpassing other macroscopic identification methods such as visual inspection of mineral color or crystal morphology. PXRD is particularly indispensable for analyzing complex multi-phase systems and amorphous materials, where conventional identification approaches are insufficient.

The findings highlight that XRD techniques extend beyond simple phase identification, providing valuable insights into short- and intermediate-range atomic structures, especially in non-crystalline materials such as glasses. This capability opens avenues for understanding structural disorder and its influence on the physical properties of advanced materials, thereby driving innovations in fields such as photonics, catalysis, and nanotechnology. Moreover, XRD enables simultaneous evaluation of lattice parameters, crystallite size, strain, and defect distributions, establishing its role as a cornerstone technique for correlating structural characteristics with functional performance.

The review also indicates that XRD applications have expanded significantly across diverse domains, including pharmaceutical sciences, archaeology, electronics, and material engineering,

where non-destructive, high-precision analysis is critical. In these fields, XRD provides essential information on the composition, crystallinity, and stability of substances without altering their intrinsic properties, making it invaluable for both research and industrial quality control.

Recent technological advancements—such as high-resolution XRD, grazing-incidence XRD (GIXRD), and synchrotron-based diffraction methods—have greatly enhanced analytical precision and sensitivity. These developments enable the detection of subtle structural features such as strain gradients in thin films, epitaxial layer mismatches in semiconductors, and nanoscale heterogeneities in composite materials. The integration of XRD with complementary techniques (e.g., SEM, TEM, and spectroscopy) further strengthens its potential for multi-modal characterization.

The reviewed literature underscores that XRD remains a fundamental and irreplaceable tool in modern materials science, playing a pivotal role in understanding the relationship between structure and material properties. Its non-destructive nature, high accuracy, and adaptability to different sample types make it essential for the design, development, and optimization of new materials. As industries increasingly move towards high-performance functional materials, demand for more advanced, rapid, and automated XRD solutions is expected to grow, particularly in high-throughput research environments.

Based on the synthesis of current knowledge, several promising research directions can be outlined:

−Development of in-situ and operando XRD techniques to monitor structural transformations of materials under real-world conditions (e.g., high temperature, high pressure, electrochemical cycling).

−Improvement of spatially resolved XRD methods for nanoscale structural mapping, particularly relevant for next-generation electronics and nanomaterials.

−Advancements in data processing and machine learning algorithms for automated phase identification, noise reduction, and quantitative analysis of complex diffraction patterns.

−Integration of XRD with complementary multi-scale characterization tools, enabling correlative studies that bridge atomic-scale and macroscopic material behavior.

−Expansion of XRD applications to emerging materials, such as perovskite solar cells, 2D materials, and hybrid organic–inorganic frameworks, where understanding defect structures and phase stability is crucial.

Overall, XRD continues to be an indispensable technique for the structural elucidation and optimization of functional materials. Ongoing methodological improvements, coupled with enhanced data analysis capabilities, are expected to broaden its applicability and accelerate material discovery in the coming decades.

References

[1] "Introduction to X-ray Powder Diffraction X-Ray Analytical Methods Uses of X-Ray Powder Diffraction Introduction to X-ray Powder Diffraction".

[2] S. V. Borisov and N. V. Podberezskaya, "X-ray diffraction analysis: A brief history and achievements of the first century," *J. Struct. Chem.*, vol. 53, no. 1, pp. 1–3, Dec. 2012, doi: 10.1134/S0022476612070013/METRICS.

[3] A. A. Bunaciu, E. gabriela Udriştioiu, and H. Y. Aboul-Enein, "X-Ray Diffraction: Instrumentation and Applications," *Crit. Rev. Anal. Chem.*, vol. 45, no. 4, pp. 289–299, Oct. 2015, doi: 10.1080/10408347.2014.949616.

[4] N. K. Subramani, "Revisiting Powder X-ray Diffraction Technique: A Powerful Tool to Characterize Polymers and their Composite Films," *Res. Rev. J. Mater. Sci.*, vol. 04, no. 04, 2016, doi: 10.4172/2321-6212.1000158.

[5] J. Lee, J. Oba, N. Ohba, and S. Kajita, "Creation of crystal structure reproducing X-ray diffraction pattern without using database," *npj Comput. Mater.*, vol. 9, no. 1, pp. 1–9, Dec. 2023, doi: 10.1038/S41524-023-01096-3;SUBJMETA=1032,1034,1037,12,301,639,930;KWRD=CHARACTERIZATION+AND+ANALYTICAL+TECHNIQUES,COMPUTATIONAL+METHODS,DESIGN.

[6] K. Kozlovskaya *et al.*, "Determination of Absolute Structure of Chiral Crystals Using Three-Wave X-ray Diffraction," *Cryst. 2021, Vol. 11, Page 1389*, vol. 11, no. 11, p. 1389, Nov. 2021, doi: 10.3390/CRYST11111389.

[7] M. A. Rodriguez *et al.*, "Characterization of MoS2 films via simultaneous grazing incidence X-ray diffraction and grazing incidence X-ray fluorescence (GIXRD/GIXRF)," *Powder Diffr.*, vol. 39, no. 2, pp. 60–68, Jun. 2024,

doi: 10.1017/S0885715624000319.
[8] S. Rashid *et al.*, "A Critical Comparison Among High-Resolution Methods for Spatially Resolved Nano-Scale Residual Stress Analysis in Nanostructured Coatings," *Int. J. Mol. Sci. 2025, Vol. 26, Page 3296*, vol. 26, no. 7, p. 3296, Apr. 2025, doi: 10.3390/IJMS26073296.
[9] M. Arivanandhan *et al.*, "Directional growth of organic NLO crystal by different growth methods: A comparative study by means of XRD, HRXRD and laser damage threshold," *J. Cryst. Growth*, vol. 310, no. 21, pp. 4587–4592, Oct. 2008, doi: 10.1016/J.JCRYSGRO.2008.08.036.
[10] A. Y. Seregin, P. A. Prosekov, F. N. Chukhovsky, Y. A. Volkovsky, A. E. Blagov, and M. V. Kovalchuk, "Experimental and Theoretical Study of the Triple-Crystal High-Resolution X-Ray Diffraction Scheme in Reciprocal Space Mapping Technique," *Crystallogr. Reports*, vol. 64, no. 4, pp. 545–552, Jul. 2019, doi: 10.1134/S1063774519040175/METRICS.
[11] Z. Chen *et al.*, "Combining x-ray real and reciprocal space mapping techniques to explore the epitaxial growth of semiconductors," *J. Phys. D. Appl. Phys.*, vol. 56, no. 24, p. 245102, Apr. 2023, doi: 10.1088/1361-6463/ACC597.
[12] V. V. Chernyshev, "Structural Characterization of Pharmaceutical Cocrystals with the Use of Laboratory X-ray Powder Diffraction Patterns," *Cryst. 2023, Vol. 13, Page 640*, vol. 13, no. 4, p. 640, Apr. 2023, doi: 10.3390/CRYST13040640.
[13] C. Scheuerlein, M. Di Michiel, and F. Buta, "Synchrotron radiation techniques for the characterization of Nb 3Sn superconductors," *IEEE Trans. Appl. Supercond.*, vol. 19, no. 3, pp. 2653–2656, Jun. 2009, doi: 10.1109/TASC.2009.2019101.
[14] V. S. Vinila *et al.*, "XRD Studies on Nano Crystalline Ceramic Superconductor PbSrCaCuO at Different Treating Temperatures," *Cryst. Struct. Theory Appl.*, vol. 3, no. 1, pp. 1–9, Mar. 2014, doi: 10.4236/CSTA.2014.31001.
[15] R. J. Rodbari, R. Wendelbo, L. C. L. Agostinho Jamshidi, E. Padrón Hernández, and L. Nascimento, "STUDY OF PHYSICAL AND CHEMICAL CHARACTERIZATION OF NANOCOMPOSITE POLYSTYRENE / GRAPHENE OXIDE HIGH ACIDITY CAN BE APPLIED IN THIN FILMS," *J. Chil. Chem. Soc.*, vol. 61, no. 3, pp. 3120–3124, Sep. 2016, doi: 10.4067/S0717-97072016000300023.
[16] B. Lavina, P. Dera, and R. T. Downs, "Modern X-ray Diffraction Methods in Mineralogy and Geosciences," *Rev. Mineral. Geochemistry*, vol. 78, no. 1, pp. 1–31, Jan. 2014, doi: 10.2138/RMG.2014.78.1.
[17] A. Ghasemi, "Ferrite characterization techniques," *Magn. Ferrites Relat. Nanocomposites*, pp. 49–124, Jan. 2022, doi: 10.1016/B978-0-12-824014-4.00002-0.
[18] P. Sarrazin, D. Blake, S. Feldman, S. Chipera, D. Vaniman, and D. Bish, "Field deployment of a portable X-ray diffraction/X-ray flourescence instrument on Mars analog terrain," *Powder Diffr.*, vol. 20, no. 2, pp. 128–133, Jun. 2005, doi: 10.1154/1.1913719.

Information about authors:
Hersh F Mahmood – PhD, Lecture, Civil Engineering Department, University of Halabja, Halabja, Kurdistan region, Iraq, hersh.faqe@uoh.edu.iq
Soran Abdrahman Ahmad – MSc, Lecture, Civil Engineering Department, University of Sulaimani, Sulaimani, Kurdistan region, Iraq, soran.abdrahman@univsul.edu.iq
Masood Abu-Bakr – MSc, Lecture, Civil Engineering Department, University of Halabja, Halabja, Kurdistan region, Iraq, masoud.mohammed@uoh.edu.iq

Author Contributions:
Hersh F Mahmood – concept, methodology, interpretation, editing.
Soran Abdrahman Ahmad – modeling, analysis, visualization, drafting;
Masood Abu-Bakr – resources, data collection, testing, funding acquisition.

Conflict of Interest: The authors declare no conflict of interest.

Use of Artificial Intelligence (AI): The authors declare that AI was not used.

Received: 15.06.2025
Revised: 25.07.2025
Accepted: 04.08.2025
Published: 06.08.2025