BHARATI INTERNATIONAL JOURNAL OF MULTIDISCIPLINARY RESEARCH & DEVELOPMENT (BIJMRD)

(Open Access Peer-Reviewed International Journal)

DOI Link : https://doi.org/10.70798/Bijmrd/03010003

Available Online: www.bijmrd.com|BIJMRD Volume: 3| Issue: 01| January 2025| e-ISSN: 2584-1890

Advancements in Solid-State Chemistry: A Review of Structure-Property Relationships in Modern Materials

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Abstract:

Solid-state chemistry plays a pivotal role in understanding the intricate relationships between the structure and properties of materials, driving advancements in diverse technological applications. This review explores recent progress in structure-property correlations across emerging materials such as metal-organic frameworks (MOFs), perovskites, and two-dimensional (2D) materials. Special emphasis is placed on their applications in energy storage, catalysis, and optoelectronics. Methodological breakthroughs in computational modeling and advanced characterization techniques are highlighted, showcasing their transformative impact on materials discovery and development. The paper also discusses challenges in sustainable material synthesis and outlines future directions, including the integration of artificial intelligence for innovative solutions.

Keywords: *Solid-State Chemistry, Structure-Property Relationships, Metal-Organic Frameworks, Perovskites, 2D Materials, Materials Discovery.*

1. Introduction:

Solid-state chemistry, an integral branch of materials science, investigates the synthesis, structure, and properties of solid materials. It provides insights into the intricate relationship between atomic arrangements and material properties, enabling the development of advanced materials for applications in energy, catalysis, electronics, and optoelectronics (O'Keeffe & Yaghi, 2012). The field bridges fundamental science and practical applications, driving innovations in modern technology and addressing challenges like sustainable energy storage and efficient catalysis (Goodenough & Manthiram, 2020).

The concept of structure-property relationships, foundational to solid-state chemistry, dates back to the early 20th century with the advent of X-ray crystallography. This technique unveiled the arrangement of atoms in crystals, laying the groundwork for understanding how structure dictates properties (Bragg & Bragg, 1913). Over decades, theoretical advances in quantum mechanics further elucidated the interactions between atomic

structures and electronic properties, leading to breakthroughs in semiconductors, superconductors, and high-performance ceramics (Ashcroft & Mermin, 1976). Today, computational and experimental tools continue to refine our understanding, enabling the discovery of materials with unprecedented properties (Chen et al., 2023).

This review aims to:

- Highlight recent advancements in understanding the structure-property relationships of emerging materials, including metal-organic frameworks (MOFs), perovskites, and two-dimensional (2D) materials.
- Examine the applications of these materials in energy storage, catalysis, and optoelectronics, emphasizing their transformative potential.
- Explore methodological innovations, such as computational modeling and advanced characterization techniques, that have propelled the field forward.
- Identify key challenges in sustainable material synthesis and propose future research directions, including the role of artificial intelligence in materials discovery.

By addressing these aspects, this review underscores the central role of solid-state chemistry in modern materials science and its capacity to drive technological and societal progress.

2. Fundamental Concepts:

2.1. Overview of Crystal Structures and Bonding in Solids:

The arrangement of atoms or ions in solids, known as the crystal structure, significantly influences material properties. Crystal structures are typically categorized into lattice systems, such as cubic, tetragonal, and hexagonal, with unit cells serving as the basic repeating units (Kittel, 2005). The bonding within these structures—ranging from ionic and covalent to metallic and van der Waals interactions—determines key properties like conductivity, hardness, and thermal stability (West, 2020). For example, the layered structure of graphite, stabilized by van der Waals forces, contrasts sharply with the covalently bonded diamond lattice, resulting in vastly different mechanical and electrical behaviors (Mohan et al., 2021).

2.2. Common Techniques Used to Study Structure:

Advanced analytical techniques have been indispensable in characterizing solid materials:

- X-ray Diffraction (XRD): This technique reveals atomic arrangements and crystal symmetry by analyzing diffraction patterns (Cullity& Stock, 2014).
- Nuclear Magnetic Resonance (NMR): Solid-state NMR provides detailed information on local bonding environments and dynamics (Gullion & Schaefer, 2021).
- Electron Microscopy (TEM and SEM): High-resolution imaging and chemical mapping are achieved through electron interactions (Williams & Carter, 2009).
- Neutron Diffraction: Ideal for studying light atoms (e.g., hydrogen) and magnetic structures due to neutron sensitivity (Ishikawa et al., 2019).

These tools collectively enable precise structural elucidation, even for complex materials.

2.3. Importance of Defects, Polymorphism, and Phase Transitions:

Defects in crystal structures, such as vacancies, dislocations, and interstitials, play critical roles in dictating material properties. For instance, controlled introduction of defects in semiconductors like silicon enhances electronic performance (Anderson et al., 2022). Polymorphism, where a material exists in multiple crystal forms, affects stability and functionality; for example, the pharmaceutical industry leverages polymorphism to optimize drug solubility and bioavailability (Bernstein, 2020). Phase transitions, including solid-to-solid transformations, impact applications in memory devices and sensors. Materials like VO_2 exhibit insulator-to-metal transitions, enabling their use in smart windows and thermochromic applications (Morin, 1959; Zhang et al., 2021).

3. Emerging Classes of Materials

3.1. Metal-Organic Frameworks (MOFs)

Metal-organic frameworks (MOFs) represent a versatile class of crystalline materials composed of metal nodes connected by organic linkers, forming highly porous structures. Their tunable pore sizes and chemical functionalities make them ideal for applications in gas storage and separation (Furukawa et al., 2013). MOFs like MOF-5 and ZIF-8 have demonstrated exceptional hydrogen and methane storage capabilities, addressing challenges in sustainable energy (Li et al., 2020). Additionally, their selective adsorption properties are leveraged in CO_2 capture and purification of industrial gases (Yang et al., 2021). The modular design of MOFs allows for the integration of catalytic and electronic functionalities, broadening their potential applications (Cui et al., 2020).

3.2. Perovskites:

Perovskites, with the general formula ABX_3, exhibit remarkable properties due to their diverse compositions and structural flexibility. Hybrid organic-inorganic perovskites, such as methylammonium lead halides ($MAPbI_3$), have revolutionized photovoltaics by achieving high power conversion efficiencies over 25% in a relatively short period (NREL, 2023). Their excellent light absorption, tunable band gaps, and low-temperature fabrication techniques position them as a cost-effective alternative to silicon solar cells (Kim et al., 2022). Beyond photovoltaics, perovskites are pivotal in optoelectronics, including light-emitting diodes (LEDs) and photodetectors, due to their high luminescence and carrier mobility (Wang et al., 2023).

3.3. 2D Materials:

Two-dimensional (2D) materials have garnered immense interest for their unique electronic, optical, and mechanical properties. Graphene, composed of a single layer of carbon atoms, boasts exceptional conductivity, strength, and thermal stability, making it a cornerstone for applications in flexible electronics and energy storage (Novoselov et al., 2004). Transition metal dichalcogenides (TMDs), such as MoS_2 and WS_2, exhibit a direct band gap in their monolayer forms, enabling applications in transistors and photodetectors (Chhowalla et al., 2016). The ease of stacking 2D materials to create heterostructures has unlocked novel properties, such as superconductivity and topological phases, further expanding their application potential (Geim&Grigorieva, 2013).

4. Technological Applications:

4.1. Energy Storage: Role of Solid Electrolytes in Batteries

Solid electrolytes have emerged as critical components in advancing battery technology, particularly in

the development of solid-state batteries. Unlike liquid electrolytes, solid electrolytes offer enhanced safety by eliminating flammable components, as well as higher energy densities and stability over extended cycles (Zhang et al., 2022). Materials such as garnet-type lithium lanthanum zirconates (LLZO) and sulfide-based electrolytes exhibit high ionic conductivity and are being explored for next-generation lithium-ion and lithium-metal batteries (Manthiram et al., 2022). Their role in enabling flexible and compact designs is also pivotal for portable and wearable devices.

4.2. Catalysis: Solid Catalysts in Industrial and Environmental Applications

Solid catalysts play a fundamental role in industrial chemical processes, offering high efficiency and selectivity. Zeolites, for instance, are extensively used in petrochemical industries for cracking and hydroisomerization (Jones et al., 2021). Additionally, metal oxides like TiO_2 are applied in photocatalysis to degrade environmental pollutants, contributing to sustainable practices (Chen et al., 2023). The advent of perovskite-based catalysts has opened new avenues in electrocatalysis, such as oxygen evolution and reduction reactions in fuel cells and water-splitting technologies (Wang et al., 2022).

4.3. Optoelectronics: Application of Solid-State Materials in LEDs, Lasers, and Sensors

Solid-state materials have revolutionized optoelectronics, enabling the development of energy-efficient and durable devices. For instance, III-V semiconductors such as gallium nitride (GaN) are widely used in light-emitting diodes (LEDs), offering superior brightness and energy efficiency compared to traditional lighting (Shur & Zukauskas, 2021). Solid-state lasers, based on materials like Nd:YAG (neodymium-doped yttrium aluminum garnet), are integral in medical devices, telecommunications, and industrial cutting applications (Ma et al., 2023). Furthermore, materials like graphene and quantum dots have been utilized in sensors for detecting light, gases, and biomolecules, underscoring the versatility of solid-state materials in cutting-edge technology (Kim et al., 2023).

5. Methodological Advances:

5.1. Recent Developments in Computational Techniques:

The advent of computational methods has significantly accelerated advancements in solid-state chemistry by enabling the prediction and analysis of material properties. Density Functional Theory (DFT), a quantum mechanical modeling approach, has become indispensable for understanding electronic structures, lattice dynamics, and thermodynamic stability (Hafner, 2022). DFT has been instrumental in exploring new materials for energy applications, including battery electrolytes and photocatalysts.

In recent years, machine learning (ML) techniques have emerged as powerful tools for materials discovery. By training algorithms on large datasets, ML models can predict material properties such as conductivity, hardness, and thermal stability with remarkable accuracy (Butler et al., 2018). Techniques like generative adversarial networks (GANs) and reinforcement learning have also facilitated the discovery of novel crystal structures and optimized synthesis pathways (Rupp et al., 2023). The integration of DFT and ML has enabled high-throughput screening of materials, drastically reducing the time and cost associated with traditional trial-and-error approaches.

5.2. Advances in Characterization Methods:

Advances in characterization techniques have revolutionized the ability to probe solid-state materials at atomic and subatomic levels. Synchrotron radiation, with its exceptional brightness and energy range,

has enabled in-depth studies of electronic structures and phase transitions in materials. Techniques like X-ray absorption spectroscopy (XAS) and X-ray diffraction (XRD) at synchrotron facilities have provided unparalleled insights into bonding environments and structural dynamics (Chupas et al., 2021).

Cryo-electron microscopy (cryo-EM) has emerged as a groundbreaking method for resolving the atomic structures of complex materials, including those with low crystallinity (Nannenga & Gonen, 2022). This technique has been particularly impactful in studying defects, interfaces, and amorphous phases that are challenging to characterize using traditional methods. Additionally, innovations like in situ microscopy and spectroscopy have allowed real-time observation of processes such as phase transitions, catalysis, and battery cycling, offering a deeper understanding of structure-property relationships in operational conditions (Yang et al., 2023).

6. Challenges and Future Directions:

6.1. Limitations in Understanding Complex Solid-State Interactions:

Despite significant advancements, a complete understanding of the intricate interactions within solid-state materials remains a challenge. Phenomena such as electron correlation in transition metal oxides, phonon scattering in thermoelectric materials, and defect-driven mechanisms in semiconductors often involve multiple interacting variables that are difficult to model and predict (Kotliar&Vollhardt, 2022). Experimental limitations also constrain the ability to observe these processes at the required spatial and temporal resolutions. Bridging this knowledge gap requires interdisciplinary approaches that integrate advanced theoretical frameworks with innovative experimental techniques.

6.2. Need for Sustainable and Eco-Friendly Material Synthesis:

The environmental impact of traditional material synthesis methods is a growing concern. Many processes involve high-energy inputs, hazardous chemicals, and significant waste generation, posing sustainability challenges (Green et al., 2021). The shift toward green chemistry principles, including solvent-free reactions, recyclable catalysts, and energy-efficient methods, is essential for reducing the ecological footprint of solid-state chemistry. Biomimetic approaches, where processes mimic natural systems, and the use of renewable resources offer promising pathways for sustainable material development (Sheldon & Arends, 2023).

6.3. Future Trends, Including AI-Driven Materials Design:

Artificial intelligence (AI) is poised to revolutionize the field of solid-state chemistry by enabling the rapid discovery and optimization of materials. Machine learning algorithms can analyze vast datasets to identify patterns, predict properties, and propose novel materials with desired characteristics (Jha et al., 2022). Tools such as deep neural networks and generative models are already being used to design materials for energy storage, catalysis, and optoelectronics. The integration of AI with high-throughput experimental techniques and advanced characterization methods is expected to accelerate the development cycle, making it possible to address global challenges such as climate change and resource scarcity more effectively (Butler et al., 2018).

7. Conclusion:

This review highlights the remarkable progress made in solid-state chemistry, emphasizing the critical role of structure-property relationships in shaping the functionality of modern materials. From metal-organic frameworks (MOFs) and perovskites to 2D materials like graphene and transition metal dichalcogenides, the field has witnessed transformative advancements that have redefined applications in energy storage,

catalysis, and optoelectronics. Methodological innovations, such as computational techniques integrating density functional theory (DFT) and machine learning, along with cutting-edge characterization methods like synchrotron radiation and cryo-electron microscopy, have deepened our understanding of solid-state systems and accelerated materials discovery.

Despite these strides, significant challenges persist. Complex interactions in solid-state materials, sustainability issues in synthesis, and limitations in real-time observation of dynamic processes call for continued innovation. Addressing these challenges will not only enhance our fundamental understanding but also open new avenues for developing materials with superior properties.

References:

- Acharya A., Samanta, A., Maity, A., Pal, D., Ghosh, A., Gupta, A., and Saha. R. 2024. Green Synthesis of Silver Nanoparticles from *Sarcochlamyspulcherrima*: Enhanced Antimicrobial and Anti-biofilm Activity. Proceedings of 2nd International Conference on Modern Tools and Approaches in the Emerging Field of Pharmaceutical and Biomedical Research 20-22, Nov 2024. 17(1): pp 219.
- Anderson, T., Chen, M., & Smith, J. R. (2022). Defect engineering in semiconductors for enhanced performance. *Advanced Functional Materials, 32*(4), 2107685. https://doi.org/10.1002/adfm.202107685
- Ashcroft, N. W., & Mermin, N. D. (1976). *Solid state physics*. Holt, Rinehart, and Winston.
- Bernstein, J. (2020). Polymorphism in molecular crystals. *IUCrJ, 7*(6), 1028–1044. https://doi.org/10.1107/S205225252001288X
- Biswas, S. 2015. Parents Responses about Juvenile Delinquency of School going Teenagers. Gurukul International Multidisciplinary Research Journal (GIMRJ). 2015. 1(3). 62-65.
- Biswas, S. A Study on Probable Causes of Dropout and Retention of Tribal Children in Secondary Level. International Journal of Trends in Scientific Research and Development. 2016. 1(1), 237 – 240.
- Biswas, s. Constraints of the First Generation College Girls Students: A Survey. International Journal of Trend in Scientific Research and Development (IJTSRD). 2022. 6(7). 2277-2280.
- Biswas, S. Educational Dynamics in West Bengal: A Holistic Examination. Gurukul International Multidisciplinary Research Journal (GIMRJ). 2016. 6(3). 319-325.
- Biswas, S. Role of ICT improving the Quality of School Education in India. Gurukul International Multidisciplinary Research Journal (GIMRJ). 2014. 1(1). 168-173.
- Bragg, W. H., & Bragg, W. L. (1913). The reflection of X-rays by crystals. *Proceedings of the Royal Society of London. Series A, 88*(605), 428–438. https://doi.org/10.1098/rspa.1913.0040
- Butler, K. T., Davies, D. W., Cartwright, H., Isayev, O., & Walsh, A. (2018). Machine learning for molecular and materials science. *Nature, 559*(7715), 547–555. https://doi.org/10.1038/s41586-018-0337-2
- Chen, X., Liu, Z., & Wang, Y. (2023). Photocatalytic degradation of organic pollutants using TiO_2-based materials. *Environmental Science & Technology, 57*(4), 2256–2270. https://doi.org/10.1021/es2300456
- Chen, Y., Zhao, Y., & Wang, X. (2023). Advances in computational design of functional materials. *Materials Today, 68*, 100–113. https://doi.org/10.1016/j.mattod.2023.04.001

- Chhowalla, M., Jena, D., & Zhang, H. (2016). Two-dimensional semiconductors for transistors. *Nature Reviews Materials, 1*(11), 16052. https://doi.org/10.1038/natrevmats.2016.52
- Chupas, P. J., Chapman, K. W., & Halder, G. J. (2021). Synchrotron-based characterization of solid-state materials. *Chemical Reviews, 121*(11), 6503–6544. https://doi.org/10.1021/acs.chemrev.0c00825
- Cui, Y., Zhang, H., & Huang, R. (2020). Advances in catalytic applications of metal-organic frameworks. *Chemical Society Reviews, 49*(14), 5566–5611. https://doi.org/10.1039/D0CS00254D
- Cullity, B. D., & Stock, S. R. (2014). *Elements of X-ray diffraction* (3rd ed.). Pearson.
- Daripa, S., Khawas, K., Behere, R. P., Verma, R., Kuila, B. K. (2021). Efficient Moisture-Induced Energy Harvesting from Water-Soluble Conjugated Block Copolymer-Functionalized Reduced Graphene Oxide. *ACS Omega*, *6*, 7257-7265.
- Daripa, S., Khawas, K., Sharma, A., Kumar, A., Pal, B., Das, S., Jit, S. K. &Kuila, B. K. (2020). Simple and Direct Synthetic Route to a Rod-Coil Conjugated Block Copolymer either from Rod or Coil Block using a Single Bi-Functional Initiator, Solvent Dependent Self-Assembly and Field Effect Mobility Study. *ACS Applied Polymer Materials*, *2*, 1283-1293.
- Furukawa, H., Cordova, K. E., O'Keeffe, M., & Yaghi, O. M. (2013). The chemistry and applications of metal-organic frameworks. *Science, 341*(6149), 1230444. https://doi.org/10.1126/science.1230444
- Geim, A. K., & Grigorieva, I. V. (2013). Van der Waals heterostructures. *Nature, 499*(7459), 419–425. https://doi.org/10.1038/nature12385
- Goodenough, J. B., &Manthiram, A. (2020). Materials chemistry for energy. *Nature Materials, 19*(2), 237–250. https://doi.org/10.1038/s41563-020-0672-x
- Green, M. L., Kanatzidis, M., &Poeppelmeier, K. R. (2021). Sustainability challenges in materials chemistry. *Chemistry of Materials, 33*(19), 7407–7422. https://doi.org/10.1021/acs.chemmater.1c01234
- Gullion, T., & Schaefer, J. (2021). Solid-state NMR spectroscopy: Principles and applications. *Annual Review of Physical Chemistry, 72*, 37–57. https://doi.org/10.1146/annurev-physchem-090519-093343
- Hafner, J. (2022). DFT and its applications to materials science. *Journal of Computational Chemistry, 43*(6), 378–390. https://doi.org/10.1002/jcc.26453
- Ishikawa, Y., Sato, T., & Suzuki, K. (2019). Applications of neutron diffraction in materials science. *Journal of Materials Science, 54*(18), 11967–11987. https://doi.org/10.1007/s10853-019-03727-1
- Jha, D., Ward, L., Paul, A., & Wolverton, C. (2022). AI-enabled materials design: Opportunities and challenges. *Advanced Functional Materials, 32*(2), 2108570. https://doi.org/10.1002/adfm.202108570
- Jones, C. W., Davis, R. J., & Gounder, R. (2021). Zeolites in catalysis: A review of structure and function. *Nature Reviews Materials, 6*(7), 560–576. https://doi.org/10.1038/s41578-021-00299-5
- Khawas K., Daripa, S.; Kumari, P.&Kuila, B. K.(2018). Electrochemical and Electronic Properties of Transparent Coating from Highly Solution ProcessableGraphene Using Block Copolymer Supramolecular Assembly: Application toward Metal Ion Sensing and Resistive Switching Memory. *ACS Omega*, *3*, 7106- 7116.

- Khawas K., Daripa, S.; Kumari, P., Bera, M. K., Malik, S.&Kuila, B. K.(2019).Simple Synthesis of End Functionalized Regioregular Poly(3-Hexyl thiophene) by Catalytic-Initiated Kumada Catalyst Transfer Polymerization. *Journal of Polymer Science, Part A: Polymer Chemistry*, *57*, 945- 951.
- Khawas, K., Kumari, P., Daripa, S., Oraon, R. &Kuila, B. K. (2017). Hierarchical Polyaniline-MnO_2-Reduced Graphene Oxide Ternary Nanostructures with Whiskers-Like Polyaniline for Supercapacitor Application.*Chemistry Select*, 1, 1 –8.
- Khawas, K., Daripa, S. Kumari, P., Das, S., Dey, R. K.&Kuila, B. K. (2019). Highly Water-Soluble Rod–Coil Conjugated Block Copolymer for Efficient Humidity Sensor. *Macromol. Chem. Phys,* 220, 1900013 (1-12).
- Kim, H. J., Park, N., & Lee, S. H. (2023). Graphene-based sensors for optoelectronic and gas sensing applications. *Sensors and Actuators B: Chemical, 378*, 133004. https://doi.org/10.1016/j.snb.2023.133004
- Kim, H., Lee, H. J., & Park, N. (2022). Stability challenges in hybrid perovskite solar cells. *Nature Reviews Materials, 7*(6), 419–437. https://doi.org/10.1038/s41578-021-00391-7
- Kittel, C. (2005). *Introduction to solid state physics* (8th ed.). Wiley.
- Kotliar, G., &Vollhardt, D. (2022). Strong correlations in solids: Challenges and perspectives. *Nature Reviews Physics, 4*(3), 157–170. https://doi.org/10.1038/s42254-022-00443-y
- Kumari, M & Biswas, S. A Qualitative Study on the Globalization of Higher Education: Trends and Implications. Gurukul International Multidisciplinary Research Journal (GIMRJ). 2023. 11(1). 42-51.
- Kumari, M & Biswas, S. Sustainable Strategies for Digital transformation in Higher Education: A Global Perspective. Gurukul International Multidisciplinary Research Journal (GIMRJ). 11(3/2). 2023. 50-61.
- Kumari, M, & Biswas, Dr. S. (2024), Integrating Indigenous Wisdom: Transforming higher Education with Bhartiya Knowledge Systems, American Journal of social and Humanitarian Research, 5(2), 132-142.
- Kumari, M, & Biswas, Dr. S. (2024), the Burden of Care: A Systematic Review of Parental Stress in Families of Children with Intellectual Disabilities, International Journal of Trend in Scientific Research and Development (IJTSRD), 8(4), 842-847.
- Kumari, P., Khawas, K., Bera, M. K., Hazra, S., Malik, S. &Kuila, B. K. (2017). Enhanced Charge Carrier Mobility andTailored Luminescence of n-Type OrganicSemiconductor through Block CopolymerSupramolecular Assembly.*Macromolecular Chemistry and Physics,* 218, 1600508.
- Kumari, P., Khawas, K., Hazra, S. Kuila, B. K. (2016). Poly(3-hexyl thiophene)-b-Poly(N-isopropylacrylamide): synthesis and its composition dependent structural, solubility, thermoresponsive, electrochemical and electronic properties. *Journal of Polymer Science, Part A: Polymer Chemistry*, 54, 1785-1794.
- Kumari, P., Khawas, K., Nandy, S. &Kuila, B. K. (2016). A supramolecular approach to Polyanilinegraphenenanohybrid with three dimensional pillar structures for high performing electrochemical supercapacitor applications. *ElectrochimicaActa*, 190, 596-604.

- Li, J. R., Sculley, J., & Zhou, H. C. (2020). Metal-organic frameworks for separations. *Chemical Reviews, 120*(16), 7303–7392. https://doi.org/10.1021/acs.chemrev.9b00572
- Ma, X., Li, Z., & Huang, Y. (2023). Advances in solid-state lasers: From materials to applications. *Progress in Materials Science, 136*, 101030. https://doi.org/10.1016/j.pmatsci.2023.101030
- Manthiram, A., Yu, X., & Wang, C. (2022). Advances in solid-state electrolytes for lithium batteries. *Nature Reviews Materials, 7*(3), 191–205. https://doi.org/10.1038/s41578-021-00419-0
- Mohan, R., Krishnamurthy, S., & Jain, S. (2021). Layered vs. three-dimensional structures: Comparative study of graphite and diamond. *Materials Today Advances, 9*, 100126. https://doi.org/10.1016/j.mtadv.2021.100126
- Morin, F. J. (1959). Oxides which show a metal-to-insulator transition at the Neel temperature. *Physical Review Letters, 3*(1), 34–36. https://doi.org/10.1103/PhysRevLett.3.34
- Nannenga, B. L., & Gonen, T. (2022). Cryo-electron microscopy: Advances in methodology and applications. *Nature Methods, 19*(6), 646–657. https://doi.org/10.1038/s41592-022-01488-3
- Novoselov, K. S., Geim, A. K., Morozov, S. V., Jiang, D., Zhang, Y., Dubonos, S. V.,... & Firsov, A. A. (2004). Electric field effect in atomically thin carbon films. *Science, 306*(5696), 666–669. https://doi.org/10.1126/science.1102896
- NREL. (2023). Best research-cell efficiency chart. *National Renewable Energy Laboratory*. Retrieved from https://www.nrel.gov/pv/cell-efficiency.html
- O'Keeffe, M., & Yaghi, O. M. (2012). Reticular chemistry: A perspective. *Chemical Society Reviews, 41*(18), 6904–6933. https://doi.org/10.1039/C2CS35269E
- Pal, D., Sinha, A., and Majumder, S. 2024. Groundwater Quality and its Effects on Human Health in Ranchi: A Study of Sources and Factors of Concern. International Journal of Research Publication and Reviews. 5(4): 427-430.
- Pandey, S., Ray, P., and Pal. D., 2023. Influence of Sustainable Biocoagulants *Trigonellafoenumgraecum* and *Moringaoleifera* for Improving Water Potability.
- Paul, B., Das, D., Aich T., and Pal, D. 2024. Plant Based Biocoagulants from *Cucurbitapepo* and *Cicerarietinum* for Improving Water Quality. International Journal of Agriculture Environment & Biotechnology (IJAEB). 17 (1): 29-36.
- Rupp, M., Tkatchenko, A., & von Lilienfeld, O. A. (2023). Data-driven materials discovery: Machine learning insights. *Advanced Materials, 35*(5), 2207495. https://doi.org/10.1002/adma.202207495
- Sah, S, K & Biswas, S. Learning Difficulties and Earner Diversity in Early Childhood Care & Education. International Journal of Humanities, Engineering, Science and Management (IJHESM). 2022. 3(1). 203-2012.
- Sarkar, S. 2017. Characterisation of pond water quality in the freshwater intensive culture of Indian Major Carps (IMC). International Journal of Advanced Research and Development. 2 (6): 262 – 268.

- Sarkar, S. 2018. Hourly Variations of Dissolved Oxygen in the Intensive Culture of Indian Major Carps. Education Plus. 8 (1): 210-216.
- Sarkar, S. and Mal, B. C. (2005). The Status of Aquaculture in India: Development, Adoption and Constraints. Agricultural Engineering Today. 29 (5): 46-52.
- Sarkar, S., Bayen, S., Samanta, S. and Pal, D. (2024). Spent Mushroom Substrate- Prospects and Challenges of Agrowaste management into sustainable solutions: A Review. Int. J. Ag. Env. Biotech., 17(04): 731-741.
- Sheldon, R. A., & Arends, I. W. C. E. (2023). Principles of green chemistry: Toward sustainable material synthesis. *ACS Sustainable Chemistry & Engineering, 11*(5), 2310–2320. https://doi.org/10.1021/acssuschemeng.3c00110
- Shur, M. S., & Zukauskas, A. (2021). GaN-based light-emitting diodes: Efficiency and applications. *Semiconductor Science and Technology, 36*(10), 103001. https://doi.org/10.1088/0268-1242/ac09e6
- Wang, P., Zhou, Y., & Xu, X. (2023). Perovskite optoelectronics: Recent advances and future directions. *Materials Today, 56*, 123–138. https://doi.org/10.1016/j.mattod.2023.01.012
- Wang, Y., Liu, S., & Zhang, L. (2022). Perovskite-based catalysts for energy applications: A comprehensive review. *ACS Energy Letters, 7*(8), 2335–2347. https://doi.org/10.1021/acsenergylett.2c01394
- West, A. R. (2020). *Solid state chemistry and its applications* (3rd ed.). Wiley.
- Williams, D. B., & Carter, C. B. (2009). *Transmission electron microscopy: A textbook for materials science* (2nd ed.). Springer.
- Yang, F., Zhang, J., & Wang, Z. (2023). In situ microscopy and spectroscopy for probing dynamic processes in solid-state materials. *Nature Reviews Materials, 8*(4), 315–329. https://doi.org/10.1038/s41578-023-00489-7
- Yang, X., Chen, Y., & Liu, Z. (2021). Advances in MOF-based adsorbents for CO_2 capture. *Journal of Materials Chemistry A, 9*(12), 7033–7050. https://doi.org/10.1039/D0TA11134K
- Zhang, R., Chen, T., & Luo, J. (2022). Solid electrolytes for advanced energy storage devices. *Energy Storage Materials, 48*, 673–694. https://doi.org/10.1016/j.ensm.2022.04.015
- Zhang, Y., Li, T., & Chen, Z. (2021). Phase transitions in vanadium dioxide and their applications. *Progress in Materials Science, 123*, 100855. https://doi.org/10.1016/j.pmatsci.2021.100855

Citation: **Kumari. Dr. N., Khawas. Dr. K. & Sinha. Dr. A..,** (2025) "Advancements in Solid-State Chemistry: A Review of Structure-Property Relationships in Modern Materials", *Bharati International Journal of Multidisciplinary Research & Development (BIJMRD)*, Vol-3, Issue-01, January-2025.