Development of Environmentally Benign Green Synthesis Protocols for the Preparation of ABO_3/ABO_2-Type Perovskite Oxide Nanoparticles: A Sustainable Chemistry Approach

Dushyant Kumar Tyagi[1], Dr. Navneet Sharma[2]
[1]*Research Scholar, Department of Chemistry, HRIT University, Ghaziabad, U.P., India*
[2]*Supervisor, Department of Chemistry, HRIT University, Ghaziabad, U.P., India*

Abstract **- The development of environmentally benign synthesis routes for functional nanomaterials has become an important area of modern chemistry because conventional nanoparticle synthesis often involves high temperature, toxic solvents, hazardous reducing agents, and energy-intensive procedures. Perovskite oxide nanoparticles, generally represented as ABO_3, and in some oxygen-deficient or related structural forms as ABO_2-type oxides, have attracted significant scientific attention due to their structural flexibility, tunable electronic properties, catalytic activity, photocatalytic efficiency, magnetic behavior, and environmental applications. The present research paper focuses on the development of green synthesis protocols for the preparation of ABO_3/ABO_2-type perovskite oxide nanoparticles using eco-friendly precursors, plant extracts, bio-based fuels, aqueous media, and low-waste processing methods.. The proposed green protocol includes precursor selection, preparation of plant extract, metal ion complexation, gel formation, controlled drying, calcination, and nanoparticle characterization through XRD, FT-IR, SEM/TEM, UV–Vis spectroscopy, BET surface area analysis, and photocatalytic testing. The paper also discusses the environmental benefits, limitations, and future prospects of green synthesized perovskite oxide nanoparticles in photocatalysis, wastewater treatment, energy conversion, antimicrobial activity, and sustainable material chemistry. Recent studies show that ABO_3 perovskite oxides are promising catalytic and photocatalytic materials because their properties can be tuned by changing A-site and B-site cations, oxygen vacancies, morphology, and synthesis route.**

Keywords: **(Green synthesis, ABO_3 perovskite oxide, ABO_2-type oxide, nanoparticles, plant extract, sustainable chemistry, photocatalysis, nanomaterials, environmental remediation. XRD, FT-IR, SEM/TEM,)**

I. INTRODUCTION

Nanotechnology has become one of the most influential fields in modern materials chemistry because it enables the preparation of materials with unique structural, optical, magnetic, catalytic, and electronic properties. Nanoparticles show properties that are often different from their bulk counterparts due to their small size, large surface area, quantum effects, and high surface reactivity. Among different classes of nanomaterials, perovskite oxide nanoparticles have gained special importance due to their versatile crystal structure and wide range of applications.

Perovskite oxides are commonly represented by the formula ABO_3, where A is usually a larger cation such as La, Sr, Ba, Ca, or rare-earth metal ions, and B is generally a smaller transition metal cation such as Fe, Mn, Co, Ti, Ni, or Cu. The oxygen atoms form an octahedral coordination around the B-site cation. This flexible crystal structure allows controlled substitution at both A and B sites, producing materials with adjustable band gaps, oxygen vacancy concentration, catalytic activity, conductivity, magnetism, and thermal stability. Review literature on sol–gel synthesis confirms that perovskite structures such as $LaMnO_3$, $SrTiO_3$, and $BaTiO_3$ can be synthesized through controlled chemical routes and show significant functional properties.

Although the standard formula of perovskite oxides is generally ABO_3, oxygen-deficient structures and related oxide systems may also be represented as ABO_2-type depending on stoichiometry, oxidation state, and crystallographic arrangement. Therefore, in this paper the term ABO_3/ABO_2-type perovskite oxide nanoparticles is used to include ideal perovskite oxides as well as oxygen-deficient related structures.

Traditional synthesis methods for perovskite oxide nanoparticles include solid-state reaction, co-precipitation, hydrothermal synthesis, sol–gel synthesis, combustion synthesis, microwave-assisted synthesis, and sonochemical methods. These methods are effective, but many of them require high temperature, long reaction time, organic solvents, synthetic chelating agents, and costly processing conditions. The sol–gel method is widely used because it provides good compositional homogeneity, lower processing temperature, and better control over particle size compared with many conventional approaches.

However, the increasing demand for sustainable chemistry has encouraged researchers to develop green synthesis protocols. Green synthesis aims to reduce or eliminate hazardous substances, minimize energy consumption, use renewable biological resources, and produce materials through safer and more economical methods. Plant extracts, agricultural waste, natural sugars, starch, amino acids, and other bio-based materials can act as reducing, capping, chelating, stabilizing, and fuel agents during nanoparticle synthesis. Recent reports on green synthesis of perovskite oxides such as $LaFeO_3$ and $LaMnO_3$ show that plant extracts and bio-derived materials can be successfully used for preparing functional oxide nanoparticles with photocatalytic and environmental applications.

II. SIGNIFICANCE OF THE STUDY

The significance of this research lies in its focus on combining perovskite oxide nanomaterial chemistry with green and sustainable synthesis principles. Perovskite oxide nanoparticles are useful in photocatalysis, sensors, solid oxide fuel cells, supercapacitors, water purification, antimicrobial systems, and environmental remediation. However, their large-scale application requires synthesis methods that are not only scientifically effective but also environmentally safe.

Green synthesis protocols reduce the dependence on toxic solvents and synthetic stabilizers. They also make the synthesis process more cost-effective and suitable for academic laboratories and sustainable industrial development. Bio-based synthesis routes are particularly valuable because plant extracts contain natural compounds capable of binding metal ions and supporting controlled nanoparticle formation. The use of plant extracts, sugars, starch, and natural fuels has been reported in the synthesis of oxide and perovskite-type nanomaterials, supporting the scientific relevance of this research direction.

This research is important because it provides a systematic framework for preparing ABO_3/ABO_2-type perovskite oxide nanoparticles through environmentally benign routes while maintaining structural purity, nanoscale morphology, and functional performance.

III. OBJECTIVES OF THE STUDY

The major objectives of the present research paper are:

1. To develop environmentally benign green synthesis protocols for preparing ABO_3/ABO_2-type perovskite oxide nanoparticles.
2. To explore the role of plant extracts and bio-based materials as natural complexing, stabilizing, and fuel agents.
3. To reduce the use of hazardous chemicals, toxic solvents, and synthetic surfactants in nanoparticle preparation.
4. To optimize synthesis parameters such as pH, precursor ratio, extract concentration, drying temperature, and calcination temperature.
5. To characterize the synthesized nanoparticles using suitable physicochemical techniques.
6. To evaluate the potential application of green synthesized perovskite oxide nanoparticles in photocatalysis and environmental remediation.
7. To propose a sustainable chemistry model for future preparation of functional perovskite oxide nanomaterials.

IV. REVIEW OF RELATED LITERATURE

Perovskite oxide nanoparticles have been widely investigated due to their unique structural and functional properties. The general ABO_3 structure provides flexibility for cation substitution, oxygen vacancy engineering, and band-gap modification. These features make perovskite oxides suitable for catalytic, photocatalytic, electrochemical, magnetic, and energy-related applications.

Navas et al. reviewed the sol–gel synthesis of perovskite and oxide nanomaterials and emphasized that sol–gel routes offer better control over chemical homogeneity, phase formation, and nanostructure development. This is significant for the present research because green synthesis can be combined with sol–gel chemistry by replacing synthetic chelating agents with bio-based extracts or natural fuels.

Saleem et al. reported the fabrication of $LaFeO_3$ perovskite oxide using Terminalia arjuna leaf extract and evaluated its photocatalytic degradation ability for malachite green dye. The study indicates that plant extract-mediated synthesis can produce ABO_3-resembled perovskite oxides with environmental application potential.

Mehdizadeh et al. investigated $LaFeO_3$ nanostructures prepared using natural materials such as corn, starch, and rice and observed photocatalytic and antibacterial potential. Their study supports the idea that food-derived and bio-based fuels can influence morphology and functional performance of perovskite oxide nanostructures.

Dara et al. reported green sol–gel auto-combustion synthesis of double perovskite Tb_2ZnMnO_6 nanoparticles using sugars such as lactose, fructose, maltose, and liquorice powder as fuel. This study demonstrates that natural fuels can participate in gel combustion and influence nanoparticle homogeneity and particle size.

Hasan et al. demonstrated the green synthesis of $LaMnO_3$ and Ag-modified $LaMnO_3$ using Citrus limon peel extract and highlighted photocatalytic and antibacterial activities. This indicates that fruit peel waste can be used as a low-cost and eco-friendly synthesis medium for perovskite-based functional materials.

Recent review studies also suggest that perovskite-type ABO_3 oxides are promising photocatalytic materials due to their adjustable electronic structure, catalytic activity, and modification possibilities. These studies collectively confirm that green synthesis of ABO_3/ABO_2-type perovskite oxide nanoparticles is a scientifically relevant and environmentally significant research area.

V. RESEARCH METHODOLOGY

5.1 Research Design:
The present research is designed as an experimental and analytical study focused on developing green synthesis protocols for ABO_3/ABO_2-type perovskite oxide nanoparticles. The study follows a laboratory-based synthesis and characterization approach. The research design includes selection of metal precursors, preparation of biological extract, synthesis of nanoparticles, calcination, characterization, and application testing.

5.2 Selection of Perovskite System
For the purpose of this research, representative perovskite oxide systems may include:

Perovskite System	A-Site Cation	B-Site Cation	Possible Application
$LaFeO_3$	La^{3+}	Fe^{3+}	Photocatalysis, sensors, antibacterial activity
$LaMnO_3$	La^{3+}	Mn^{3+}	Catalysis, environmental remediation
$SrTiO_3$	Sr^{2+}	Ti^{4+}	Photocatalysis, energy conversion
$BaTiO_3$	Ba^{2+}	Ti^{4+}	Dielectric and electronic applications
$CaMnO_3$	Ca^{2+}	Mn^{4+}	Catalysis and energy materials

For experimental simplicity and environmental relevance, $LaFeO_3$ or $LaMnO_3$ may be selected as model ABO_3 perovskite oxide nanoparticles.

5.3 Materials Required
The following materials may be used:
- Lanthanum nitrate hexahydrate or lanthanum chloride
- Ferric nitrate nonahydrate or manganese nitrate
- Distilled water
- Fresh plant leaves or fruit peel extract
- Natural fuel such as glucose, starch, citric acid, or plant extract
- Sodium hydroxide or ammonia solution for pH adjustment
- Ethanol for washing
- Filter paper
- Magnetic stirrer
- Hot air oven
- Muffle furnace
- Mortar and pestle

5.4 Selection of Green Extract:

Plant extract plays a central role in the green synthesis protocol. Leaves, fruit peels, seed extracts, or agricultural waste may be used. Suitable examples include:

- Neem leaf extract
- Tulsi leaf extract
- Citrus peel extract
- Aloe vera gel extract
- Green tea extract
- Terminalia arjuna leaf extract
- Rice starch or corn extract

These extracts contain phytochemicals such as flavonoids, tannins, alkaloids, terpenoids, phenolic acids, sugars, and proteins. These compounds may act as natural chelating, reducing, stabilizing, and combustion-supporting agents during nanoparticle formation.

5.5 Preparation of Plant Extract

Fresh plant leaves or fruit peels are washed properly with tap water and then with distilled water to remove dust and impurities. Approximately 20 g of plant material is cut into small pieces and boiled in 100 mL distilled water for 20–30 minutes. The solution is cooled at room temperature and filtered using Whatman filter paper. The clear filtrate is used as green extract for nanoparticle synthesis.

5.6 Green Synthesis Protocol for ABO_3 Perovskite Oxide Nanoparticles

A general green synthesis procedure may be described as follows:

1. Required stoichiometric amounts of A-site and B-site metal salts are dissolved separately in distilled water.
2. Both solutions are mixed under continuous magnetic stirring.
3. Plant extract is added dropwise to the metal precursor solution.
4. The pH of the solution is adjusted between 7 and 9 using mild alkaline solution.
5. The mixture is heated at 70–90°C under continuous stirring until a gel-like mass is formed.
6. The gel is dried in a hot air oven at 100–120°C.
7. The dried precursor is ground into fine powder.
8. The powder is calcined at 500–800°C for 2–4 hours to obtain crystalline perovskite oxide nanoparticles.
9. The final powder is washed, dried, and stored for characterization.

5.7 Proposed Green Reaction Model:

For $LaFeO_3$ synthesis, the simplified reaction may be represented as:

La^{3+} precursor + Fe^{3+} precursor + plant extract → La–Fe organic complex → dried gel → $LaFeO_3$ nanoparticles after calcination

The plant extract assists in metal ion complexation and gel formation. During calcination, organic compounds decompose and provide heat for phase formation, while metal ions rearrange into the perovskite oxide structure.

VI. CHARACTERIZATION TECHNIQUES

6.1 X-Ray Diffraction Analysis

XRD is used to determine the crystalline phase, purity, and average crystallite size of synthesized nanoparticles. The formation of characteristic diffraction peaks confirms the perovskite crystal structure. The average crystallite size can be calculated using the Debye–Scherrer equation:

$D = K\lambda / \beta \cos\theta$

Where D is crystallite size, K is shape factor, λ is X-ray wavelength, β is full width at half maximum, and θ is Bragg angle.

6.2 FT-IR Spectroscopy:

FT-IR analysis is used to identify functional groups involved in nanoparticle synthesis. Before calcination, FT-IR peaks may show organic functional groups such as –OH, –COOH, C=O, and C–O from plant extract. After calcination, characteristic metal–oxygen vibrations confirm the formation of perovskite oxide bonds.

6.3 SEM and TEM Analysis:

Scanning Electron Microscopy and Transmission Electron Microscopy are used to study surface morphology, particle size, shape, and degree of agglomeration. Green synthesized perovskite oxide nanoparticles may show spherical, irregular, porous, or slightly agglomerated morphology depending on the nature of extract and calcination temperature.

6.4 UV–Visible Spectroscopy:

UV–Vis spectroscopy is used to study optical absorption and estimate band gap energy. Perovskite oxides with suitable band gaps can absorb visible light and participate in photocatalytic degradation of organic pollutants.

6.5 BET Surface Area Analysis

BET analysis provides information about surface area, pore volume, and pore size distribution. A higher surface area is generally beneficial for catalytic and photocatalytic applications because it provides more active sites.

6.6 Photocatalytic Activity Test

The photocatalytic activity of synthesized nanoparticles can be evaluated by degradation of organic dyes such as methylene blue, malachite green, methyl orange, or rhodamine B under visible or UV light. The dye degradation percentage may be calculated as:

Degradation (%) = $[(C_0 - C_t) / C_0] \times 100$

Where C_0 is initial dye concentration and Ct is dye concentration at time t.

VII. RESULTS AND DISCUSSION

7.1 Formation of Perovskite Oxide Nanoparticles

The green synthesis protocol is expected to produce ABO_3/ABO_2-type perovskite oxide nanoparticles through a controlled gel-combustion or bio-assisted sol–gel route. The plant extract acts as a natural complexing agent and helps distribute metal ions uniformly in the precursor gel. Uniform metal ion distribution is important because it supports phase purity during calcination.

During heating, the organic components present in the extract decompose gradually and generate gases such as CO_2, water vapor, and other volatile products. This may create porous structures and reduce particle agglomeration. The final calcination step helps crystallize the oxide phase and remove residual organic matter.

7.2 Role of Plant Extract

The phytochemical content of plant extract plays an important role in nanoparticle formation. Polyphenols and flavonoids may bind metal ions through oxygen-containing functional groups. Sugars and organic acids may act as fuel during combustion. Proteins and polysaccharides may stabilize the growing particles and prevent uncontrolled aggregation.

Thus, the plant extract performs multiple functions:

- Metal ion complexation
- Gel formation
- Particle stabilization
- Combustion support
- Morphology control
- Reduction of hazardous chemical use

7.3 Effect of pH

pH is an important parameter in green synthesis. At low pH, metal ions may remain highly soluble and gel formation may be slow. At high pH, hydroxide precipitation may occur rapidly, leading to non-uniform particles. Therefore, a near-neutral to mildly alkaline pH range is generally suitable for controlled synthesis.

7.4 Effect of Calcination Temperature:

Calcination temperature strongly influences crystallinity, particle size, and phase purity. Lower calcination temperatures may produce poorly crystalline material, while very high temperatures may cause particle growth and agglomeration. A moderate calcination range of 500–800°C is commonly used for perovskite oxide nanoparticles depending on the selected system.

7.5 Structural and Morphological Properties

The XRD pattern is expected to confirm the formation of the perovskite phase. SEM and TEM analysis may show nanoscale particles with some agglomeration due to magnetic and surface interactions. The presence of pores may improve catalytic performance because porous structures provide higher contact area between pollutant molecules and catalyst surface.

7.6 Photocatalytic Performance:

Green synthesized perovskite oxide nanoparticles may show photocatalytic activity due to generation of electron–hole pairs under light irradiation. When light energy is absorbed, electrons move from the valence band to the conduction band, leaving holes behind. These electrons and holes react with water and oxygen molecules to generate reactive oxygen species such as hydroxyl radicals and superoxide radicals. These reactive species degrade organic pollutants into less harmful products.

The photocatalytic process may be represented as:

Perovskite oxide + light $\rightarrow e^- + h^+$

$h^+ + H_2O \rightarrow \bullet OH + H^+$

$e^- + O_2 \rightarrow \bullet O_2^-$

Organic dye + reactive radicals → degradation products:

Recent studies on $LaFeO_3$ and $LaMnO_3$-based perovskite oxides support their potential in dye degradation and photocatalytic environmental remediation.

VIII. PROPOSED GREEN SYNTHESIS FRAMEWORK

Stepwise Framework:

Step	Process	Green Chemistry Role
Step 1	Selection of metal salts	Use water-soluble and less hazardous precursors
Step 2	Preparation of plant extract	Renewable biological source
Step 3	Metal ion complexation	Natural chelation by phytochemicals
Step 4	Gel formation	Avoidance of toxic surfactants
Step 5	Drying	Low-waste processing
Step 6	Calcination	Formation of crystalline oxide
Step 7	Characterization	Confirmation of structure and properties
Step 8	Application testing	Environmental remediation and functional use

Flowchart of Green Synthesis Protocol:

Plant material selection
↓
Washing and extraction in distilled water
↓
Preparation of A-site and B-site metal salt solution
↓
Addition of plant extract under stirring
↓
pH adjustment and gel formation
↓
Drying of gel precursor
↓
Grinding and calcination
↓
Formation of ABO_3/ABO_2-type perovskite oxide nanoparticles
↓
Characterization and application testing

IX. APPLICATIONS OF GREEN SYNTHESIZED ABO_3/ABO_2-TYPE PEROVSKITE OXIDE NANOPARTICLES

9.1 Photocatalytic Degradation of Pollutants:
Perovskite oxide nanoparticles can degrade dyes, pesticides, and organic contaminants under light irradiation. This makes them useful in wastewater treatment.

9.2 Antibacterial Activity:
Some perovskite oxides show antibacterial activity due to generation of reactive oxygen species and interaction with microbial cell walls. Green synthesis may further improve biocompatibility.

9.3 Energy Conversion:
Perovskite oxides such as $SrTiO_3$ and La-based oxides are studied for photocatalytic hydrogen generation, oxygen evolution reactions, and fuel cell applications. Recent research continues to explore ABO_3 perovskite oxides for photocatalysis and energy-related applications.

9.4 Sensors:
Due to their tunable electrical conductivity and surface reactivity, perovskite oxide nanoparticles can be used in gas sensors and chemical sensors.

9.5 Catalysis:
ABO_3 perovskite oxides are useful in oxidation reactions, pollutant degradation, oxygen reduction, and other catalytic processes because their A-site and B-site chemistry can be modified.

X. ENVIRONMENTAL BENEFITS OF GREEN SYNTHESIS

Green synthesis protocols provide several environmental advantages:

1. Reduction in toxic chemical usage
2. Use of renewable plant-based materials
3. Lower environmental pollution
4. Cost-effective synthesis process
5. Reduced need for synthetic stabilizers
6. Possibility of using agricultural waste
7. Better alignment with green chemistry principles
8. Safer laboratory and industrial procedures

The use of bio-based fuels such as sugars, plant extracts, starch, and fruit peels makes the synthesis route more sustainable and economically attractive.

XI. CHALLENGES AND LIMITATIONS

Although green synthesis is promising, it also has some limitations:

1. Plant extract composition may vary with season, location, and plant age.
2. Reproducibility can be challenging without proper standardization.
3. Complete phase purity may require optimization of calcination temperature.
4. Some green methods still require high-temperature calcination.
5. Particle size control may be less precise than highly controlled chemical methods.
6. Large-scale production requires process optimization and quality control.
7. Mechanistic understanding of phytochemical–metal ion interaction is still developing.

Therefore, future research should focus on standardization of extract concentration, identification of active phytochemicals, optimization of energy use, and scale-up studies.

XII. FUTURE SCOPE

The future scope of this research is broad. Green synthesized ABO_3/ABO_2-type perovskite oxide nanoparticles may be further explored for:

- Visible-light photocatalysis
- Industrial wastewater treatment
- Hydrogen production
- CO_2 reduction
- Antibacterial coatings
- Smart sensors
- Supercapacitors
- Solid oxide fuel cells
- Sustainable catalytic systems
- Doped and composite perovskite nanostructures

Future work may also involve artificial intelligence-based optimization of green synthesis parameters, life-cycle assessment of nanoparticle production, and comparative study between conventional and green synthesis methods.

XIII. CONCLUSION

The present research paper highlights the development of environmentally benign green synthesis protocols for the preparation of ABO_3/ABO_2-type perovskite oxide nanoparticles. Perovskite oxides are highly valuable functional materials because of their structural flexibility, tunable composition, catalytic activity, optical response, and environmental applications. However, conventional synthesis methods may involve toxic reagents, high energy input, and complex procedures. Green synthesis provides a sustainable alternative by using plant extracts, natural fuels, aqueous media, and low-waste processing routes.

The proposed protocol uses plant extract as a multifunctional agent for metal ion complexation, gel formation, stabilization, and combustion support. The synthesized nanoparticles can be characterized by XRD, FT-IR, SEM/TEM, UV–Vis spectroscopy, BET analysis, and photocatalytic testing. Green synthesized perovskite oxide nanoparticles have strong potential in photocatalysis, wastewater treatment, antibacterial activity, sensors, catalysis, and energy applications.

Overall, this study supports the idea that green chemistry and perovskite nanomaterial science can be integrated to develop sustainable, cost-effective, and environmentally safe functional nanomaterials for future technological and environmental needs.

REFERENCES

[1] Ashraf, A., Saleem, A., & co-authors. (2023). Fabrication of lanthanum-ferrite perovskite oxide $LaFeO_3$ using *Terminalia arjuna* leaf extract for the efficient photocatalytic

degradation of malachite green. *Inorganic Chemistry Communications, 158*, 111580.

[2] Dara, M., Aghazadeh, M., & Ganjali, M. R. (2021). Green sol–gel auto-combustion synthesis and characterization of double perovskite nanoparticles using natural fuels. *RSC Advances, 11*, 8225–8236.

[3] Hasan, N., Shah, M. S., Khan, S., & co-authors. (2024). Green synthesis of $LaMnO_3$–Ag nanocomposites using *Citrus limon* peel aqueous extract: Photocatalytic degradation of Rose Bengal dye and antibacterial applications. *Catalysts, 14*(9), 609.

[4] Irshad, M., Ain, Q. U., Zaman, A., Ali, M., Ahmad, N., & Kousar, N. (2022). Photocatalysis and perovskite oxide-based materials: A review. *Materials Science in Semiconductor Processing, 147*, 106707.

[5] Kanhere, P., & Chen, Z. (2014). A review on visible light active perovskite-based photocatalysts. *Molecules, 19*(12), 19995–20022.

[6] Kumar, S., Sharma, A., & Kumar, R. (2020). Green synthesis of metal oxide nanoparticles: A review of recent advances and future perspectives. *Journal of Cleaner Production, 256*, 120364.

[7] Lee, Y. L., & Kleis, J. (2016). Perovskite oxides as photocatalysts for solar fuel production. *Journal of Physical Chemistry C, 120*(39), 21991–22003.

[8] Li, X., Yu, J., Jaroniec, M., & Chen, X. (2019). Cocatalysts for selective photoreduction of CO_2 into solar fuels. *Chemical Reviews, 119*(6), 3962–4179.

[9] Mehdizadeh, P., Tavakoli, O., & co-authors. (2020). Effective removal of organic pollution using $LaFeO_3$ nanostructures prepared with natural materials. *Journal of Environmental Chemical Engineering, 8*(2), 103546.

[10] Navas, D., Fuentes, S., Castro-Alvarez, A., & Chavez-Angel, E. (2021). Review on sol–gel synthesis of perovskite and oxide nanomaterials. *Gels, 7*(4), 275.

[11] Peña, M. A., & Fierro, J. L. G. (2001). Chemical structures and performance of perovskite oxides. *Chemical Reviews, 101*(7), 1981–2018.

[12] Phuruangrat, A., Thongtem, S., & Thongtem, T. (2017). Hydrothermal synthesis and characterization of perovskite oxide nanoparticles for photocatalytic applications. *Ceramics International, 43*(5), 4320–4327.

[13] Ramesh, S., & Kumar, R. (2021). Bio-inspired synthesis of functional oxide nanoparticles and their environmental applications. *Environmental Nanotechnology, Monitoring & Management, 16*, 100521.

[14] Royer, S., Duprez, D., Can, F., Courtois, X., Batiot-Dupeyrat, C., Laassiri, S., & Alamdari, H. (2014). Perovskites as substitutes of noble metals for heterogeneous catalysis: Dream or reality. *Chemical Reviews, 114*(20), 10292–10368.

[15] Sahoo, S., Parida, K. M., & co-authors. (2020). Perovskite-based photocatalysts for environmental remediation and energy conversion. *Catalysis Science & Technology, 10*(5), 1307–1341.

[16] Singh, J., Dutta, T., Kim, K. H., Rawat, M., Samddar, P., & Kumar, P. (2018). Green synthesis of metals and their oxide nanoparticles: Applications for environmental remediation. *Journal of Nanobiotechnology, 16*, 84.