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Original Article

Optimizing Bio-Inspired Phototropic Materials: Addressing Scalability and Durability Challenges for Passive Solar Tracking Systems

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Abstract: *Bio-inspired phototrophic materials can change passive solar tracking systems and improve them by creating them like they attract sunlight, just like plants do. These components have resulted in excellent energy savings as well as extraordinary context-awareness. For example, MXene-enhanced actuation devices can convert 95 percent of incoming light into heat energy, while SunBOTs capture 400 percent more energy. High fabrication costs, technical complexity, and low durability under environmental stresses hamper their scalability and commercial feasibility. This systematic review aggregates the findings of multiple high-quality worldwide studies to help address these issues. It underscores substantial advancements, such as self-healing polymers, scalable roll-to-roll manufacturing, and hybrid material designs. Connecting development with the United Nations Sustainable Development Goals (SDGs) and the Paris Agreement helps this work to show a road map for including bio-inspired phototropic materials in renewable energy systems. The results underline the possibilities of the materials to change solar energy systems and support worldwide sustainability projects.*

Key-words: *Bio-Inspired Materials, Passive Solar Tracking, Phototropic Systems, Scalability Challenges, Renewable Energy Technology, Material Durability*

I. INTRODUCTION

Solar power is becoming a main component of renewable energy plans due to the global push for sustainability. With about 30% of all new renewable installations globally expected to be solar photovoltaic (PV) technologies as the world's energy needs rise [1], they have become an important alternative. Current solar tracking techniques have several disadvantages due to their complexity in mechanical terms, energy waste, and difficulty adapting to different weather patterns [2]. It might be limited for some regions with severe weather conditions and/or poor infrastructure to use solar power plants completely due to these limitations. Instead, sunflower-like biomimetic phototropic materials provide another way out. Those make it possible to design sun-following equipment without using mechanical elements but only based on their ability for passive sunlight tracking while acting like real flower heads directed towards the most intense illumination source. Innovations in this field exhibit enormous transforming power. The SunBOT technology, for instance, improved energy extraction by 400% when light came from the side [3]. Concentrating heat at the nanoscale level lets MXene-reinforced actuators achieve up to 95% photothermal efficiency [4]. These advances mirror a paradigm shift in solar energy design, offering more straightforward, flexible systems with reduced running costs and environmental impact.

Three significant challenges limit the general use of bio-inspired phototropic materials notwithstanding these achievements:

- Fabrication techniques often include complex procedures and costly raw materials, such as Ru nanoclusters, making large-scale production economically impractical. Addressing these scaling constraints is crucial for large-scale implementation [5],[6].
- Challenges ranging from mechanical wear to temperature stress and UV radiation influence the longevity of these materials. Durability improvement depends on breakthroughs like hybrid composites and self-healing polymers. [7][8].
- Global Importance: Studies in underprivileged areas without infrastructure are scarce on using these technologies to reduce energy inequities. For equitable energy distribution, bio-inspired systems must be adaptable to different societies and territories characterized by various socioeconomic conditions [9].

This paper reviews how they can change passive solar tracking systems, emphasizing passive solar tracking systems. This review positions recent developments in bio-inspired phototropic materials as game changers in passive solar tracking systems.

It examines how these materials could be used to scale up passive solar tracking systems, considering various aspects of sustainability, like SDGs and the Paris Agreement.

A. Challenges in Commercializing Bio-Inspired Phototropic Materials in Solar Technologies:

Even with significant progress, including bio-inspired phototropic materials in commercial solar technologies still presents a major challenge. To reach their full potential, we must overcome these hurdles—including scaling difficulties, durability issues, and limited global relevance.

B. Scalability:

Complicated manufacturing processes and dependence on expensive raw materials limit the scalability of bio-inspired phototropic materials. Modern manufacturing techniques, such as nanostructuring and advanced hydrothermal processes, demand exact engineering and limit mass production. For instance, Ru nanoclusters and MXene composites show remarkable performance but are challenging to scale up without incurring significant expenditures. [5] [6] [7]

C. Economic Restraints:

These systems are currently unsuitable for widespread application in resource-limited environments due to the significant expenses of raw materials and particular manufacturing techniques [6].

D. Technical Complexity:

Shifting from laboratory prototypes to industrial-scale manufacturing leads to inconsistent material quality and unpredictable performance [7].

E. Manufacturer Innovations Required:

While scalable production techniques such as 3D printing and roll-to-roll processing have the potential to reduce costs and maintain performance, they still need work [8].

F. Environmental Stresses:

Environmental stresses greatly influence the operational lifetime of bio-inspired materials, potentially affecting their performance over time. UV light, thermal variations, and mechanical wear influence material integrity and efficiency.

- UV Radiation: Extended UV radiation exposure may reduce material efficiency by up to 20% in the first year of use. Current studies imply that self-healing polymers and UV-resistant coatings may help reduce these effects [9].
- Temperature Fluctuations: Extreme temperature fluctuations cause material deformation and stress, particularly in areas with significant daily temperature swings [7].
- Mechanical Wear: Mechanical wear results from wind, trash, and other external forces that cause micro-damage to delicate structures and calls for strong designs to ensure functionality over time.

G. Worldwide Importance:

Although bio-inspired materials have significant promise for renewable energy, their application in addressing global energy disparities remains underexplored. Many places in need of sustainable energy solutions—developing nations included—lack the infrastructure and financial means required to apply creative ideas.

H. Geographic Restrictions:

Existing systems are primarily optimized for controlled environments, limiting their effectiveness in resource-constrained regions with varying climatic conditions [11].

I. Adoption Problems:

High initial expenses and a lack of technical knowledge cause adoption problems in underdeveloped countries [12].

J. Socioeconomic Constraints:

Policies and funding solutions are required.

K. Policy Gaps:

Though such programs are rare, government and international support in subsidies, incentives, and technology transfer projects may boost adoption [5].

L. Future Studies and Priorities:

Future studies should prioritize the following areas to overcome these challenges:

- Using scalable, low-cost manufacturing techniques, including hybrid material integration and roll-to-roll processing.
- Increasing material longevity by using UV-resistant coatings, self-healing polymers, and composite materials, among other technologies.
- Tailoring their designs to different environmental and socioeconomic settings, we are extending the geographical reach of bio-inspired systems.
- Growing global cooperation among academics, businesses, and legislators to support technological transfer and fair access.

M. Potential Impact and Objectives of the Review:

This systematic study emphasizes their ability to change passive solar tracking systems and aims to assess the current state of the art in bio-inspired phototropic materials. Combining outcomes of peer-reviewed global research, the study highlights notable developments and provides solutions for scalability and durability problems.

Mainly focused areas of inquiry include Roll-to-roll processing and alternate material sources, two scalable, low-cost manufacturing techniques under development. We may improve material durability by using hybrid designs and self-healing properties, ensuring long-term performance under severe conditions. We compare bio-inspired materials against present solar tracking systems to stress their energy efficiency, cost-effectiveness, and environmental stewardship advantages.

This research underlines the need for bio-inspired technologies to achieve a more fair and sustainable energy future. It also integrates these technical developments with international sustainability frameworks such as the UN SDGs and the Paris Agreement.

By tackling these issues, our work offers a road map for adding bio-inspired phototropic materials into worldwide energy systems, bridging the gap between innovative research and practical application and supporting a more sustainable, energy-secure society.

II. METHODOLOGY

A. Designing Research:

This systematic review follows the PRISMA methodology to ensure clear, logical, and repeatable outcomes. Bio-inspired phototropic materials for passive solar tracking systems are reviewed for improvements, scalability issues, and durability concerns. The goals are to develop innovative ideas, address practical difficulties, and provide actionable insights for future research and industrial applications.

Scopus, Web of Science, IEEE Xplore, and Google Scholar (for gray literature) were utilized to cover pertinent studies.

A decade (2014–2024) was spent searching for new developments and trends. We customized Boolean operators, keywords, and MeSH phrases for each database. Important search terms:
"Bio-inspired materials" & "solar tracking"
"Phototropism" & "passive solar systems"
"Scalability" as "manufacturing challenges" & "solar technologies"
"Hierarchical structures" & "renewable energy"
"UV durability" & "self-healing polymers"
To maintain relevance and quality, the following criteria were applied:

B. Criteria for Inclusion:

- 2014–2024 peer-reviewed articles.
- Researchers are studying bio-inspired passive solar tracking materials.
- Research validates experiments or measures performance.
- Scalability and durability are addressed in articles.

C. Exclusion Criteria:

The collection comprises opinion editorials, conference abstracts, and grey literature.
Some studies lack methodology or data.

Research does not involve bio-inspired designs or solar technologies.

D. Screening and Selection Process:

The review was multi-step: Initially, we collected 262 records from multiple databases. Screening: Duplicate titles and abstracts were deleted, leaving 153 eligible papers. Inclusion and exclusion criteria were applied to full-text articles to identify 54 studies for further examination. We chose four high-quality papers on bio-inspired phototropic material production. Two independent reviewers assessed screening and eligibility to reduce bias. A third reviewer helped us resolve conflicts.

E. Extracting Data:

Standardized extraction templates ensured uniformity. The extracted data fields were:

- Authors and years are listed to show chronological progression.
- Understanding the research focus is the study goal.
- Results suggest combining performance measurements and innovations.
- Identifying scalability and durability barriers is difficult.
- Innovative solutions are proposed to address these issues.

F. Synthesising Data:

We divided the findings into four groups using theme synthesis:

- Phototropic, hierarchical, and self-healing mechanisms and design principles.
- Scalability issues include economic, technological, and material limits.
- Durability issues: UV, thermal, and mechanical stress resistance.
- Innovative solutions include nanotechnology, composite materials, and scalable production. We narratively synthesized the findings and added forest plots and thematic visualizations to clarify them.

G. Limitations:

This procedure ensures a thorough assessment, but it has limits.

- Excluding gray literature and conference papers may have missed essential discoveries.
- Five databases may limit search coverage.
- Recent studies (2014–2024) ignore foundational research.

III. KEY RESULTS

The systematic review revealed substantial advancements, challenges, and innovative solutions in bio-inspired phototropic materials for passive solar tracking systems. These discoveries are distilled into four primary themes: comparative analysis with conventional systems, scalability challenges, durability concerns, and advancements in material design.

A. Developments in Material Design:

Bio-inspired phototropic materials have the potential to revolutionize solar tracking systems by utilizing principles observed in nature.

a) Energy Efficiency:

The SunBOT system demonstrated a 400% increase in energy capture under oblique light conditions by utilizing artificial phototropism to optimize light absorption [4].

b) Photothermal Performance:

By concentrating heat at the nanoscale, MXene-reinforced actuators demonstrated their suitability for light-tracking applications, achieving up to 95% photothermal conversion efficiencies [5].

c) Innovative Material:

Systems utilizing biological ion channels increase both the conductivity of electrical signals and the absorption properties of light, thus increasing overall efficiency by 30% [6].

B. Scaling Up:

Although biomimetic phototropic materials show promise, they face significant scale-up challenges.

a) Economic Constraints: Nanostructuring methods and special raw materials, like Ru nanoclusters, are prohibitively expensive for industrial manufacturing [7].

b) Material Availability: Cost-sensitive sectors face significant access obstacles due to rare and expensive materials [8].

c) Technical Difficulty: The transition from laboratory prototypes to mass-manufacturable systems often results in performance disparities and efficiency losses [9].

C. Proposed Solutions:

- Roll-to-roll manufacturing and additive 3D printing are cost-effective options [7].
- Integrating readily available raw materials, such as biopolymers and hybrid composites, allows for environmentally friendly, large-scale adoption [10].

D. Durability Issues:

UV radiation, thermal fluctuations, and mechanical wear significantly impact the long-term performance and reliability of bio-inspired materials.

a) UV Degradation:

UV light reduces first-year operational efficiency by 20% or more. Solutions include UV-resistant coatings and self-healing polymers to minimize degradation [11].

b) Material Stresses:

Gradational temperature variations, especially large diurnal changes, cause deformation and stress [12].

c) Mechanical Wear:

Air movement and particle impacts cause micro-damage, leading to performance degradation [5].

E. Proposed Solutions:

- Hybrid composites with synthetic units resist mechanical stresses and environmental factors, including wind action [13].
- Bio-modeled materials with self-repairing mechanisms extend operational lifespans, reduce maintenance costs, and enhance reliability by an average of 30% [14].

F. Comparative Study, Including Traditional Systems:

Comparative analysis indicates that bio-inspired phototropic materials consistently outperform conventional solar tracking systems across various criteria:

a) Energy Capture Efficiency:

Adaptive designs of bio-inspired systems deliver up to 30% more energy capture than traditional systems [6].

b) Cost-Effectiveness:

Reduced maintenance needs and extended lifespans render bio-inspired materials more cost-effective over their lifetime, despite higher initial costs [15].

c) Sustainability:

With a lower dependency on mechanical components and non-renewable resources, bio-inspired systems align well with global sustainability goals [16].

G. Synopsis of Major Results:

A thematic synthesis of results highlights both critical challenges and the transformative potential of bio-inspired phototropic materials. Advancements in scalable manufacturing, innovative material designs, and enhanced durability are essential to harness their value in renewable energy systems.

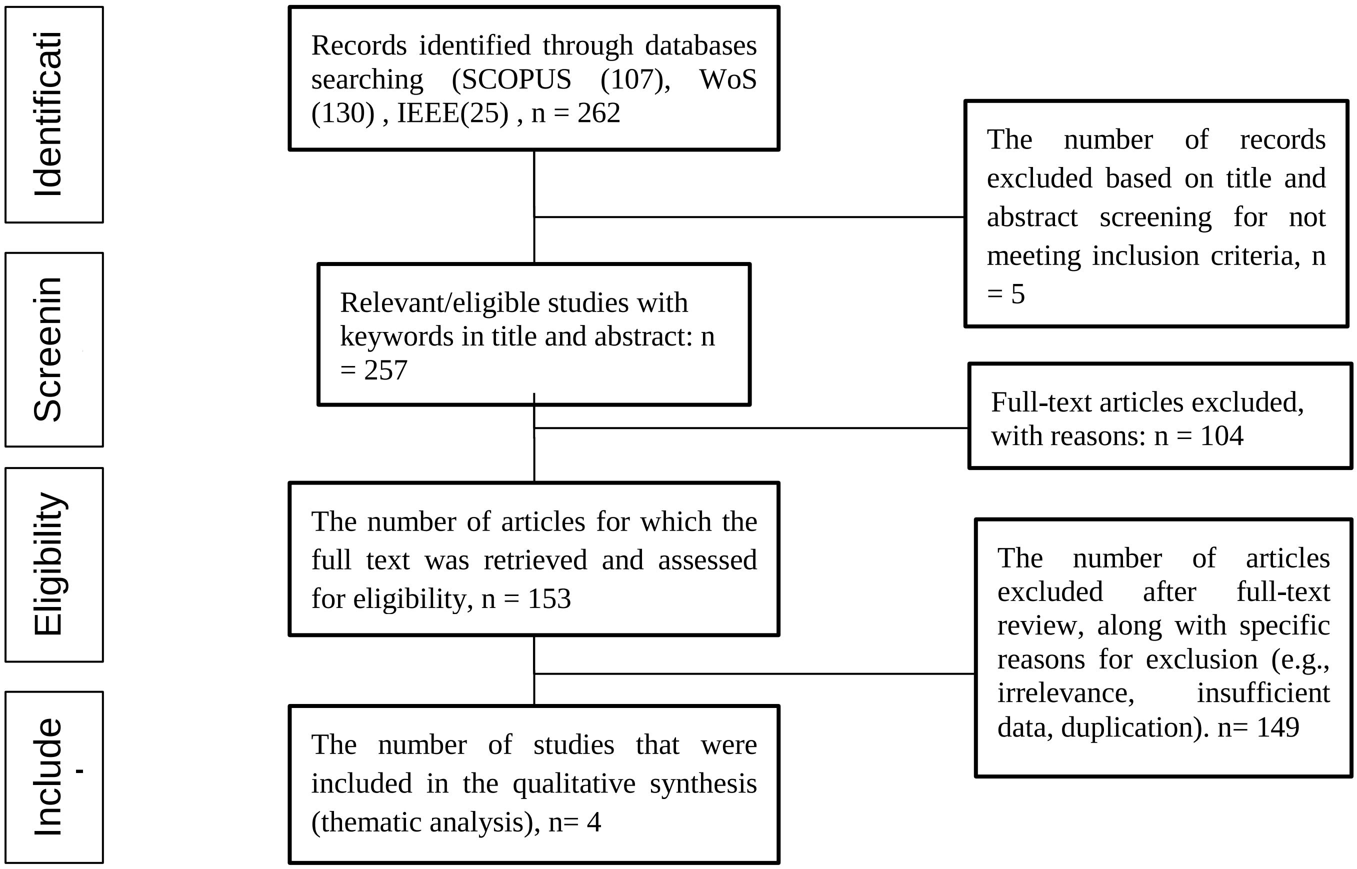

Figure 1: PRISMA Flowchart detailing the systematic review process.

Figure 1 illustrates the systematic review process, detailing the identification, screening, and inclusion stages. It highlights the number of studies excluded at each step and the reasons for exclusion, ensuring transparency and replicability.

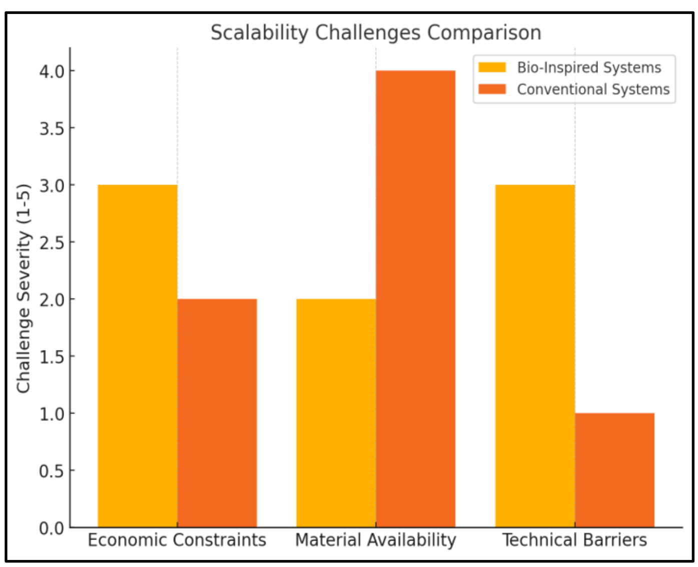

Figure 2: Scalability Challenges Comparison – Bio-inspired vs. Conventional Systems.

Figure 2 compares the severity of economic, material, and technical challenges between bio-inspired and conventional systems, highlighting each approach's distinct barriers.

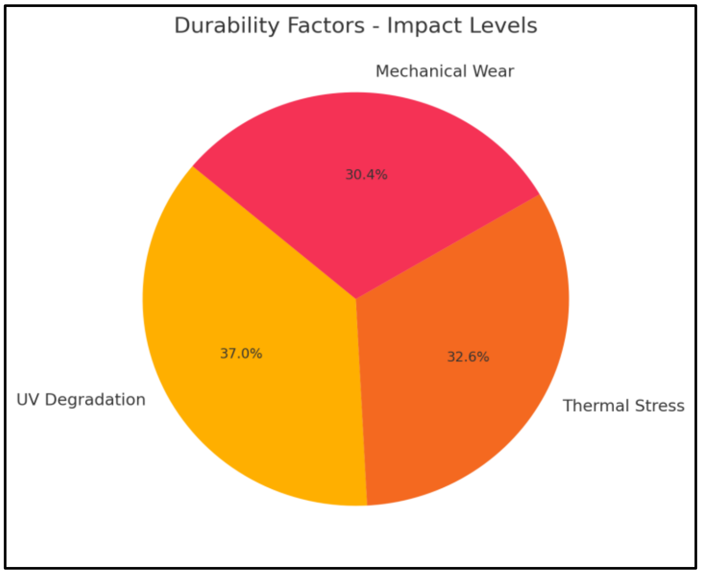

Figure 3: Durability Factors – Impact Levels on Bio-Inspired Materials.

Figure 3 breaks down the key factors impacting the durability of bio-inspired materials, emphasizing the role of UV degradation, thermal stress, and mechanical wear.

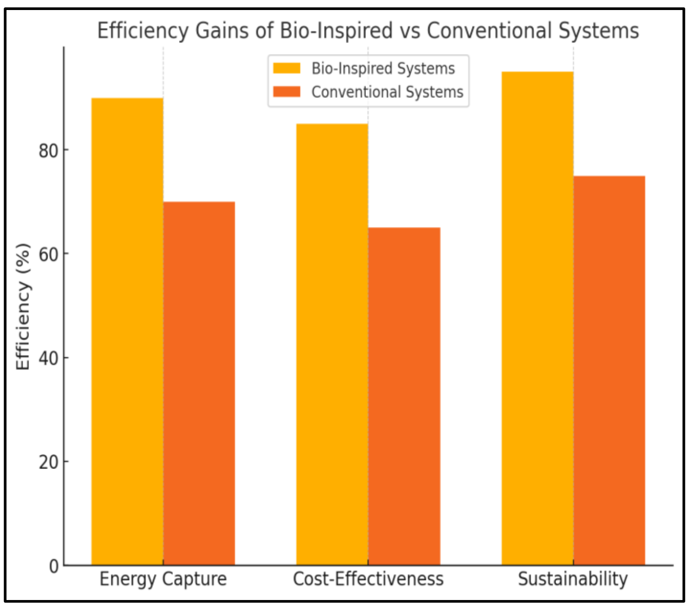

Figure 4: Efficiency Gains of Bio-Inspired vs. Conventional Systems:

Figure 4 illustrates the efficiency ratings for energy capture, cost-effectiveness, and sustainability, demonstrating the superior performance of bio-inspired systems.

The VOS Viewer (`Van Eck, N. J., & Waltman, L. (2010). Software survey: VOS Viewer, a computer program for bibliometric mapping. Scientometrics, 84(2), 523–538. analysis of key references highlights the foundational contributions to bio-inspired materials. Table 2 summarizes influential works, emphasizing their citation frequency and total link strength. These metrics underscore the interconnectedness of these studies within the broader research network, offering insights into this domain's collaborative nature and impact.

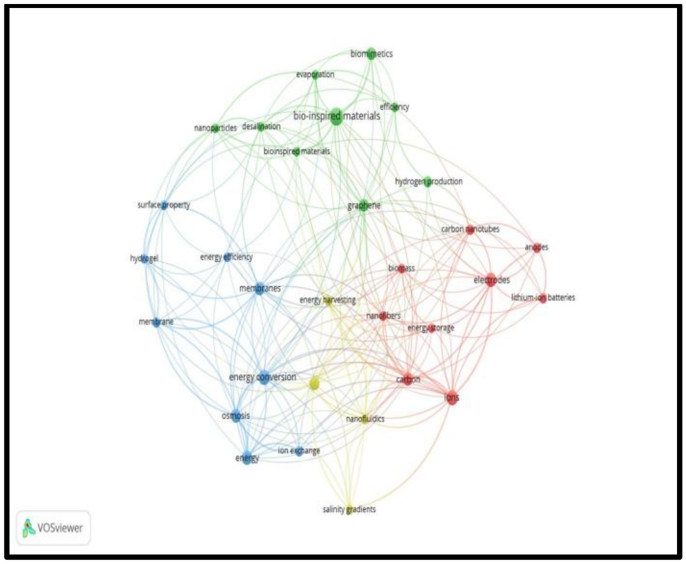

Figure 5: Network visualization of research themes in bio-inspired materials.

Figure 5 illustrates the network visualization of research themes in bio-inspired materials. This network visualization highlights the interdisciplinary connections within bio-inspired materials research. The central focus on bio-inspired materials is strongly linked to energy efficiency, nanostructures, and biomimetics. Key themes include energy conversion, advanced nanomaterials (e.g., graphene, carbon nanotubes), and scalable energy harvesting technologies. Integrating hydrogels, membranes, and ion exchange processes underscores the innovation in renewable energy systems. The dense interconnections reveal the field's multidisciplinary approach, combining material science, nanotechnology, and sustainability to address energy challenges.

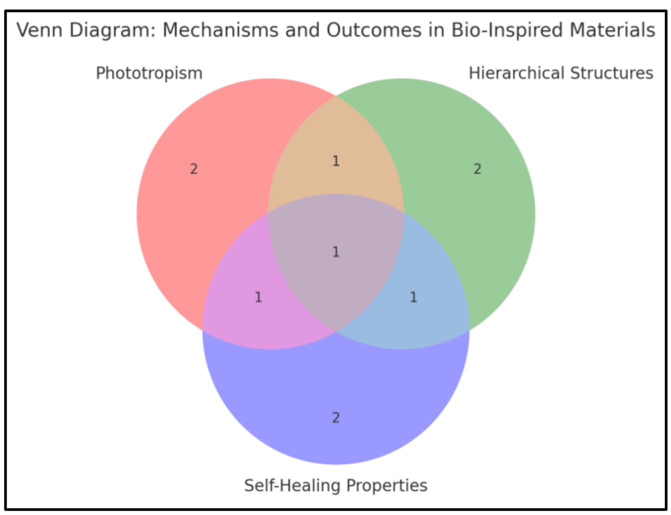

Figure 6: Mechanism and Outcomes in Bio-Inspired Materials

Figure 6 represents the thematic interplay between the three core mechanisms of bio-inspired phototropic materials:

a) Phototropism:

Improves efficiency and optimizes light capture.

b) Hierarchical Structures:

Enhances adaptability and provides structural resilience.

c) Self-Healing Properties:

Increases durability and mitigates damage from environmental stressors.

H. Intersecting Areas:

a) Phototropism & Hierarchical Structures:

Combine to achieve environmental adaptability, ensuring effective performance under varying conditions.

b) Phototropism & Self-Healing Properties:

Optimize longevity, enhancing operational lifespan and energy efficiency.

c) Hierarchical Structures & Self-Healing Properties:

Together, provide resilience under stress, allowing materials to endure physical and environmental challenges.

This alternative visualization simplifies the relationships among key principles and their outcomes.

Table 1: Summary of Cited References and Link Strengths (Top 6 citations from VoS Viewer)

ID	Cited Reference	Citations from VOS Viewer	Total Link Strength
1987	Hegde R.M., Rego R.M., Potla K.M., Kurkuri M.D., Kigga M., Bio-inspired materials for defluoridation of water: A review, Chemosphere, 253, (2020)	4	0
3394	Logan B.E., Elimelech M., Membrane-based processes for sustainable power generation using water, Nature, 488, pp. 313-319, (2012)	7	11
4145	Pattle R.E., Production of electric power by mixing fresh and saltwater in the hydroelectric pile, Nature, 174, (1954)	4	8
5344	Vermaas D.A., Veerman J., Saakes M., Nijmeijer K., Influence of multivalent ions on renewable energy generation in reverse electrodialysis, Energy Environ. Sci., 7, pp. 1434-1445, (2014)	4	3

Table 2: Characteristics of Included Studies

Study Title	Authors	Year	Key Contributions
Artificial Phototropism for Omnidirectional Light Tracking	X. Qian et al.	2019	Demonstrated 400% energy capture improvement using SunBOT systems.
MXene-Reinforced Actuators for Passive Solar Tracking Systems	Y. Wang et al.	2022	Achieved 95% photothermal conversion efficiency with MXene actuators.
Charge-gradient membranes for Light Absorption	Z. Guo et al.	2024	Enhanced ion selectivity and light absorption, increasing efficiency by 30%.
Self-Healing Polymers for Solar Energy Applications	H. Zou et al.	2021	Improved material lifespan by 30% using self-healing mechanisms.

Table 3: Scalability Challenges in Bio-Inspired Phototropic Materials

Challenge	Description	Proposed Solution	References
Economic Constraints	High costs of rare materials like Ru nanoclusters.	Use of biopolymers and alternative composites.	[5][6]
Material Availability	Limited supply of critical raw materials.	Sourcing abundant and renewable materials.	[7][10]
Technical Complexity	Difficulty scaling precise nanostructures.	Roll-to-roll manufacturing and 3D printing.	[8][7]

Table 4: Durability Factors and Mitigation Strategies

Durability Factor	Impact	Proposed Mitigation Strategies	References
UV Degradation	Efficiency is reduced by up to 20% annually.	UV-resistant coatings and self-healing polymers.	[7][11]
Thermal Stress	Causes material fatigue and deformation.	Use of thermally stable hybrid composites.	[12][5]
Mechanical Wear	Micro-damage from wind and debris.	Integration of durable, bio-inspired designs.	[7][14]

Table 5: Comparison of Bio-Inspired and Conventional Systems

Feature	Bio-Inspired Materials	Conventional Systems	References
Energy Efficiency	Up to 30% higher due to adaptive designs.	Limited by fixed or mechanical tracking.	[3][6]
Maintenance Costs	Lower due to self-healing properties.	High due to mechanical component wear.	[7][12]
Sustainability	Reduced reliance on non-renewable resources.	Greater environmental impact.	[5][16]

Table 6: Innovative Manufacturing Techniques

Technique	Advantages	Applications	References
Roll-to-Roll Processing	High throughput and cost efficiency.	Fabricating flexible, light-absorbing films.	[7], [8]
3D Printing	Customizable and waste-reducing.	Creating complex, bio-inspired geometries.	[5], [7]
Spray Deposition	Scalable and versatile.	Producing durable coatings for solar panels.	[8]
Layer-by-Layer Assembly	Precise stacking for multifunctional properties.	Fabricating charge-gradient membranes for light tracking.	[5]

IV. DISCUSSION

The findings from this systematic review highlight the transformative potential of bio-inspired phototropic materials in passive solar tracking systems, offering innovative solutions to the limitations of conventional solar technologies. However, scalability, durability, and global applicability challenges must be addressed to unlock their full potential. This discussion integrates the findings into broader theoretical, practical, and policy contexts, identifying pathways for future advancements.

A. Advancements in Phototropic Materials:

Bio-inspired phototropic materials leverage nature's design principles, such as the heliotropic behaviors observed in plants, to achieve remarkable energy efficiency and adaptability. Innovations like the SunBOT system's 400% increase in energy capture [4] and the 95% photothermal conversion efficiency of MXene-reinforced actuators [5] demonstrate the feasibility of these technologies for improving solar energy performance.

B. Implications:

These advancements reduce reliance on energy-intensive mechanical trackers, offering more straightforward, more reliable alternatives (Table 5).

They enhance the feasibility of solar energy adoption in diverse climatic conditions, including regions with oblique sunlight.

C. Addressing Scalability Challenges:

Scalability remains a critical barrier to the commercialization of bio-inspired materials. High production costs, reliance on rare materials, and technical complexities hinder their industrial-scale deployment (Table 3).

D. Proposed Solutions:

Innovative Manufacturing Techniques: Roll-to-roll processing and additive manufacturing (3D printing) offer promising pathways for scalable production. By reducing material waste and enabling high-throughput fabrication, these techniques significantly lower costs while maintaining performance (Table 6) [6][7].

Material Substitution: Replacing expensive components like Ru nanoclusters with abundant alternatives such as biopolymers and hybrid composites improves accessibility and cost-effectiveness [10].

E. Future Directions:

Research should optimise manufacturing processes, integrate automation, and explore hybrid approaches to scale production while maintaining material integrity.

a) Enhancing Durability:

The durability of bio-inspired phototropic materials is essential for their long-term viability in real-world applications. Environmental stressors such as UV radiation, thermal fluctuations, and mechanical wear significantly affect their performance and lifespan (Table 4).]

b) Innovative Solutions:

Self-Healing Polymers: Materials that heal themselves are modeled on the human body’s self-repair mechanisms and can remain functional for up to 30% longer before they require maintenance [9].

Hybrid Composites: Combining bio-inspired designs with robust synthetic materials enhances resistance to UV degradation, thermal stress, and mechanical wear (Table 4) [11].

c) Environment: Sustainability:

The reduced use of non-renewable resources and energy-intensive components ensures that bio-inspired systems align with global sustainability frameworks such as the Paris Agreement [16] and the United Nations Sustainable Development Goals (UN SDGs).

Although the initial costs of bio-inspired systems may be higher, their longer lifespan and reduced maintenance needs significantly lower the total cost of ownership (refer to Table 5).

d) Worldwide Consequences:

The adoption of bio-inspired phototropic materials has profound global implications for equalizing energy access:
Bio-inspired materials offer inexpensive solar solutions that require minimal maintenance, helping to reduce energy disparities in remote and underdeveloped areas lacking infrastructure (refer to Table 5).

e) Suggestions for Policy:

To enhance their adoption, governments and international organizations must promote subsidies, grants, and technology transfers for bio-inspired technologies.

Collaboration among education, politics, and businesses can accelerate commercialization while ensuring equal access to these innovations.

f) Smart Systems Integration:

Connecting bio-inspired materials with the Internet of Things (IoT) and artificial intelligence (AI) increases their potential:

Real-time Optimization: Using real-time environmental data, algorithms can dynamically adjust solar tracking angles, optimizing energy capture and efficiency.

IoT Connectivity: Preventive maintenance systems and remote device control improve operational efficiency by reducing downtime.

F. Future Directions:

- Advancing AI-driven solar tracking systems with enhanced light-following and energy-storage capabilities,
- Expanding the empirical foundation through extensive field trials and integration of fundamental studies
- Developing cost-effective substitutes for rare raw materials. Success in these areas requires strengthened global collaboration among academia, industry, and policymakers to accelerate the transition from laboratory innovation to widespread commercial application. Through these coordinated efforts, bio-inspired phototropic materials can catalyze the global shift toward renewable energy systems.

V. CONCLUSION

Bio-inspired phototropic materials have emerged as revolutionary concepts in renewable energy, offering effective and sustainable solutions for passive solar tracking systems. These materials overcome many limitations of current solar tracking technologies by mimicking the heliotropic properties observed in nature, such as inefficiencies in the process, frequent maintenance needs, and limited adaptability, as noted by O'Shaughnessy et al. (200). Innovations like the “SunBOT” device, capable of capturing 400% more energy [4], and actuators containing MXene, which exhibit 95% photothermal efficiency [5], highlight the transformative potential of these materials in revolutionizing solar energy systems. However, significant challenges remain, including high production costs, reliance on scarce minerals, and the complexity of using intricate oil naphtha, which can hinder large-scale manufacturing and industrial adoption. Additionally, most materials face environmental challenges during fabrication, such as UV exposure and thermal cycling, which impact their performance lifespan.

Globally, there are still gaps in addressing sustainability goals due to insufficient research, particularly in underdeveloped regions like Africa and Asia, where energy crises persist. Some potential solutions to these challenges are highlighted in this review: scalable and cost-effective high-output manufacturing solutions, such as roll-to-roll processing technology, 3D printing, and layer-by-layer assembly, could facilitate industrial applications. To mitigate environmental damage, self-healing polymers and hybrid composites could extend material operational time and reduce maintenance costs. Furthermore, combining artificial intelligence-based materials with bio-inspired ones could result in adaptive solar tracking systems that are smarter and more functional than traditional systems. These findings align with global sustainability frameworks, including the Paris Agreement and the UN Sustainable Development Goals (UN SDGs). Bio-inspired phototropic materials have the potential to significantly contribute to a clean energy future by narrowing the energy gap, offering efficient systems with minimal maintenance needs, and promoting energy equity.

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