



ORIGINAL RESEARCH PAPER

Engineering

SUSTAINABLE MATERIALS AND COMPOSITE APPLICATIONS: A REVIEW

KEY WORDS: Basalt fiber composites, electronic waste management, carbon storage, SiO₂-based supercapacitors, sustainable materials, circular economy, printed circuit boards (PCBs), recycling technologies, energy storage, biodegradable materials.

Mr. Shyam Sankar S	Research Schooler, Department of Mechanical Engineering, Adhiyamaan College of Engineering (Autonomous), Hosur
Mr. Shylin S Jose	Assistant Professor, Department of Mechanical Engineering, Adhiyamaan College of Engineering (Autonomous), Hosur
Dr. S. V. Suresh Babu	Head of Mechanical Department, Adhiyamaan College of Engineering (Autonomous), Hosur

ABSTRACT The advancement of materials science has led to significant developments in sustainable materials and their applications. This paper reviews recent research in basalt fiber composites, electronic waste management, carbon storage in basalt formations, and SiO₂-based supercapacitor electrodes. Key findings indicate that basalt fibers offer superior mechanical properties and environmental benefits, sustainable electronic waste management techniques enhance recyclability, and carbon storage in basalt formations shows promise for climate change mitigation. Additionally, SiO₂-based supercapacitors contribute to efficient energy storage solutions. The review emphasizes the importance of integrating these materials into engineering and electronic applications to promote sustainability.

INTRODUCTION

The increasing demand for sustainable and high-performance materials has driven extensive research into basalt fiber composites, carbon sequestration, and waste reduction technologies. Basalt fibers, derived from volcanic rock, are gaining prominence due to their excellent mechanical properties and environmental benefits. Similarly, advancements in electronic waste management and supercapacitor electrode materials highlight the need for innovative recycling and energy storage solutions. The integration of sustainable materials in printed circuit boards (PCBs) and related electronic components is a crucial step toward achieving a circular economy. However, challenges such as material compatibility, thermal stability, manufacturing costs, and performance trade-offs hinder widespread adoption. Developing scalable production techniques and ensuring industry compliance with sustainability standards remain key obstacles in this transition.

Basalt Fiber Composites Mechanical Properties and Applications

Basalt fibers exhibit superior mechanical properties compared to traditional glass fibers. They offer high tensile strength, excellent thermal stability, and superior resistance to chemical degradation. Studies on basalt fiber-reinforced polymer composites have shown improved durability and flexural properties, making them ideal for aerospace, automotive, and construction applications. Their cost-effectiveness and recyclability further contribute to their adoption in industrial applications.

Moisture Absorption and Aging Behavior

Research indicates that basalt fiber composites absorb less moisture compared to glass fibers, leading to enhanced long-term stability in humid environments. The impact of moisture absorption on mechanical properties, such as tensile and flexural strength, has been analyzed through water immersion tests, demonstrating the suitability of basalt composites for marine and structural applications.

Carbon Storage in Basalt

Basalt formations have emerged as a promising medium for carbon dioxide sequestration. However, challenges such as the high cost of carbon capture, the energy-intensive nature of CO₂ injection, and the long-term monitoring required to ensure stable mineralization remain barriers to widespread adoption. The mineralization process converts CO₂ into stable carbonate minerals, effectively reducing atmospheric carbon

levels. Field studies, such as those conducted in the CarbFix project in Iceland, have demonstrated rapid mineralization rates, where injected CO₂ reacts with basalt formations to form stable carbonate minerals within two years. This highlights basalt's significant potential in mitigating climate change. The ability to store large volumes of carbon within basalt formations makes this method an attractive long-term solution for industrial emissions.

Electronic Waste Management and Circular Economy

The linear economy model in electronics manufacturing has led to significant waste production. Sustainable approaches, such as biodegradable printed circuit boards and resource-efficient manufacturing, aim to minimize environmental impact. However, challenges such as high production costs, limited scalability, and the need for industry-wide adoption hinder widespread implementation. Advances in material selection and processing techniques enhance recyclability, promoting a circular economy for electronic waste. Innovations such as bio-based resins, recyclable thermoplastics, and advanced metal recovery techniques have significantly improved material reuse. Additionally, the development of lead-free soldering and modular electronic components has facilitated easier disassembly and recycling, reducing the environmental footprint of discarded PCBs. Electronic waste recycling methods, including physical separation, chemical extraction, and advanced pyrolysis techniques, are being developed to improve recovery rates of valuable metals from discarded PCB.

SiO₂-Based Composite Electrodes for Supercapacitors

Silicon dioxide (SiO₂)-based composite electrodes have been extensively studied for supercapacitor applications. Despite challenges related to low electrical conductivity, coating and nanostructuring techniques have improved performance metrics. The integration of SiO₂ with conductive materials enhances electrochemical properties, paving the way for high-energy-density storage solutions. These advancements contribute to the development of more efficient and environmentally friendly energy storage systems.

Methodology

This review employs a systematic approach by analyzing relevant literature on basalt fiber composites, carbon storage, and electronic waste management, particularly focusing on printed circuit board (PCB)-related factors. Sources were gathered from peer-reviewed journals, conference proceedings, and scientific databases such as ScienceDirect, IEEE Xplore, and SpringerLink to ensure a comprehensive

and high-quality analysis. The methodology involves:

- Reviewing the structural and mechanical properties of basalt fibers and their composite applications.
- Examining studies on carbon storage mechanisms in basalt formations.
- Analyzing PCB-related waste management strategies, including material composition, recycling technologies, and sustainability factors.
- Evaluating the role of SiO^2 -based electrodes in enhancing supercapacitor performance with applications in PCB technology.
- Investigating the use of eco-friendly resin systems and conductive inks in PCB manufacturing.
- Assessing advancements in biodegradable PCB substrates and their potential impact on electronic waste reduction.
- Synthesizing findings to assess the potential of these materials in promoting sustainability and a circular economy.

CONCLUSION

The research on basalt fiber composites, carbon storage, electronic waste management, and supercapacitor electrodes underscores the potential of sustainable materials in modern engineering. The transition towards environmentally friendly materials and circular economy practices will play a crucial role in addressing global sustainability challenges, particularly in industries such as electronics, construction, and automotive manufacturing, where material sustainability and waste management are pressing concerns. As industries move towards greener technologies, the integration of basalt fibers and recyclable materials in PCB production presents a viable pathway for reducing the ecological footprint of electronics manufacturing.

REFERENCES

1. Yan et al. (2020). Review of research on basalt fibers and basalt fiber-reinforced composites.
2. Pandian et al. (2014). Effect of moisture absorption behavior on mechanical properties of basalt fiber composites.
3. Gislason & Oelkers (2014). Carbon storage in basalt formations.
4. Chakraborty et al. (2022). Electronic waste reduction through devices and printed circuit boards designed for circularity.
5. Sajjad (2021). Recent advances in SiO^2 -based composite electrodes for supercapacitor applications.
6. Pareek & Saha (2019). Basalt fiber and its composites: An overview.
7. Subagia & Kim (2013). A study on flexural properties of carbon-basalt/epoxy hybrid composites.
8. Wang et al. (2018). Thermally conductive boron nitride nanosheet composite paper for flexible PCBs.
9. Rajagopal et al. (2016). Activated carbon derived from non-metallic PCB waste for supercapacitor applications.
10. Oelkers et al. (2014). Advances in carbon capture and storage in basalt formations.
11. Chakraborty et al. (2022). Sustainable electronic waste management and circular economy approaches.
12. Liu et al. (2021). Recent developments in SiO^2 -based composite materials for energy applications.
13. Dahiya et al. (2022). Emerging trends in flexible electronics and biodegradable PCBs.
14. Tuo et al. (2021). Physicochemical properties of basalt fibers and their reinforced composites.
15. Bhat et al. (2016). Utilization of PCB waste for carbon-based energy storage solutions.