

Environmental and Health Impacts of Sustainable Materials: A Risk–Benefit Perspective

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Abstract—Sustainable materials are increasingly adopted to minimize environmental footprints and promote human health. This review critically examines the environmental and health impacts of sustainable materials from a risk–benefit perspective. While sustainable materials — including bio-based composites, recycled aggregates, and green building components — offer significant advantages in reducing emissions and toxic exposures, emerging evidence highlights potential unintended impacts and uncertainties that warrant comprehensive assessment. The review integrates life cycle studies, toxicological evidence, and policy considerations to balance the benefits and risks associated with sustainable material deployment.

Keywords— Sustainable materials, Human health, Environment risk, Green Materials

I. INTRODUCTION

Sustainable materials are designed to reduce ecological degradation and health hazards associated with conventional materials derived from non-renewable resources. As global efforts toward sustainability intensify, there is growing interest in replacing traditional industrial materials with alternatives that are renewable, recyclable, or less toxic. Sustainable materials are central to the United Nations Sustainable Development Goals (SDGs), particularly in enabling responsible consumption and production, climate action, and healthy living environments.

However, even materials with sustainability labels may pose environmental stresses or human health risks across their life cycle — from raw material extraction to disposal. Therefore, a risk–benefit perspective is essential to understand whether the adoption of sustainable materials genuinely improves environmental and health outcomes across their entire life span.

II. DEFINING SUSTAINABLE MATERIALS

Sustainable materials broadly include:

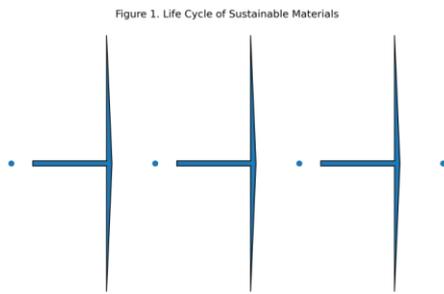
- Bio-based materials derived from renewable resources (e.g., agricultural biomass, plant oils).
- Recycled and reuse materials such as recycled concrete powder or industrial waste-based cementitious compounds.
- Green materials developed to minimize toxic emissions during production, use, and disposal.
- Low-impact composites that reduce reliance on fossil fuels and hazardous additives.

These materials are often evaluated using life cycle assessment (LCA), which measures energy use, greenhouse gas emissions, toxicity potential, and resource depletion throughout the material’s life cycle.

Table 1. Classification of Sustainable Materials and Key Applications

Sustainable Material Type	Source	Major Applications	Key Sustainability Advantage
Bio-based polymers	Plants, biomass	Packaging, textiles	Renewable, low carbon
Recycled composites	Industrial waste	Construction	Waste reduction
Green building materials	Natural minerals	Housing	Improved indoor air quality
Biodegradable materials	Natural polymers	Medical, packaging	Reduced persistence

Figure-1 Life Cycle of Sustainable Materials



emissions compared to conventional counterparts. For example, integrating recycled concrete powder (RCP) in concrete mixes substantially lowers environmental impacts such as resource depletion and ozone-depleting emissions, with mixes containing 15% RCP showing pronounced reductions in emissions categories such as ozone depletion and photochemical oxidant formation. [frontiersin.org](https://www.frontiersin.org)

Similarly, industrial waste-based cementitious materials can reduce reliance on virgin cement, which is highly energy intensive and contributes to large volumes of CO₂ emissions during production. MDPI

III. ENVIRONMENTAL BENEFITS

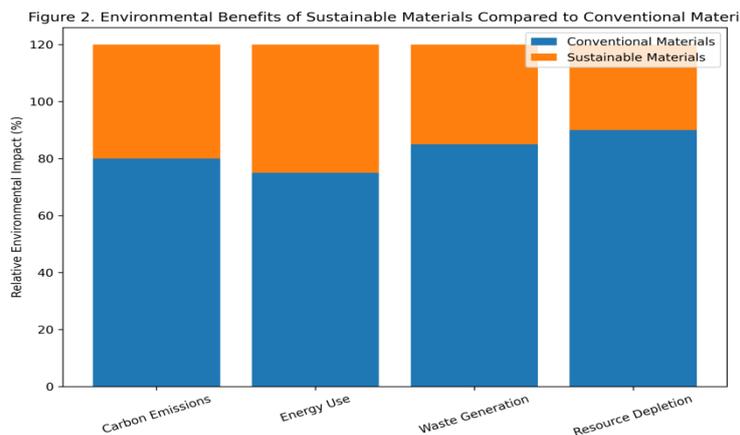
3.1 Reduced Carbon Footprint and Resource Use

One of the most significant benefits of sustainable materials is the reduction of greenhouse gas

Table 2. Environmental Benefits of Sustainable Materials

Impact Category	Conventional Materials	Sustainable Materials
Carbon emissions	High	Low
Energy consumption	High	Moderate to low
Waste generation	Significant	Reduced
Resource depletion	Non-renewable	Renewable / recycled

Figure 2- Environmental Benefits of Sustainable Materials Compared to Conventional Materials



3.2 Less Pollution and Waste Generation

Sustainable materials often promote circular economy principles that reduce waste generation. By reclaiming industrial by-products (e.g., fly ash, slag) and agricultural residues, the environmental burden of landfill disposal and harmful pollutants can be mitigated.

contaminants that contribute to respiratory problems, headaches, and long-term chronic diseases. Sustainable materials — particularly green building materials (GBMs) constructed from non-toxic, natural compounds — are associated with reduced VOC emissions and have lower overall human health impacts. PubMed+1

IV. HUMAN HEALTH BENEFITS

4.1 Lower Toxic Exposure

Conventional building materials often emit volatile organic compounds (VOCs) and other indoor air

When properly manufactured and certified, such materials can improve indoor air quality and reduce toxic exposures in living and working environments, directly benefiting occupant health.

Table 3. Health Benefits and Potential Risks of Sustainable Materials

Aspect	Benefits	Potential Risks
Chemical exposure	Reduced VOCs	Legacy contaminants
Indoor air quality	Improved	Additive emissions
Occupational health	Safer processing	Inadequate hazard screening
End-of-life	Lower toxicity	Unknown degradation products

V. POTENTIAL RISKS AND CHALLENGES

Despite many benefits, sustainable materials are not without potential risks:

5.1 Chemical Risks and Unintended Exposures

A recent global health assessment of synthetic chemicals highlights how widespread use of additives like phthalates, bisphenols, pesticides, and per- and polyfluoroalkyl substances (PFAS) in material applications can drive significant health burdens — estimated at \$2.2 trillion annually — including endocrine disruption, cancers, and developmental disorders.

The Guardian Although many sustainable materials reduce reliance on harmful substances, there is no universal guarantee that all bio-based or recycled materials are free from chemical hazards. For example, recycled composites may contain legacy contaminants that were introduced during previous applications.

5.2 Material Performance and Degradation Products

Another concern arises from the long-term stability of sustainable materials. Some bio-based polymers may degrade differently than conventional equivalents, potentially releasing microplastics,

degradation products, or by-products that affect ecosystems or human health if not safely managed.

VI. LIFE CYCLE AND TOXICOLOGICAL ASSESSMENT

A comprehensive risk–benefit analysis must incorporate life cycle assessment (LCA) and toxicological evaluation. Tools such as OpenLCA software and ReCiPe impact assessment methodologies allow integrated evaluation of environmental and human health impacts over a material’s entire life span.

For example, LCA studies comparing bio-based composites with petroleum-based composites demonstrate more than a 50% reduction in human health impacts by switching to bio-based alternatives, indicating robust environmental and health benefits when sustainable materials are thoughtfully designed and assessed. IDEAS/RePEc However, LCA outcomes can vary widely based on assumptions regarding energy sources, manufacturing processes, end-of-life scenarios, and geographic context, underscoring the need for standardized assessment frameworks.

Table 4. Life Cycle Assessment Tools Used for Sustainable Materials

Tool / Method	Purpose	Key Impact Categories
ISO 14040/44	LCA framework	Environmental impacts
ReCiPe	Impact assessment	Human health, ecosystems
USEtox	Toxicity modeling	Human toxicity
OpenLCA	Software tool	Multi-impact evaluation

VII. POLICY AND REGULATORY CONSIDERATIONS

For sustainable materials to deliver on their promise, regulatory frameworks must evolve to incorporate hazard screening, standardized labeling, and safety assessments. Policies should require transparent disclosure of material compositions, life cycle impacts, and compliance with health and environmental safety standards.

Emerging international environmental agreements are increasingly indicating such approaches, but oversight remains inconsistent across jurisdictions.

VIII. FUTURE RESEARCH DIRECTIONS

- Standardized LCA protocols: To ensure comparability and transparency in sustainability claims.

- Toxicological profiling of new materials: Including long-term exposure assessments and breakdown product analysis.
- Real-world monitoring studies: To validate laboratory and model-based findings.
- Material recycling innovation: To limit contamination pathways and hazardous remnants in circular systems.

IX. CONCLUSION

Sustainable materials present important opportunities to reduce environmental degradation and human health hazards relative to conventional alternatives. Their adoption aligns with global sustainability goals and delivers clear benefits, especially in terms of emissions reduction and lower toxic exposures in building environments.

However, it remains critical to evaluate sustainable materials from a risk–benefit perspective across their entire life cycle, considering potential chemical risks, performance limitations, and environmental trade-offs. By coupling rigorous life cycle assessment with comprehensive regulatory oversight and continued research, sustainable materials can fulfill their promise as safer, healthier, and more environmentally responsible alternatives.

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