

Chapter-14

Smart Materials and Emerging Green Technologies for a Cleaner Future

Tushar Mukhtaram Dalimbkar¹, Onkar Suresh Dhindale²

¹SET, Pursuing PhD, M.Sc. Organic Chemistry, Assistant Professor, Department of Chemistry, Chandmal Tarachand Bora, College of Arts, Commerce and Science, Shirur

² NET, Pursuing PhD, M.Sc. Analytical Chemistry, Assistant Professor, Department of Chemistry, Chandmal Tarachand Bora College of Arts, Commerce and Science, Shirur

Email- dalimbkartushar2724@gmail.com

Abstract

The global transition toward sustainability demands transformative technological advancement in energy systems, environmental protection, and materials engineering. While renewable energy solutions such as solar and wind are widely deployed, next-generation technologies—ranging from perovskite photovoltaics to hydrogen fuels, carbon-negative materials, and bio-inspired manufacturing—are redefining how energy is produced, stored, and consumed. Concurrently, breakthroughs in environmental remediation, such as nanomaterial-based water purification, advanced carbon capture, and AI-driven monitoring, are addressing the growing pressures on ecosystems. Sustainable materials, including biodegradable polymers, mycelium composites, and recyclable thermosets, are accelerating the shift toward circular economies. This expanded chapter provides an in-depth analysis of these technologies, evaluating their scientific foundations, engineering challenges, environmental implications, and future deployment pathways.

Introduction

Humanity stands at a pivotal moment. Climate change, biodiversity loss, increasing pollution, and rising energy demands are simultaneously intensifying, threatening ecological stability and economic well-being. Traditional industrial systems—built on fossil fuels, linear resource use, and environmentally harmful materials—are inadequate for achieving a sustainable global future. In response, researchers, policymakers, and industries are investing in advanced technologies that can accelerate the transition toward environmental resilience and climate neutrality. This chapter explores the intersection of three interconnected domains: energy innovation, environmental protection, and sustainable materials. These fields cannot be treated separately; each directly influences the others. For instance, renewable energy requires efficient storage solutions, while sustainable materials reduce the embedded carbon footprint of clean technologies. Similarly, environmental systems benefit from circular material strategies and clean energy adoption. The chapter provides a comprehensive, science-based, and forward-looking analysis of emerging innovations capable of driving a greener future.

Emerging Energy Technologies

1. Next-Generation Solar Energy

Solar energy is already the fastest-growing renewable technology, but emerging innovations promise an even more profound transformation of global energy systems.

1.1. Perovskite Solar Cells

Perovskites—crystal structures defined by the formula ABX_3 —have revolutionized photovoltaic research. Their key benefits include:

- **High absorption coefficients**, capturing more sunlight with less material.
- **Low-temperature fabrication**, enabling roll-to-roll manufacturing.
- **Mechanical flexibility**, supporting applications in curved surfaces, vehicles, and wearable systems.

Stability remains the major challenge, as perovskites degrade under moisture and UV exposure. Current research focuses on encapsulation, improved charge-transport layers, and lead-free perovskite alternatives using tin or germanium.

1.2. Organic Photovoltaics (OPVs)

OPVs use carbon-based semiconductors and offer:

- Lightweight and flexible modules
- Semi-transparency for architectural integration
- Low manufacturing energy demand

Although OPVs currently lag in efficiency and lifespan, advances in non-fullerene acceptors, tandem configurations, and stability-enhancing additives are closing the gap with inorganic photovoltaics.

1.3. Solar Fuels and Artificial Photosynthesis

Solar-driven hydrogen production involves:

- **Photoelectrochemical cells** that split water using sunlight.
- **Catalysts** such as transition-metal oxides or metal–organic frameworks (MOFs).
- **Bio-hybrid systems** combining biological components with semiconductor materials.

Artificial photosynthesis aims to convert CO_2 and water into hydrocarbons or alcohols, mimicking natural processes but with higher efficiency. These technologies have the potential to create carbon-neutral fuels.

2. Advanced Energy Storage Technologies

2.1. Solid-State Batteries

Solid-state batteries replace flammable liquid electrolytes with solid ceramics, polymers, or sulfides. Advantages include:

- Higher energy density (potentially >500 Wh/kg)
- Enhanced thermal stability
- Safer operation under extreme conditions

Challenges include solid–solid interface resistance, mechanical degradation, and the need for scalable manufacturing processes.

2.2. Sodium-Ion, Magnesium-Ion, and Beyond

Post-lithium batteries are attracting global attention due to concerns around lithium availability and cost.

- **Sodium-ion batteries** use abundant materials, making them ideal for stationary storage.
- **Magnesium and calcium batteries** offer higher volumetric capacities and reduced dendrite issues.
- **Zinc-air batteries** are emerging for grid-scale, metal-air applications.

2.3. Redox Flow Batteries

Flow batteries store energy in external tanks containing liquid electrolytes. The ability to independently scale power and energy makes them ideal for stabilizing renewable grids. Research is advancing low-cost electrolytes, such as organic redox molecules and recyclable vanadium systems.

2.4. Hybrid Storage Systems

Integration of batteries with supercapacitors enables:

- Rapid charge–discharge cycles
- Extended battery lifespan
- Enhanced performance in e-mobility and renewable integration

3. Hydrogen Economy and Fuel Cell Technologies

3.1. Green Hydrogen Production

Green hydrogen, generated through electrolysis powered by renewable energy, plays a key role in decarbonizing heavy industry.

Technological progress includes:

- More efficient membrane materials
- Reduced dependency on platinum-group metals

3.2. Fuel Cells

Fuel cells convert hydrogen into electricity with water as the only byproduct. Innovations include:

- Durable catalysts resistant to poisoning
- Proton-conducting ceramics for high-temperature operation
- Lightweight stacks for long-range transport and aviation

3.3. Hydrogen Storage & Transport

Storage remains a bottleneck due to hydrogen's low density. Emerging solutions include:

- Metal hydrides with high volumetric storage capacity
- Liquid organic hydrogen carriers that release hydrogen on demand
- Hydrogen-to-ammonia conversion for global shipping networks

Innovations in Environmental Technologies

1. Carbon Capture, Utilization, and Storage (CCUS)

1.1. Direct Air Capture (DAC)

DAC systems use chemical sorbents (amines, hydroxides) or advanced materials (MOFs, ionic liquids) to extract CO₂ from ambient air. While energy intensive, improvements in sorbent stability, regeneration efficiency, and heat integration are lowering costs.

1.2. Point-Source Capture

Industries such as cement and steel emit CO₂ as a process byproduct. Innovations include:

- Oxy-fuel combustion
- Calcium looping
- Chemical looping combustion

These technologies capture CO₂ before it enters the atmosphere.

1.3. Carbon Utilization

Captured CO₂ can be transformed into valuable products:

- Synthetic fuels (methanol, hydrocarbons)
- Polymer precursors and polycarbonates
- Carbonated construction materials
- Algal biomass for bioplastics and nutraceuticals

This approach shifts carbon from a waste product to a resource.

2. Water Purification and Wastewater Treatment

2.1. Nanomaterial-Based Filtration

Graphene oxide, carbon nanotubes, and other nanomaterials enable ultra-efficient water purification. Benefits include:

- High flux due to atomic-scale thickness
- Selective filtration of salts, bacteria, and heavy metals
- Potential for solar-powered desalination

Challenges include nanomaterial stability, fouling, and scalable production.

2.2. Photocatalytic Water Treatment

Materials such as TiO₂, g-C₃N₄, and doped semiconductors utilize sunlight to degrade pollutants, pharmaceuticals, pesticides, and dyes. Combined with solar light, they offer energy-efficient purification for remote communities.

3.2.3. Biological Remediation

Biological systems offer low-cost and sustainable environmental remediation:

- Bacteria engineered to degrade plastics, oils, and toxins
- Mycoremediation using fungi to absorb heavy metals
- Phytoremediation using plants to capture contaminants from soil

3. Digital Environmental Management

3.1. AI-Assisted Environmental Monitoring

Machine learning enhances pollution prediction, ecosystem modeling, and detection of anomalies in emissions or water quality. Applications include:

- Forest fire risk prediction
- Precision agriculture
- Urban air quality forecasting

3.2. IoT Sensor Networks

Distributed sensor networks measure:

- Particulate matter
- Soil health

- Water contamination
- Real-time meteorological data

These data support smarter environmental policies and industrial compliance.

3.3. Satellite and Drone-Based Monitoring

Remote sensing enables large-scale environmental assessments of deforestation, mining, coral bleaching, and coastal erosion.

Sustainable Materials and Circular Manufacturing

1. Bio-Based and Biodegradable Materials

1.1. Biopolymers

Biopolymers from starch, cellulose, chitin, polylactic acid (PLA), and bio-PET offer renewable alternatives to petroleum plastics. Innovations focus on strength, thermal resistance, and compostability.

1.2. Mycelium Composites

Mycelium—the root structure of fungi—forms lightweight structural materials when grown in agricultural waste substrates. Benefits:

- Low-energy production
- High insulation performance
- Compostable at end-of-life

Applications include packaging, construction panels, and interior design.

1.3. Algae-Based Materials

Algae serve as feedstocks for:

- Bioplastics
- Bio-based foams
- Pigments
- Carbon-sequestering building materials

The rapid growth and low land requirements make algae highly scalable.

2. Carbon-Negative Construction Materials

2.1. CO₂ Cured Concrete

Concrete production is responsible for ~8% of global CO₂ emissions. CO₂ curing not only reduces emissions but strengthens concrete via mineral carbonation.

2.2. Engineered Timber, Bamboo, and Bio-Composite Structures

Cross-laminated timber (CLT) and bamboo composites are emerging as sustainable alternatives to steel and concrete. Their benefits include:

- Negative embodied carbon
- Structural durability
- Earthquake resilience

2.3. Geopolymers

Geopolymer cement, derived from aluminosilicate materials, provides:

- Up to 80% lower CO₂ emissions
- High chemical and thermal resistance
- Utilization of industrial waste streams

3. Smart and Functional Materials

3.1. Phase-Change Materials (PCMs)

PCMs absorb and release heat during phase transitions, contributing to energy-efficient buildings and thermal management. Ongoing research targets improved stability, encapsulation, and fire resistance.

3.2. Self-Healing Materials

These materials use microcapsules, vascular networks, or microbial action to repair damage automatically, extending lifespans and reducing maintenance.

3.3. Recyclable Thermosets

Traditional thermosets cannot be re-melted, creating significant waste. New dynamic covalent polymers enable chemical reprocessing and circular material systems.

Systems Integration for Sustainability

1. Smart Grids and Microgrids

Smart grids integrate renewable energy, storage, and digital controls. Microgrids provide localized resilience, especially in climate-vulnerable regions.

2. Industrial Symbiosis

Industrial clusters exchange waste heat, water, and materials. Examples include:

- Waste plastic converted into fuel
- CO₂ from power plants fed to algae farms
- Steel mill slag used in cement

3. Circular Economy Enabled by Digital Tools

Digital twins, blockchain-based material passports, and AI-driven recycling enhance resource efficiency and material recovery rates.

Challenges, Risks, and Future Prospects

1. Technical Barriers

- Efficiency degradation in perovskites
- Scaling nanomaterial synthesis
- Durability of biodegradable materials
- High cost of electrolyzers and advanced batteries

2. Economic and Policy Limitations

- Need for supportive regulations
- Long payback periods for large-scale infrastructure
- Lack of standardized certification for new materials

3. Environmental and Ethical Considerations

- Mining impacts for battery minerals
- Risk of microplastic release from biopolymers
- Social equity in energy transition

4. Future Prospects

- AI-enabled design of catalysts and materials
- Integration of green hydrogen with heavy industries
- Carbon-negative construction as a global norm
- Circular design frameworks across all manufacturing sectors

Conclusion

The global shift toward sustainability requires disruptive innovations that span energy, environment, and materials science. Emerging technologies such as advanced photovoltaics, hydrogen systems, solid-state batteries, carbon-negative materials, and AI-based environmental monitoring have the potential to fundamentally reshape modern industries. Harnessing these innovations responsibly—supported by policy, investment, and global collaboration—will enable societies to transition toward a greener, more resilient, and equitable future.

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