

Green Technologies for Climate Change Mitigation and Environmental Sustainability: A Comprehensive Review

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Abstract-- The accelerating threats of climate change, environmental pollution, biodiversity loss, and depletion of natural resources have made sustainable development a global priority. Green technologies have emerged as critical tools for addressing these challenges by promoting clean energy, efficient resource utilization, waste reduction, and ecological conservation. This review article explores the major domains of green technology, including renewable energy, energy efficiency, sustainable transportation, waste management, green agriculture, water conservation, carbon capture, eco-friendly materials, and green artificial intelligence. Special emphasis is given to India's initiatives such as the National Solar Mission, Green Hydrogen Mission, electric mobility programs, and river restoration projects. The paper highlights the technological advances, environmental benefits, and socio-economic significance of green innovations, and discusses their role in shaping a sustainable and resilient future.

Keywords-- Green technology, sustainability, renewable energy, climate change, circular economy, sustainable development, India.

I. INTRODUCTION

The twenty-first century is characterized by unprecedented environmental challenges that threaten ecological stability and human well-being. Accelerated global warming, rising sea levels, extreme climate events, biodiversity loss, and widespread air and water pollution have become defining issues of modern development. These challenges are largely driven by rapid industrialization, urban expansion, population growth, and unsustainable patterns of resource consumption. While industrial and technological advancements have significantly improved living standards, healthcare, and economic productivity, they have simultaneously intensified ecological degradation and environmental inequities [1].

The dominant development paradigm of the past century has relied heavily on fossil fuels, extractive industries, and linear economic models characterized by “take-make-dispose” consumption patterns.

This model has resulted in excessive greenhouse gas emissions, depletion of natural resources, accumulation of waste, and degradation of ecosystems [10]. As global energy demand continues to rise, dependence on coal, oil, and natural gas has not only exacerbated climate change but has also increased geopolitical and economic vulnerabilities. Consequently, the traditional growth-centric approach is increasingly recognized as environmentally unsustainable and socially inequitable.

In response to these challenges, green technology, also referred to as environmental technology or clean technology, has emerged as a critical pathway toward sustainable development. Green technology encompasses the design, development, and application of products, systems, and processes that reduce environmental harm, improve resource efficiency, and promote ecological balance. These technologies aim to decouple economic growth from environmental degradation by minimizing emissions, conserving energy and water, reducing waste, and enhancing the use of renewable and biodegradable resources [2].

Green technologies span multiple sectors, including renewable energy (solar, wind, hydropower, and bioenergy), energy-efficient infrastructure, sustainable transportation, waste management and recycling, water conservation, eco-friendly materials, and digital innovations such as artificial intelligence for environmental monitoring. Together, these innovations support a transition toward low-carbon, resource-efficient, and circular economic systems [21]. Importantly, green technologies also contribute to social well-being by creating green jobs, improving public health, and increasing access to clean energy and water.

At the global level, the adoption of green technologies is closely aligned with the United Nations Sustainable Development Goals (SDGs), particularly goals related to climate action (SDG 13), affordable and clean energy (SDG 7), sustainable cities (SDG 11), responsible consumption and production (SDG 12), and clean water and sanitation (SDG 6).

Governments, industries, and international organizations increasingly recognize that technological innovation, supported by appropriate policy frameworks, is essential for achieving these targets.

India, as one of the world's fastest-growing economies, plays a crucial role in the global sustainability transition. The country faces significant environmental pressures, including air pollution, water scarcity, waste management challenges, and climate vulnerability. At the same time, India has demonstrated strong commitment to green transformation through initiatives such as the National Solar Mission, National Green Hydrogen Mission, electric mobility programs, smart city development, and river rejuvenation projects. These efforts position India as both a major beneficiary and a key contributor to global green technology adoption [8].

This review provides a comprehensive overview of the major sectors of green technology and critically evaluates their potential to support global and national sustainability goals, with particular emphasis on India's green transformation. By synthesizing current research and policy perspectives, the review highlights the role of green technologies in addressing environmental challenges while fostering inclusive and resilient development [12].

II. RENEWABLE ENERGY TECHNOLOGIES

Renewable energy technologies play a central role in mitigating climate change, enhancing energy security, and promoting sustainable economic development. Unlike fossil fuels, renewable energy sources are naturally replenished and generate minimal greenhouse gas emissions during operation. Advances in technology, declining costs, and supportive policy frameworks have significantly accelerated their global deployment, particularly in emerging economies such as India [5].

Solar Energy

Solar energy harnesses sunlight using photovoltaic (PV) cells and solar thermal systems to generate electricity and heat. Owing to its vast availability and declining installation costs, solar power has emerged as one of the fastest-growing renewable energy sources worldwide. Technological improvements in PV efficiency, energy storage, and grid integration have further enhanced its reliability and scalability.

In India, solar energy has gained prominence through large-scale solar parks, rooftop solar systems, and decentralized off-grid applications, especially in rural and remote areas.

The National Solar Mission aims to position India as a global leader in solar energy by expanding installed capacity, reducing dependence on fossil fuels, and lowering carbon emissions. Solar energy also contributes to energy access, employment generation, and regional development, reinforcing its role in sustainable growth [4].

Wind Energy

Wind energy converts the kinetic energy of wind into electrical power through wind turbines. Both onshore and offshore wind farms have become integral components of modern renewable energy systems. Wind power offers significant advantages, including low operational emissions, scalability, and compatibility with existing grid infrastructure [17].

India possesses substantial wind energy potential, particularly in coastal and semi-arid regions. States such as Tamil Nadu, Gujarat, Maharashtra, and Karnataka host large-scale wind installations that contribute significantly to national renewable capacity. Continued advancements in turbine design, taller towers, and improved forecasting techniques have increased energy output and reduced generation costs, making wind energy a competitive alternative to conventional power sources [20].

Hydropower

Hydropower is one of the oldest and most reliable forms of renewable energy, generating electricity by utilizing the energy of flowing or falling water. Large hydropower projects provide stable base-load power and play a critical role in balancing grid variability caused by solar and wind energy. Additionally, pumped-storage hydropower systems support energy storage and grid stability [15].

Despite its benefits, hydropower development raises environmental and social concerns, including ecosystem disruption, sedimentation, and displacement of local communities. As a result, environmentally responsible planning, impact assessments, and the promotion of small and micro-hydropower projects are essential to ensure sustainable hydropower expansion [24].

Biomass and Biofuels

Biomass energy is derived from organic materials such as agricultural residues, forestry waste, animal manure, and municipal solid waste. Biomass-based technologies convert these materials into energy through processes such as combustion, anaerobic digestion, and gasification. Biofuels, including biogas, bioethanol, and biodiesel, offer cleaner alternatives to fossil fuels for cooking, electricity generation, and transportation [19].

In the Indian context, biomass and biofuels play a dual role by addressing energy demand and waste management challenges. Biogas plants in rural areas improve energy access while reducing indoor air pollution. Bioethanol blending programs further contribute to emission reductions and energy diversification, supporting India's transition toward a low-carbon economy [16].

III. ENERGY EFFICIENCY AND GREEN INFRASTRUCTURE

Energy efficiency is a cornerstone of sustainable development, enabling reduced energy consumption without compromising economic productivity or quality of life. By optimizing energy use across sectors such as buildings, transportation, and industry, energy efficiency measures help lower greenhouse gas emissions, reduce energy costs, and enhance system resilience [22].

Smart Grids

Smart grids integrate digital communication, automation, and information technologies into traditional electricity networks. These systems enable real-time monitoring, demand-side management, and efficient integration of renewable energy sources. Smart grids improve grid reliability, reduce transmission losses, and empower consumers to actively manage their energy consumption [7].

In renewable-rich energy systems, smart grids play a crucial role in balancing variable power generation and ensuring stable electricity supply. Their adoption supports decentralized generation, electric vehicle integration, and energy storage solutions, thereby accelerating the transition to sustainable energy systems.

Green Buildings

Green or sustainable buildings are designed to minimize environmental impact throughout their lifecycle, from construction to operation and disposal. Key features include natural lighting, efficient insulation, rainwater harvesting, renewable energy integration, and the use of eco-friendly construction materials. These measures significantly reduce energy and water consumption while enhancing indoor environmental quality [14].

Certification frameworks such as LEED (Leadership in Energy and Environmental Design) and GRIHA (Green Rating for Integrated Habitat Assessment) promote standardized sustainability practices in building design and construction. In India, green buildings contribute to climate mitigation, urban sustainability, and improved occupant health, reinforcing their importance in sustainable infrastructure development.

Efficient Appliances and Lighting

Energy-efficient appliances and lighting systems play a crucial role in reducing household and commercial electricity consumption. Light-emitting diode (LED) lighting consumes significantly less energy and has a longer lifespan compared to incandescent and fluorescent lamps, resulting in reduced operational costs and lower greenhouse gas emissions [23]. Similarly, star-rated appliances, promoted through energy labeling programs, enable consumers to make informed choices regarding energy efficiency.

In India, appliance efficiency standards have contributed to peak load reduction and emission mitigation while supporting national climate commitments. The widespread adoption of efficient appliances represents a cost-effective pathway to achieve energy conservation at the demand side without compromising user comfort or productivity [22].

IV. SUSTAINABLE TRANSPORTATION TECHNOLOGIES

The transportation sector is a major contributor to global greenhouse gas emissions and urban air pollution. Sustainable transportation technologies aim to decarbonize mobility systems while improving energy efficiency and accessibility [18].

Electric Vehicles

Electric vehicles (EVs) operate using battery-powered electric drivetrains and produce zero tailpipe emissions, making them a cleaner alternative to internal combustion engine vehicles. EV adoption significantly reduces urban air pollution and dependence on imported fossil fuels, especially when powered by renewable electricity [11].

In India, government initiatives such as the Faster Adoption and Manufacturing of Electric Vehicles (FAME II) scheme and supportive state-level EV policies have accelerated electric mobility adoption. These initiatives promote domestic manufacturing, charging infrastructure development, and consumer incentives, positioning EVs as a cornerstone of India's low-carbon transport transition.

Hydrogen Fuel Cells

Hydrogen fuel cell technology generates electricity through electrochemical reactions between hydrogen and oxygen, producing water as the only byproduct. Fuel cell vehicles offer high energy density and rapid refueling, making them suitable for long-distance transport, freight, and heavy-duty applications [21].

While hydrogen technologies remain at a developmental stage, ongoing research and national initiatives such as India's National Green Hydrogen Mission highlight their long-term potential for deep decarbonization in transport and industry.

Public Transport Innovations

Public transportation systems such as electric buses, metro rail networks, and shared mobility services contribute to reduced congestion, lower per-capita emissions, and inclusive urban development. Electrification of public transport improves energy efficiency while enhancing urban air quality. Integrated transport planning and digital mobility platforms further support sustainable urban mobility systems [3].

V. WASTE MANAGEMENT AND CIRCULAR ECONOMY

Modern waste management emphasizes minimizing waste generation and maximizing material recovery through reuse and recycling. These approaches support resource efficiency and reduce environmental pollution.

E-Waste Management

The rapid growth of electronic consumption has made electronic waste (e-waste) one of the fastest-growing waste streams globally. E-waste contains valuable metals such as copper, gold, and rare earth elements, but improper disposal poses significant environmental and health risks [1].

Effective e-waste management involves safe collection, dismantling, recycling, and recovery of materials, supported by extended producer responsibility frameworks and public awareness.

Zero-Waste Technologies

Zero-waste technologies such as composting, biogas digesters, and refill systems aim to divert waste from landfills while generating valuable outputs. Organic waste composting improves soil fertility, while biogas plants produce renewable energy and reduce methane emissions from unmanaged waste [19].

Circular Economy Models

The circular economy promotes continuous material reuse, recycling, and remanufacturing, replacing the linear "take-make-dispose" model. By retaining material value within economic systems, circular models enhance sustainability across production and consumption cycles and reduce resource extraction pressures [10].

VI. SUSTAINABLE AGRICULTURE AND FOOD SYSTEMS

Agriculture faces increasing pressure from climate change, land degradation, and water scarcity. Sustainable agricultural technologies aim to improve productivity while minimizing environmental impacts.

Vertical and Controlled Environment Farming

Vertical farming uses hydroponics, aeroponics, and controlled environment systems to grow crops in stacked layers within urban spaces. These systems require less land and water, reduce pesticide use, and enable year-round production close to consumers, thereby lowering transportation emissions [3].

Organic Farming

Organic farming eliminates synthetic fertilizers and pesticides, promoting soil health, biodiversity, and ecosystem resilience. India has gained international recognition for organic initiatives, particularly Sikkim's transition to 100% organic farming, which demonstrates the environmental and socio-economic benefits of sustainable agricultural practices.

Precision Agriculture

Precision agriculture integrates sensors, drones, satellite imagery, and artificial intelligence to monitor crop health, soil moisture, and nutrient levels. These technologies enable site-specific input application, optimizing resource use and improving yields while reducing environmental impact [9].

VII. WATER CONSERVATION AND PURIFICATION TECHNOLOGIES

Water scarcity has emerged as a critical global challenge due to climate variability, population growth, and over-extraction.

Desalination

Desalination technologies convert seawater into potable water using thermal or membrane-based processes. While energy-intensive, advancements in membrane efficiency and renewable-powered desalination have improved sustainability, particularly in coastal and arid regions [6].

Waste water Recycling

Advanced wastewater treatment technologies enable the reuse of treated water in agriculture, construction, and industrial applications. Water recycling reduces freshwater withdrawal and enhances urban water resilience.

Smart Irrigation

Smart irrigation systems use sensors, weather data, and AI-based decision tools to deliver water precisely when and where needed. These systems significantly reduce water waste and improve crop productivity, particularly in drought-prone regions [8].

VIII. CLIMATE TECHNOLOGIES AND CARBON MANAGEMENT

Carbon Capture and Storage

Carbon capture and storage (CCS) and direct air capture (DAC) technologies aim to remove carbon dioxide from industrial emissions or directly from the atmosphere and store or reuse it. These technologies are considered essential for achieving net-zero emissions in hard-to-abate sectors [13].

Carbon Markets

Carbon trading mechanisms incentivize emission reductions by assigning economic value to carbon savings. Well-designed carbon markets promote cost-effective mitigation while encouraging sustainable industrial practices [14].

Eco-Friendly Materials and Green Manufacturing

The use of eco-friendly materials such as biodegradable plastics, bamboo-based products, fly ash bricks, and recycled metals reduces pollution and life-cycle environmental impacts. Green manufacturing practices emphasize resource efficiency, waste minimization, and sustainable supply chains. Sustainable fashion initiatives further promote ethical sourcing, reduced textile waste, and circular production models [15].

IX. GREEN AI AND DIGITAL SUSTAINABILITY

Green artificial intelligence focuses on reducing the environmental footprint of digital technologies by developing energy-efficient algorithms, low-power hardware, and sustainable data centers. Renewable-powered computing infrastructure and carbon-neutral strategies adopted by Indian IT companies demonstrate the role of digital innovation in sustainability transitions [21].

X. INDIAN INITIATIVES IN GREEN TECHNOLOGY

India's sustainability framework integrates technological innovation with social development through initiatives such as the National Green Hydrogen Mission, solar rooftop programs, electric mobility incentives, PM-KUSUM solar agriculture schemes, and river restoration projects such as Namami Gange.

These programs enhance energy access, reduce emissions, and support inclusive economic growth while addressing environmental challenges.

XI. CONCLUSION

Green technologies are not optional alternatives but fundamental necessities for sustainable development. They provide solutions to environmental degradation while creating economic opportunities and improving quality of life. Through continued research, responsible governance, industrial innovation, and public participation, green technologies can transform current development pathways into resilient, inclusive, and environmentally harmonious systems. The green revolution ultimately begins with informed decisions, institutional commitment, and collective responsibility.

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