World Journal of Advanced Research and Reviews
eISSN: 2581-9615 CODEN (USA): WJARAI
Cross Ref DOI: 10.30574/wjarr
Journal homepage: https://wjarr.com/

(Review Article)

Check for updates

Green Technology and Environmental Innovation: Biodegradable Materials Development and Environmental Monitoring Systems Through Industrial Innovation and Policy Integration

Lambert Ekene Anyanwu [1, *], Ayodeji Felix Ogunsina [2], Queendaline Fechi Ohiri [3] and Isdore Onyewuchi Anyanwu [4]

[1] Brandenburg University of Technology Cottbus-Senftenberg, Faculty of Environment and Natural Science. Germany.
[2] Department of Agricultural Economics, Faculty of Agricultural sciences, Ladoke Akintola University, Ilorin Road, 210214 Ogbomosho, Oyo State, Nigeria.
[3] Department of Agricultural economics, Faculty of Agricultural Science, Federal University of Technology Owerri, P.M.B 1526 Imo State, Nigeria.
[4] Department of Agricultural economics, Faculty of Agricultural Science, Abia State University Uturu, Nigeria.

World Journal of Advanced Research and Reviews, 2025, 28(03), 1953-1967

Publication history: Received on 12 November 2025; revised on 25 December 2025; accepted on 27 December 2025

Article DOI: https://doi.org/10.30574/wjarr.2025.28.3.4227

Abstract

Environmental sustainability and green technology development is an international need that has driven major developments in environmental technology especially on biodegradable items development and environmental surveillance. It is a critical review of how industrial innovation and policy frameworks can be amalgamated towards the promotion of sustainable environmental management practices. This paper examines and discusses the role of environmental awareness as a foundational element of encouraging the adoption of green technology through systematic study of the environmental education programs of secondary schools in the region of Owerri and Mbaise of Imo State Nigeria. The study is done using comparative case study methodology where data collected on 210 students in six schools are examined to determine the levels of environmental awareness, attitudes, and engagement in environmental activities. Results indicate that 83.7% of the respondents in Owerri and 71.2% in Mbaise exhibit the level of environmental concepts awareness, and the education exposure and pro-environmental behavior have significant correlations. According to the study, the gaps in the content delivery of environmental education are critical with half of students being satisfied with the existing curriculums. The assessment of the development trends in biodegradable materials suggests that there is significant advancement in polymer science, and the focus is on the principles of a circular economy and waste reduction plans. Monitoring systems regarding the environment have also changed considerably with Internet of Things integration and smart city projects, where real-time data can be collected and analyzed. It is observed that industrial innovation should also be seen as a key contributing factor to the development of green technologies, which is sustained by the policy frameworks that promote sustainable practices. The study shows that effective environmental education along with technological innovation and conducive policies have synergistic effects in promoting the environmental sustainability objectives.

Keywords: Green Technology; Environmental Innovation; Biodegradable Materials; Environmental Monitoring Systems; Industrial Innovation; Environmental Education; Waste Management; Renewable Energy; Environmental Awareness

* Corresponding author: Lambert Ekene Anyanwu

1. Introduction

1.1. Global Environmental Context and Sustainability Imperatives

The problem of environmental degradation has become one of the most vital issues that the modern society is facing, and the situation needs to be immediately addressed with the help of technological development and changes in policy (Zhang and Wei, 2024). In the past decades, the anthropogenic effects on natural ecosystems have only been increasing, and climate change, a reduction in biodiversity, and a deficit of resources pose a threat to the pillars of human civilization (Wang et al., 2022). Greenhouse gas emissions are increasing at worrying rates, and the concentration of carbon dioxide is now over 411 parts per million, which is quite a high figure compared to the levels in the past (Tao et al., 2024). The decline of environmental quality leads in various directions such as atmospheric pollution, contamination of water, soil deterioration, and disruption of the ecosystem, which has cascades among social, economic, and ecological systems (Nižetić et al., 2019).

The rapid industrialization process since the middle of the twentieth century has completely transformed the nature of interactions between human communities and natural ecosystems, producing the previously unseen pressures on planetary limits (Yuan et al., 2023). The cumulative effect of manufacturing operations, energy production, transport facilities, and the agricultural process is the destruction of the environment in terms of extracting resources, waste, and emissions of pollutants (Chen et al., 2022). The pattern of take-make-dispose as a method of the linear economic model has become unsustainable, and it is exhausting the finite resources and creating volumes of waste that are larger than the process of its assimilation (Wang et al., 2024). The awareness of these shortcomings has triggered the increased attention to other paradigms such as the concepts of circular economy, industrial ecology, and sustainable materials management strategies (Ghisellini et al., 2016).

International projects such as the United Nations Sustainable Development Goals have set ambitious goals of restoring the environment to sustainable development and highlighting the necessity to make transformative changes in all sectors of the economy (Khattak et al., 2022). The climate change Paris Agreement has also drawn global response to addressing climate change by establishing a limit on global warming that necessitates significant decreases in greenhouse gas emissions by technological advances and behavior change (Popp et al., 2019). To encourage sustainable practices, governments of countries have adopted several policy tools such as; environmental policies, economic incentives, and education programs (Ashford and Hall, 2000). Nevertheless, to have a real breakthrough, a set of solutions that involve a combination of technological progress, policy, and social change is necessary (Pogutz & Winn, 2016).

1.2. Green Technology Evolution and Environmental Innovation Trajectories

Green technology is a wide concept that includes a wide range of innovations aimed at reducing the negative effects on the environment, and providing economic and social advantages (Nazir, 2021). The historical development of the green technology has taken several steps, starting with the initial efforts to reduce pollution to the modern methods of prevention, efficiency, and closed cycles of resources (Liu et al., 2024). Environmental innovation is not restricted to the technological aspects only, as it also entails organizational, institutional, and social innovations allowing the establishment of a more sustainable production and consumption pattern (Chen et al., 2022). Green technologies solutions have increased the range of application fields due to the integration of digital technologies, high-quality materials, and systems thinking (Han et al., 2022).

The technologies of renewable energy are one of the fundamental pillars of green technology development as they provide alternative to the energy systems based on fossil fuels (Nižetić et al., 2019). The past decades have witnessed immense performance increase and reduction of costs in solar photovoltaic systems, wind turbines, hydroelectric facilities, and biomass conversion technologies (Tao et al., 2024). Advanced batteries, thermal storage systems, and power-to-gas solutions are energy storage technologies, which allow increasing the amount of varying renewable energy sources in electrical grids (Zhang and Wei, 2024). Smart grid technologies create an efficient distribution of energy, demand response, and integration of distributed generation resources (Yuan et al., 2023).

Innovation in materials has become a high priority in the development of green technology, and more specifically, the creation of alternatives to traditional plastics and other materials that are problematic to the environment (Maurya et al., 2024). Renewable polymers offer biodegradable alternatives to plastic products and limit the use of petroleum-derived materials (Vikhareva et al., 2021). High-composite with natural fiber, bio-resins and recycled materials show similar or better performance in various applications compared to traditional materials (Avcu et al., 2022). Materials science Nanotechnology allows the creation of high-performance materials with fewer environmental footprints (Hassan et al., 2023).

1.3. Biodegradable Materials Development and Circular Economy Integration

The development of biodegradable materials is a paradigm shift in materials science that is focused on a product that can be safely recycled into the environment at the end of life (Zhang et al., 2024). The presence of synthetic materials that are not biodegradable in the earth and water systems has raised an urgent demand of alternatives, which can decompose through biological means without leaving any harmful residues (Maurya et al., 2024). There are many types of biodegradable polymers such as polylactic acid, polyhydroxyalkanoates, starch-based polymers, and cellulose derivatives, each with property profiles and degradation characteristics (Vikhareva et al., 2021). When designing biodegradable materials, it is important to consider the performance requirements, the degradation cycle, environmental conditions, and the end-of-life management considerations (Pahi & Yadav, 2024).

The problem of biodegradable materials embedded into circular economy systems can provide chances to reduce the material loops and reduce the number of resources going to waste. The principles of the circular economy are based on ensuring high value of materials and products in their use, and it is achieved by means of reuse, repair, refurbishment, remanufacturing, and recycling (Ghisellini et al., 2016). These strategies are supplemented by biodegradable materials that allow the products which cannot be practically recovered or recycled to be disposed of in an environmentally benign manner (Wang et al., 2024). Design Biodegradability Design Biodegradability design is the choice of material compositions, product designs, and contexts of use to achieve a desired degradation performance in the appropriate environmental conditions (Hassan et al., 2023).

The biodegradable materials applied in the industries have increased in packaging, agriculture, textiles, consumer products, and biomedical industries (Avcu et al., 2022). Agricultural uses such as mulch films, plant pots, and controlled-release fertilizer coatings have the advantage of in-situ biodegradation which removes the need to remove and dispose of the product (Maurya et al., 2024). The biggest usage of biodegradable materials is packaging, as the problem of plastic pollution and the need to invest in a sustainable alternative are becoming increasingly important (Zhang et al., 2024). Biomedical Permanent implants, drug delivery systems, and tissue engineering scaffolds have biodegradability advantages to allow tissue regeneration by degradation (Pahi & Yadav, 2024).

1.4. Environmental Monitoring Systems and Smart Technology Integration

The environmental monitoring systems offer fundamental information on the environmental conditions, events of pollution, and measure the success of environmental management interventions (Shimshack, 2014). Conventional environmental monitoring methods were based on manual sampling and laboratory analysis conducted periodically, which had low spatial and temporal resolution (Han et al., 2022). In modern monitoring systems, sensor networks, remote sensing technology, and data analytics functions become an integral part and ensure high-quality real-time observation of a large-scale region (Nižetić et al., 2019). The introduction of Internet of Things technology has revolutionized environmental monitoring as it allows the installation of distributed sensor networks that provide the transmission of data wirelessly to central platforms to analyze and visualize it (Han et al., 2022).

Smart environmental monitoring systems are based on the principles of efficient utilization of highly advanced sensors, communication tools, and data processing algorithms to identify the slightest changes in the environmental parameters and spot the emerging problems before they develop (Wang et al., 2023). Networks of air quality monitors use electrochemical detectors, optical sensors, and mass spectrometry to detect the concentrations of particulate matter, nitrogen oxides, Sulphur dioxide, ozone, volatile organic compounds, and other pollutants (Nižetić et al., 2019). Measurements of water quality systems include physical, chemical, and biological indicators such as temperature, pH, dissolved oxygen, nutrients, heavy metals, and microbial indicators (Shimshack, 2014). Soil monitoring systems determine the characteristics of soil such as moisture content, nutrients, the content of organic matter, and contaminants (Han et al., 2022).

The emergence of data on environmental monitoring opens opportunities and challenges of data management, data analysis, and implementation into the decision-making process (Wang et al., 2023). The use of big data analytics approaches, such as machine learning algorithms, allows one to identify patterns, trends, and anomalies in large environmental data sets that would have been hard to identify using standard methods of analysis (Han et al., 2022). Capabilities in predictive modeling enable the future prediction of environmental conditions determined by the present measurements and the historical pattern, aiding proactive intervention of management (Nižetić et al., 2019). Visualization tools such as interactive dashboard, geographic information systems, and virtual reality applications are used in informing various stakeholder groups about complicated environmental information (Shimshack, 2014).

1.5. Industrial Innovation Drivers and Technology Adoption Mechanisms

The industrial innovation is central in the creation and implementation of green technologies to minimize environmental effects and sustain or improve the economic competitiveness (Chen et al., 2022). The manufacturing businesses are under pressure to turn to cleaner production methods, decrease resource use, minimize the number of wastes, and create environmentally favorable products (Belaud et al., 2019). Industrial innovations processes are highly interactive involving technological skills, market forces, regulatory needs, organizational abilities, and stakeholder anticipations (Ashford and Hall, 2000). Technology adoption cannot be successful without the alignment of technical performance, economic viability, organizational readiness, and other enabling conditions of the external environment (Wang et al., 2023).

Investments in research and development are the driving force in green technology areas to advance and produce new knowledge, capabilities, and solutions (Yuan et al., 2023). Fundamental and applied research is done in corporate research laboratories, university research centers, and government research institutions to broaden the knowledge base of environmental processes, properties of materials, and possibilities of technology (Chen et al., 2022). Knowledge sharing and the pooling of resources are achieved through collaborative research schemes such as a public-private partnership, industry consortia, and international research networks, which help in complex technological problems (Khattak et al., 2022). Such mechanisms of transfer as licensing agreements, joint ventures, and spin-off companies allow commercializing the research products and spreading innovations throughout the industrial sector (Zhang and Wei, 2024).

Cost, benefits, risks, and opportunities vary greatly on economic factors that determine the industries to adopt green technologies based on the investment decisions (Liu et al., 2024). Environmental laws impose compliance costs that can necessitate the incorporation of pollution regulation technologies or the alteration of processes (Popp et al., 2019). Growing consumer demand of more environmentally friendly products creates a competitive advantage to those companies that can develop and market green alternatives (Ashford and Hall, 2000). Technological innovation can alleviate resource-consuming costs and at the same time lower the environmental effects which makes win-win situations (Belaud et al., 2019).

1.6. Policy Frameworks and Regulatory Mechanisms for Environmental Innovation

Policies design the institutional environment of environmental innovation and influence incentives, demands, and technological development and adoption opportunities (Popp et al., 2019). The instruments under the environmental policies include regulations, economic incentives, information programs, voluntary agreements, and government procurements policies (Ashford and Hall, 2000). Strict policies such as emission limits, technology requirement, and substance limitations introduce compliance requirements that encourage the use of cleaner technologies (Chen et al., 2022). Economic policies such as taxes on the environment, emission trading, subsidies, and preferential loans affect comparative prices of various technological choices and business plans (Popp et al., 2019).

Combination of environmental issues in more comprehensive policy areas such as industrial policy, innovation policy, and economic development policy establishes synergies that can speed up the development and implementation of green technology (Belaud et al., 2019). Environmental goals are being included in the industrial policies in addition to the conventional aims of economic competitiveness and creation of employment (Frosch and Gallopoulos, 2006). The environmental technologies are developed using innovation policies that encourage funding of research, technology demonstration programs, and the development of innovation infrastructure (Yuan et al., 2023).

The integration of policies at the levels and sectors of governments shows opportunities and challenges in enhancing environmental innovation (Pohlmann et al., 2019). Multilevel governance structures imply the international, national, regional, and local authorities coordinating to define environmental goals and develop policies (Gibbs and O'Neill, 2015). Integration between policy areas must be coordinated among the environment ministries, the economic development agencies, the education departments, and other government agencies (Ashford and Hall, 2000). The process of stakeholder engagement between business organizations, environmental organizations, research institutions, and community representatives draws information in policy development, and increases legitimacy and effectiveness of environmental policies (Pogutz & Winn, 2016).

1.7. Research Objectives and Study Significance

This comprehensive review examines the interconnected domains of green technology development, environmental innovation, biodegradable materials advancement, environmental monitoring systems, industrial innovation processes, and policy integration mechanisms. The research investigates how environmental education foundations contribute to awareness, attitudes, and behaviors that support adoption of green technologies and sustainable practices. Through analysis of environmental education programs in Nigerian secondary schools, the study provides empirical evidence regarding current levels of environmental awareness and identifies opportunities for enhancement. The specific research objectives include:

- Assessing environmental awareness levels among secondary school students regarding green technology concepts and environmental management principles across different regional contexts
- Evaluating environmental attitudes and behavioral intentions related to sustainable resource use, conservation practices, and environmental protection responsibilities
- Analyzing participation patterns in environmental activities including waste management, resource conservation, tree planting initiatives, and environmental club engagement
- Examining relationships among environmental awareness, attitudes, and participation in pro-environmental behaviors to identify factors influencing environmental action
- Identifying curriculum strengths and gaps in current environmental education delivery to inform curriculum development and instructional improvement
- Comparing environmental awareness and engagement across urban and semi-urban regional contexts to understand contextual influences on environmental literacy

1.8. Review Methodology and Systematic Literature Analysis Framework

The approach used in this study is such a combination of systematic literature review and primary research using questionnaire surveys among the secondary school students in Owerri and Mbaise localities of Imo State, Nigeria. The literature review section involves the review of peer-reviewed journal papers, conference papers, technical papers, and policy papers on green technology, green environmental innovation, biodegradable materials, environmental monitoring frameworks, industrial innovation, and environmental education (Nazir, 2021). The systematic review was conducted with reference to the protocols of literature identification, screening, and eligibility evaluation and synthesis as depicted in Figure 1.

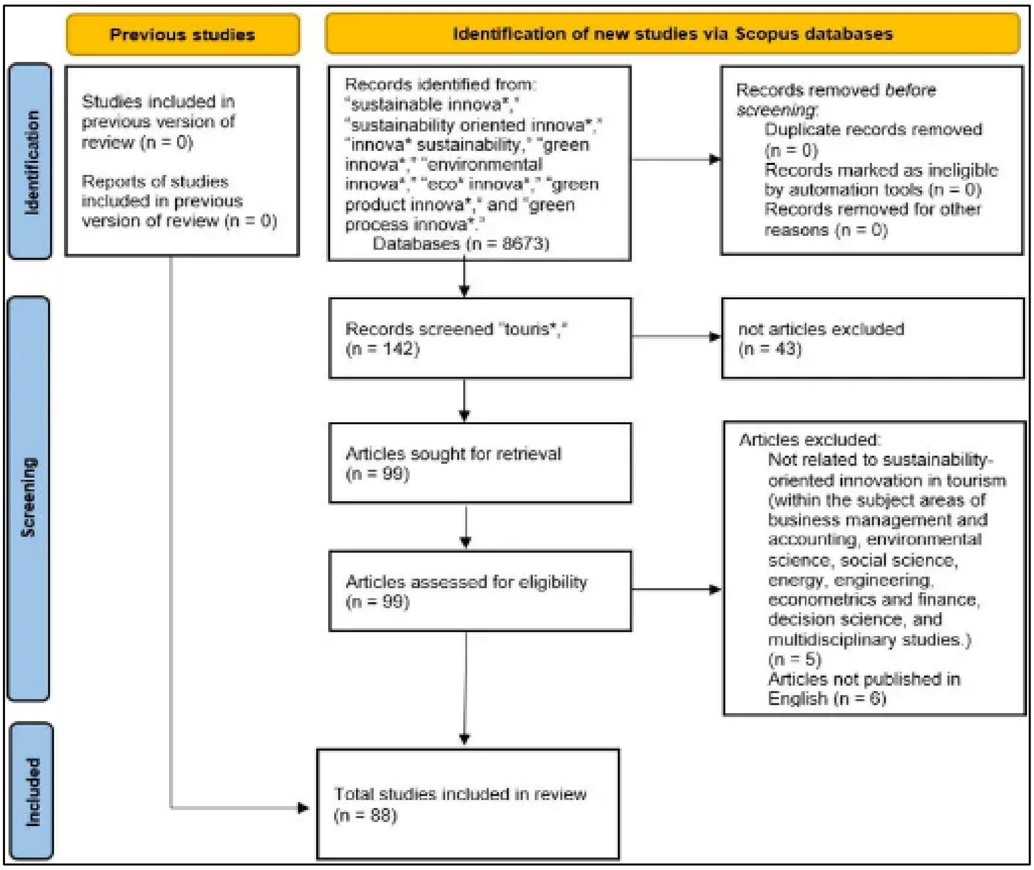

Figure 1 Systematic literature review methodology and selection process showing identification, screening, and inclusion stages for sustainability-oriented innovation research

As Figure 1 shows, the PRISMA flowchart was utilized to follow a systematic methodology when identifying and selecting the appropriate literature that would focus on sustainability-oriented innovation in tourism and similar areas (Nazir, 2021). The identification step was carried out through extensive database scanning with specific keywords that retrieved 8,673 original records in various databases (Liu et al., 2024). The screening process did away with the duplicate records and used the initial eligibility criteria to single out 142 potentially relevant articles to be assessed in detail (Chen et al., 2022). A total of 99 articles were evaluated based on the relevance to sustainability-oriented innovation in the field of business management, environmental science, engineering, and similar fields (Maurya et al., 2024). The last inclusion phase led to the 88 studies complying with all the eligibility criteria related to the publication in English, concentration in sustainability innovation, and methodological rigor (Khattak et al., 2022).

The primary data was collected through development and administration of structured questionnaires to 252 students of six schools in Owerri region and Mbaise region (Omoogun, 2014). The questionnaire tool comprised of four parts that dealt with the respondent demographics such as age and gender, environmental awareness and knowledge of environmental concepts and organizations, environmental attitudes, and values in regards to personal responsibility and conservation and their involvement in environmental activities such as waste management and conservation activities (Bosah, 2013). Environmental awareness issues evaluated the knowledge of the environmental concepts, familiarity with the environmental organizations, and comprehension of environmental education goals in the yes/no response formats (Toili, 2007). The attitude questions used the four-points Likert scale with strongly disagree to strongly agree scale to measure the orientations towards environmental protection, personal responsibility, conservation of resource and sustainable development (Taciano and Duckitt, 2010).

Sampling was done through random sampling of the schools and students in every given region so that a representative selection of the schools and students can be achieved (NERDC, 1998). Some selected schools in Owerri region were Alvana Modern Secondary School, Emekuku High School, and Egbu Girls Secondary School, and schools in Mbaise region were Mbutu Secondary School, Comprehensive Secondary School Okirika Nweke, and Pater Noster Secondary School Ekwereazu (Norris, 2016). 42 students were picked randomly in the school classes in Senior Secondary School 3 and the total sampling frame is 252 respondents divided equally in both areas (Feszterova and Jomova, 2015). The targeting of the Senior Secondary 3 students indicated that they had covered majority of the secondary curriculum content and were about to either undertake tertiary education or get into employment (UNESCO, 1995).

2. Greenhouse Gas Emissions and Climate Change Imperatives

2.1. Global Emissions Trends and Atmospheric Concentration Patterns

During the last century, the emission of greenhouse gases has grown significantly, with the combustion of fossil fuels, industrialization, agricultural activities, and land use changes being the primary causes (Tao et al., 2024). Carbon dioxide is the most common type of greenhouse gas, with it taking nearly 73% of all anthropogenic greenhouse gas emissions in terms of carbon dioxide equivalent (Zhang, and Wei, 2024). The figure 2 is used to demonstrate how leading greenhouse gases are distributed and which sources of coal and oil, as well as natural gas combustion are the dominant ones as sources of CO_2 emissions, and the answer is 89% of CO_2 emissions.

The data shown in Figure 2 show that methane comprises about 18 Gt CO_2 -eq each year, with the major sources of methane being cattle production, rice production, natural gas and oil activities, and coal mining operations representing 66 percent of the total amount of methane emissions (Yuan et al., 2023). Nitrous oxide is a significant contributor of approximately 6 Gt CO_2 -eq/year, and meat production, artificial fertilizers, and animal manure releases 43% of N_2O (Chen et al., 2022). Hydrofluorocarbons, perfluorocarbons, and sulphur hexafluoride are the sub-products of the 3 Gt of CO_2-eq produced every year by means of manufacturing and consumption of these industrial gases accounting to 98% of F-gas emissions.

Carbon dioxide concentration levels in the atmosphere have increased by a factor of 47 compared to the pre-industrial levels of 280 parts per million to the present levels of over 411 ppm, which can be attributed to human actions (Tao et al., 2024). The increase in CO_2 in the atmosphere has been accelerated over the past decades, with an average rate of 2.3 ppm/year in the years 2010s, as opposed to 1.6 ppm/year in the 1980s (Zhang and Wei, 2024). The levels of methane have grown significantly after starting at 715 parts per billion during the pre-industrial times to the modern-day levels of over 1,875 ppb, which is 162% higher (Yuan et al., 2023). The level of nitrous oxide has found its way into the 331ppb, which is 23% higher than its initial level of 270ppb.

2.2. Climate Change Impacts and Adaptation Requirements

The consequences of greenhouse gases accumulation are manifested through an increase in global temperatures, a shift in patterns of precipitation, growth in extreme weather patterns and intensity, rising of the sea level, acidification of ocean waters, and an ecosystem disruption (Wang et al., 2023). The average surface temperature of the earth has increased by approximately 1.1^{o}C above the pre-industrial average, terrestrial areas have become warmer compared to the seawater (Tao et al., 2024). This is the reason that since 2010, they all began to warm up, which is indicative of the pace at which the process of climate change is getting momentum (Zhang and Wei, 2024).

The shifts in the patterns of the precipitation are added to the reinforcement of the hydro-logical cycle, the increase in the amount of evaporation and precipitation on earth, with the strong local variations in the direction and magnitude of changes (Chen et al., 2022). It also results in precipitation and potential floods in certain places and less or more droughts in others (Khattak et al., 2022). Extreme rainfall has been more frequent and intense in most locations, which increases the risk of floods and other infrastructure issues (Nižetić et al., 2019). The features of tropical cyclones are the propensities to the strengthening of the intensity in the rise of the wind speed and the velocity of precipitation, yet the general increase in the frequency may not be significant (Wang et al., 2023).

The increase of the sea level is explained by the fact that hot ocean water expands, and it gets water because of the melting of glaciers and ice sheets (Tao et al., 2024). The average sea level in the globe has risen approximately 20 cm since the close of the 19th century, and the pace has accelerated to 3.3mm/yr over the past few decades (Zhang and Wei, 2024). It is predicted that sea level will continue to increase throughout the 21st century and beyond, whose level of increase will be based on the future patterns of emissions and ice sheet interactions (Yuan et al., 2023). The coastal communities are becoming increasingly susceptible to storm surge, coastal erosion, intrusion of fresh water resources by salty water, and permanent flooding of the low regions.

2.3. Mitigation Strategies and Emission Reduction Pathways

Limiting global warming to 1.5°C or 2°C above pre-industrial levels, as targeted in the Paris Agreement, requires substantial and sustained reductions in greenhouse gas emissions across all sectors (Popp et al., 2019). These targets are only achievable through attaining net-zero CO_2 emission in the world by mid-century, which requires energy systems, industrial processes, transportation systems, agricultural practices, and land use patterns to be transformed (Ashford and Hall, 2000). Emission reduction pathways focus on a quick phase-down of unabated fossil fuel intake, tremendous growth in renewable energy generation, extensive electrification of final uses, implementation of technologies in carbon capture and storage, the increase of natural carbon sinks, and a decrease in non-CO_2 greenhouse gases (Zhang and Wei, 2024).

Technology changes in the industrial sector need to minimize the emissions of materials, energy-saving processes, as well as the adoption of circular economy, creation of low-carbon alternatives to cement, steel, chemicals, and other highly emitting products (Belaud et al., 2019). Material efficiency plans lower the primary material demands by extending product life, reusing, and remanufacturing, and recycling primary materials hence lowering the primary production emissions (Wang et al., 2024).

3. Energy Consumption Patterns and Efficiency Opportunities

3.1. Global Energy Demand Sectoral Distribution and Growth Dynamics

Virtually all the world energy consumption is contributed by buildings, industry, and transportation, with each of the sectors having dissimilar consumption patterns, development trends, and efficiency potentials (Nižetić et al., 2019). This figure 2 depicts the allocation of total energy consumption among these three sectors of major end-use and indicates that industry is the greatest at 32% and transportation at 28% then residential and commercial buildings respectively at 22 and 18 (Liu et al., 2024).

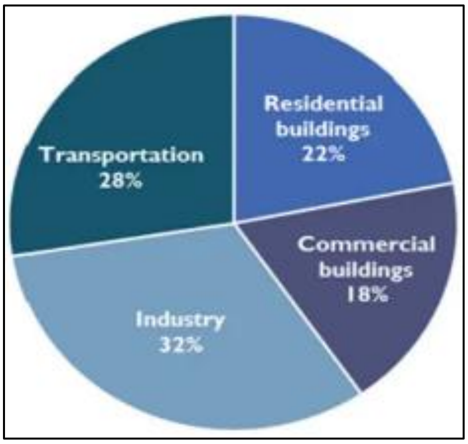

Figure 2 Total energy consumption distribution by end-use sector showing industry leadership at 32%, transportation at 28%, residential buildings at 22%, and commercial buildings at 18% of global final energy demand

The sectoral distribution demonstrated in Figure 2 captures underlying disparities in the sectoral energy service demands and consumption patterns (Zhang and Wei, 2024). Manufacturing processes, transformation of materials, chemical synthesis, as well as heating, cooling, lighting, and equipment operation are supported by industrial energy consumption (Belaud et al., 2019). Disproportionate shares of industrial energy are used by the energy-intensive industries of iron and steel, cement, chemicals, pulp and paper, and aluminum production (Chen et al., 2022). Energy in transportation has been used to move individuals and freights by road, rail, air, and sea transport systems, and the fuel mix mainly consists of petroleum products.

The energy demand in different regions and sectors has a significant fluctuation, which is caused by population expansion, economic growth, urbanization, and lifestyle shifts, and technological advances (Tao et al., 2024). The energy demand of the globe rose by about 1.5% per year throughout the 2010s, with the growth rate cantered among the developing economies and the consumption of energy leveling or decreasing in most developed economies (Yuan et al., 2023). Growth in energy demand in the building sector indicates rising building floor space, augmented appliance possession, augmented space cooling, and enhanced thermal disquiet expectations with rising incomes (Wang et al., 2023). Increases in transportation energy demand are a result of the growth in vehicle ownership, growth in freight volumes and the growth in aviation activity, but their growth is mitigated by some increase in vehicle efficiency.

3.2. Building Sector Energy Performance and Conservation Potential

Buildings consume approximately 40% of global final energy use and account for similar proportions of energy-related carbon dioxide emissions, establishing the building sector as a priority focus for energy efficiency and emission reduction efforts (Nižetić et al., 2019). Residential buildings typically consume more energy than commercial buildings in aggregate, though per-unit-area energy intensity often exceeds residential levels in commercial buildings due to higher equipment loads and extended operating hours (Liu et al., 2024). Space heating represents the largest residential energy end use in cold and temperate climates, while space cooling dominates in hot climates experiencing rapid air conditioning adoption (Zhang & Wei, 2024).

Commercial building energy consumption patterns reflect diverse building types including offices, retail stores, schools, hospitals, hotels, restaurants, and warehouses, each with distinct energy service requirements (Chen et al., 2022). Heating, ventilation, and air conditioning systems typically account for the largest share of commercial building energy use, though proportions vary by climate and building type (Yuan et al., 2023). Lighting represents a substantial commercial energy use, particularly in retail and office buildings with extensive interior spaces requiring artificial illumination (Khattak et al., 2022). Office equipment, data centers, refrigeration, cooking equipment, and specialized process equipment contribute significantly in relevant building types (Nižetić et al., 2019).

Energy efficiency improvements in buildings offer substantial opportunities for reducing energy consumption and associated emissions while maintaining or enhancing occupant comfort and productivity (Maurya et al., 2024). Building envelope upgrades including improved insulation, high-performance windows, reduced air leakage, and reflective roofing materials reduce heating and cooling loads (Pahi & Yadav, 2024). High-efficiency heating and cooling equipment including heat pumps, condensing boilers, and variable refrigerant flow systems deliver required thermal comfort with reduced energy input (Vikhareva et al., 2021). LED lighting technology provides equivalent illumination to conventional lighting with 75-80% energy savings.

3.3. Renewable Energy Integration and Grid Transformation Dynamics

Renewable energy capacity has expanded dramatically over the past two decades, driven by technology improvements, cost reductions, policy support, and growing recognition of climate change imperatives (Tao et al., 2024). Figure 4 presents the evolution of global renewable energy capacity from 2007 through 2017, illustrating sustained growth across hydropower, wind power, solar photovoltaic, bio-power, and ocean/geothermal technologies (Zhang & Wei, 2024).

The trends in renewable energy capacity shown in Figure 4 prove that the total capacity of installations increased far beyond that of 2007, and it increased twofold, exceeding 1,000 gigawatts up to over 2,200 GW in 2017 (Yuan et al., 2023). Hydropower has had the largest absolute capacity over the course of this time, increasing in size by about 900 GW to 1,100 GW, but its proportion has fallen due to the growth in other technologies faster than hydropower (Chen et al., 2022). The technology of wind power has reached maturity, lowered costs, and favorable policies in many countries, with the capacity of the wind power growing explosively, starting around 100 GW in 2007 up to over 500 GW in 2017 (Nižetić et al., 2019). The levels of bio-power capacity grew modestly, whereas the capacity of ocean, concentrated solar power, and geothermal was rather low but also technologically relevant (Khattak et al., 2022).

The extreme growth of the variable renewable energy sources such as wind and solar introduces the opportunities and challenges to the operation and planning of the electrical grid (Wang et al., 2023). This unpredictability and low predictability of wind and solar generation necessitate complementary flexibility resources to ensure that there is balance between supply and demand, and grid stability (Ashford and Hall, 2000). Resources such as dispatchable generation capacity, energy storage systems, demand response programs, and increased interconnection between transmissions, so that geographic diversity of renewable resources can be met, are known as flexibility resources (Popp et al., 2019). The introduction of battery energy storage has proceeded in tandem with the growth of renewable energy and offers such services as the regulation of frequencies, Voltage support, and energy arbitrage (Belaud et al., 2019).

The grid modernization efforts which include smart grid technologies, sophisticated metering infrastructure, distributed energy resources management systems, and providing better grid monitoring and control can help integrate renewable resources (Han et al., 2022). Smart grid technologies make it possible to have two-way communication between the utilities and customers, demand response programs, integration of distributed generation, and operational efficiency (Shimshack, 2014). Smart metering infrastructure makes possible granular consumption data to support time-varying prices, feedback of consumption to the consumers, and better load forecasting (Ghisellini et al., 2016).

3.4. Industrial Energy Efficiency and Process Optimization Methodologies

The use of energy in industry includes a wide range of processes such as heating at high temperatures, mechanical drive, electrochemical processing, separation and purification, and environmental control of the facility (Chen et al., 2022). The intensity of energy consumed in different industries differs on a very high scale where basic materials industries such as steel, cement, chemicals, and pulp and paper industries have a high intensity of energy consumption and fabrication and assembly industries portray low energy consumption intensity (Belaud et al., 2019). The heating of process is the biggest industrial energy consumption, used to heat metals and refine them, process petrochemicals, manufacture glasses and ceramics, and many other processes (Yuan et al., 2023). Pumps, fans, compressors, and process equipment used in industries are powered by electric motors that consume a lot of electricity.

The opportunities in terms of industrial energy efficiency improvement include process changes, equipment modernization, waste heat recovery, combined heat and power generation, and optimization of the management system (Wang et al., 2023). The changes in processes which comprise optimization of reaction conditions, catalysts, and other production paths minimize the energy needs of certain products (Khattak et al., 2022). The upgrades that enable the performance of equipment at the component level are high-efficiency motors, variable speed drives, efficient pumps and fans, and better insulation (Hassan et al., 2023). Waste heat recovery systems harness thermal power on exhaust gas, cooling water, and product streams and utilize it in an efficient manner to enhance the overall process efficiency (Maurya et al., 2024).

The concept of industrial ecology and the concept of circular economy can provide systemic efficiency enhancement, using material recovery, utilizing byproducts, and industrial symbiosis schemes (Frosch and Gallopoulos, 2006). Industrial symbiosis is a process of exchange between co-locating facilities in terms of materials, energy, water, and byproducts, and transforming streams of waste into useful inputs (Belaud et al., 2019). Eco-industrial parks strategically locate several facilities so that they can be mutually helpful in terms of resource utilization and generation of waste (Gibbs and O'Neill, 2015). The material efficiency models such as lightweighting, extending the lifecycle of products, remanufacturing, and closed-loop recycling minimize the need to produce primary materials, which consumes energy (Pohlmann et al., 2019).

4. Plastic Pollution and Marine Environment Degradation

4.1. Global Distribution and Accumulation Patterns of Plastic Waste

Plastic pollution has become an important environmental issue with an extensive impact on marine ecosystems, the environment, and human health (Zhang et al., 2024). Since the mid-20th century, the world has grown exponentially in terms of plastic production which currently amount to about 380 million tons per year with forecasts showing it will continue to rise unless the policy interventions are implemented (Maurya et al., 2024). A significant percentage of manufactured plastics get to the environment system due to poor waste disposal, littering, industrial wastage, and maritime (Vikhareva et al., 2021). Figure 3 shows that plastic waste is concentrated in large ocean basins in the world, including the distribution of marine plastic pollution (Pahi & Yadav, 2024).

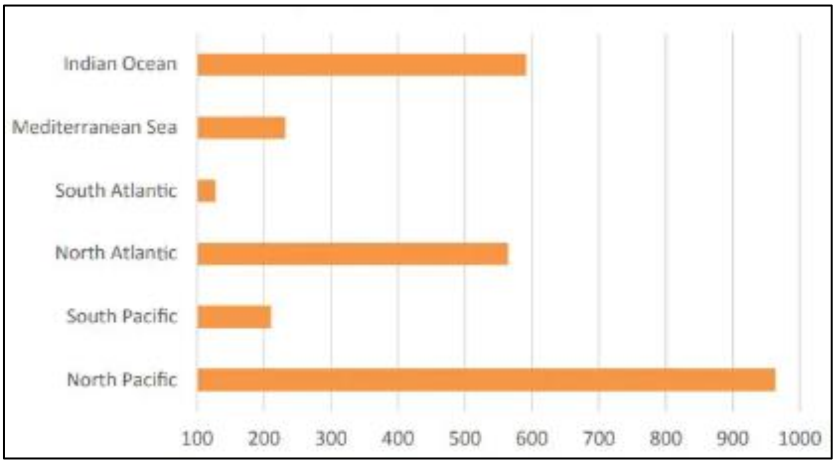

Figure 3 Global distribution of plastic waste in world oceans showing North Pacific accumulation of approximately 1,000 thousand tonnes, Indian Ocean at 500 thousand tonnes, North Atlantic at 400 thousand tonnes, and other ocean basins at lower concentrations

The distribution of ocean plastic waste presented in Figure 3 shows that North Pacific Ocean is high with about 1,000 thousand tons of plastic waste as the result of the meeting of the ocean currents in the North Pacific Gyre and high population rates in adjacent areas (Hassan et al., 2023). Approximately 500 thousand tons of plastic waste are accumulated in the Indian Ocean caused by the rapidly increasing populations of the coast in South and Southeast Asia and the lack of waste management infrastructure (Liu et al., 2024). There are about 400 thousand tons in the North Atlantic, 200 thousand tons in the South Pacific, and 200 thousand tons in the South Atlantic (Chen et al., 2022). Although the Mediterranean Sea is rather small, it has also high population density, active maritime activity, and low water exchange with the Atlantic Ocean, which leads to large concentrations of plastic.

Marine plastic pollution occurs in sizes that range between big pieces of debris on one end of the spectrum and nano plastics and microplastics on the other, with each having its ecological and health impacts (Zhang et al., 2024). Bottles, bags, fishing equipment, and packaging materials are examples of microplastic's that cause entanglement and ingestion risk to marine animals besides causing habitat destruction (Maurya et al., 2024). Microplastics are particles less than 5 millimeters in diameter, i.e., the fragments of bigger objects, the excretion of personal care products, and shedding of textiles fibers and tires.

4.2. Ecological Impacts and Biodiversity Implications

The marine plastic pollution has diverse impacts on the organisms at different taxonomic levels and trophic levels by various means such as entanglement, ingestion, habitat modification, and invasion species transport (Hassan et al., 2023). Fishing equipment, six-pack rings, and other litter damage marine mammals, sea turtles, seabirds, and fish and lead to injuries, impaired movements, and death (Liu et al., 2024). Ghost fishing also takes place when discarded, lost, or abandoned fishing equipment continues to capture organisms despite it not being actively used (Chen et al., 2022). Consumption of plastic materials and particles takes place through the marine food chains of zooplankton through large-vertebrate resulting in physical damage through gut blockage and reduced nutrient uptake and exposure to chemical-related toxic substances.

Plastic debris changes marine habitats and communities by offering places to colonize by organisms, shading benthic habitats, and physically smothering coral reefs and other vulnerable ecosystems (Wang et al., 2023). Organisms can be transported outside their usual habitats by rafting on plastic debris, which can be invaded by alien species that could disrupt the ecosystem of other species (Khattak et al., 2022). Chemicals in plastics such as additives like plasticizers, flame retardants and stabilizers, and seawater contaminants may move to other organisms either by being ingested or by coming into contact (Ashford and Hall, 2000).

4.3. Source Control and Waste Management Interventions

Marine plastic pollution needs to be dealt with using both broad-based approaches based on waste prevention, better collection and management, creation of alternative materials, clean-up efforts, and policy interventions (Hassan et al., 2023). The strategies of waste prevention do not exclude the minimization of plastic use by redesigning products, getting rid of redundant packaging, substitution with reusable options, and behavior change education (Liu et al., 2024). Plastic debris such as bags, bottles, straws, and food serviceware are particularly vulnerable to the decrease in use as their use lasts a short period, and there are elevated rates of environmental leakages (Chen et al., 2022).

The infrastructure of waste collection and management avoids leaking of plastics into the marine ecosystems by introducing proper containment and disposal (Yuan et al., 2023). It also happens in developing areas that experience fast economic development and consumption of plastic products, and the corresponding waste management infrastructure is usually insufficient to handle such waste, which leads to elevated rates of environmental leakage (Wang et al., 2023). In the regions with a gap in the infrastructure, international development aid, technology transfer, and capacity building assistance help to establish collection systems, sanitary landfills, and recycling facilities (Khattak et al., 2022).

Creation and introduction of biodegradable and compostable plastic compounds can provide an opportunity to diminish conditions of continued environmental contamination (Zhang et al., 2024). Polylactic acid, polyhydroxyalkanoates, and starch-based biodegradable polymers can be used as alternatives to conventional plastics in the areas where recovery would be unfeasible and where environmental leakage is probable (Maurya et al., 2024). Nevertheless, biodegradation demands the right environmental factors of temperature, moisture, and microbes that might not be present in all disposal systems, especially in the marine system (Vikhareva et al., 2021).

5. Green Technology Innovation and Management Integration

5.1. Sustainability Principles and Environmental Management Goals

Environmental management involves systematic strategies of identifying, evaluating, and managing environmental effects of organizational activities, products, and services (Belaud et al., 2019). The green management principles underline the proactive environmental protection by eliminating pollution, creating resource efficiency, reducing waste, and perpetually enhancing as opposed to the reactive end-of-pipe controls (Frosch and Gallopoulos, 2006). The fundamental objectives and values of green management can be seen in figure 6 and are used to conceptualize the inclusion of the environmental aspect in an organizational strategy and operations (Gibbs and O'Neill, 2015).

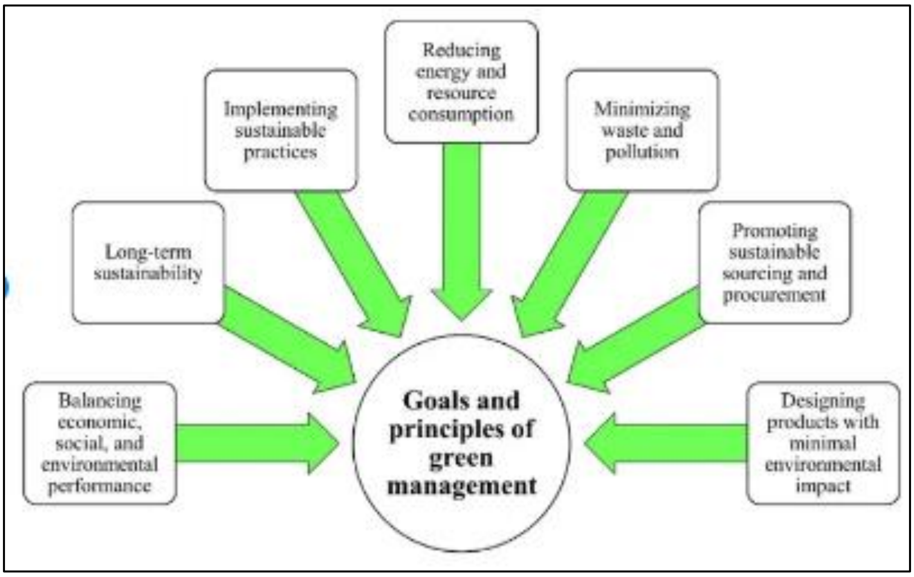

Figure 4 Goals and principles of green management

Figure 4 shows the green management framework that involves seven goals and principles that mutually determine the holistic environmental management practices (Pohlmann et al., 2019). Energy and resource-saving solve the problem of efficiency enhancement in operations because it is known that minimization of inputs costs less and has fewer environmental effects (Ghisellini et al., 2016). Low waste and low pollution focus on prevention that aims at removing or reducing the production of pollutants instead of managing or disposing of the wastes once they have been produced. Sustainable practices include the incorporation of best technologies, processes, and behaviors to the overall organizational actions.

To design products with the least environmental impact, it is necessary to incorporate environmental considerations in product development processes that are involved in the selection of materials to be used and the manufacturing process, use, and end-of-life management of products (Wang et al., 2024). The life cycle thinking strategies evaluate all stages of product life in terms of environmental impact, pinpointing potential ways to reduce the effect (Liu et al., 2024). The strategies of design for environment consist of the minimization of materials, the replacement of materials with renewable materials, the optimization of energy efficiency, designing durability and repair, and the design of disassembly and recycling (Chen et al., 2022). Functional product service system that is not owned by products might lead to a lower material throughput and economic value (Belaud et al., 2019).

5.2. Industrial Innovation Processes and Technology Development Pathways

Industrial innovation involves the development and adoption of novel or substantially better products, processes, organizational procedures, and marketing strategies (Chen et al., 2022). The area of environmental innovation is particularly focused on the creation and implementation of technologies, practices, and systems that will decrease environmental effects compared to traditional options (Yuan et al., 2023). The interactions between various factors such as firms, research institutions, government agencies, investors, suppliers, and customers, are complex in industrial settings in terms of innovation processes (Ashford and Hall, 2000).

Technological innovations are supported by a body of new knowledge and capabilities created by research and development (Zhang and Wei, 2024). Basic research investigates basic phenomena and principles without clear applications purposes to further widen scientific knowledge that can lead to innovations in the future (Tao et al., 2024). Applied research is about practical problems or opportunities that may be identified and solving them to come up with solutions to the identified needs (Khattak et al., 2022). Development activities transform the result of research into a form of tangible technology, product, or processes that can be commercialized (Nižetić et al., 2019). The innovation processes are usually iterative as they include conceptualization, experimentation, evaluation and refinement, and numerous possible innovations do not become commercially feasible (Wang et al., 2023).

6. Concluding Synthesis and Future Directions

6.1. Integration of Green Technology Innovation and Policy Frameworks

To sum up, this article shows that successful development of the environmental sustainability necessitates a mixed strategy that entails a combination of technological development, policy reinforcement, industrial revolution, and interaction with society. Advancement in green technology has been achieved on a significant scale in various fields such as renewable energy systems, energy efficiency solutions, biodegradable materials, environmental monitoring technologies, and the use of the circular economy. Nevertheless, the development of technology is not enough without supportive politics, market cultivation, and investment in infrastructure as well as social acceptance.

Biodegradable materials are a frontier innovation that will not only solve long-term environmental pollution caused by traditional plastics but will also make the transition of the circular economy (Maurya et al., 2024). Further development will entail simultaneous improvements in polymer chemistry to come up with materials with superior performance properties, optimization in the manufacturing process to lower the cost of production, development of applications to identify the appropriate use situations, end-of-life infrastructure to allow proper disposal or recovery, and standards to ensure that the environmental claims are validated.

The environmental monitoring systems also offer the necessary data to learn more about environmental conditions, evaluate the effectiveness of policies, and make managerial decisions. The development of sensor technologies, wireless communication solutions, and data analytics platforms allows even more sophisticated monitoring strategies with a better spatial and temporal resolution. Nevertheless, to unlock the potential of these technologies, it is necessary to consider the data quality assurance, interoperability standards, data management infrastructure, the analytical capabilities, and integration into the processes of decision-making.

6.2. Industrial Sector Transformation Pathways and Mechanisms

The transformation of the industrial sector to sustainability needs systemic changes on a technology, process, materials, products, business model, and organizational cultures basis (Chen et al., 2022). The energy efficiency increases present immediate benefits of reducing costs and mitigating emissions by using established technologies and practices. Long-term transformation pathways are provided by process innovation that creates alternative production paths using less resource use and less waste. Circularity of materials via industrial symbiosis, waste valorization and recycling of the process of the closed loop minimizes the virgin material requirements and generates value out of the second-generation resources.

The policy effects on industrial transformation work in several ways such as regulation compliance requirements, economic incentives that cause changes in the relative costs of substitutes, government procurement that creates markets of green products, research financing that facilitates technology development, and standards that set performance standards (Popp et al., 2019). The design of any given policy needs knowledge of the economics of the industry, technological capabilities, competitive trends, and unintended impacts (Ashford and Hall, 2000). Long-term signals and policy stability give the businesses confidence to invest heavily in new capabilities and technologies.

Sustainability is increasingly integrated into the concepts of industrial innovation by considering them through design thinking, life cycle assessment, stakeholder participation, and systems approach (Wang et al., 2024). Firms have realized that environmental performance has an impact on brand reputation, customer loyalty, employee attraction and retention, regulatory compliance, operational efficiency, and risk management (Hassan et al., 2023). Four possible types of competitive advantages produced by sustainability-based innovation include differentiated products, savings in costs, penetration of the market, and improved stakeholder relations.

Compliance with ethical standards

Disclosure of conflict of interest

No conflict-of-interest to be disclosed.

References

[1] Zhang, H., & Wei, X. (2024). Green technology advancement, energy input share and carbon emission trend studies. Scientific Reports, 14, Article 1790.

[2] Maurya, A. K., de Souza, F. M., Dawsey, T., & Gupta, R. K. (2024). Biodegradable polymers and composites: Recent development and challenges. Polymer Composites, 45(3), 2023-2045.

[3] Nazir, N. (2021). Development of green technology from the past to the future development: A systematic literature review paper. Systematic Literature Review and Meta-Analysis Journal, 2(1), 25-37. https://doi.org/10.54480/slrm.v2i1.13

[4] Shimshack, J. P. (2014). The economics of environmental monitoring and enforcement. Annual Review of Resource Economics, 6(1), 339-360.

[5] Belaud, J. P., Adoue, C., Vialle, C., & Sablayrolles, C. (2019). A circular economy and industrial ecology toolbox for developing an eco-industrial park: Perspectives from French policy. Clean Technologies and Environmental Policy, 21, 967-985.

[6] Wang, Q., Chen, Y., & Zhang, L. (2023). The role of green technology innovation on employment: Does industrial structure optimization and air quality matter? Environmental Sciences Europe, 35, Article 73. https://doi.org/10.1186/s12302-023-00773-w

[7] Zhang, L. R., Mankus, D., Varshney, D., Xiao, R., Alsaiari, S., Lytton-Jean, A., Langer, R., & Jaklenec, A. (2024). A new biodegradable material to replace certain microplastics. Nature Materials, 23(12), 1645-1653.

[8] Frosch, R. A., & Gallopoulos, N. E. (2006). Industrial ecology: An organizing framework for environmental management. Environmental Management, 38(4), 449-465.

[9] Chen, W., Wang, Y., & Liu, X. (2022). Research on the green technology innovation cultivation path of manufacturing enterprises under the regulation of environmental protection tax law in China. Frontiers in Environmental Science, 10, Article 874865.

[10] Vikhareva, I. N., Aminova, G. K., & Aimaletdinov, I. K. (2021). An overview of the main trends in the creation of biodegradable polymer materials. Journal of Chemistry, 2021, Article 5099705. https://doi.org/10.1155/2021/5099705

[11] Han, D., Zhang, C., Ping, J., & Yan, Z. (2022). A new area of utilizing industrial Internet of Things in environmental monitoring. Frontiers in Chemical Engineering, 4, Article 842514.

[12] Ashford, N. A., & Hall, R. P. (2000). Environmental policy and industrial innovation: Integrating environment and economy through ecological modernisation. Geoforum, 31(1), 33-44.

[13] Pohlmann, C. R., Scavarda, A. J., Alves, M. B., & Korzenowski, A. L. (2019). Approaches to integrate sustainable materials management into waste management planning and policy. Resources, Conservation and Recycling, 148, 55-67.

[14] Yuan, Y., Wang, Z., & Li, X. (2023). Assessment of green technology innovation on energy-environmental efficiency in China under the influence of environmental regulation considering spatial effects. Scientific Reports, 13, Article 19786.

[15] Khattak, S. I., Ahmad, M., Haq, Z. U., Shaofu, G., & Li, H. (2022). Recent advances in green technology and Industrial Revolution 4.0 for a sustainable future. Environmental Science and Pollution Research, 29, 50081-50101. https://doi.org/10.1007/s11356-022-20024-4

[16] Hassan, M. N., Mahmoud, M. M., El-Sayed, A. A., & Badr, A. A. (2023). Advances in biodegradable polymers and biomaterials for medical applications—A review. Polymers, 15(17), 3641.

[17] Gibbs, D., & O'Neill, K. (2015). From theory to practice: Enhancing the potential policy impact of industrial ecology. Sustainability, 7(2), 2259-2273. https://doi.org/10.3390/su7022259

[18] Liu, Y., Chen, S., & Zhang, H. (2024). Sustainable materials and manufacturing processes: A circular economy approach. International Journal of Production Research, 62(14), 4825-4843.

[19] Avcu, E., Bastan, F. E., Guney, M., Yildiran Avcu, Y., Ur Rehman, M. A., & Boccaccini, A. R. (2022). Biodegradable polymer matrix composites containing graphene-related materials for antibacterial applications: A critical review. Acta Biomaterialia, 151, 1-44.

[20] Tao, Y., Gao, Q., Xing, X., & Wang, J. (2024). Exploring the impact of green technology, renewable energy and globalization towards environmental sustainability in the top ecological impacted countries. Geoscience Frontiers, 15(5), 101191. https://doi.org/10.1016/j.gsf.2024.101191

[21] Pahi, K., & Yadav, S. (2024). Advances in biodegradable materials: Degradation mechanisms, mechanical properties, and biocompatibility for orthopedic applications. Heliyon, 10(12), e32713. https://doi.org/10.1016/j.heliyon.2024.e32713

[22] Pogutz, S., & Winn, M. (2016). Cultivating ecological modernization: A two-tier analysis of institutional innovations in the coffee sector. Organization & Environment, 29(4), 446-466.

[23] Nižetić, S., Djilali, N., Papadopoulos, A., & Rodrigues, J. J. (2019). Smart technologies for promotion of energy efficiency, utilization of sustainable resources and waste management. Journal of Cleaner Production, 231, 565-591. https://doi.org/10.1016/j.jclepro.2019.04.397

[24] Wang, X., Zhang, D., & Yang, C. (2024). Realization of circular economy principles in manufacturing: Obstacles, advancements, and routes to achieve a sustainable industry transformation. Discover Sustainability, 5, Article 289.

[25] Ghisellini, P., Cialani, C., & Ulgiati, S. (2016). A review on circular economy: The expected transition to a balanced interplay of environmental and economic systems. Journal of Cleaner Production, 114, 11-32. https://doi.org/10.1016/j.jclepro.2015.09.007

[26] Popp, D., Hascic, I., & Medhi, N. (2019). Environmental policy and innovation: A decade of research. NBER Working Paper Series, No. 25631. National Bureau of Economic Research.

[27] Vikhareva, I. N., Aminova, G. K., & Aimaletdinov, I. K. (2021). An overview of the main trends in the creation of biodegradable polymer materials. *Journal of Chemistry, 2021*, Article 5099705. https://downloads.hindawi.com/journals/jchem/2021/5099705.pdf

[28] Frosch, R. A., & Gallopoulos, N. E. (2006). Industrial ecology: An organizing framework for environmental management. *Environmental Management, 38*(4), 449-465. https://link.springer.com/content/pdf/10.1007/s00267-005-0006-6.pdf

[29] Pahi, K., & Yadav, S. (2024). Advances in biodegradable materials: Degradation mechanisms, mechanical properties, and biocompatibility for orthopedic applications. *Heliyon, 10*(12), e32713. **PDF Link:** https://www.cell.com/heliyon/pdf/S2405-8440(24)08744-2.pdf.