

## Review Article

# Green Technology for Sustainable Energy and Development: Applications in Bioenergy, Agro-Waste, and Eco-Friendly Materials

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## ABSTRACT

In light of growing global challenges like climate change, population growth, environmental pollution, and inefficient use and depletion of natural resources, it is essential for countries to adopt technologies and approaches that promote environmentally responsible economic activity. These measures aim to reduce environmental harm and preserve natural resources for future generations. Sustainable development, which prioritizes minimal environmental damage, relies on comprehensive and all-encompassing policies. These policies, both international and national, recognize the long-term needs of humanity and emphasize balancing economic growth with ecological preservation. A key component of these policies is the employment of green technologies, which are designed to minimize environmental impact. Countries that adopt green technologies are better positioned to mitigate the effects of climate change, reduce pollution, and ensure the sustainability of resources, which is crucial for the well-being of future generations. Through policy support, investment in innovation, and collaboration at the global level, green technologies can facilitate the transition to more sustainable economic models.

## Introduction

Green technology, often referred to as "green tech" or "clean tech," is of paramount importance because it provides solutions for some of the world's most pressing environmental and economic challenges. Its significance can be summarized across three main pillars:

Environmental, Economic, and Social. Green technology is essential for mitigating environmental damage and fostering a healthier planet. It is key to reducing greenhouse gas emissions (such as CO<sub>2</sub>) by promoting renewable energy (solar, wind, and hydro) and technologies such as Carbon Capture and Storage. It minimizes air and water pollution through cleaner industrial processes, advanced

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waste management, and sustainable transportation (such as electric vehicles). This leads to improved public health. Green tech fosters energy efficiency (smart grids and energy-efficient appliances) and promotes the circular economy through better recycling and waste-to-energy systems, helping conserve finite natural resources. Sustainable agriculture and eco-friendly practices reduce the ecological footprint of human activities, aiding in the protection of ecosystems and biodiversity.

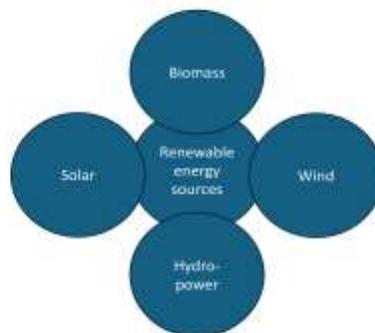
Green technology drives economic growth, stability, and efficiency. Technologies focused on energy and resource efficiency often lead to significant long-term cost reductions for businesses and consumers (*e.g.*, lower energy bills from LED lighting or better insulation) [1]. The green tech sector is a rapidly growing industry, creating new jobs in areas like renewable energy installation, manufacturing, research, and environmental consulting. It spurs innovation and opens up new domestic and international markets. By utilizing diverse, domestic renewable energy sources, countries can reduce their reliance on volatile global fossil fuel markets, enhancing national energy security and economic stability. Companies that adopt green practices and technologies often improve their brand reputation, attracting eco-conscious customers and investors seeking sustainable investment opportunities.

Green technology is a core pillar of sustainable development, aiming for a balance between people, planet, and profit. By reducing air and water pollution, green technologies directly contribute to lower rates of respiratory diseases and other health issues in communities [2,3]. Sustainable infrastructure, such as green buildings and smart grids, is often more resilient to climate impacts and natural disasters. The

need for green solutions continually drives innovation and research, leading to breakthroughs that benefit various sectors of society.

In essence, the adoption of green technology is critical for ensuring a sustainable future where economic development and human well-being can be achieved without compromising the environment.

The percentage of households with access to electricity, whether from the national grid or solar energy, reflects significant progress towards increasing energy access in line with government strategies. According to the government's strategic plan, the aim is to achieve universal electricity access through a combination of short, medium, and long-term programs. These programs focus on increasing electricity generation from diverse sources, including natural gas, coal, liquid fuel, nuclear energy, and renewable energy sources such as solar, wind, and hydropower (Figure 1). In the short term, the focus has been on increasing the capacity of the existing infrastructure, particularly by utilizing natural gas and liquid fuel. In the medium term, efforts are directed toward developing coal-based power plants and further expanding renewable energy projects, such as solar and wind power. The long-term vision includes integrating nuclear energy and a substantial increase in the contribution of renewables to the national energy mix, aiming to reduce dependency on non-renewable sources and enhance sustainability. Solar energy plays a crucial role in rural electrification, especially in off-grid areas, and combined with grid expansion, it is steadily improving the percentage of households with reliable access to electricity.



**Figure 1:** Renewable energy sources for sustainable energy.

Biomass is increasingly being used as a source of renewable energy across many countries, contributing significantly to the global energy mix. Currently, biomass accounts for approximately 50 exajoules per year of the total primary energy demand worldwide. The use of biomass for energy generation offers several advantages. One key benefit is its low cost, as biomass residues such as agricultural waste, forest residues, and organic by-products are inexpensive. Additionally, the energy conversion efficiency of biomass-based systems is relatively high compared to traditional fossil fuel generation techniques, which helps to reduce the overall cost of electricity production. Beyond energy generation, biomass technology provides multiple co-benefits. It produces organic fertilizers as a by-product, which can enhance soil fertility and increase crop production. Furthermore, the use of biomass promotes a cleaner, greener environment by reducing greenhouse gas emissions and minimizing the dependence on fossil fuels. This makes biomass a sustainable option that supports both energy security and environmental sustainability.

The Europe 2020 strategy for smart, sustainable, and inclusive growth identifies key factors that contribute to strengthening the economy by focusing on three main pillars: building an economy centered on knowledge, research, and innovation; promoting a resource-efficient, greener, and more competitive economy; and encouraging a high-employment economy that ensures social and territorial cohesion. This strategy has dedicated sections aimed at the

smart use of resources and energy in Europe, encouraging a shift towards a low-carbon economy. It emphasizes the benefits of renewable energy adoption and modernization of the transport sector. The strategy promotes energy efficiency, reduction of emissions, and economic sustainability, laying the foundation for transitioning away from hydrocarbon dependence [4]. However, despite its broad scope, the Europe 2020 strategy has limitations. It did not fully encompass the wide range of green sectors, leaving gaps in areas like circular economy practices and addressing emerging renewable technologies comprehensively. The strategy's focus on renewable energy and transportation modernization is a step forward, but broader, more inclusive policies are needed to cover the entire spectrum of the green economy.

The proliferation of metrics related to sustainability provides researchers, business leaders, and politicians with tools to measure and communicate progress toward achieving sustainability goals. Each group tends to prioritize different aspects of green chemistry according to their specific needs, which influences their choice of metrics. While the diversity of these metrics has helped to promote green chemistry concepts, it also creates challenges [5]. The wide range of metrics can lead to confusion when interpreting and validating claims of "greenness." This situation is further complicated by press and marketing campaigns that emphasize the potential of green jobs and the broader green economy. These

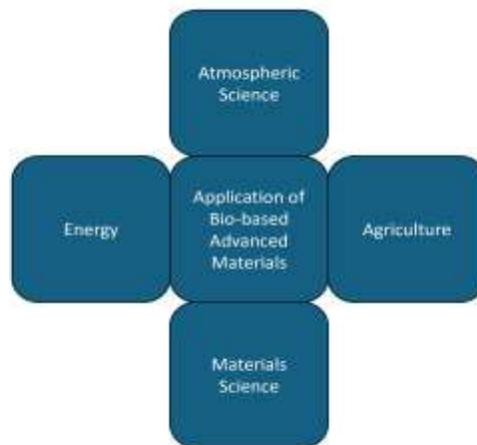
campaigns often bring new claims of environmental benefits, which require careful scrutiny to ensure that they reflect genuine sustainability improvements rather than superficial or misleading assertions. As green chemistry continues to evolve, it becomes increasingly important to establish clear, standardized metrics to accurately assess and communicate the real environmental impact of these technologies and initiatives.

Green technology is the essential enabler of the energy transition, providing the tools and innovations necessary to replace fossil fuels, decarbonize industries, and build a sustainable, net-zero global energy system. The energy transition is the global shift from energy production based on fossil fuels (coal, oil, and gas) to a system based primarily on low-carbon, renewable energy sources. Green technologies

drive this change across three main areas: supply, storage, and consumption.

### Green Technology (GT) for a Sustainable Energy

Scientists are continuously working toward creating a sustainable future for upcoming generations by developing innovations in green technology (GT). These advancements aim to help industries adopt alternative, eco-friendly methods for waste disposal and promote the use of bio-based advanced materials, leading to more affordable, safe, and environmentally friendly products. Green technology is a broad field that applies science and technology to reduce human impact on the environment [6]. It spans across various areas of research, including energy, atmospheric science, agriculture, materials science, and hydrology (Figure 2).



**Figure 2:** Bio-based advanced materials uses in different sectors.

Many green technologies aim to combat climate change by minimizing emissions of carbon dioxide and other greenhouse gases. One of the most effective green technologies is solar power, which in many countries has become more affordable to install than fossil fuel-based energy sources. Additionally, green technologies can be supported by investing in stocks, mutual funds, and bonds that focus on ecologically sustainable

technologies, further encouraging the growth of environmentally responsible innovations [7]. These efforts are essential for driving long-term environmental conservation and sustainability. Climate is a complex interaction of various physical and natural environmental factors, encompassing ecological challenges such as global warming, ozone layer depletion, biodiversity loss, resource depletion, and

overpopulation. These environmental issues make societies increasingly vulnerable to natural disasters and environmental catastrophes. Biotechnology, by integrating engineering design, leverages biological systems such as cells and molecular structures to develop substances and services that can address these challenges. One of the critical aspects of climate action is carbon emission efficiency, which measures the effectiveness of efforts to reduce carbon emissions. However, the connection between green technology (GT) innovations and carbon emission efficiency remains insufficiently explored. The exact mechanisms through which GT innovations influence carbon emission reductions are not fully understood, making it difficult to assess the full impact of these technologies on sustainability goals [8]. Further investigation into this relationship is essential to optimize the role of green technologies in achieving carbon emission targets and enhancing global environmental resilience.

Green supply chains are logistical frameworks designed to promote environmentally friendly manufacturing, distribution, and delivery of products worldwide. These systems focus on reducing the environmental impact at each stage of the supply chain, from sourcing raw materials to delivering finished goods. To achieve this, companies must engage in optimizing the design and planning of their logistics systems, balancing the trade-offs between profitability and environmental impact. This often involves incorporating sustainable practices such as reducing waste, minimizing carbon emissions, improving energy efficiency, and using eco-friendly packaging, all while maintaining economic viability [9].

### Bio-Fertilizer

Bio-fertilizers significantly aid the bioenergy/biofuel cycle and contribute to CO<sub>2</sub> reduction by boosting biomass yield and reducing the reliance on energy-intensive synthetic nitrogen fertilizers. Biofuels are produced from biomass (*e.g.*, dedicated energy crops such as switchgrass, or sugar crops such as sugarcane, or oilseeds). The efficiency of the entire cycle depends on maximizing the

harvestable biomass yield. By improving the soil ecosystem, bio-fertilizers ensure the long-term sustainability and productivity of the land used for energy crops. Healthier soil leads to more consistent, high-quality biomass over multiple growing seasons. The industrial process for producing synthetic nitrogen fertilizer, known as the Haber-Bosch process, is extremely energy-intensive, consuming large amounts of natural gas and releasing significant quantities of CO<sub>2</sub> (and other greenhouse gases) during manufacturing, transport, and application. Excess synthetic nitrogen fertilizer applied to fields can lead to denitrification, where soil microbes convert nitrates into nitrous oxide (N<sub>2</sub>O). N<sub>2</sub>O is a potent greenhouse gas, with a global warming potential nearly 300 times that of CO<sub>2</sub> over a 100-year period.

Biofertilizers are living microorganisms that enhance plant nutrition by improving nutrient availability and stability in soils. A wide range of microbial taxa, including beneficial bacteria and fungi, are used as biofertilizers, as they actively colonize the root interior, rhizoplane, or rhizosphere of plants. One of the most well-known biofertilizers, *Azotobacter*, has been in use for over a century [10]. It fixes nitrogen aerobically, produces plant hormones, solubilizes phosphates, and suppresses or mitigates the harmful effects of phytopathogens. The application of wild-type *Azotobacter* has been shown to increase yields in various crops, including cereals, oilseeds like sunflower and mustard, fruits such as sugarcane and mango, fiber crops like cotton and jute, as well as vegetables and tree species such as oak. In addition to this, hydrolysates can also be used as biofertilizers, serving as protein supplements, animal feed, and sources of bioactive peptides. They enhance soil nutrients, improve the carbon-to-nitrogen (C/N) ratio, and increase water retention capacity. The plant growth-promoting activities of hydrolysates also make them suitable for organic farming, helping to enrich microbiota and improve soil ecosystems [11].

Biofertilizers contribute to sustainable energy in an indirect yet fundamental way, primarily through their role in biofuel production and by making the entire agricultural system for energy crops more environmentally sound. Their

microorganisms that fix nitrogen, solubilize phosphorus, and produce plant growth hormones significantly enhance the health, growth rate, and size of plants. This leads to a greater overall biomass yield (*e.g.*, sugarcane, corn, oilseed crops, and algae) per unit of land. More biomass means more raw material for generating biofuels (such as bioethanol and biodiesel) or for direct combustion in biomass energy plants. By improving soil structure, water retention, and microbial diversity, biofertilizers ensure the long-term productivity of the land. This is critical for sustainable energy production, as it means the land used for energy crops remains viable without constant chemical inputs, preventing soil degradation. The process of anaerobic digestion breaks down organic waste (agricultural residues, food scraps, and manure) to produce biogas (a sustainable energy source). The solid and liquid residue remaining after this process, called digestate, is rich in nutrients and is highly effective when used as a biofertilizer, thus closing the nutrient loop and creating a co-product of sustainable energy production.

### Bioenergy and Bioengineering

Biohydrogen production is increasingly recognized as a crucial process for simultaneous energy generation. Hydrogen ( $H_2$ ) is considered an ideal alternative energy source due to its renewable nature, carbon neutrality, and high energy yield. One promising method for producing hydrogen is through the anaerobic fermentation of biomass, such as water hyacinth, which involves heat treatment to optimize hydrogen production [12]. This approach utilizes biological processes, making it a potential solution to meet the rising demand for clean energy.

Among biological methods, anaerobic fermentation stands out as a sustainable option for biohydrogen production. It relies on microorganisms to break down organic material, generating hydrogen as a byproduct. Optimizing key factors such as pH, temperature, substrate concentration, and microbial communities is critical for maximizing hydrogen yields [13]. Using biomass like water hyacinth not only helps in energy generation, but also aids

in managing invasive plant species, providing an eco-friendly method for waste management and clean energy production.

Water hyacinth, a widely available aquatic biomass, can be effectively utilized as a valuable resource, transforming it into a cash crop if properly processed. As a lignocellulosic biomass, it comprises three primary chemical components: cellulose, hemicellulose, and lignin, each with direct industrial applications and potential as raw materials for the synthesis of various chemicals. The goal of this study was to co-extract cellulose, hemicellulose, and lignin from water hyacinth. Hemicellulose and lignin were isolated using acidic and basic treatments, respectively, with the process conditions (such as concentration, temperature, and time) optimized to maximize yield. After the removal of hemicellulose and lignin, the remaining solid residue was subjected to an oxidation process (bleaching) to extract cellulose [14]. The results showed yields of 20.5% for cellulose, 7.9% for hemicellulose, and 13.8% for lignin-rich solids. These components can be further processed for various applications, such as in biofuels, bioplastics, and other biochemical products, showcasing the potential of water hyacinth as a sustainable source of lignocellulosic biomass for industrial use.

Bioenergy is a diverse and renewable resource derived from recently living organic materials, commonly known as biomass. It plays a vital role in generating products, heat, transportation fuels, and electricity in an environmentally friendly manner. However, replacing natural ecosystems with bioenergy crops, especially first-generation and high-yield crops, can negatively impact biodiversity [15]. To mitigate these adverse effects, bioenergy production using marginal lands or integrating biomass extraction within existing agricultural landscapes presents a more biodiversity-friendly alternative than converting natural ecosystems for biofuel production.

Biofuels are a key product of bioenergy, with benefits such as reducing carbon monoxide (CO) and nitrogen oxide (NO<sub>x</sub>) emissions when used as alternatives to traditional diesel fuels. Ethanol, another important bioproduct, contributes to the conservation of natural resources and the reduction of pollution [16]. By

focusing on creating biofuels from raw materials that are not harmful to the environment, bioenergy helps limit pollution. Notably, bioethanol has shown positive results in reducing environmental pollutants and is increasingly being used as an alternative to diesel fuel in vehicles, contributing to cleaner air and a healthier environment.

In the pursuit of meeting energy demands while reducing carbon emissions, crop residues like wheat straw have been explored as potential feedstock for biofuel production. To assess the feasibility of using crop residues for bioenergy, a postal survey was conducted, focusing on wheat straw usage, its current destination, and potential future supply among farm businesses. The survey responses were predominantly from larger, more commercially driven farms, representing a significant portion of wheat straw production. The results revealed diverse practices regarding current straw use and the willingness to supply straw to different markets in the future [17]. Despite the potential for bioenergy, 28.5% of respondents indicated that, even with generous payments, they would not sell straw that is currently chopped and incorporated into the soil. This suggests that the availability of straw for bioenergy feedstock might be more limited than initially expected. However, the survey also found that higher straw prices could incentivize farmers to explore methods to increase straw yield, which could potentially expand the supply for bioenergy use.

Unsustainable rice straw management contributes to environmental problems, making the utilization of rice straw for bioenergy a promising solution for sustainable management [18]. While rice straw has significant potential for bioenergy generation, its entire production cycle and application may result in environmental impacts that are not fully understood. Therefore, it is crucial to conduct environmental performance studies to identify the most effective methods for rice straw utilization.

A Life-Cycle Assessment is a comprehensive approach that evaluates the potential environmental effects of rice straw use for bioenergy. This study provides a brief overview of the LCA of rice straw utilization, highlighting

that using rice straw for bioenergy can reduce global warming potential compared to fossil fuel-based energy production. However, it is important to also evaluate other environmental impact categories in future research, such as water usage, land degradation, and air pollution, to assess the overall sustainability of rice straw-based bioenergy production [19]. This holistic assessment provides clearer insights into the environmental benefits and drawbacks of rice straw utilization.

The reliance on natural resources for diesel production has contributed to rising prices, prompting a shift toward bioenergy to help reduce pollution globally. In response, the focus has increasingly turned to alternative energy sources such as wind, nuclear, and solar power. These renewable resources are being utilized to develop energy efficient fuels that are more sustainable and can be recycled and reused, offering a cleaner alternative to traditional fossil fuels [20]. This transition to bioenergy and renewable energy sources is seen as a key strategy to mitigate environmental damage and promote a more sustainable energy future.

### Biodegradable Eco-Friendly Materials

Nonbiodegradable plastic waste has emerged as a major pollutant in water bodies such as rivers and oceans, with approximately 8 million tonnes of plastic waste being dumped annually. If this trend continues, it is projected that by 2050, there could be more plastic than fish in the oceans. In response, scientists are focusing on the use of biodegradable materials like starch, cellulose, chitosan, biomass, resins, gums, jute, gelatin, pectin, and waxes, as well as inorganic compounds such as  $TiO_2$  and  $ZnO$  [21]. These materials are being explored to promote sustainable alternatives to plastic.

Efforts are being made to integrate eco-friendly habits into everyday life, such as replacing plastic with jute or cloth bags for grocery shopping and utilizing biodegradable films made from cornstarch and chitosan for industrial packaging. In the realm of technology, renewable or biodegradable materials are being used to create electronic devices that disintegrate into harmless byproducts, reducing environmental impact [22]. For these "green"

electronic devices to be viable on an industrial scale, low-energy, low-cost processes using nontoxic or minimally toxic functional materials and solvents are needed, further advancing the goal of sustainability. New natural biopolymer combinations offer promising applications due to their ability to degrade into non-toxic, harmless compounds while enhancing biocompatibility and high loading efficiency [23]. These biopolymers are particularly effective in drug delivery systems for targeted tumor therapy.

Biochar, produced from the pyrolysis of biomass, is another versatile biodegradable material. It can be utilized in drug delivery and detoxification, providing an effective solution for treating poisoning or drug overdose. Additionally, biochar helps in waste management and has agricultural applications, such as promoting crop growth with cornstarch gelatin composites and modified tapioca coatings over controlled-release urea particles to improve nitrogen availability for plants [24]. Biochar also aids in fixing CO<sub>2</sub> from the atmosphere, contributing to climate change mitigation.

In electronic technology, starch-based coatings can enhance the electrochemical performance of batteries. Combining starch from arrowroot and corn with chemicals like sodium perchlorate (NaClO<sub>4</sub>) and glutaraldehyde results in highly conductive electrolyte membranes. Moreover, biochar coated with graphene can serve as effective anode materials for batteries and supercapacitors, showcasing its potential in energy storage technologies [25].

Using bio-fertilizer derived organisms for energy materials provides a direct pathway for CO<sub>2</sub> reduction by embedding biogenic carbon into technology. Algae and cyanobacteria actively pull CO<sub>2</sub> from the atmosphere during their growth (photosynthesis). When this biomass is harvested and incorporated into a solar film or battery electrode, the captured carbon is sequestered within a durable material, rather than being released back into the atmosphere upon decomposition. Substituting microbe-derived components for conventionally manufactured, petroleum-based, or metal-intensive components reduces the embodied energy of the final product. This translates to

lower manufacturing CO<sub>2</sub> emissions compared to producing purely synthetic materials under high heat or pressure.

### Sustainable Renewable Energy in Industrial Levels

Renewable energy, also known as alternative energy, is derived from natural sources that are replenished naturally and do not deplete with use. This form of energy has gained significant attention in recent years due to its environmental benefits [26]. Unlike traditional energy sources that contribute to pollution and ecological degradation, renewable energy supports environmental sustainability.

The rapid advancement of science and technology, while driving industrial progress, has often outpaced effective pollution control measures. This imbalance has led to significant environmental concerns, emphasizing the need for stringent regulations to maintain ecological integrity. The goal of eco-industrial development is to address these challenges by integrating environmental sustainability into renewable energy management and climate change mitigation strategies [27].

Renewable energy, including wind, solar, geothermal, tidal, and biomass sources, represents the most viable and cost-effective alternative to conventional energy sources. Its vast potential, especially in countries like India, offers a promising solution to reduce the global impact of climate change [28]. By optimizing the use of these renewable resources, a more sustainable future can be provided, improving climate resilience and ensuring stable food production.

The shift towards a greener, eco-friendly, and sustainable lifestyle has spurred significant changes across various sectors, involving individuals, communities, governments, and the global community. One notable area of transition is green housing, which plays a crucial role in promoting sustainable living.

The growing trend toward purchasing sustainable products and appliances reflects increasing environmental awareness among consumers [29]. Individuals who prioritize eco-friendliness are more likely to choose energy-efficient products, such as LED lights over

traditional incandescent bulbs. However, for this transition to be effective, both governments and industries must ensure that green technologies are accessible and accurately promoted to consumers.

Another significant area of sustainable transition is at the industrial level, particularly in the development of green composites. Research in this field has led to the creation of strong, durable polymers through various treatments physical, chemical, biological, and thermal [30]. These polymers are derived from organic materials and enhance mechanical properties while promoting degradability. Plant fibers are used to produce eco-friendly products such as ropes, textiles, mats, and curtains. These materials are sustainable and provide antimicrobial benefits.

Microalgae grow quickly, making them a viable resource for large-scale applications. They produce a significant amount of oil, useful for various applications. Microalgae are effective in addressing heavy metal pollution. Microalgae also have promising applications in the biopharmaceutical and nutraceutical industries, representing an advanced green technology with significant environmental and health benefits [31].

The connection between renewable industries and waste-to-energy (WtE) manufacturing is one of synergy and circular economy principles. WtE serves as a crucial bridge between waste management and renewable energy supply, ensuring non-recyclable materials are utilized as a resource rather than being landfilled. Waste-to-Energy (WtE) is the process of generating energy (electricity and/or heat) from the treatment of waste. While the most common method, incineration, is only considered partially renewable, other WtE technologies are fully aligned with renewable industries. Unlike intermittent renewables like solar and wind, WtE plants especially those using established thermal methods can provide baseload power (consistent, reliable energy). This makes WtE a crucial complementary partner to the renewable industry, ensuring the energy grid remains stable when the sun isn't shining or the wind isn't blowing. WtE manufacturing is essential to the circular economy a system designed to keep

resources in use for as long as possible which underpins sustainable renewable development.

### Agro-Waste to Sustainable Energy

The global energy crisis and environmental degradation are critical concerns impacting sustainable development. With over 80% of current energy consumption reliant on fossil fuels, these resources are leading contributors to climate change, global warming, and the depletion of natural energy reserves [32]. As a result, countries worldwide are actively seeking alternative and sustainable energy sources to mitigate these challenges.

One promising area of research is the development of green fuels, such as bioethanol and biodiesel, which offer eco-friendly alternatives to traditional fossil fuels. These first-generation biofuels are derived from resources like sugarcane, palm oil, and corn [33]. They are economical and possess the potential to significantly reduce global dependence on non-renewable energy sources.

However, to further enhance sustainability, second-generation biofuels have emerged. These are produced by converting entire plants, including agricultural residues, into biofuels [34]. By utilizing non-food biomass, second-generation biofuels provide a more sustainable solution that addresses resource depletion without competing with food production.

In response to the looming threats of resource depletion and climate change, the development of alternative, sustainable, and clean energy sources has become a top global priority [35]. These efforts are not only aimed at large-scale energy production, but also cater to the growing demands of modern technology. Innovations in energy sourcing are increasingly focused on powering smart/wearable devices, portable electronics, flexible/stretchable gadgets, and wireless sensor networks, all of which play key roles in today's high-tech era [36]. Sustainable energy solutions for these devices can contribute significantly to reducing the environmental footprint of technology while ensuring continued innovation and growth in various sectors.

The smart and sustainable use of scarce natural resources and efficient waste management have

made biowaste an increasingly attractive alternative [37]. By converting biowaste into valuable products, several environmental challenges can be addressed while promoting circular economy principles.

Developing novel pathways to reduce environmental difficulties through biowaste transformation is crucial. These pathways not only focus on reducing waste and environmental impact, but also aim to create useful products from waste, such as biofuels, bioplastics, or fertilizers. This contributes to resource conservation and minimizes reliance on fossil-based or non-renewable materials [38]. By harnessing biowaste effectively, sustainable resource management can reduce environmental degradation, and support eco-friendly product innovation.

The growing global population has significantly increased energy demands and exacerbated the solid-waste management crisis, leading to environmental degradation. Agricultural waste (agro-waste) contributes a substantial portion to this problem, with improper management contaminating the environment and posing serious health risks [39]. Addressing these challenges is critical for the circular economy, which aims to achieve sustainable development goals (SDGs) by efficiently managing waste and energy.

This review highlights the role of nanotechnology-based processing strategies in converting agro-waste into energy, offering solutions to both the energy crisis and waste management issues. Specifically, it explores the state-of-the-art applications of nanomaterials in:

- Energy harvesting from agro-waste sources
- Energy storage technologies that utilize sustainable materials

Key aspects of agro-waste conversion into energy resources include:

- Green nanomaterials derived from agro-waste
- Biofuels and biogas production for renewable energy
- Utilization in thermal and solar energy generation
- Triboelectricity and green hydrogen production

- Development of energy storage modules such as supercapacitors and batteries

The review also addresses the challenges involved in agro-waste-to-energy technologies, proposing alternative solutions and future prospects for further innovation. The use of nanomaterials in energy generation and storage from agro-waste represents a promising approach for smart solid-waste management that aligns with the goals of a green and circular economy [40]. It provides a foundation for future research and technological advancements dedicated to transforming waste into sustainable energy sources without harming the environment.

Globally, approximately 25% of total agricultural biomass is burned, contributing significantly to environmental pollution and degradation. This highlights the urgent need to find economical and sustainable solutions for utilizing crop residues and reducing the negative impacts of burning and decomposition in open environments. The scientific community is increasingly focused on valorizing lignocellulosic-based agri-waste, which is rich in cellulose, hemicellulose, and lignin, for the production of biofuels and industrial enzymes [41].

As the world confronts energy and environmental challenges, transitioning from non-renewable to renewable energy sources has become essential. Utilizing agri-waste as a renewable resource can mitigate the environmental damage caused by burning, while also providing cleaner energy solutions. Projections indicate that renewable energy has the potential to meet 20-40% of total global energy demand by 2050, offering a viable path to a more sustainable energy future. The conversion of agri-waste into biofuels is a key component of this transition, addressing both energy needs and the environmental impact of waste management [42]. This approach not only helps reduce carbon emissions, but also promotes circular economy practices, where waste materials are repurposed for valuable applications.

## Textile Waste for Sustainable Green Technology

Millions of tons of textile waste are generated globally each year, with significant regional variations due to factors like culture, population density, lifestyle, fashion trends, and income levels. For instance, the annual textile waste production is estimated to be 26 million tons in China, 15.1 million tons in the US, and 1.7 million tons in the UK. This waste accounts for approximately 6% of total municipal solid waste generation globally. The staggering volume highlights the need for sustainable waste management strategies, such as recycling, repurposing, and promoting circular fashion practices to reduce environmental impact.

Waste jeans, or waste denim fabric, form the largest fraction of textile waste. They primarily consist of cotton and polyester, often with different weight ratios, though most denim is made from virgin cotton coated with textile dyes [43]. Approximately 2.16 million tons of waste jeans are generated annually, with 35% to 50% of this collected in Western Europe for reuse or recycling after sorting. Specialized companies handle this sorting, with rewearable jeans being sold to second-hand shops or third-world countries, while the damaged fraction is sent for recycling. This process helps reduce the environmental burden of textile waste and promotes sustainable fashion practices.

The recovery of cotton fibers and polyester from waste jeans presents a promising sustainable approach to addressing the shortage of cultivated cotton and reducing textile waste [44]. In this research, a green technology was developed to achieve this goal.

*Stage 1:* Textile dyes were removed from waste jeans using nitric acid leaching (with a concentration of less than 60%). The spent acid was then regenerated using activated carbon.

*Stage 2:* Polyester was separated from cotton by utilizing a switchable hydrophilicity solvent. To extract polyester and regenerate the solvent, CO<sub>2</sub> was added to the solution, which, after mixing with distilled water at 0 °C for one hour, allowed the polyester to solidify and be collected by filtration. The solvent was then returned to its hydrophobic state by heating and removing the CO<sub>2</sub>.

Various methods, such as optical microscopy, SEM, and FTIR, were used to analyze the morphology and composition of the liberated fibers and extracted polyester. The regenerated solvent and acid were analyzed using FTIR and titration-based methods.

The performance of the technology was evaluated within a circular economy framework. The study determined recycling rates, conducted an economic evaluation, and estimated greenhouse gas emissions [45]. The results demonstrated potential economic returns of up to \$1,629 per ton of waste, along with a significant reduction in the carbon footprint by 1,440 kg of CO<sub>2</sub> equivalent per ton of waste. This technology offers a viable solution for sustainable textile waste management and material recovery.

## Future Prospects and Conclusion

The future prospects for sustainable energy are overwhelmingly positive, driven by technological advancements, falling costs, supportive policies, and increasing global commitments to combat climate change. The transition from fossil fuels to clean energy is accelerating, though challenges remain. Solar photovoltaic (PV) and wind power are expected to lead the global growth in electricity generation. Solar, in particular, has seen massive capacity additions and is projected to be responsible for a large share of new renewable growth. Renewable energy sources are becoming the most affordable sources of power in most parts of the world, with costs for solar and wind technologies dropping rapidly, making them more attractive investments than fossil fuels. Innovations like advanced PV systems (*e.g.*, perovskites and thin-film cells) for solar and floating offshore wind farms (accessing deeper, stronger wind areas) are expanding potential deployment locations and increasing efficiency. Continued research into lithium-ion battery improvements (*e.g.*, higher energy density and longer life) and emerging technologies like solid-state batteries and lithium-glass batteries will be vital for grid-scale storage and electric vehicles. Solutions like green hydrogen (produced via renewable electricity), pumped hydro, and thermal energy

storage (TES) are gaining traction for storing energy for hours, days, or even months. Produced using renewable electricity, green hydrogen is seen as essential for decarbonizing "hard-to-abate" sectors like heavy industry (steelmaking, ammonia production) and long-haul transport. It offers a high energy-density, clean fuel. The future of sustainable energy is characterized by exponential growth, continuous cost reduction, and deeper integration across all sectors of the economy, positioning it to become the dominant energy source globally by mid-century.

Countries with the highest carbon dioxide emissions are typically highly developed industrial nations or major oil-exporting countries. Nations such as the United Arab Emirates, Kazakhstan, the United States, South Korea, and Russia report significantly higher CO<sub>2</sub> emissions due to their extensive oil, gas, and mining industries. In contrast, island nations and countries with fewer natural resources to exploit tend to have much lower emissions.

Each country's CO<sub>2</sub> emission levels are influenced by factors such as economic development, industrialization, geographical location, and resource availability. As a result, pathways toward sustainable development and green energy transitions can vary greatly between countries, based on these unique national circumstances. Tailored strategies for reducing emissions and adopting sustainable practices must take these differences into account to be effective.

The future research direction for green technology will be driven by the need for systemic, scalable, and cost-effective solutions to achieve global net-zero emissions and establish a true circular economy. Research will focus on overcoming the limitations of current renewable energy technologies and integrating them seamlessly into the grid. Future research must develop solid-state batteries for electric vehicles with higher energy density, faster charging, and lower costs. For grid-scale storage, the focus is on alternatives to lithium-ion, such as flow batteries, compressed air energy storage (CAES), and advanced thermal storage to provide long-duration backup. Research is centered on dramatically reducing the cost and increasing the efficiency of electrolysis powered

by renewables. This includes developing new, low-cost catalysts and membranes for large-scale production, and creating reliable infrastructure for their storage, transport, and use in fuel cells.

Green technology's future relies heavily on the integration of computing and biological systems. Using Artificial Intelligence (AI) to optimize smart grids, predicting renewable energy output, and create "digital twins" of urban areas to manage energy, water, and waste with maximum efficiency. Research into vertical farming, precision agriculture (using AI and IoT sensors to optimize resource use), and advanced biotechnology develops drought-resistant, high-yield crops to secure food production while minimizing land and water use. Developing genetically engineered microbes cleans up pollutants (oil spills and heavy metals) and serves as living factories to produce bio-based materials and fuels.

Countries must adopt strategies and legislative acts that clearly interpret sustainable development within the framework of the green economy, aligning with recognized international standards. This requires a robust commitment to global sustainability goals, such as those set by the United Nations and other international agreements. This holistic approach will help nations balance economic growth with environmental responsibility, addressing the pressing need for climate action while fostering sustainable, long-term development.

Worlds require clearly defined action programs and indicators to effectively monitor sustainable development and green growth. The transition to green technologies must align with global efforts to enhance well-being and promote social equality, while simultaneously reducing environmental risks. By addressing these key areas, countries can drive progress toward green growth, promote long-term environmental sustainability, and contribute to global efforts aimed at addressing climate change and fostering socioeconomic well-being. A limitation of the proposed approach is that the baseline data only allow for macro-level assessments, which may not capture finer, context-specific details needed for targeted actions. Ensuring collaboration between different sectors (such as energy, agriculture,

industry, and health) to create synergistic policies and strategies for sustainable development. Utilizing local expertise, traditional knowledge, and region-specific approaches makes the solutions more adaptable and relevant to the unique challenges of each area. Actively involving various stakeholders, including communities, private sector, government bodies, and NGOs, ensures inclusive and participatory decision-making, leading to more widely accepted and supported outcomes. Strengthening the capacity of local organizations and institutions to take a more proactive role in driving sustainability efforts involves providing them with tools, funding, and training. This expanded framework can create a more dynamic and responsive system, allowing for more effective and localized sustainable development initiatives.

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