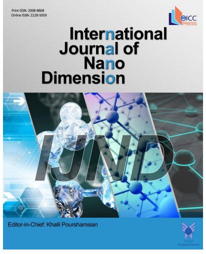


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Review Paper

# Exciting Future of Nanotechnology in Renewable Energy Sector

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**Abstract:**

Fossil fuels have historically been the foundation of our energy system, driving both industries and households. Nevertheless, we are becoming more aware of the constraints of these resources, which are not only limited but also significant contributors to the troubling increase in greenhouse gas emissions. This realization marks a crucial moment in our timeline, a unique opportunity to begin a transformative shift towards renewable energy options. These alternatives hold the promise of satisfying the rising energy needs of the planet in a manner that is both effective and environmentally friendly. Within the multitude of innovative technologies emerging during this transition, nanotechnology stands out as particularly remarkable. By precisely manipulating materials at the atomic and molecular levels, it uncovers immense potential to improve renewable energy sources while also tackling the pressing issues brought about by climate change. Utilizing this advanced method, we can unlock new efficiencies, enhance energy storage capabilities, and tap into natural forces in ways we have only just started to envision. Together, we can create a pathway to a brighter, cleaner future that can fulfil human needs while respecting and maintaining the delicate balance of our valuable ecosystems. This is our opportunity to welcome change and innovation for a sustainable future. This analysis investigates the various ways nanotechnology can promote advancements in renewable energy. It looks into different applications, such as solar cells and biofuels, underlining the crucial role that nanotechnology plays in enabling the shift to sustainable energy sources. The paper highlights the importance of continued research and development in this area, demonstrating how these nanoscale innovations can lead us toward a future dependent on clean, renewable energy.

**Keywords:** Bioenergy; Energy storage; Nanotechnology; Renewable energy; Wind energy

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## 1. Introduction

For many years, technological advancements have transformed human lifestyles, provided comfort and happiness while also addressed fundamental challenges. Throughout history, numerous technologies have been developed that are now indispensable to the daily existence of the average person. Disruptive technologies are those that have been created and integrated into society to such a degree that they have become essential for everyday life, making it exceedingly challenging for people to live without them. Instances of such groundbreaking technologies include the invention of the wheel, the internal combustion engine, electricity, the automobile, the telephone, the radio, the television, the computer, the mobile phone, the Windows operating system, and smartphones powered by the Android operating system. Numerous technologies that were initially intended for specific uses evolved into all-purpose tools that impacted every aspect of society and organizations. For instance, information and communication technologies, such as computer technology, have evolved into general-purpose technologies that are indispensable to the advancement of all other fields and have become an integral aspect of daily life.

This review highlights recent surveys and articles (up to 2025) focused on nanomaterials across various energy sectors. Nanoparticles (such as magnetite and metal oxides) can increase biogas production, improve microbial electron transfer, or serve as supports for enzymes and biocatalysts, resulting in reported productivity gains in the laboratory [1, 2]. The existing literature indicates that nanotechnology is a significant enabler across energy fields, showing consistent and repeatable improvements in lab-scale performance.

Over the past 20 years, a different technology has emerged as a game-changer for applications. Its significance and prospective benefits have made it a general-purpose technology that can significantly alter society. To create novel materials, structures, devices, and systems with qualities and phenomena exclusive to these scales, nanotechnology manipulates matter at the atomic level. In addition to being a general-purpose technology, nanotechnology also enables the creation of new tools and methods for enhancing human lives. Existing industries employ nanotechnology, and within those industries, new research fields are created that extend existing ones from microelectronics to nano-electronics, photonics to nano-photonics, biotechnology to nano-biotechnology [3, 4, 5, 6], and energy to nano-energy (Fig. 1).

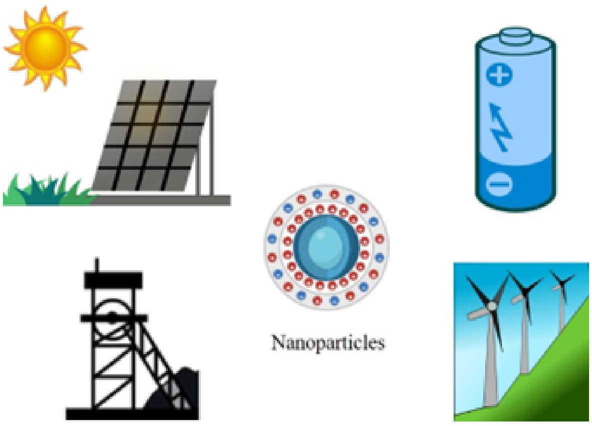


**Figure 1.** Nanotechnology in different fields of energy.

Savolainen et al. claim that the use of nanotechnology can fundamentally alter the properties of batteries and supercapacitors. Using nanotechnology, materials can be created to produce heat-resistant, flexible, and high-performing electrodes for the corresponding parts of lithium-ion batteries. Nanoporous materials, like zeolites, can be employed as heat stores throughout residential and industrial settings and can help improve thermal energy storage [7, 8]. Numerous applications for carbon nanotubes (CNTs) have been suggested. However, despite these potential uses, they are not widely employed due to several fundamental challenges associated with their use, such as their insolubility in both aqueous and non-aqueous solutions [9].

Daryoush and Darvish investigated the use of nanomaterials in energy-saving applications. They claimed that energy loss in the network and electricity production may be decreased by using nanowires for electrical energy transmission. In addition, they claimed that nanoparticles may be utilized to lessen the amount of energy lost to heat and cooling as a result of electricity use in the architecture of buildings and industrial sectors [10]. Semiconductor band spacing can be altered using nanostructures to match the spectrum of the light incident on the material. Furthermore, it is ensured that nanostructured materials are applied to the surfaces of solar cells to reduce reflection and increase solar cell absorption.

Nanotechnology-produced insulating materials use 30% less energy than conventional materials. These insulating materials are applied as a thin coating on any surface or squeezed in between solid panels. Fuel cells are increasingly recognized as an essential part of the renewable energy landscape, serving stationary, transportation, and portable power needs. Advanced fuel cell technology significantly benefits from the integration of nanotechnology in the development of nanostructured membranes, catalysts, and electrodes. Recently, Lee and Kjeang [11] introduced the first-ever nanofluidic fuel cell that employed fluid movement through nanoporous materials (Fig. 2). Nanomaterials help to boost the efficiency of solar cells and wind panels. Nanostructures in hydrogen storage allow for an increase in storage rate. It is possible to reduce losses in transmission cables and power lines. Furthermore, nanomaterials with excellent insulating properties contribute to energy savings [12, 13, 14]. It is possible to minimize radiator diameters and facilitate easier placement by employing nanofluids as coolants. Due to their excellent thermal performance, truck engines can operate at higher temperatures to produce more horsepower while using less working fluid and a smaller coolant system pump. The plasmonic nanostructures adjacent to the luminescent dielectric layer have created a strong electromagnetic field resonator, enhancing power by up to three times under ideal conditions [15]. According to research by Saidur et al., using nanofluid as a working fluid in radiators may result in a 10% decrease in the system's volume [16].

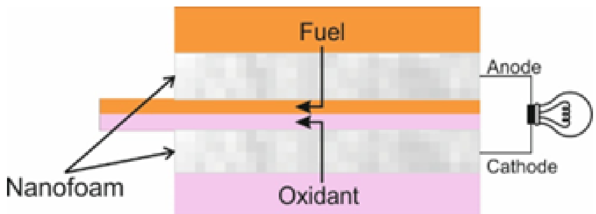


**Figure 2.** Nanofluidic fuel cell [11].

The market for wind turbines is expanding globally, and there is a growing demand for new turbine blade types with enhanced characteristics. To ensure long-term operation, excellent stiffness and fatigue resistance must be incorporated into the design and production of blades. Nanotech polymer matrix composites dominate the market for wind turbine blades due to their low cost, reduced weight-to-power ratios, excellent fatigue properties, high specific strength and modulus, and ability to create complex geometries. Manufacturers of wind turbine blades must overcome the difficulty of building larger, more complicated, and technologically advanced wind turbines at the lowest feasible total cost of production per turbine. The use of nanoparticle

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lubricant additives to wind turbine gearboxes will boost power generation by reducing the turbines' resistance to rotation.

The only affordable and accessible alternative energy source available to the entire globe is bioenergy. Ngo et al. [17] used highly active and readily recyclable magnetic nano biocatalyst aggregates to efficiently and environmentally turn waste grease with a high concentration of free fatty acid into a biodiesel fuel. It was studied that the nonlinear flow of nanofluids influenced by Arrhenius kinetics and Lorentz forces through a porous surface. They assessed the effects of various factors, including Brownian motion, porous media, magnetic fields, the Arrhenius function, radiation, and thermophoresis, on the velocity, distribution of nanoparticles (concentration), and temperature. Their findings indicated that increasing the values of the activation energy parameter significantly enhances the concentration of nanoparticles [18, 19].

## 2. Materials innovations in renewable energy sector

Possibly, the opportunity and challenge for the scientific community, as well as for human prosperity, lies in finding a way to generate, store, and convert energy into the necessary form at any time and for any duration, a process known as "ubiquitous energy." This would address human needs for food, drink, shelter, health, and a clean environment. The energy sector can harness the potential of nanotechnology by producing various forms of energy, transferring generated energy from one location to another, storing energy in different forms to reduce losses, and utilizing stored or instantaneously produced energy for productive work, leveraging nanotechnology principles. It is common practice to analyze any system by comparing it to an ideal system of the same kind [20, 21].

A system that satisfies all requirements for energy efficiency can constantly supply an endless amount of energy to its user and transform energy forms without experiencing any internal loss (Fig. 3). Energy transfer from one form to another with up to 100% efficiency is another area where nanotechnology is expected to play a significant role (Table 1). This discovery has a significant impact on the economies of all nations, as it makes energy readily accessible for people, homes, workplaces, businesses, and industries at almost no cost.

### 2.1 Energy sources

Nanotechnology can impact the production of energy in several ways. Through the conversion of other natural forms of energy, nanotechnology facilitates the efficient generation of electrical energy. This includes the use of photo-electric converters to convert light or electromagnetic energy into electrical energy, wind turbines optimized through nanotechnology to convert wind energy into electrical energy, hydro-electric turbines optimized through nanotechnology to convert mechanical energy of motion into electrical energy, gravitational energy conversion to electrical energy, or nuclear energy conversion to electrical energy using steam-based turbines optimized through nanotechnology, etc. Electrical energy is the most practical of the several energy forms that can be stored using current technologies and utilized for productive purposes. Researchers working on nanotechnology are focusing on finding ways to convert all other forms of energy into an electrical form for easy use, storage, and transmission, at the lowest possible cost and with the highest efficiency.

### 2.2 Energy transmission

Nanotechnology may impact energy transfer by increasing efficiency and reducing losses. Transmission cables based on nanotechnology should also be more affordable, more durable, and environmentally benign. Additionally, research is progressing to develop wireless energy transmission systems that will be made feasible by nanotechnology. These systems will transfer electrical energy with the least amount of loss possible between far-flung locations on Earth and between Space and Earth. When wireless energy transmission between far-off locations reaches this level, a significant amount of solar energy can be captured by deploying numerous solar space stations near the sun, where it will be converted into electrical energy and sent back to Earth to help alleviate civilization's energy crisis.

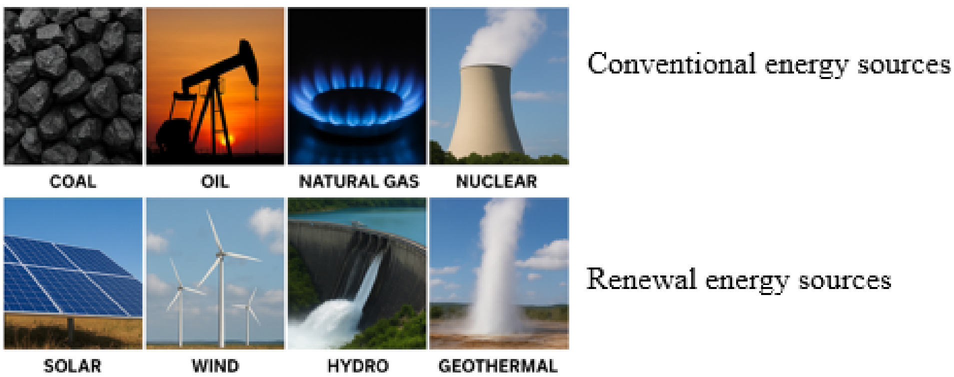


**Figure 3.** Nanotechnology in different fields of energy.

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**Table 1.** Comparative analysis: Nanotechnology in energy sources.

| Energy Source | Role of Nanotechnology | Nanomaterials Used | Advantages Achieved | Challenges / Limitations |
|---|---|---|---|---|
| Coal (Conventional) | Nano catalysts for cleaner coal conversion; nano filters for reducing emissions | Metal oxide nanoparticles ($TiO_2$, $Fe_2O_3$), Carbon nanotubes (CNTs) | Improved efficiency in coal gasification; reduction of SOx/NOx emissions; better carbon capture | High cost of large-scale nano catalyst deployment; disposal of used nanomaterials |
| Oil & Petroleum | Nanofluids for enhanced oil recovery (EOR); sensors for pipeline monitoring | Silica nanoparticles, CNTs, Graphene, Magnetic nanoparticles | Increased extraction efficiency; reduced corrosion; better oil-water separation | Economic feasibility in bulk; environmental risks of nanofluids in reservoirs |
| Natural Gas | Nano catalysts for methane reforming & hydrogen production | Ni-based nano catalysts, $CeO_3$, Pd nanoparticles | Higher conversion rates, cleaner hydrogen production, improved fuel cell compatibility | Catalyst deactivation; scaling issues |
| Nuclear | Nanomaterials for radiation shielding, nuclear waste management, advanced fuels | Boron nitride nanotubes (BNNTs), Nano-ceramics, $ZrO_2$ nanoparticles | Improved radiation resistance; safer fuel cladding; efficient storage of radioactive waste | Long-term stability under high radiation; regulatory hurdles |
| Solar | Nanostructures for light trapping, quantum dots for higher efficiency | Quantum dots (CdSe, PbS), Perovskite nanomaterials, Graphene | Increased solar cell efficiency (>30% in labs), flexible solar panels, low-cost thin films | Toxicity of Cd/Pb-based dots; stability of perovskites under moisture |
| Wind | Nanocoatings for turbine blades, sensors for wear monitoring | CNT composites, Graphene coatings, Nanostructured polymers | Stronger, lighter blades; reduced maintenance; anti-icing & anti-corrosion surfaces | Cost of nanocomposites; long-term durability in harsh environments |
| Hydropower | Nanocoatings for turbines to reduce biofouling & corrosion | $TiO_2$, ZnO, Graphene oxide, Nanoceramics | Increased turbine lifespan; reduced frictional losses; self-cleaning surfaces | Limited field testing; cost of coating large structures |
| Biomass & Biofuels | Nano catalysts for faster conversion; nanomembranes for purification | Metal oxides ($Fe_3O_4$, $TiO_2$), CNTs, Enzyme–nanoparticle hybrids | Higher biofuel yield, efficient biodiesel purification, hydrogen from biomass | Nanoparticle recovery and recycling issues |

### 2.3 Energy storage

The development of fuel cells and batteries with large storage capacities, extended lifespans, low weight, and compact sizes is one way nanotechnology may impact energy storage. The development and maintenance of perfect batteries that can store enormous amounts of electricity in small spaces is made possible by nanotechnology. Depending on the need, fuel cells produce electricity instantly, and nanotechnology is helping to design fuel cells with optimal properties. Batteries and fuel cells based on nanotechnology will revolutionize industrial production, automotive, electronic communication, aerospace, and space exploration, ushering in a new era of industrial revolution. A list of some nanomaterial components utilized in research on batteries and fuel cells can be found in Table 2 [22].

## 3. Systems integration

### 3.1 Wind energy

Wind energy is a vital component of the world's renewable energy portfolio and offers significant advantages for generating power sustainably. It remains challenging to maximise the lifespan and efficiency of wind turbines, so innovative ways to improve their durability and performance are required. With its ability to engineer materials at the molecular level, nanotechnology has become a game-changer in the wind energy industry, bringing new ideas for optimizing energy storage and transmission systems, lowering maintenance through sophisticated coatings, and strengthening turbine blades.

#### *3.1.1 Improvements in turbine blades*

The design and composition of wind turbine blades have a direct impact on their performance and efficiency. Materials lead to turbine blade developments that are lighter, stronger, and more durable, thanks to nanoengineered properties. Engineers can significantly improve the mechanics of blades by integrating nanocomposites, or materials that blend nanoparticles with traditional composite materials, into the blade construction [28]. The durability and resistance to fatigue of the composite materials used in blades, for example, can be increased by adding carbon nanotubes or graphene nanoparticles, making them more resilient to severe operating stresses and weather conditions.

These nano-engineered composites also decrease the overall weight of the turbine blades. Less energy is needed for lighter blades to begin spinning. They can function more effectively, particularly when there is less wind, which raises the wind turbines' energy conversion efficiency. In addition, the increased durability of these materials reduces the likelihood of blade damage and failure, thereby extending the turbines' lifespan

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**Table 2.** Nanomaterial components utilized in research on batteries and fuel cells [22].

| Nanomaterial Used | Advantage | Reference |
|---|---|---|
| $Co_3O_4$/CuO nanowire | Connected directly to nickel foam to make them potential anode materials for high-performance lithium-ion batteries. | [23] |
| $TiO_2$ nanotubes | Serve as a power source for mobile electronics. | [24] |
| Activated carbon nanotubes | Improved electrochemical properties of batteries. | [25] |
| Nanostructured $FePO_4$ | Improved capacity and power performance. | [26] |
| Nano-Sn electrode | Improved stability of lithium-ion battery. | [27] |

and decreasing the need for expensive maintenance and upgrades [29, 30].

### 3.1.2 Coatings and maintenance

Wear and tear are other factors that reduce wind turbines' operational efficiency and lifespan, but they can be lessened with nanotechnology in surface coatings [31]. Turbine blades with nano-coatings can be designed to possess ice-phobic, anti-corrosion, and self-healing properties, significantly reducing maintenance needs and downtime. For instance, coatings containing nanoparticles can produce a hydrophobic surface on the blades, which can lessen the aerodynamic drag created by rough blade surfaces and minimize ice formation in cold conditions. In a similar vein, nano-coatings can offer protection against mechanical wear, UV radiation, and seawater corrosion, all of which can cause blade materials to deteriorate over time [32]. Moreover, adding these cutting-edge coatings can improve wind turbine aerodynamic performance. Airflow across the blades is maximized by preserving a finer blade surface, which lowers drag and boosts energy generation efficiency [33]. Wind turbines with improved aerodynamics will produce more electricity and operate more efficiently overall.

### 3.1.3 Energy storage and transmission

Due to wind variability and the need for effective energy transmission and storage systems, integrating wind energy into the power grid presents some challenges. To overcome these obstacles, nanotechnology is crucial, particularly in creating cutting-edge materials for energy storage devices and enhancing electrical transmission components. The efficiency and capacity of energy storage devices are enhanced by nanostructured materials, which offer a higher surface area and improved electrical conductivity. Examples of these materials are nanoscale electrodes found in batteries and supercapacitors [34]. By enabling surplus energy storage during periods of peak wind and its release during periods of low wind, these advancements are essential for regulating the energy supply from wind turbines [35]. The efficiency and effectiveness of the materials employed by conductors, transformers, and other electrical transmission components can be enhanced via nanotechnology. For instance, energy loss during transmission can be reduced through the use of nano-engineered conductive materials, enabling more effective long-distance delivery of wind-generated electricity. Nanotechnology helps to minimize energy losses and maximize the total effectiveness of wind energy systems by lowering the resistivity and improving the thermal conductivity of these materials [36].

Finally, Raina et al. [37] conclude that nanotechnology presents promising ways to improve wind energy's durability, efficiency, and integration into the mix of renewable energy sources. Wind power's role in the shift to a sustainable energy future is being further cemented by nanotechnology, which is paving the way for more dependable, efficient, and affordable wind energy systems through advancements in energy storage and transmission technologies, surface coatings, and turbine blade materials. Table 3 presents an overview of different nanomaterials utilised in wind turbine research [22].

**Table 3.** Different nanomaterials utilized in wind turbine research [22].

| Nanomaterial Used | Advantage | Reference |
|---|---|---|
| Carbon nanofibers | Wind energy conversion systems. | [38] |
| Nano-particle lubricant additives | Wind turbine gearbox decreases Friction and wear. | [39] |
| Multifunctional carbon nanofiber | Usage with wind turbine blades. | [40] |
| Carbon nanotubes | Good fatigue resistance and good stiffness properties to ensure operational longevity. Structural reinforcement, fouling release coating. | [41, 42] |

## 3.2 Bioenergy

Bioenergy is an exciting and renewable energy source derived from natural and biological materials. It can be categorized into three main types: solid bioenergy, like wood and straw; liquid bioenergy, such as plant oils and animal fats; and gas bioenergy, including methane and carbon dioxide. With the innovative application of nanotechnology, we can transform previously unusable wasteland into valuable bioenergy resources. Bioenergy encompasses various forms, including biomass, biogas, algae biofuels, solid biofuels, biodiesel, and bioethanol. Embracing bioenergy holds great promise for a sustainable and greener future.

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Applications of nanomaterials in bioenergy have been documented through both direct and indirect methods (Table 4). Nanoparticles exhibit high catalytic activity, crystallinity, durability, effective storage, stability, and adsorption capabilities. They affect the metabolic reactions that are part of biological processes crucial for biofuel production, thus enhancing their output potential through the use of nanofibers, metallic nanoparticles, and nanotubes. Nanoparticles negatively influence inhibitory substances while positively impacting electron transfer efficiency by acting as catalysts. Nano-additives such as nanocrystals and nanomagnets are utilized to improve the blending ability of biofuels with petroleum fuels [58].

**Table 4.** Different nanomaterials utilized in bioenergy research.

| Nanomaterial | Key advantage / reported effect | Reference |
|---|---|---|
| Carbon-based nanomaterials (CNTs, graphene, graphene-oxide) | Much higher electrode surface area and conductivity → enhanced biofilm formation, faster electron transfer and higher power density. | [43, 44] |
| Magnetite / iron-oxide nanoparticles ($Fe_3O_4$, $Fe^{2+}/Fe^{3+}$ NPs) | Stimulate microbial activity, accelerate acidogenesis/acetogenesis and increase methane yield; can act as conductive bridges for DIET. | [45] |
| Zero-valent iron (ZVI) nanoparticles | Improves hydrolysis and methanogenesis, reduces lag time, enhances overall biogas output. | [46, 47] |
| Mixed metal nanoparticles (Fe, Ni, Co and combinations) | Certain metal NP mixtures significantly increase biogas production rate and yield (kinetic improvements reported). | [48] |
| Metal-oxide and supported nano catalysts (e.g., $TiO_2$, MgO, CaO, supported metal NPs) | Higher catalytic activity, faster reaction rates, reusability and easier separation compared to homogeneous catalysts. | [49] |
| Nano biocatalysts / enzyme-immobilized nanoparticles | Improved enzyme stability & reusability, higher conversion at milder conditions. | [50, 51] |
| Nanomaterials for feedstock pretreatment (e.g., nanoporous silica supports, nano-additives during hydrolysis) | Enhanced accessibility of cellulose, improved enzyme adsorption/retention, higher sugar yields. | [52, 53] |
| Nanostructured catalysts for thermochemical routes (pyrolysis, gasification, hydrogenation) | Increase selectivity, lower activation energy, improve bio-oil stability and gas yield/quality. | [54] |
| Magnetic nanoparticle-based separations / catalysts | Easy magnetic separation enables catalyst reuse and reduces downstream processing costs. | [53, 55] |
| Biomass-derived 3D carbon / graphitized nanocomposites | Low-cost, sustainable electrode materials from agri-waste with high power density and good stability. | [56, 57] |

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### 3.3 Biofuels

Biofuels were thought to have a promising future as an automotive fuel. As a relatively new field of study, it is developing rapidly to offer alternative renewable energy sources. Examples of good biofuels are methanol and ethanol, which are produced by specific yeasts and are highly flammable. Plant fibers or plant sugars can be used to make them. Currently, around 80% of the world's biofuels are produced in Brazil and the USA. The United States produces bioethanol mostly from maize, while Brazil produces it primarily from sugarcane. Because bioethanol has auto-ignitability qualities comparable to those of gasoline fuel, it is the most widely used biofuel for spark ignition (gasoline) engine applications. The demand for transportation fuel is predicted to rise dramatically over the next few decades, rising by as much as 55% by 2030 when compared to 2004. This will spur the demand for biofuels, as they are predicted to contribute more and more to supplying the world's energy demands in the future [59]. One of the numerous benefits of biofuels is that they burn cleaner than gasoline and provide greater power. Since plants can be grown year-round, biofuels are considered renewable. Plant sugars dissolved in water serve as the primary building blocks for biofuel production.

Bioethanol production from vegetable waste, oils, fats, and carbohydrates currently demand fermentation and transesterification methods, which are often plagued by high costs and significant industrial challenges [60]. However, nanotechnology stands as a groundbreaking solution. By harnessing the exceptional properties of nanoparticles, we can significantly enhance bioethanol production and effectively tackle both environmental and economic issues. This innovative strategy not only enables efficient recovery and reuse but also champions a more sustainable future [61].

Magnetic nanomaterials have various applications in the bioenergy sector, particularly in producing bioethanol through immobilized enzymes like cellulases and hemicelluloses, which can be magnetically recovered and reused. Numerous researchers have noted that carbon nanoparticles are employed in biofuel production due to their distinct characteristics such as conductivity, porosity, three-dimensional electro-active surface area, and increased enzyme abundance [62]. Metal or metal oxide nanoparticles utilize different approaches to generate bioethanol, including gas-phase deposition, oxidation reactions, hydrothermal reactions, sono chemical methods, biological processes, and nanoreactor synthesis [63, 64, 65]. The immobilization of enzymes in nanoparticles improves their reusability, increases the area of free surfaces, and addresses the instability of enzymes, which can be a challenge in large-scale industrial applications [66]. The enzyme hemicellulose breaks down hemicellulose into pentose, which certain microorganisms can then ferment to produce ethanol [67]. Recent research has also demonstrated that lipases play a crucial role in producing biodiesel through the transesterification of triglycerides with ethanol in the presence of a biological catalyst [68], leading to improved stability, enhanced reaction control, and reduced production costs [69].

Hydrocarbon and NOx component emissions were found to be significantly reduced when nanosized cerium oxide particles were added to biodiesel fuel, as demonstrated by an experiment by Sajith et al. [70]. This was achieved by promoting complete combustion and enhancing hydrocarbon oxidation. Using nanobiotechnology, Mahmood and Hussain [71] conducted an experimental conversion of waste tea into hydrocarbon fuels, including charcoal, bioethanol, and biodiesel. Three steps were involved in the experimental endeavor to turn wasted tea into biofuels. Using a co-nano catalyst, wasted tea was initially disposed of at 300 degrees Celsius at atmospheric pressure. After the discarded tea was gasified catalytically, 60% of the material was liquid extract, 28% was fuel gas, and 12% was charcoal. Ethane made up 53.03% of the gaseous products, methanol 37.18%, and methane 9.79%. The liquid extract of waste tea from gasification was used in the experiment's second step, and upon transesterification, it produced 40.79% ethyl ester, also known as biodiesel. The final phase was the production of 5749% bioethanol by "Aspergillus niger" growing on discarded tea. Mahmood and Hussain [71] concluded that spent tea, or solid waste, was utilized to produce hydrocarbon fuel gases in addition to biodiesel and bioethanol. Nanobiotechnology was used to convert experimentally the spent tea into hydrocarbon fuels (i.e., bioethanol, biodiesel and charcoal) as shown in Fig. 4. Magnetic single-walled carbon nanotubes (mSWCNTs) were developed by Goh et al. [72] through combining iron oxide nanoparticles with single-walled carbon nanotubes. The previously immobile enzyme was recycled and effectively utilized in the biofuel production processes. Their research, along with the unique properties of the nanotubes, contributed to improved efficiency in biofuel production, reduced capital costs for industrial enzyme systems, and enhanced performance in carbon nanotube-enzyme bioreactors.

### 3.4 Biogas

It's a flammable gas that resembles natural gas and is primarily composed of a mixture of gases, most commonly carbon dioxide and methane. Microorganisms create oxygen in the absence of either. In place of natural gas, biogas is considered a renewable energy source that can be utilized for heating and cooking. This is because the ability to generate biogas depends on the availability of grass, which regrows typically each year. The transportation sector also utilizes biogas. For example, in Sweden in 2008, biogas powered about 15,000 automobiles in addition to many buses and lorries. Biogas can be produced in four primary methods [59]: Facilities for treating sewage, Waste disposal sites, processing organic waste streams from industry, and the breakdown of organic waste by thermophiles and mesophiles. These techniques are capable of converting just 30 to 40% of the organic matter, which is quite ineffective when compared to other energy sources [73]. Consequently,

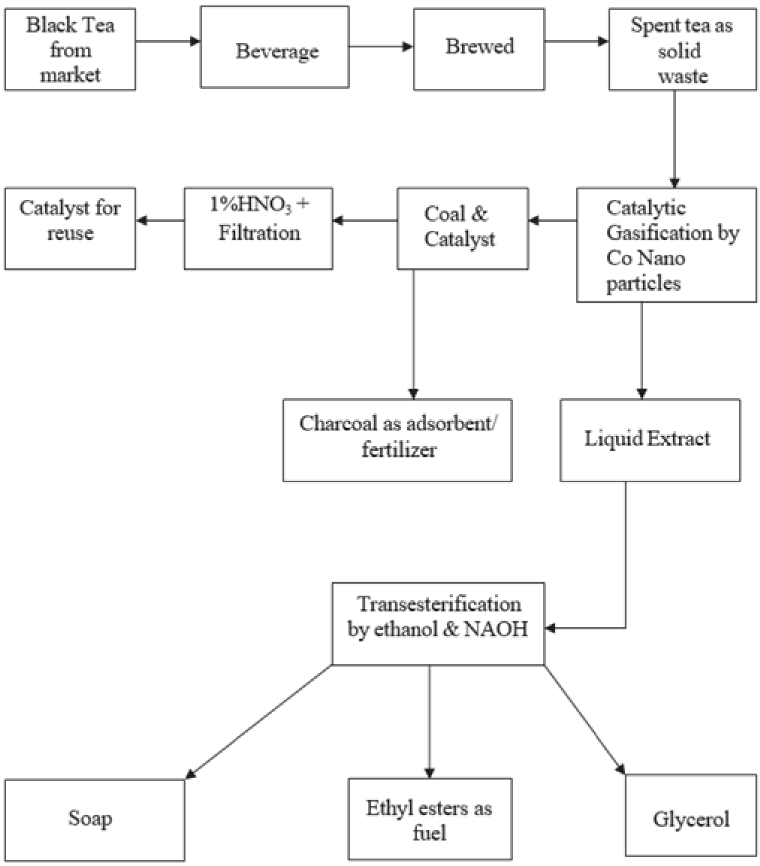


**Figure 4.** Flow chart of the biofuel production process using spent tea [71].

there is an urgent demand for innovative methods to enhance biogas production. A notable modern method is nanotechnology, which has been extensively applied across diverse sectors.

The application of nanoparticles in biogas production has varying effects. For instance, the addition of iron oxide nanoparticles (FeO) can improve yield. M. Sai Ram et al. reported that methane output significantly rose within 2 days when 5 mM of Fe was introduced [74]. Iron oxide nanoparticles measuring 7 nm were utilized in an anaerobic waste digester at a concentration of 100 ppm, resulting in a 180% increase in biogas production compared to the control group [75]. Another investigation indicated an 11% rise in biogas yield following the addition of 10 mg/L cerium oxide (CeO), although a 30% reduction was observed with 640 mg/L of CeO [76]. The use of nano-zero-valent iron (NZVI) positively impacted aerobic digestion, leading to increases of 30.4 in biogas and 40% in methane after 17 days [77]. Al-Ahmad et al. found beneficial effects on biogas production when using metal nanoparticles (Fe, Pd, Pt, Ni, Co, Ag, and Cu) embedded in porous silicon dioxide (SiO) at a concentration of 5 mg/L, resulting in methane production increases of 70% for Ni, 48% for Co, 7% for Fe, and 6% for Pt [78].

Unlike other nanoparticles, metal oxide nanoparticles have been shown to have a detrimental effect on biogas and biofuel production. Otero-González et al. studied the long-term impact of copper oxide (CuO) nanoparticles with a size of 37 nm at a concentration of 1.4 mg/L [79]. Their research indicated a notable reduction in methane production in the anaerobic digestion reactor that contained the CuO nanoparticles after 126 days. In summary, different nanomaterials have been reported to have both additive and negative effects on biogas production during anaerobic digestion [80, 81].

### 3.5 Biodiesel

Biodiesel is a methyl or ethyl ester of fatty acid derived from recycled vegetable oils, animal fats, and leftover cooking oil. Carbon monoxide (CO) and unburned hydrocarbon emissions are significantly reduced when biodiesel is used in conventional diesel engines. The lowest-emission diesel fuel is pure biodiesel (B100). As biodiesel has a higher concentration of hydrogen and oxygen and less carbon than fossil diesel, it is also regarded as an oxygenated fuel. This eliminates particle emissions from unburned carbon and greatly enhances biodiesel combustion. Moreover, fuel injection systems and metallic parts that have sliding contacts with one another have a longer lifespan due to the high lubricity of biodiesel. An experimental study was conducted by Wen et al. [82] regarding the fabrication of KF/CaO nano catalyst and its use in the generation of biodiesel from Chinese tallow seed oil. The catalyst's structure was described, and the effects of various preparation settings on the yield of biodiesel were examined. They concluded that the addition of KF/CaO nano catalyst increased the biodiesel output to 96.8% and demonstrated its potential for effectively converting oil with a higher acid value into biodiesel. Hu et al. [83] produced biodiesel using a nano-magnetic solid base catalyst (KF/CaO–$Fe_3O_4$).

According to the findings, biodiesel production exceeded 95% after three hours of reaction time when the reaction was conducted at 65 °C with a methanol-to-oil molar ratio of 12:1 and a catalyst concentration of 4%. They concluded that there were promising prospects for biodiesel research and use due to the use of a nano-magnetic solid base catalyst during the production process. A heterogeneous solid base nano-catalyst for the transesterification of soybean oil with methanol to biodiesel was prepared by an experimental investigation conducted by Qiu et al. [84]. The test findings indicated that the best outcomes and a biodiesel yield of approximately 98.03% were obtained with a 16:1 molar ratio of methanol to oil, 6.0% catalyst, a reaction temperature of 600 °C, and a reaction time of 2 h. Lithium impregnated calcium oxide was synthesized by Kaur and Ali [37] and utilized as a solid catalyst for the transesterification of Karanja and jatropha oils to produce biodiesel. Using a 12:1 molar ratio of methanol to oil, the full transesterification of the Karanja and jatropha oils was accomplished in 1 and 2 hours, respectively, at 65 °C. They concluded that their process was effective in producing biodiesel. Yan et al. [85] proposed a novel idea and developed a workable technique for the one-pot esterification and transesterification of grease using tandem lipases, yielding a high biodiesel yield of 95%. The outcomes demonstrated the significant potential for waste grease to be converted into biodiesel using the developed tandem-lipases method. The prospect of employing well-dispersed sulfated zirconia nanoparticles as highly efficient catalysts for the synthesis of bis (indolyl) methane and biodiesel was experimentally studied by Chen et al. [86]. It was also suggested how the artificial zirconia nanoparticles were formed. Optimal reaction conditions yielded satisfactory results, including a high esterification ratio. They concluded that this process produced biodiesel from grease with a high yield (98%) and good recyclability in a single pot.

Experimentally, Zhang et al. [87] used a medium acid density carbon-based nanostructured catalyst for catalytic distillation to produce biodiesel. By avoiding some of the shortcomings of earlier techniques, they concluded that the generated biodiesel synthesis was promising and could be easily scaled up. Using sodium titanate nanotubes (STNT) as a catalyst, Hipólito et al. [88] generated the biodiesel fuel in an experimental setting. Before the transesterification reaction, it was discovered that the (STNT) catalyst did not need a high-temperature thermal pre-treatment or activation. After an 8-hour chemical reaction, they used (STNT) to produce high biodiesel yields (97 – 100%). They concluded that the biodiesel output was positively impacted by increasing the reaction temperature to between 100 and 120 degrees Celsius. A review of recent advancements in the use of carbon-based catalysts for biodiesel production was provided by Konwar et al. [89]. They stated that esterification and transesterification were the two main processes in the synthesis of biodiesel. It was claimed that by removing issues with the commonly employed reaction schemes, the use of carbon-based (AC) catalysts in these reactions opened opportunities for cost minimization and ecologically friendly biodiesel synthesis. They concluded that the use of a catalyst enhanced the "greenness" of the biodiesel synthesis process and played a significant role in its manufacture.

Significant obstacles exist from an economic standpoint due to the high cost of nanomaterials and the technology needed for their manufacturing and integration into renewable energy systems. Achieving competitive pricing for nanotechnology-enhanced renewable energy solutions is challenging, as the initial investment required is typically higher than for standard energy systems. Economic analyses are also necessary to fully comprehend the long-term cost savings and return on investment that nanotechnology can provide for renewable energy.

## 4. Challenges and future perspectives

The future of nanotechnology in the renewable energy sector is inspiring and holds great potential. As we adopt cleaner energy solutions, nanotechnology is poised to make a significant impact by enhancing efficiency, reducing costs, and paving the way for innovative energy systems. Imagine utilizing quantum dots, perovskite nanocrystals, and nanowires to enhance solar panel performance by improving light absorption and energy conversion. These remarkable nanostructures can produce lightweight, flexible solar cells that are ideal for various applications, including wearables, vehicles, and building integration. Additionally, nanostructured electrodes such as silicon nanowires and graphene can significantly enhance the performance of both lithium-ion and solid-state batteries, improving both capacity and charging speed. With their increased surface area and conductivity, these advancements enable fast charge/discharge cycles, making them ideal for renewable energy grids. The possibilities are truly inspiring, and together we can create a sustainable, brighter future powered by cutting-edge nanotechnology. Platinum nanoparticles and innovative nano catalysts are revolutionizing hydrogen production through water electrolysis, making it more cost-effective for fuel cells. With advanced nanostructured membranes, we're boosting the efficiency and lifespan of these fuel cells. Imagine reducing wear and tear on turbine blades while enhancing performance by minimizing drag and icing. Using carbon nanotube composites and other nanostructured materials reduces weight, improving power output and durability.

In the realm of biofuels, nanotechnology accelerates the breakdown of biomass, enhancing production efficiency. It also plays a vital role in purifying and separating products in waste-to-energy systems. Smart sensors and materials powered by nanotech are making energy

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management more efficient than ever. Plus, materials like graphene promise ultra-efficient power transmission with minimal losses. We can even capture mechanical energy from motion or sound, which is exciting for wearable and micro-energy applications. By mimicking plant processes, nano-engineered systems can convert sunlight, water, and $CO_2$ into fuels, while self-repairing coatings extend the lifespan of renewable infrastructure. Moving from innovative lab-scale breakthroughs to robust industrial-scale production is an exciting journey with its own set of challenges. It's crucial to thoroughly assess the toxicity of nanoparticles and their environmental effects to ensure safety and sustainability [90, 91].

## 5. Conclusion

The most practical energy sources are fossil fuels, particularly coal and oil, which will also significantly contribute to energy security and diversity. Nevertheless, strategies for reducing $CO_2$ emissions in the future, as well as for managing $SO_2$, NOx, and carbon in ash, must be developed. Additionally, to achieve more sustainable energy systems, improvements in recycling must be considered. Utilizing nanotechnologies to harness renewable energy resources will be a dependable and suitable solution to reduce the reliance of energy systems on finite fossil fuels and address associated problems. The application of nanotechnology in the production of biofuels to enhance output appears to be an emerging reality. Notably, various nanomaterials like carbon nanotubes, nanofibers, magnetic nanoparticles, and other metal oxides have demonstrated positive impacts on biofuel production. Magnetic nanoparticles have undergone significant testing in biofuel production due to their straightforward recovery from bioreactors. While the integration of nanotechnology in biofuel production has proven advantageous and is recommended for large-scale manufacturing, there are specific safety concerns that require careful attention for long-term research. The use of nanoparticles and nanomaterials in bioenergy production has yielded some beneficial outcomes; however, their release into the environment, whether directly or indirectly, could pose certain health risks to living organisms. Because nanoparticles are incredibly small, they can be rapidly absorbed by living systems and enter our bodies. The inhalation of these nanoparticles and nanomaterials can lead to health toxicity, and prolonged exposure could negatively impact the environment. These minute particles can enter our bodies through inhalation, injection, or penetration of the dermis layer. When these nanoparticles are ingested, they may accumulate in our respiratory system, potentially leading to lung inflammation and cardiovascular issues. Given the harmful effects of nanoparticles on biological systems, thorough investigations and comprehensive studies aimed at reducing or eliminating toxicity for our safety are critically important.

**Availability of data and materials**
The authors declare that the data supporting the findings of this study are available within the paper.

**Conflict of interests**
The authors assert that they do not have any identifiable conflicting financial interests or personal relationships that might be perceived to influence the work presented in this paper.

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