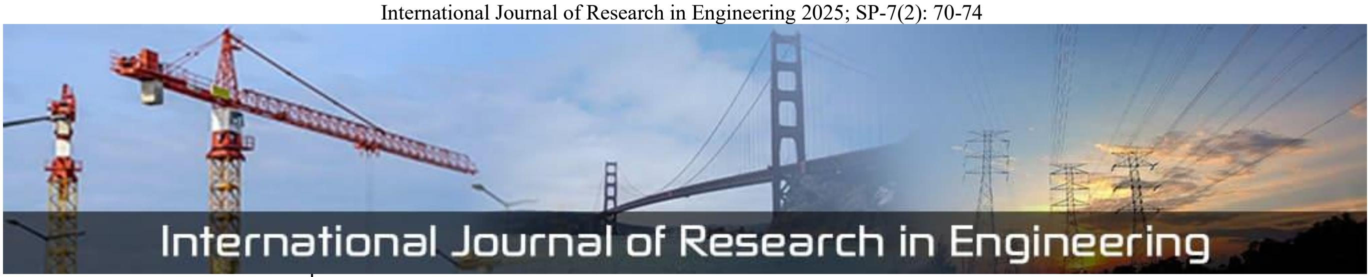

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Nanotechnology in biofuel production: Current trends and future directions

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Abstract
The persistent dependence on fossil fuels is unsustainable and contain verified environmental consequences. The rapid exhaustion of fossil fuel reserves poses a crucial obstacle to meet future needs for energy. As an outcome exploration, research and innovation of substitute of energy source have become priority to endure increasing demand of global energy, particularly in highly commercialized nations. Nanoparticles present a potential avenue for advancing biomass amplification through improved product selectivity, increased efficiency of energy and altering reaction pathways along with reduction of economic constraints. The application of widespread nanoparticles species, embracing magnet, metallic and metal oxide as nanoparticle, has witnessed significant increase in production of biological fuel methodologies because of current advancement in technologies. The competency of nanoparticles as biofuel additives is characterized to their unique physicochemical distinctions accommodating controlled topology, elevated stability, enhanced surface area to volume ratios, catalytic effectiveness and recyclability. Moreover, nanomaterials such as carbon nanosheet, carbon nanotubes and carbon nanofibers, have demonstrated optimistic economic feasibility and structural durability as support for enzyme confinement leading to upgraded biofuel production yields. This study provides a systematic review of the utilization of various nanoparticles for biofuel production highlighting prevalent challenges and potential future prospective lane for technological advancement.

Keywords: Biofuels, recyclability, nanoparticle, durability, feasibility

1. Introduction

The global demand for energy endures to rise as a reaction of global demographic expansion. The expenditure of fossil fuels has amplified to a rate of 106 time faster than their natural creation. At the ongoing rate of employment, the requirement for primary energy source is anticipated to double by 2035 and triple by 2065. [1]. The deployment of fossil fuel is afflicted with critical problems including global warming compelled by the rise in green house gases (GHGs) emission and economic anxiety. Hence, attention has shifted towards usage of replenishable fuels like biogas, bioethanol, biodiesel and biohydrogen. These fuels have assembled significant investment in recent years due to their lower greenhouse gas emissions, decreased carbon imprint and their sustainable nature [2]. Among the fundamental substitute to fossil fuels, biomass has evolved as an optimistic candidate in present years due to its ubiquitous appearance, minimal price, recyclability and non-caustic nature [3].

The pie chart in fig 1 depicts the shift in planetary initial power source between 2011 and 2030, highlighting a reduction in fossil fuel addiction, from 83% to 76%. Parallelly, the share of Hydro and renewable energy accelerated showcasing a gradual transition towards an environmental benign energy sources [4].

Green fuel production is being executed worldwide using a wide range of agricultural feedstock. Biodiesel contain fatty acid ethyl and methyl esters obtained from recycled cooking oil, plant oils and animal fats. In supplement to its recyclable nation, the application of biodiesel leads a contraction in carbon dioxide and carbon monoxide emissions. Microalgae evolved as a exceptional feedstock for biodiesel formation due to high growth rate and lipid accumulation. Nanotechnology is a swiftly transforming field that has earned significant attention in recent years. Currently, a ample range of modified nanoparticles are being deployed across various organizations [5].

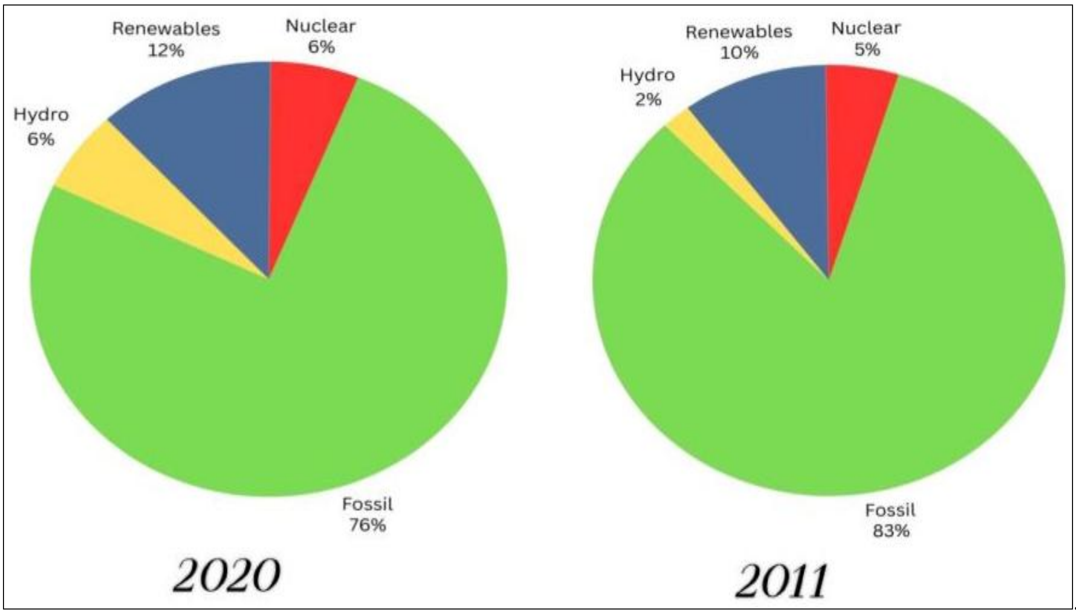

Fig 1: Total primary energy supply by resource 2011 and 2020

2. Biofuel Production via Different Nanotechnologies

Various nanotechnologies can be employed for production of biofuels to prevent dependence on traditional fossil fuels.

2.1. Green nanotechnology

The consolidation of nanotechnology into biofuel formation depicts a significant refinements, particularly in the consumption of lignocellulosic biomass and microalgae. Enzyme immobilization on nanoparticles, given as magnetic, MnO2 and silica nanoparticles facilitates reusability, amplify catalytic efficiency and cut down overall production costs, leading to better yields in bioethanol and biodiesel production. Highlighting ecological safety, green nanotechnology advocates for extensive lifecycle analysis to address potential environmental risks referred with nanoparticles. In algae-dependent biofuel formation, nanomaterials play a critical role in optimizing lipid extraction and transesterification processes, although scalability obstacles, accomodating water consumption and harvesting expenses, remains. Even after its promising potential, the scope of green nanotechnology is in its prior stages and mandates further research to produce economically effective and sustainable solutions [6].

2.2. Nanoparticles

Nanotechnology is a paradigm for crafting and the application of materials with molecular-level delicacy, exclusively at dimensions of 100 nanometers or less [7]. They unveil a considerably higher surface area-to-volume ratio w.r.t. to bulk materials of the same mass. It has been witnessed that the physical characteristics of several materials undergo appreciable amendments at the nanoscale, for example. Physical properties of carbon nanotubes are distinguishable to conventional carbon based materials [8]. It is pivotal to analyze whether nanoparticles or their invention processes pose any unfortunate effects that could restrict the practical applications. To advance nanomaterials in a path that amplify community benefits while eliminating risks to human and environmental health, some academics have incorporated the principles green chemistry into nanoscience [9].

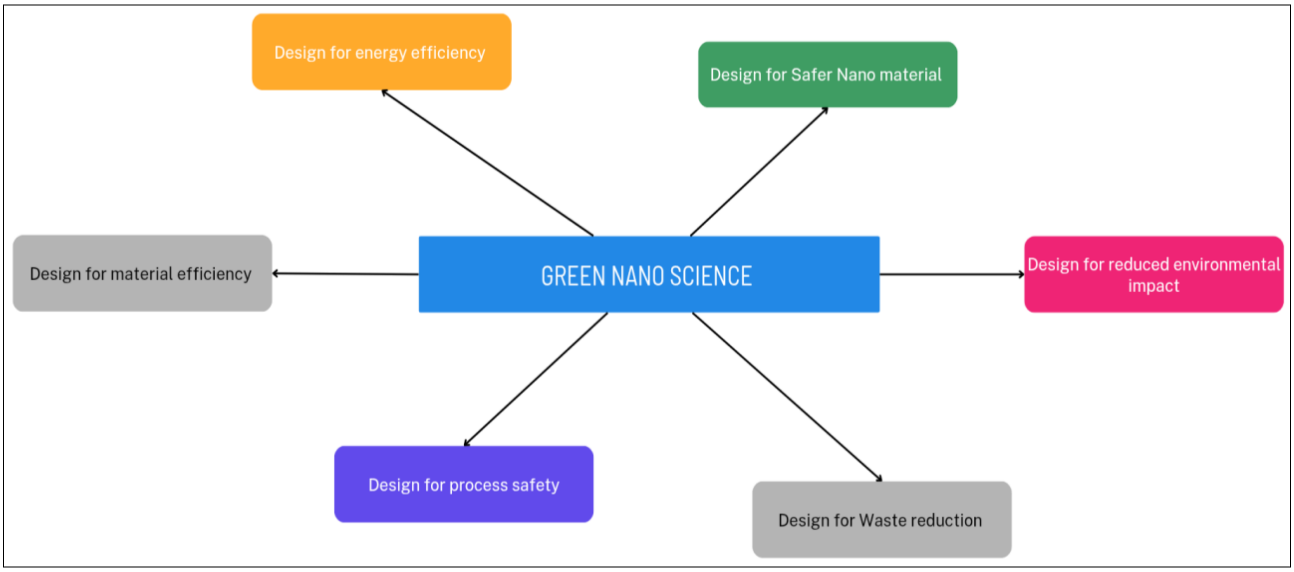

Fig 2: Nanotechnology design principles

Figure 2 depicts the combination of microtechnology principles overall the product lifespan, from material gathering to end of life evacuation. On the top of that, the design of benign nanomaterials ensure sustainability and eliminate latent health and biophysical risks [10].

2.3. Carbon nanotubes (CNTs) polymorphs

Carbon nanotubes (CNTs) are allotropes of carbon, built by rolling graphene sheets into cylindrical structures. They are indexed into Single-Walled Carbon Nanotubes (SWCNTs) and Multi-Walled Carbon Nanotubes (MWCNTs), with the subsequent consisting of multi/numerous graphene layers [11, 12, 13]. CNTs display enhanced stability, enlarged surface area and reduced toxicity which make them valuable catalyst for creation of biofuels [14]. These illustrate transfer of electrons and electrochemical reactions, boosting the deployment microbial based fuel cells and biosensors. Their recyclable initiators lead to affordability. Specialized MWCNTs (MWCNT-COOH) paralyzing Enterobacter aerogenes further accelerated production of hydrogen and efficiency of degradation of glucose [15]. A large no. of procedures like arc discharge, laser ablation and chemical vapour deposition are used for formation of CNTs. Their enhanced surface area permits greater enzyme loading capacity, catalytic activity and make enzyme reusable [16]. MWCNTs contain greater performance over SWCNTs because of their physical properties which increase enzyme confinement. Their effectiveness in hydrolysis of cellulose by Aspergillus Niger reaches 85-97%, in nurturing reusability at 52-75% after six hydration cycles. These characteristics make CNTs an inspiring nano particle for biofuel formation [17, 18].

2.4. Magnetic nanoparticles

Biocatalysts such as cellulases and lipases are broadly consumed in biofuel based organizations, with magnetic nanoparticles (MNPs) playing a pivotal role in bioenzyme incapacitation for biological material hydrolysis [19]. Analyzed enzymes after nanostructure-based coating supported lattice intensified replicability, upgrading lignocellulosic biomass hydrolysis streamlining [20]. Paramagnetic MNPs assist enzyme isolation, amplifying their functional lifespan. Researches have manifested cellulose inactivation of MNPs for hydrolytic breakdown, with CoSO4/Al2O3-SiO2 nanomaterial securing 94% biodiesel harvest from Jatropha curcus, through reduction over cycles due to orifice congestion [21]. Furthermore, Fe3O4-NH2 and decreased graphene oxide consolidated in polyaniline (PANI) matrices boost transfer of electron in biocatalyzed biofuel cells. Calcium-doped magnetic microfouriers refine biodiesel output by 85%, whereas MnO2 nanosubstances magnify bioethanol formatioprocesses

2.5. Acid functionalized nanoparticles

Acid and base preliminary treatment initiatives are generally used for lignocellulosic biomass transforming, with acid functionalized nanomaterial amusing a critical role in biomass hydrolysis for formation of biofuel. Transesterification and esterification triggered by acids and bases, amplify biodiesel formation, with base catalyzed operations being straightforward, whereas acid catalyzed methods are reasonably priced [23]. Sulfonic and sulfamic acid-customized magnetic nanoparticles (MNPs) have depicted high catalytic productivity, attaining up to 100% modification in transesterification and esterification reactions. Acid-functionalized MNPs with 6% sulfur data greatly refined cellulose hydrolyses over conventional methods [24]. Moreover MNPs favours enzyme paralysis for biodiesel or bioethanol formation and exhibit sturdy magnetic characters constructive for biogas synthesis. The robust paramagnetism and coercive properties of magnetic nanoparticles regarding methanogenesis amplify their aptness for anaerobic digestion [25, 26].

3. Current trend and future challenges of biofuels production via nanotechnology.

Biofuels, encompassing bioethanol and biodiesel, are principally synthesized in regions like Brazil, European Union and USA [27]. If generation biofuels, obtained from food-based raw material such as sugarcane, corn etc, meanwhile amplifying prices of food has shifted a gradual evolution of second generation. These are acquired from lignocellulosic biomass - non-food raw material that are present in excess and don't clash with agrarian food synthesis [28]. The embracement of II generation biofuels is supposed to overpower the market, with over one half of planetary synthesis particularly in India and China.

Table 1: Comparison of petroleum fuel, first and second-generation biofuel

	Advantages	Hurdles
Petroleum Refinery		Depletion of petroleum reserve
		Environmental pollution - Economic and ecological problems
First Generation Biofuels	Environmentally friendly	Limited feedstock (food vs. fuel)
	Economic and social security	Blended partly with conventional fuel
Second Generation Biofuels	Not competing with food	
	Advanced technology still under development to reduce cost of conversion	
	Environmentally friendly	

Nanotechnology prevailing remarkable promise for proceeding sustainable biofuel synthesis, yet numerous critical obstacles must be tackledl. Firstly, nanoparticles (NPs) are comprehend to cultivate reactive oxygen species (ROS), which can unfavourably affect marine habitat, curb microalgal growth, and diminish biofuel yields [29]. This dilemma is particularly emphasized with metal oxide nanoparticles such as ZnO, CuO, and Fe2O3, which escalate these harmful effects [30]. Secondly, NPs pose professional health obstruction, as they may stimulate oxidative stress, DNA damage, and chronic specifications, accommodating cancer, among unveiled workers. Additionally, the environmental consequences of NPs include soil fertility deteriorate due to disturbances in microbial societies, potentially undermining crop harvest and overall agarian efficiency. Lastly, the high functional costs affiliated with nanotechnology applications, such as the implementation of nanocatalysts for lignocellulosic biomass alteration, present a significant hindrance to scalability, especially in resource-impeded regions. To achieve the effective assimilation of nanotechnology into biofuel formation, it is obligatory to address nanoparticle risk, assess prolonged environmental consequence, and develop price-effective, scalable solutions to guarantee safe and environmental benign implementation. Nanotechnology has appeared as a transformative techniques in biofuel synthesis by addressing crucial hurdles across its different stages. Innovative nanofiltration membranes and magnetic nanoparticles dramatically amlify separation and purification techniques, ensuring the formation of better-quality biofuels. Photocatalytic nanoparticles and other nanomaterials upgrade the effectiveness of biomass preliminary treatment, particularly in the disintegration of lignocellulose. Furthermore, nanomaterials have facilitated improvements in energy storage and dissemination technologies, incorporating biobatteries and fuel cells. The accommodation of bimetallic nanoparticles and nanocatalysts has maximize biomass metamorphosis, substantially strengthening their effectivity. Nanotechnology also supplements to sustainability via its function in carbon dioxide immobilization and subsequent conversion into significant products. In the province of waste acknowledgement, it supports wastewater treatment and the transformation of by-products into valuable materials. Furthermore, nanoparticles accelerate microalgae cultivation, amplifying growth rates and lipid assemblation, thereby escalating biofuel yields. Collaboratively, these developments emphasize the important role of nanotechnology in facilitating sustainable energy solutions [31].

Table 2: Solutions to address the obstacles associated with biofuel production through the application of nanotechnology

Areas	Potential solutions	Required technology improvements
Improved separation and purification	The use of sophisticated nanofiltration membranes allows for the selective separation of biofuel molecules from contaminants and by-products, improving the product's overall purity and quality To simplify the purification process, magnetic nanoparticles can efficiently separate biofuel components from biomass slurry	The advancement of nanofiltration membranes with high selectivity, improved chemical stability, and increased fouling resistance Optimizing the synthesis of magnetic NPs to achieve both a strong magnetic response and biocompatibility [32]
Energy storage and distribution	Improved energy storage from biofuels is possible with the help of nanomaterials designed for use in biobatteries	Researching and developing nanomaterials with large storage capacity and long-lasting durability for biobattery use [33]
Improved catalysts for biomass conversion	Nanotechnology can enhance the effectiveness and performance of fuel cells operating on biofuels, facilitating more efficient energy storage and distribution To further enhance catalytic performance, combining two distinct metals at the nanoscale can produce synergistic effects For the generation of biofuels from biomass, NPs can act as catalysts with exceptional efficiency. A greater yield of biofuels can be achieved by using these nanocatalysts, which can improve reaction rates and selectivity	Innovation in developing nanostructured catalysts and electrolytes to increase the efficiency and longevity of fuel cells Advancing the synthesis of bimetallic NPs for maximum surface area and synergistic catalysis The development of thermally stable and recyclable nanocatalysts with enhanced selectivity [34]
Utilization of enhanced CO2	Nanomaterials can significantly improve the efficiency of CO2 capture from fermentation processes or industrial emissions, allowing for its subsequent conversion into biofuels Incorporating carbon capture and usage into biofuel production processes, nanostructured photocatalysts can transform CO2 into valuable fuels and chemicals by utilizing sunlight (35)	Development of nanomaterials with large surface areas to enhance the adsorption and conversion of CO2 Increased conversion efficiency and photocatalyst sensitivity to visible light when exposed to solar light
Waste reduction and valorization	Nanomaterials can be employed to treat wastewater produced during the production of biofuels, thereby guaranteeing resource recovery and environmental compliance Minimizing waste and enhancing sustainability, nanotechnology can assist in converting by-products of biofuel production into valuable chemicals or more fuels	Creation of multifunctional NPs that can recover resources while also removing pollutants The development of catalytic processes that facilitate the effective conversion of low- value by- products into high-value outputs through innovation(36)

4. Conclusion

As it is obligatory to produce and execute alternative, safe energy sources to modify them away from reliance on fossil fuels. This review put spotlight that the accomodation of nanomaterial has considerably amplified biofuel formation. This advancement is attributed to their properties of greater reactivity, superior specificity and remarkable surface area to volume ratio. Moreover, application of nanoparticles support the synthesis of stable and flexible enzyme system qualified of bearing damaging effects of different solvents deployed in formation of biodiesel. The inflation of biofuel production with nanotechnology provides a auspicious pathway for amplifying economically favourable synthesis of biofuel in future. Yet, beforehand the synthesis using this integrated approach, it is mandatory to check latent safety concerns associated to ecological impact and human well-being comprehensively.

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