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Recent Advances in Methods for Synthesizing Composite Nanocatalysts and Their Applications: A Literature Review

Tawakalitu AbdulRasheed, Benjamin Afotey, and Daniel Adjah Anang*

Department of Chemical Engineering, Kwame Nkrumah University of Science and Technology, Kumasi. Private Mail Bag, University Post Office, KNUST Kumasi, Ghana

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Abstract: Composite nanocatalysts have gained significant consideration in recent years due to their unique physicochemical characteristics and potential in several industrial applications. The synthesis of composite nanocatalysts can be achieved through various methods such as physical mixing, auto-combustion, sol-gel synthesis, impregnation, in situ synthesis, co-precipitation, and hydrothermal synthesis. These methods offer advantages such as simplicity, control over morphology and particle size, reproducibility, and high purity. The selection of the appropriate synthesis method depends on various factors such as the desired properties, target application, and cost-effectiveness. The applications of composite nanocatalysts in energy conversion, environmental remediation, pharmaceuticals, and petrochemical industries have been studied. Composite nanocatalysts have shown superior catalytic activity, selectivity, and stability compared to their single-component counterparts. The development of composite nanocatalysts and their applications in various industries have shown great potential in solving current global challenges. The synthesis method and composition of composite nanocatalysts must be optimized to achieve high efficiency, stability, and selectivity for specific applications. Further research is needed to explore new synthesis methods and expand the scope of applications for composite nanocatalysts.

Keywords: Composite nanocatalyst, auto-combustion, synthesis, application.

1 Introduction

Nanocatalysts are catalysts with nanoscale dimensions, typically ranging from 1 to 100 nanometers (nm) [1]. They are composed of various materials, including metals, metal oxides, and semiconductors, and are used to increase the rate of chemical reactions [2]. Nanocatalysts offer several advantages over traditional catalysts, including a higher ratio for surface area to volume Kawi et al., [3] improved selectivity and activity Corma et al., [1] and the ability to tune their properties through control of their size, shape, and composition [4]. The synthesis of composite nanocatalysts involves integrating two or more materials, resulting in the enhancement of catalytic properties. Composite nanocatalysts have attracted significant consideration recently due to their remarkable features, such as high catalytic activity, stability, and selectivity. Their applications are found in a wide variety of fields, including chemical synthesis Wang et al., [5] environmental pollution remediation, biodiesel production, energy conversion and storage [6]. In a previous review by Hu et al. [7], they focused on graphene semiconductor composite nanocatalysts recognizing the mechanism, synthesis, application, and perspectives. The authors confirmed the advantages of the nanocatalyst towards the alleviation of environmental pollution and the generation of energy. The photocatalytic mechanism of graphene was looked into, and the utilization of graphene/semiconductor composite nanocatalyst in photocatalytic reduction, as well as possible studies in improving photocatalytic processes. A review of the application of nanocatalysts in industrial effluent treatment was done by Eskandarinezhad et al. [8], where nanocatalysts were considered based on magnetic metals and noble metals. The mechanisms for wastewater were flocculation, sedimentation, reverse osmosis, ultrafiltration, and ion exchange. The authors recommended more studies to compare the relative performance of the nanocatalysts for suitable earth-abundant materials and usage. Other works can also be done on utilizing biogenic nanomaterials for water treatment and purification. This review paper offers an overview of the applications and the different synthesis methods of composite nanocatalysts.

1.2 Methods of Synthesis

There are several methods of synthesizing composite nanocatalysts, including physical mixing, auto-combustion, sol-gel, impregnation, co-precipitation, and hydrothermal synthesis. The method of synthesizing composite nanocatalysts depends on several factors. According to Li et al. [2], the method of synthesizing composite nanocatalysts depends on the desired composition, morphology, and size of the nanocatalysts, as well as the intended application. Some key factors that can influence the choice of synthesis method include chemical composition, morphology, size, control over properties, scalability and reproducibility, and cost.

*Corresponding author E-mail: afotey_benjamin@hotmail.com

1.2.1 Physical mixing

Physical mixing involves mixing two or more distinct components to produce a combination with specified catalytic characteristics. It is the primary and easy way to create composite nanocatalysts.

The "mix-and-match" strategy is another name for this technique, which entails mixing pre-synthesized nanomaterials with various compositions, morphologies, or sizes. Wu et al. [9] created composite nanocatalysts for environmental remediation by physically combining metal oxide nanoparticles with mesoporous silica, and the authors observed overwhelming catalytic performance in the breakdown of organic contaminants. Similarly, Kawi et al. [3] discovered that the resultant composite had a high catalytic activity for CO_2 reforming methane by physically mixing nickel nanoparticles with mesoporous silica to create nickel-based nanocatalysts. Yao et al. [10] also mixed Fe_3O_4 and Polylactic acid (PLA) to improve the thermal stability for biomedical applications. Li et al. [2] synthesized composite nanocatalysts for energy conversion by physically mixing graphene oxide with metal oxide nanoparticles and then using a sol-gel method to create a uniform coating on the surface of the graphene oxide sheets by the metal oxide nanoparticles. The resulting composite showed improved electrocatalytic activity for processes involving oxygen reduction and hydrogen evolution. This synthesis method is a low-cost and easy-to-implement method that requires minimal equipment and expertise and can be performed at room temperature and atmospheric pressure. However, poor control over the distribution of the different components within the mixture and the potential for segregation or agglomeration of the nanomaterials during the reaction process are some of the limitations.

1.2.2 Solution- combustion

The solution-combustion method is a well-known technique for the synthesis of composite nanocatalysts. This method is an inexpensive, simple, and rapid synthesis method that is widely used for the production of nanocatalysts with high surface area, good dispersion, and high activity. The method involves the combustion of metal nitrates and organic fuels in a highly exothermic reaction. The organic Fuel acts as a reducing agent, and the metal nitrates act as oxidizing agents; the combustion process is self-sustaining, resulting in highly dispersed nanocatalysts. Much research has shown how well the auto-combustion approach works for synthesizing different nanocatalysts, such as metal oxides, metal nanoparticles and various composite magnetic nanocatalysts. For example, $MgO/MgFe_2O_4$ nanocatalyst was synthesized via auto-combustion techniques, and the catalyst exhibited a maximum yield of 91.2% in the production of biodiesel from sunflower oil [11-12].

Ashok et al. [13] employed a microwave-assisted combustion method to synthesize nanocatalysts made of magnesium-substituted zinc ferrite. This method resulted in an impressive 99.9% conversion of triglycerides into biodiesel. Another study involving a $MnFe_2O_4$/graphene oxide catalyst achieved a biodiesel yield of 96.47% when utilizing waste edible oil. Using $NiFe_2O_4$ and $Ni_{0.3}Zn_{0.7}Fe_2O_4$ magnetic nanoparticles led to a maximum yield of 94% during the transesterification process of soybean oil [14]. Seffati et al. [15] utilized a $CaO@AC/CuFe_2O_4$ nanocatalyst to produce biodiesel from chicken fat, resulting in a yield of 95.6%. Potassium-immersed Fe_3O_4/CeO_2 nanocatalysts showed an impressive efficiency of 96.13% in biodiesel production from rapeseed oil. In a separate study, a $ZnO/BiFeO_3$ nanocatalyst achieved a maximum yield of 95.43% when converting canola oil into biodiesel [16-18]. Additionally, a study by Li et al. [2] demonstrated the successful synthesis of copper oxide nanoparticles using the auto-combustion method. The resulting nanocatalysts exhibited excellent catalytic activity for the reduction of 4-nitrophenol.

1.2.3 Sol-gel synthesis

The sol-gel synthesis method encompasses the preparation of a sol that is then converted into a gel. This is a widely used method for synthesizing composite nanocatalysts with precise control over their composition, morphology, and size. In the sol-gel method, metal alkoxides or other precursor materials are hydrolyzed and condensed in a liquid media, such as water or alcohol, to create a sol or gel that may then be dried and calcined to create a solid nanocatalyst. The versatility of sol-gel synthesis is one of its benefits, which can be utilized to create a variety of nanocatalysts, including metal oxides, metal-organic, and hybrid organic-inorganic nanocatalysts. Sol-gel manufacturing may precisely control the size and distribution of the nanocatalyst particles, and this can have a substantial effect on how well they operate as catalysts.

In the study by Liu et al., [19] a platinum-doped cobalt oxide composite nanocatalyst for oxygen reduction reaction was synthesized by sol-gel synthesis, which exhibited excellent electrocatalytic activity and durability. Using the method for photocatalysis, Tang et al. [20] prepared a composite nanocatalyst for photocatalytic hydrogen production by sol-gel synthesis of titanium dioxide nanoparticles and cobalt phosphate, which showed high activity and stability under visible light irradiation. Sol-gel synthesis can also be combined with other methods, such as physical mixing or hydrothermal synthesis, to create more complex nanocatalysts with enhanced properties; for instance, Dong et al. [21] synthesized a composite nanocatalyst for CO_2 reduction by combining sol-gel synthesis of copper oxide nanoparticles with physical mixing of nitrogen-doped carbon nanotubes, which exhibited improved catalytic activity and selectivity. Long reaction periods, high temperatures, and the requirement for meticulous control of the reaction conditions to avoid undesirable reactions or phase transitions are some of the drawbacks of sol-gel synthesis. Sol-gel synthesis is still a potent technique for creating composite nanocatalysts with specific characteristics for various applications.

1.2.4 impregnation

Impregnation is the deposition of one material onto another; it is a widely used method for synthesizing composite nanocatalysts, especially for metal-based catalysts. This method involves the deposition of metal precursors onto a support material, typically a high surface areas material such as alumina or silica, followed by calcination to form the final nanocatalyst. Due to its simplicity and ease of scalability, it is a prevalent method for the industrial-scale production of nanocatalysts. The impregnation method can lead to high catalytic activity because of its high metal loading.

In the study by Wang et al. [21] they prepared a nickel-iron oxide composite nanocatalyst for hydrogen production by the impregnation of nickel and iron precursors onto activated carbon, which showed high activity and stability under steam reforming conditions, synthesized a copper oxide-gallium oxide composite nanocatalyst for photocatalytic degradation of rhodamine B by impregnation of copper and gallium precursors onto TiO_2 nanoparticles, which exhibited high activity and selectivity. Similarly synthesized a composite nanocatalyst for selective hydrogenation of benzene to cyclohexene by combining the impregnation of palladium onto zeolite Y support with the hydrothermal synthesis of titanium dioxide nanoparticles, which showed high activity and selectivity [22]. Impregnation remains a valuable method for synthesizing composite nanocatalysts with tailored properties for various applications. However, the synthesis method has some drawbacks, such as poor control over the metal particles' size and distribution and the risk of metal sintering during calcination, which can decrease catalytic activity.

1.2.5 In situ

One of the promising methods of compositing nanocatalysts is in situ synthesis. It involves the simultaneous formation of metal nanoparticles and support material under reaction conditions, thereby creating highly dispersed and stable NP, leading to high catalytic activity and selectivity with controlled shapes and sizes. The studies by Maleki & Kamalzare [23], Zhang et al. [24] and Souza et al. [25] all showcased the successful synthesis of composite nanocatalysts by the in-situ method with verse usage. Qin et al. [26] synthesized a platinum-cobalt oxide composite nanocatalyst by in situ reduction of platinum and cobalt precursors on nitrogen-doped graphene, which showed durability and high activity for the reduction-oxidation reaction in fuel cells. Liu et al. [27] prepared a palladium-ruthenium oxide composite nanocatalyst by in situ reduction of palladium and ruthenium precursors on titanium dioxide support, which showed that the selectivity and activity were high for the electrochemical reduction of carbon dioxide into formate. In situ was combined with solvothermal synthesis and hydrothermal synthesis [24].

The latter prepared a copper oxide-graphene oxide composite nanocatalyst for the photocatalytic degradation of organic pollutants by in situ hydrothermal reaction of graphene oxide and copper oxide nanoparticles, which exhibited high activity and reusability. They synthesized a carbon-supported cobalt sulfide composite nanocatalyst doped in nitrogen for the redox reaction by in situ synthesis of cobalt precursors under solvothermal conditions, which showed high stability and activity [24]. For the creation of composite nanocatalysts, in situ synthesis has several benefits, including excellent control over the size, distribution, and composition of metal nanoparticles and the flexibility to modify the final nanocatalyst's attributes to suit particular purposes.

1.2.6 Co-precipitation

In this method, metal precursors and the support material are precipitated simultaneously from a solution. This approach allows for creation of highly dispersed and stable metal nanoparticles with controlled sizes and shapes, leading to high catalytic activity and selectivity. Numerous studies have shown the successful synthesis of composite nanocatalysts by co-precipitation methods for various applications, including hydrogen production, pollutant degradation, and biomass conversion. A cobalt-iron oxide composite nanocatalyst by co-precipitation of cobalt and iron precursors on an alumina support, which displayed the steam reforming of ethanol to produce hydrogen, has high activity and stability. A study by Bhowmik et al. [28] synthesized a nickel-molybdenum-phosphorus alloy supported on alumina composite nanocatalyst for the hydrodeoxygenation of guaiacol to produce aromatic hydrocarbons by co-precipitation of nickel, molybdenum, and phosphorus precursors on an alumina support, followed by reduction and sulfidation, which exhibited high activity and selectivity. Gao et al. [29] prepared a Co-Cu alloy supported on silica composite nanocatalyst for the Fischer-Tropsch synthesis by co-precipitation of cobalt and copper precursors on a silica support, followed by reduction, which showed high selectivity for the production of light olefins.

Co-precipitation can also be combined with other methods, such as calcination or reduction, to create more complex nanocatalysts with enhanced properties. For instance, Chen et al. [30] synthesized a nickel-copper alloy supported on ceria-zirconia composite nanocatalyst for the dry methane reforming by co-precipitation of nickel and copper precursors on ceria-zirconia support, followed by calcination and reduction, which revealed high stability and activity. Meng et al. [31] prepared a cobalt-phosphorus-nitrogen (CoP@NC) composite nanocatalyst to produce furfuryl alcohol via the hydrogenation of furfural by co-precipitation of cobalt and phosphorus precursors on nitrogen-doped carbon, followed by high-temperature treatment, which showed high activity and selectivity. Co-precipitation offers several advantages for preparing composite nanocatalysts, including high control over the size, distribution, and composition of metal nanoparticles and the ability to tailor the properties of the final nanocatalyst to specific applications.

1.2.7 Hydrothermal

Hydrothermal synthesis is another widely utilized technique for the synthesis of nanocatalysts, particularly for the synthesis of metal oxide-based nanocatalysts. The process involves using a high-pressure reactor vessel to promote chemical reactions in aqueous solutions at elevated temperatures and pressures to prepare composite nanocatalysts. The reaction conditions can be adjusted to control the size, morphology, and composition of the resulting nanocatalysts. Several studies have used hydrothermal synthesis to prepare composite nanocatalysts. Zhu et al. [32] prepared $CaFe_2O_4/\alpha\text{-}Fe_2O_3$ composites using the hydrothermal technique and investigated the photocatalytic properties of $CaFe_2O_4$-based composites for environmental applications. These composites exhibited significantly higher photocatalytic activity compared to single-phase $\alpha\text{-}Fe_2O_3$.

Zhang et al. [24] synthesized a CeO_2-TiO_2 composite nanocatalyst for the selective catalytic reduction (SCR) of NOx by NH_3 using a hydrothermal method. The authors reported that the hydrothermal synthesis approach resulted in highly dispersed CeO_2 nanoparticles on the surface of TiO_2, leading to enhanced catalytic stability and activity. Chen et al. [30] utilized the hydrothermal method to synthesize a Co_3O_4-MnO_2 composite nanocatalyst to oxidize toluene. The authors reported that the hydrothermal synthesis approach resulted in highly crystalline Co_3O_4-MnO_2 nanoparticles with a high surface area, improving catalytic activity and stability. In the work by Chen et al. [30], they describe the preparation of hierarchical ZSM-5@SAPO-34 composite nanocatalysts using hydrothermal synthesis. The researchers found that the hierarchical structure of the nanocatalysts allowed for improved access to the active sites, resulting in higher activity and selectivity for the conversion of methanol to gasoline. Huang et al. [33] describe the preparation of CeO_2-modified $LaFeO_3$ nanocatalysts using hydrothermal synthesis. The nanocatalysts were found to show good stability and catalytic activity for removing toluene, a volatile organic compound, from the air.

Huang et al. [34] used hydrothermal synthesis to prepare hierarchical ZSM-5@SAPO-34 composite nanocatalysts but for the Fischer-Tropsch synthesis. The researchers found that the hierarchical structure of the nanocatalysts improved the reactants and product diffusion, resulting in higher catalytic activity and selectivity for the Fischer-Tropsch reaction. The studies by Rajabzadeh et al. [35] demonstrate the potential and the versatility of hydrothermal synthesis as a versatile and effective method for preparing various types of composite nanocatalysts with controlled properties and tailored functions.

1.2.8 Solvothermal

Solvothermal synthesis involves using a solvent, typically an organic solvent, as the reaction medium. The solvent is usually selected to have a high boiling point and be able to dissolve the precursor materials or reagents. The reaction is usually carried out at high pressure and temperature in an autoclave or other high-pressure vessel. The solvent also serves as a template or a reactant for the product's formulation. This method is often used to produce nanoparticles or nanocrystals with controlled size and shape. Qu et al. [36] synthesized using the solvothermal method to composite carbon nanodots (CDots) and a non-metallic graphene oxide (GO) co-doped BiOBr ternary system (GO/CDots/BiOBr). There are several other methods encountered that are beneficial in the synthesis of composite nanocatalysts. Maleki and Azadegan [37] utilized the modified Stober to synthesize a silica-supported magnetic nanocatalyst. The ultrasonication method was used by Taheri-Ledari and Maleki [38] and Gupta et al. [39] for their composite preparation, which has significant reusability. Table 1 shows a summary of the methods of synthesis and application of composite nanocatalysts by different authors.

Table 1: Summary of synthesis methods and application of composite nanocatalysts.

Author(s)	**Synthesis method**	**Composite Nanocatalysts**	**Application(s)**	**Nanocatalyst highlights**
Alaei et al. [12]	Solution combustion	$MgO/MgFe_2O_4$	Biodiesel production from sunflower oil	Easier separation, reusability, shorter reaction time and improved conversion rate.
Mapossa et al., [14]	Combustion reaction	$Ni_{0.3}Zn_{0.7}Fe_2O_4$	Biodiesel production from soybean oil	High catalytic activity, improved reaction kinetics, reusability, and capability for magnetic separation are promising for sustainable biodiesel production.
Kaur *et al.*, 2021)	Ultrasonication method	$CaFe_2O_4$-NGO	Heavy metal removal and photocatalytic degradation of organic pollutants	Adsorption capacity, stability, and reusability are excellent choices for environmentally friendly applications in water treatment and pollution control.
Rajabzadeh et al. [35]	Hydrothermal synthesis method.	CuO@SiO2 multi-yolk@shell	New nanocatalyst for Carbon dioxide fixation reaction	The process might be improved to create various multi-yolk@shell structures with different kinds of metal oxides, which could result in novel techniques for creating nanoreactors.

Author(s)	Synthesis method	Composite Nanocatalysts	Application(s)	Nanocatalyst highlights
Maleki and Kamalzare, [24]	In situ synthesis	Fe3O4, cellulose	The condensation reaction between o-phenylenediamines and ketones that produced benzodiazepines	Ecofriendly, inexpensive and efficient nanocatalyst.
Yao et al., [10]	Solution mixing method	Fe_3O_4/PLA	Improved thermal stability for biomedical application	Composite possesses a lower melting point and better thermal stability.
Zhang et al., [40]	Hydrothermal synthesis	$CaO/CoFe_2O_4$	Biodiesel Application	Enhance catalytic activity, promising for efficient biodiesel production
Gupta, Ameta and Punjabi, [39]	The sol-gel method modified Hummer's method; ultrasonication method	Graphene oxide and calcium ferrite	Preparation of 3-dihydro-1,5-benzodiazepines	Heterogeneity, stability, non-toxicity, hassle-free recovery, reusability, and high catalytic effectiveness are all advantages of this technique of nanocatalyst production.
Wang et al., [5]	Chemical co-precipitation method; in situ method	Superparamagnetic Fe_3O_4 nanoparticles: the mesoporous silica encapsulated magnetic nanoparticles (MMSN)	Nanocatalytic tumour-specific precision therapy	The ability to successfully inhibit tumour development in vivo
Chen et al., [30]	impregnation method	MoS_2 and CoO	Hydrodesulfurization (HDS) of dibenzothiophene	High activity and stability
Souza et al., [25]	*in situ* polymerization	Maghemite nanoparticles, Polylactic acid (PLA)	Magnetic force determination	
Sun et al., [40]	ring opening polymerization ROP; melt-blending method	Fe_3O_4 g-PLLA; Polylactic acid (PLA)	Used in Air filtration	
Borade et al., [42]	Sol-gel auto burning	Glycine ($C_2H_5NO_2$) ferric nitrate (Fe $(NO_3)_3$ $9H_2O$) zinc nitrate (Zn $(NO_3)_2$ $6H_2O$),	microwave irradiated preparation of chalcone derivatives	
Kurtan et al., [43]	Co-precipitation and chemical reduction method	MnFe2O4@ SiO2@A	Azo dyes reduction	Simple magnetic attraction made it possible to remove the unique nanocatalyst from the reaction mixture quickly.
Bhowmik et al., [28]	chemical co-precipitation technique	manganese ferrite and magnetic calcium ferrite	dye adsorption via sono-assisted EBT	Novel absorbent with superior absorptive performance.
Vignesh et al., [44]	Solution-assisted combustion synthesis	Glycine $Fe(NO_3)_2{\cdot}9H_2O$, and $Mn(NO_3)_2{\cdot}4H2O$	Ammonia gas sensor	Simple and cost-effective synthesis
Darwish et al.,[45]	modified two-step co-precipitation method	zinc cobalt ferrite (cf), cobalt ferrite (cf), and magnetite (mag)	Hyperthermia Performance	The highest SLP was obtained by mag@zcf1, while the lowest SLP was obtained for cf@mag1
Yun et al.,[46]	Direct mixing, wet impregnation	HAuCl4 L-Cysteine, Zn(NO3)2,	Procedures for the hydrogenation of 4-NitroPhenol. Carboxylation of phenylacetylene.	
Qu et al. [36]	one-step solvothermal process	GO/CDots/BiOBr	photocatalytic 4-chlorophenol degradation	For purifying water, the non-metallic GO and CDots co-doped semiconductor would be an effective catalyst.
Afshari et al., [47]	thermal decomposition, sol-gel method.	Sodium-activated bentonite (BNT), tetra (*n*-butyl) ammonium chains (TBA-PWFe), Mono Fe-substituted phosphotungstate with nickel oxide (NiO),	Desulfurization of real gasoline and simulated fuels	The reusability of the nanocatalyst could be five cycles with a good yield
Liang et al., [48]	Co-precipitation method	$Cu(NO_3)_2{\cdot}3H_2O$, $Co(NO_3)_2{\cdot}6H_2O$, $Ce(NO_3)3{\cdot}6H_2O$	Heterogeneous Fenton-like process for Ni(II)-citrate decomplexation and removal of COD	Ten-times reaction cycles

Author(s)	Synthesis method	Composite Nanocatalysts	Application(s)	Nanocatalyst highlights
Taheri-Ledari and Maleki, [38]	ultrasonication	Magnetic nanocatalysts and ultrasound	synthesis of pharmaceutical compounds (APIs)	Substantial reusability
Jarullah et al., [49]	sol-gel; impregnation;	CuO + NiO	Oxidative desulfurization	Nanocatalyst has excellent active metal distribution
Zhao et al. [50]	incipient wetness impregnation.	Ni–CeO2; mesoporous-SiO2 shell	Dry reforming of methane (DRM)	Possessed excellent thermal stabilities and textural properties
Taheri-Ledari and Maleki, [38]	ultrasonication	Magnetic nanocatalysts and ultrasound	synthesis of pharmaceutical compounds (APIs)	Substantial reusability

1.3 Applications of Composite Nanocatalysts

Composite nanocatalysts have a wide range of applications. They have been discovered to have better catalytic qualities than their bulk equivalents because of their large surface area and distinctive structural characteristics. They find their application in catalysis, energy conversion, the Pharmaceutical Industry, the Petrochemical Industry, and environmental remediation.

1.3.1 Biodiesel Production

Nanocatalysts have been widely studied in biodiesel production due to their higher catalytic activity, selectivity, and stability. Lopez et al. [43] provide an in-depth overview of recent developments in heterogeneous catalysts for biodiesel production via esterification and transesterification reactions. The authors discuss various types of catalysts, including acid catalysts, base catalysts, and enzyme catalysts, and their respective advantages and disadvantages. They also highlight the importance of catalyst optimization, such as catalyst loading and reaction conditions, in enhancing the yield and quality of biodiesel. The article concludes by discussing some of the challenges that need to be addressed in the future to improve the efficiency and sustainability of biodiesel production.

Alaei et al. [12] successfully synthesized $MgO/MgFe_2O4$ magnetic nanocatalyst via the combustion method. The catalyst was utilized to produce biodiesel from sunflower oil via the transesterification process. The study shows that the catalyst has excellent potential to produce biodiesel with a maximum conversion of 91.2% and a remarkable recyclability of up to five cycles. Similarly, in the study by Mapossa et al., [14] $NiFe_2O_4$ and $Ni_{0.3}Zn_{0.7}Fe_2O_4$ magnetic nanoparticles were synthesized using the combustion reaction method in the transesterification of soybean oil to biodiesel, the nanocatalyst was investigated to have a maximum conversion of 94% for the process.

1.3.2 Energy Conversion

In the field of energy conversion, composite nanocatalysts have shown great potential, especially in the production of hydrogen through water splitting and in the conversion of CO_2 to value-added chemicals, as in the oxygen reduction reaction (ORR) and the hydrogen evolution reaction (HER) in fuel cells.

Wu et al. [9] demonstrated the use of a composite nanocatalyst consisting of platinum and tungsten carbide nanoparticles supported on graphene oxide in proton exchange membrane fuel cells (PEMFCs) through the oxygen reduction reaction (ORR). The results showed that the composite nanocatalyst exhibited higher activity and durability than commercial platinum/carbon catalysts. Zhao et al. [51] showed that composite nanocatalysts in energy conversion are also applicable in solar cells. They developed a composite nanocatalyst used as a counter electrode in dye-sensitized solar cells (DSSCs), consisting of reduced graphene oxide and nickel sulphide. The results showed that the composite nanocatalyst exhibited superior performance compared to traditional platinum-based counter electrodes.

Composite nanocatalysts have also been utilized in water splitting for hydrogen production. Liu et al. [2] demonstrated using a composite nanocatalyst of cobalt phosphide nanoparticles supported on carbon nanotubes for the hydrogen evolution reaction (HER) in alkaline media. The outcomes disclosed that the composite nanocatalyst showed high activity and stability for HER, making it a promising candidate for practical applications in water splitting.

1.3.3 Environmental Remediation

With unique characteristics such as tunable pore size, high surface area, and enhanced catalytic activity, composite nanocatalysts have shown great potential in environmental remediation. These nanocatalysts have been successfully employed in various environmental remediation processes such as wastewater treatment, soil remediation, and air pollution control in the removal of air pollutants such as nitrogen oxides (NOx), volatile organic compounds (VOCs), and sulphur oxides (SOx). In the remediation of contaminated soils, Wang et al. [5] developed a magnetic $MnFe_2O_4@SiO_2@TiO_2$ composite nanocatalyst for the remediation of phenanthrene-contaminated soil. The results showed that the composite nanocatalyst had high photocatalytic activity, and the phenanthrene degradation efficiency reached 78.9% in 3 hours of irradiation. Similarly, Xiong et al. (2020) created a composite nanocatalyst composed of Fe_3O_4 $@SiO_2@TiO_2$ and used it to degrade polycyclic aromatic hydrocarbons (PAHs) in soil. The outcomes demonstrated the excellent photocatalytic activity of the composite nanocatalyst, and the PAH degradation efficiency reached 86% in just 6 hours of exposure.

In the work by Li et al., [2] a composite nanocatalyst was developed for the selective catalytic reduction of NOx with NH_3. The results showed that the composite nanocatalyst exhibited high catalytic activity, and the NOx conversion efficiency reached 94.6% at 350 °C. Graphene oxide-supported Fe_2O_3@CeO_2 composite nanocatalyst was synthesized by Wang et al. (2021) and applied in the catalytic oxidation of formaldehyde. The outcomes disclosed that the composite nanocatalyst had high catalytic activity, while the formaldehyde removal efficiency attained 99.8% at 220 °C.

1.3.4 Pharmaceutical Industry

Composite nanocatalysts have found use in the pharmaceutical sector, notably in creating novel medications and drug delivery systems. For instance, magnetic composite nanoparticles have been synthesized and employed for cancer therapy and targeted medication delivery [29]. Metal-organic frameworks (MOFs) have also been used as templates to make composite nanocatalysts for drug delivery applications because of their enormous surface area and changeable pore widths [2, 5]. Junejo et al. [52] synthesized $AgNO_3$@ Ampicillin and utilized it as a reduction catalyst for antibiotics as it is stable for up to a month in solutions. Important pharmacological intermediates have also been created utilizing composite nanocatalysts, such as creating 1,4-dioxane by oxidizing 1,4-dioxane using Au/TiO_2 catalysts [29].

1.3.5 Petrochemical Industry

Composite nanocatalysts have undergone extensive research toward prospective uses in the petrochemical industry. They have been reported to improve catalyst performance for various petrochemical reactions, including hydrocracking, oxidative coupling of methane (OCM), and hydrodesulfurization (HDS).

In an application of composite nanocatalyst in the hydrodesulfurization (HDS) of sulfur-containing compounds in petroleum feedstocks, Chen et al. [30] synthesized MoS_2 and CoO nanoparticles supported on mesoporous silica, which exhibited high stability and activity in the HDS of dibenzothiophene. Similarly, Ahmad et al. [11] worked on the synthesis of a composite nanocatalyst composed of MoS_2 and $NiMoO_4$ nanoparticles supported on alumina, which exhibited high activity and selectivity in the HDS of 4,6-dimethyl dibenzothiophene and utilized composite nanocatalysts, TBA-PWFe@NiO@BNT and PMoCu@$MgCu_2O_4$-PVA respectively in the oxidative desulfurization of gasoline, which the catalysts were highly efficient and have excellent usability with up to 5 cycles. A composite nanocatalyst composed of zeolite Y and ZSM-5 was synthesized by Hu et al. [7] for the hydrocracking of heavy crude oil. The composite nanocatalyst synthesis was supported on mesoporous silica and exhibited high activity and selectivity.

Another application of composite nanocatalysts in the petrochemical industry is in the oxidative coupling of methane (OCM). For instance, Liu et al. [19] synthesized a composite nanocatalyst composed of La_2O_3 and CeO_2 nanoparticles supported on MgO, which unveiled high selectivity and activity in the oxidative coupling of methane.

4.0 Conclusion and Recommendations

Composite nanocatalysts have great potential in catalysis, energy conversion, and environmental remediation. Solution combustion, Hydrothermal, co-precipitation, Sol-gel, and impregnation are the significant methods of synthesis; the choice of synthesis method plays a critical part in determining the properties and performance of composite nanocatalysts. It is essential to develop composite nanocatalysts with high catalytic activity, stability, and selectivity for their successful application in different fields. Further study is required to explore the potential of composite nanocatalysts in other areas of application and to optimize their properties for specific uses.

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