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Review Article

Recent Advances in Biodiesel Synthesis from Waste Cooking Oil Using Magnetic Nanoparticle-Based Catalysts: A Brief Review

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ABSTRACT

Biodiesel is known as one of the most prospective renewable fuels targeting to replace fossil-based diesel particularly when derived from waste cooking oil (WCO) which is cheap and non-food feedstock. Generally, homogeneous catalysts are used for biodiesel synthesis, which can lead to various difficulties such as separation issues and wastewater generation as well as saponification at sin higher free fatty acids (FFA) concentration.

Heterogeneous magnetic nanocatalysts have gained considerable attention due to their high catalytic efficiency, ease of separation via magnetic fields, and reusability. This review explores the progress in the use of magnetic nanoparticles (MNPs) metal oxides, spinels, and bio-derived nanocatalysts in biodiesel synthesis via transesterification and esterification reactions. Emphasis is placed on catalysts prepared with iron-based cores (Fe_2O_3, Fe_3O_4) doped or functionalized with metals such as Ca, Cu, Ni, and Co, or immobilized enzymes such as lipases. Recent studies from 2020 to 2025 are critically evaluated to catalyst composition, synthesis methods, and performance metrics (yield, reaction conditions, reusability). This approach can contribute to waste recycling and potentially reduce carbon emissions, in alignment with the Sustainable Development Goals.

Keywords: Biodiesel, Magnetic Nanocatalysts, Waste Cooking Oil (WCO).

INTRODUCTION

Lately, green chemistry strategy in biofuel synthesis has focused on the development of waste-based resources and sustainable or recyclable catalysts (Yusuf *et al.,* 2023). Biodiesel is a renewable resource and biodegradable, non-toxic biofuel that is made up mainly of fatty acid methyl esters (FAME), which are a possible substitute for fossil diesel fuel because of their similar physicochemical characteristics, availability, and improved environmental aspect (Wirawan *et al.,* 2024). Waste cooking oil (WCO) among the non-edible feedstocks is especially suitable due to its low cost, abundant availability of substrate, and its ability to solve waste management. However, traditional biodiesel production processes typically using homogeneous alkaline or acid catalysts are often deterred by soap formation during the reaction, and limitations in catalyst recovery and excessive water consumption in the purification stages (Xu *et al.,* 2023).

Magnetic nanoparticles (MNPs) have emerged as a kind of innovative heterogeneous catalyst because MNPs can incorporate high catalytic activity with surface engineering and easy magnetic retrieval (Amshawee *et al.,* 2025). In the majority of cases, these nanostructured materials are based on common Fe_3O_4 and α-Fe_2O_3 or spinel-ferrites and modified with metal oxides or functionalized by acidic or enzymatic active sites in order to improve their bio-catalytic capability in biological reactions for transesterification or esterification. An external magnet can be applied to these superparamagnetic nanocomposites, based on their special properties, and will allow rapid separation from the reaction mixtures with continuous inductor flow and provide a more eco-friendly cooling and heating power consumption in less time, which results in increased process sustainability and reduced post-synthesis clean-up costs (Stueber *et al.,* 2021). Traditional biodiesel synthesis methods have relied on homogeneous catalysts such as NaOH or H_2SO_4, which are efficient but unsustainable due to non-recyclability and corrosiveness. The use of magnetic nanomaterials in heterogeneous catalysis is an attractive concept for improving catalyst reusability and decreasing environmental harm. Latest advances have shown that these magnetic nanocatalysts catalyze high biodiesel yields under mild reaction conditions and show considerable thermal and operational stability. (Ulakpa *et al.,* 2022).

Here, we report a comprehensive overview of the recent advances in the development, functionalization and application of MNPs for biodiesel production from WCO. It delves into catalytic systems through increased reaction parameters and production yields, while also paying close attention to the challenges that lay ahead in achieving scalable based green biodiesel technologies.

Magnetic nanoparticles (MNPs)

MNPs possess several unique physicochemical characteristics that make them suitable for numerous applications in the fields of science. Applications, such as magnetic separation and detection, as well as biotechnology innovations like target drug delivery or magneto induction heating of tumor tissue with an alternating magnetic field (magnetic fluid hyperthermia) (Zhang *et al.,* 2023).

Nano-scale iron-based materials provide this very platform for both experimental and technological purposes such as n superparamagnetic characteristics in the nanocrystalline state and high surface-to-volume ratio and tunable surface chemistry. These properties have enabled potential applications of MNPs in targeted drug delivery, magnetic resonance imaging (MRI) and environmental remediation. Indeed, the attributes render MNPs a superior material over others for various catalytic applications like efficient and recyclable waste cooking oils to biodiesel conversion. The straightforward purification of MNPs due to the magnetic property not only minimizes catalyst concentration loss but also makes downstream purification process simpler. Therefore boosting the recycling of these MNPs an environmental field justification, but lowering net cost a prerequisite for final synthesis, elucidating why they are such appealing green chemistry materials (Han *et al.,* 2023).

Owing to their ferromagnetic and supermagnetic properties, MNPs are used as supports or active sites in a wide range of catalytic reactions. Catalyzed a range of organic reactions (C–C and C–N), bond-forming, redox reactions via hydrogen transfer; applied in asymmetric synthesis, MCRs under neutral conditions. Moreover, the typical acidic, basic or metallic stoichiometry of these pieces makes them also more potent and selective catalyst in nature to deliver us heterogeneously catalyst with specifically functionalized functionalities (Payamifar *et al.,* 2025).

Another application of MNPs in food/feed is the production of biodiesel according to the transesterification process, operating with triglycerides, or esterification during free fatty acid conversion. Magnetic recyclable nanocatalysts such as Fe_3O_4, $CoFe_2O_4$, $MnFe_2O_4$, and doped ferrites have been shown to have high performance in producing biodiesel from waste cooking oils and non-edible feedstocks. In addition to high conversion efficiency, these nanocatalysts allow catalyst recovery and recycling over multiple cycles with less decrement in activity.

In summary, the incorporation of magnetic nanoparticles in catalytic systems stands out as a milestone in the search for sustainable chemical processes. The dual functionality featured them as key materials in the context of modern green chemistry, especially in heterogeneous catalysis for organic synthesis and bio-fuel production, resulting from their high catalytic efficiency together with magnetic recoverability (Hassan *et al.,* 2023).

Synthesis Methods of Magnetic Nanoparticles

There are several commonly used chemical methods for the synthesis of magnetic catalysts, and each method has its own merits in terms of particle size control, magnetic properties, surface functionality, and so on. Depending on the end use (biodiesel production or organic synthesis), a method is chosen most frequently. The most widespread synthesis methods used to convert non-edible feedstocks into biodiesel are those focusing on inedible feedstock-to-biodiesel conversions:

Co-precipitation Method

- Sol–Gel Method
- Hydrothermal and Solvothermal Methods
- Thermal Decomposition
- Microemulsion Technique
- Green Synthesis

Production of Biodiesel

Biodiesel is a renewable, biodegradable alternative to conventional diesel, produced mainly from triglycerides via transesterification with short-chain alcohols such as methanol or ethanol. Similar characteristics to regular diesel and completely compatible for use in a standard diesel engine without or with only slight adaptation (Gotovuša *et al.,* 2022).

Biodiesel has been made from a lot of biological sources. They include vegetable oils as well as both edible and inedible oils (soybean oil, sunflower oil, and Jatropha), microbial oleaginous bacteria and fungi, and a variety of algal lipids. Microalgae and some bacterial strains provide the most promising lipid content to be successfully cultivated in high amounts for biodiesel production without using land suitable for agriculture (Thiyagarajan *et al.,* 2022).

In addition to the above, waste feedstocks have also been turned into a lot for their economic and environmental advantages. Waste cooking oil (WCO) is one of the most investigated sources in this category.

Production of Biodiesel from Waste Cooking Oil

Waste cooking oil (WCO) is a by-product of the food industry in which vegetable- or animal-based oils are repeatedly used for frying. It is composed mainly of glycerol esters of fatty acids and is generally hydrophobic, soluble in organic solvents. The pernicious environmental consequences of the improper handling or disposal of WCO (discarding it in drainage systems) have been well documented, along with its health risks owing to the abundance of toxic and potentially carcinogenic compounds formed as a result of oxidative, hydrolytic, and polymerization reactions that occur during frying (Mannu *et al.,* 2024).

The establishment of WCO as a feedstock for biodiesel has been proven to it can be reused in economically used and a good management waste practice. The price of WCO is 2–3 times lower than that of virgin vegetable oil, which renders it an attractive feedstock for use in industrial production of biodiesel. Raw materials are the main cost item for biodiesel production, accounting for more than 90% of the total. In addition, the use of WCO results in not encountering the common Food vs. Fuel debate and hence offering an ecologically harmless choice (Xiao *et al.,* 2021).

Magnetic Nanocatalysts in Biodiesel Synthesis: An Overview of Recent Advances

In the recent years, MNPs have received special attention for use in biodiesel production owing to their unique properties including high specific surface area, good catalytic performance, and excellent recoverability by means of magnetic separation. These materials can represent a green and efficient alternative to conventional catalysts, in particular for the transesterification and esterification of waste cooking oils and other non-edible feedstocks. They are promising candidates as such catalysts presenting mild conditions, reusability and low-cost advantages for effective biodiesel synthesis. Various types of magnetic nanocatalysts, uncoated and surface-modified, have been investigated by several research groups to produce biodiesel using different synthesis pathways and characterization methods. A study investigated magnetic metal oxide catalysts based on ferric oxide (Fe_2O_3) combined with alkaline oxides such as calcium oxide (CaO), zinc oxide (ZnO), and magnesium oxide (MgO) to introduce magnetic properties that eliminate the need for filters to retain catalysts during biodiesel production by (Echaroj *et al.,* 2023). Biodiesel was also synthesized in a water bath using ultrasonic irradiation inside a packed glass tubular reactor. Key reaction parameters (e.g.; temperature, catalyst amount, residence time, and ultrasonic power) were systematically varied.

Of the different catalysts evaluated, Fe_2O_3-supported CaO led to biodiesel yields of 94.3% at 65 ºC, a methanol-to-oil molar ratio of 11:1, a residence time of 6.2 minutes and an ultrasound power of 185 W; further raising the temperature from this point onwards resulted in reduced yields due to off-gassing methanol. The catalyst demonstrated excellent stability with only a 10% drop in activity after 34 days of continuous operation, attributed to its magnetic property, which prevented catalyst loss from the system. The produced biodiesel met ASTM D6751 fuel standards. This study highlights the advantages of magnetic heterogeneous catalysts in continuous biodiesel production with ease of separation and reusability.

Synthesized a novel supported nano-magnetic catalyst composed of CaO/Fe_2O_3/feldspar for biodiesel production from low-cost and waste plant seed oils such as wild mustard, wild safflower, and karanja oils. The catalyst's structural and magnetic properties were confirmed using X-ray diffraction (XRD), field emission scanning electron microscopy with energy-dispersive X-ray spectroscopy (FESEM/EDX), Brunauer–Emmett–Teller (BET) surface area analysis, and vibrating sample magnetometry (VSM). Optimal biodiesel yields ranging between 93.6% and 99.9% were obtained using low catalyst loadings (1.0–1.5 wt%) at methanol-to-oil molar ratios of 5:1 or 10:1, at 40 °C for 2 hours. The catalyst maintained high activity over 5 consecutive cycles, and magnetic separation was efficiently performed using an external magnet. The fuel properties of the biodiesel complied with ASTM D6751 and EN 14214 standards (Hanif *et al.,* 2023).

$CuFe_2O_4$ MNPs have been investigated as effective heterogeneous catalytic systems for the transesterification of WFO to biodiesel. The catalysts were prepared by two methods, co-precipitation, and a combined method of co-precipitation with hydrothermal treatment. A wide array of characterization techniques, such as thermogravimetric analysis (TGA), scanning electron microscopy (SEM), energy-dispersive X-ray spectroscopy (EDX), high-resolution transmission electron microscopy (HR-TEM), Fourier-transform infrared spectroscopy (FT-IR), Raman spectroscopy, nitrogen adsorption–desorption isotherms and vibrating sample magnetometry (VSM) were utilized. Hydrothermally treated CS2 catalyst showed an obvious catalytic activity improvement in contrast to that of the CS1. The yield of biodiesel was 90.24% under the optimized condition reaction time (30 minutes), methanol to oil molar ratio (18:1), catalyst (3 wt %), and temperature (60°C). The kinetic details suggested that the reaction owned pseudo first order characteristics, while the catalyst also showed good thermal stability and re-usage, which was retained over five cycles with only little loss. We believe that $CuFe_2O_4$ may become a powerful and recyclable magnetic heterogeneous catalyst for efficient biodiesel production, as demonstrated here (Ali *et al.,* 2020).

Produced Fe_3O_4/ SiO_2 MNPs, a convenient and low-cost heterogeneous catalyst for the production of biodiesel from waste cooking oil using ultrasound-assisted transesterification. Response surface methodology (RSM) was used to characterize the catalyst and optimize different parameters, such as methanol-to-oil ratio or weight percentage of catalyst and duration of sonication. The best scenarios were obtained at a methanol/oil mole ratio of 8:3, when the catalyst weight percent was set at 5.3 wt% and sonication time excessive to obtain is 30 min. As the percentage of biodiesel grew, carbon monoxide and smoke emissions were then tested in diesel engines with results showing reduced emissions; however, the nitrogen oxide emissions increased. With straightforward recovery and reuse via the catalyst's magnetic properties, this novel approach drives biodiesel production sustainably while improving engine performance and reducing pollution (Mohammad *et al.,* 2025).

Used a co-precipitation method to synthesize an α-Fe_2O_3/CuO nanocatalyst for catalyzing biodiesel production from waste cooking oil. Successful incorporation of CuO into the α-Fe_2O_3 structure was confirmed with comprehensive characterization techniques, including FTIR, X-ray diffraction (XRD), scanning electron microscopy with energy dispersive X-ray spectroscopy (SEM-EDX), Brunauer–Emmett–Teller (BET) surface area analysis and transmission electron microscopy (TEM). The high specific surface area (334 m^2/g) of the catalyst promotes the number of active sites for transesterification. Box-Behnken design response surface methodology was employed to optimize the biodiesel yield via experimental data with methanol-to-oil molar ratio as the most influencing parameter. Under optimal conditions (3 h reaction time, methanol-to-oil ratio of 11, 2 wt% catalyst loading 60 °C) is recorded as 94.27%. The catalyst showed excellent stability with a mere 12% decrease in efficiency for seven reuse cycles making it an ideal heterogeneously acting catalyst (Rezaeifar *et al.,* 2025).

Novel ternary cobalt-copper-nickel ferrites ($Co_{0.33}Cu_{0.33}Ni_{0.3}Fe_2O_4$) and investigated the influence of calcination temperature on their catalytic activity for biodiesel synthesis from waste cooking oil. The highest fatty acid methyl ester (FAME) content obtained was 99% when the catalyst calcined at 900 °C. Transesterification was optimized for 1 wt% catalyst, 60 ºC reaction temperature, 120 min reaction time and MeOH: oil molar ratio of 6:1. Improved performance can be ascribed to phase transformations, the structuring of more active sites, and promoted surface charges that were generated by calcining at high temperature. With the magnetic behavior of the catalyst, it was easily separated and reused up to 10 times with over −90% yield in six cycles before declining gradually. This study proved a design for efficient magnetic ternary ferrite catalyst with high reusability and reduced waste formation (Eldeeb *et al.,* 2025).

Immobilized Rhizomucor miehei lipase and Thermomyces lanuginosa lipase on aldehyde-functionalized silica-coated magnetic nanoparticles (Fe_3O_4@SiO_2). Using a mild multi-component reaction, high loading capacities (81 mg for RML and 97 mg for TLL) with yields of immobilization between 81–100% over the period of 1.5 to 12 hours were achieved. The enzyme immobilization imparted better stability, as evidenced by their retention of 54% and 97% activity at 65 ºC for RML and TLL respectively. These biocatalysts were successfully applied to the production of biodiesel from waste cooking oil, with maximum yields of 93.1% for TLL and 57.5% for RML when optimal reaction settings were employed. The immobilized enzymes showed good reusability capability after five reaction cycles which indicates that they can be applied as efficient biocatalysts for sustainable biodiesel production (Ashjari *et al.,* 2020).

Developed a bio-nanocomposite catalyst by immobilizing Candida antarctica lipase B (CALB) on titanium oxide-coated magnetic Fe_3O_4 nanoparticles doped with graphene oxide (MTiGO@CALB). The biocatalyst was characterized by FTIR, vibrating sample magnetometry (VSM), XRD, SEM, and EDS, showing maximum enzyme immobilization efficiency of 89% and activity recovery of 75% under optimal conditions (2 mg/mL lipase, pH 7, 35°C immobilization temperature). The catalyst achieved a maximum biodiesel yield of 92% from waste cooking oil at 45 ºC, 4 wt% catalyst loading, 40 hours reaction time, and MeOH: oil molar ratio of 5:1. This bio-nanocomposite showed high potential as an efficient heterogeneous biocatalyst combining magnetic separability with enzymatic specificity (Parandi *et al.,* 2023).

Fabricated a nanocatalyst based on magnetic graphene oxide (GO) functionalized with heterogeneous ternary mixed metal oxides (cerium, zirconium, and strontium oxides) to enhance the conversion of waste frying oil into biodiesel via esterification. The MGO@MMO catalyst was characterized using field emission scanning electron microscopy (FESEM), transmission electron microscopy (TEM), energy dispersive X-ray (EDX), and FTIR. The catalyst achieved a biodiesel yield of 94% under mild conditions (90 min reaction, methanol-to-oil ratio of 8:1, 60 ºC). The catalyst's dual Brønsted acid-base sites improved conversion efficiency at relatively low temperatures compared to individual components, indicating its high catalytic potential for biodiesel production from waste oils (Rezania *et al.,* 2021).

Synthesized $MnFe_2O_4$/graphene oxide catalysts for biodiesel production from waste edible oil. Characterization by SEM, EDX, XRD, vibrating sample magnetometry (VSM), BET surface area analysis, thermogravimetric analysis (TGA), temperature-programmed desorption of CO_2 (CO_2-TPD), and FTIR confirmed the catalyst's high surface area and strong basic sites. Due to elevated free fatty acid content in the feedstock, a pre-esterification step using hydrochloric acid was performed before transesterification with the $MnFe_2O_4$/GO catalyst. The catalyst achieved a remarkable biodiesel yield of 96.47%. Physical properties of the produced biodiesel met most fuel standards except for cloud point, suggesting blending with petroleum diesel for cold climates (Bai *et al.,* 2021).

Developed a magnetic biochar catalyst derived from sugarcane bagasse doped with $FeSO_4 \cdot 7H_2O$ for simultaneous esterification and transesterification of waste cooking oil. The catalyst was characterized by thermogravimetric analysis (TGA), FTIR, and textural properties. Using Box-Behnken Design optimization, the best biodiesel yield was achieved at 43.6 ºC, MeOH: oil molar ratio of 9.98, reaction time of 50 minutes, and catalyst loading of 1.76 wt%. FTIR confirmed typical biodiesel spectral features, and the fuel complied with ASTM and EN standards. This green, efficient, and magnetically recoverable biochar catalyst presents a sustainable approach for converting waste cooking oil into biodiesel (Majamo *et al.,* 2023).

Comparison of magnetic nanoparticle-based catalysts for biodiesel production

Comparative evaluation of the literature in (Table 1) compares apparent differences in catalytic performance, reusability, and sustainability factors of magnetic nanoparticle-based catalysts for biodiesel production from WCO and other feedstocks. The most sustainable system is Fe-BC (Entry 11), which uses a biochar derived from a sugarcane bagasse support with magnetically separable characteristics, yielding a high yield of 98% under mild conditions (43 °C) in six cycles of reusage, thereby offering environmental as well as operational advantages. Enzyme-functionalized catalysts such as Fe_3O_4@SiO_2@TLL@RML (Entry 7) and MTiGO@CALB (Entry 8) represent greener alternatives due to their biocatalytic nature and low reaction temperatures (40–45 °C), although the former requires t-butanol as a co-solvent, which reduces its environmental appeal. In comparison, MTiGO@CALB using only methanol yielded moderately (92%) across nine recycles, making it far more relevant for industrial production. Multimetal spinel ferrites, e.g.; $Co_{0.33}Cu_{0.33}Ni_{0.33}Fe_2O_4$ (Entry 6) exhibited superior catalytic capability evidenced by a yield of 99% and stability over ten consecutive cycles, however leaching and toxicity of transition metals are still common concerns. Other iron oxide-based catalysts, such as Fe_3O_4@SiO_2 (Entry 4), α-Fe_2O_3/CuO (Entry 5), and $MnFe_2O_4$/GO (Entry 10), provided also high yields of biodiesel (94–96%) under comparatively milder conditions underscoring the robustness of magnetic nanostructures for biodiesel production. In summary, these researches demonstrated that using magnetic nanocatalysts enables catalyst recovery and recycling with high efficiency under energy-saving conditions, with biochar and enzyme-support systems appear to be most promising for sustainable biodiesel production.

Table 1: Summary of studies that used magnetic nanoparticles as catalysts in biodiesel synthesis.

Study No.	Catalyst	Feedstock	Conditions	Reusability (cycles)	Yield (%)
1	CaO/Fe_2O_3	WCO	MeOH/oil: 11:1, 60 ºC, [a]RT 7 min	-	98
2	CaO/Fe_2O_3 feldspar	wild mustard, wild safflower, and karanja oils	MeOH/oil: 10:1, 40 ºC	5	99
3	$CuFe_2O_4$	WFO	MeOH/oil: 18:1, 60 ºC	5	93
4	$Fe_3O_4@SiO_2$	WCO	MeOH/oil: 12:1, 30 ºC	-	94
5	α-Fe_2O_3/CuO	WCO	MeOH/oil: 11:1, 60 ºC	7	94
6	$Co_{0.33}Cu_{0.33}Ni_{0.33}Fe_2O_4$	WCO	MeOH/oil: 6:1, 60 ºC	10	99
7	$Fe_3O_4@SiO_2@TLL@RML$	WCO	t-butanol 10.1 %, 40 ºC	5	93
8	MTiGO@CALB	WCO	MeOH/oil: 5:1, 45 ºC	9	92
9	MGO@MMO	WCO	MeOH/oil: 8:1, 60 ºC	8	94
10	$MnFe_2O_4/GO$	WCO	MeOH/oil: 18:1, 65 ºC	-	96
11	Fe-BC	WCO	MeOH/oil: 10:1, 43 ºC	6	98

[a] Retention time

Challenges and prospects

Despite those praiseworthy achievements, few hurdles expose MNPs to biodiesel production limning their commercial usages however they show promising behaviors composed of high conversion yields (up to 98%), facile magnetic separation recovering and superb reusability. Recently, one of the significant issues is catalyst deactivation in the multiple catalytic cycles. Deactivation during steady state operation due to loss of active sites through surface fouling, sintering, leaching of the active metal species or material transformations that lower the catalytic activity. In real feedstocks this becomes more problematic as they are typically contaminated by impurities (e.g.; FFAs, water and solid residues) able to hinder catalyst activity or block active sites.

For MNPs the largest hindrance is the FFA contents in waste oils which can be high. Since-high level of (FFA) can form soap in transesterification and produce emulsification which decrease the yield of biodiesel. While a number of bifunctional catalysts active for both esterification and transesterification have been reported, these are not well optimized to provide stability or activity under conditions relevant for industry. Though enzyme-based magnetic biocatalysts claim enhancing specificity and benign recrystallization conditions, they have only been applied in prolonged reactions with operational instabilities that limit process economic feasibility and scalability.

CONCLUSIONS

MNPs are observed as the highly attractive materials for biodiesel generation due to their remarkable features such as high catalytic activity, simple separation through magnetic means, and excellent reuse. The various studies discussed point out tremendous progress in an existing catalyst design especially concerning magnetic metal oxides and surface modified nanocomposites which have yielded biodiesel over 90% yields at a relatively mild reaction condition. Such catalysts allow the efficient transformation of waste cooking oils, which is a renewable and low-cost feedstock; thus, resolving both ecological issues and economic barriers related to biodiesel synthesis.

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التطورات الحديثة في تصنيع وقود الديزل الحيوي من زيت الطهي المُهدر باستخدام محفزات تعتمد على الجسيمات النانوية المغناطيسية: مراجعة موجزة

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الملخص

يُعدّ الديزل الحيوي أحد أكثر البدائل الواعدة للديزل الأحفوري، لاسيّما عند إنتاجه من زيت الطهي المستعمل (WCO)، والذي يُعتبر مادة أولية غير صالحة للأكل ومتوفرة بكثرة. إلا أن المحفزات المتجانسة التقليدية المستخدمة في تخليق الديزل الحيوي تواجه العديد من التحديات، مثل صعوبة الفصل بعد التفاعل، وتوليد مياه ملوثة، وتكوين الصابون عند وجود نسب عالية من الأحماض الدهنية الحرة. وفي السنوات الأخيرة، حظيت المحفزات النانوية المغناطيسية غير المتجانسة باهتمام متزايد بفضل كفاءتها التحفيزية العالية، وسهولة فصلها باستخدام المجال المغناطيسي، وإمكانية إعادة استخدامها. تستعرض هذه المراجعة أحدث التقدّم في استخدام الجسيمات النانوية المغناطيسية، مثل أكاسيد المعادن، والسبينيلات، والمحفزات النانوية الحيوية في تخليق الديزل الحيوي عبر تفاعلي الأسترة والتبادل الإستيري (transesterification وesterification). يُركّز التحليل على المحفزات ذات الأنوية الحديدية (Fe_3O_4، Fe_2O_3) التي تم تطعيمها أو تعديلها بوظائف معدنية مثل الكالسيوم والنحاس والنيكل والكوبالت، أو تثبيت إنزيمات مثل الليباز عليها. كما يتم تقييم الدراسات المنشورة بين عامي 2020 و2025 بشكل نقدي من حيث تركيب المحفزات، وأساليب التحضير، ومؤشرات الأداء (مثل العائد، وظروف التفاعل، وقابلية إعادة الاستخدام). يمكن أن يُسهم هذا النهج في إعادة تدوير النفايات، وربما يُقلل من انبعاثات الكربون، بما يتماشى مع أهداف التنمية المستدامة.

الكلمات الدالة: الديزل الحيوي، المحفزات النانوية المغناطيسية، زيت الطهي المستهلك.