frontiers in Energy Research

MINI REVIEW
published: 05 October 2021
doi: 10.3389/fenrg.2021.769485

RETRACTED: Recent Development of Renewable Diesel Production Using Bimetallic Catalysts

Shir Reen Chia[1,2], Saifuddin Nomanbhay[1]*, Mei Yin Ong[1], Kit Wayne Chew[3], Kuan Shiong Khoo[4], Hassan Karimi-Maleh[5] and Pau Loke Show[4]*

[1]Institute of Sustainable Energy, Universiti Tenaga Nasional (UNITEN), Kajang, Malaysia, [2]AAIBE Chair of Renewable Energy, Institute of Sustainable Energy, Universiti Tenaga Nasional (UNITEN), Kajang, Malaysia, [3]School of Energy and Chemical Engineering, Xiamen University Malaysia, Sepang, Malaysia, [4]Department of Chemical and Environmental Engineering, Faculty of Science and Engineering, University of Nottingham Malaysia, Semenyih, Malaysia, [5]Department of Chemical Engineering and Energy, Quchan University of Technology, Quchan, Iran

Renewable diesel as a potential sustainable energy source in future requires catalysts to convert the feedstocks into end products. Among various type of catalysts, bimetallic catalysts are widely applied in the renewable diesel production due to their unique catalytic properties and enhanced catalytic activities, which differ from their parent monometallic catalysts. This mini review comprised of the brief introduction on technologies in producing renewable diesel and aims to discuss the underneath knowledge of synergistic interactions in bimetallic catalysts that synthesized through various techniques. The novelty of this review reveals the recent development of renewable diesel production, highlighting the mechanisms of bimetallic catalysts in the enhancement of the catalytic activity, and exploring their possibilities as practical solution in industrial production.

Keywords: renewable diesel, bimetallic catalyst, synergistic effect, bioenergy, catalytic process

OPEN ACCESS

Edited by:
Md. Mofijur Rahman, University of Technology Sydney, Australia

Reviewed by:
Rambabu Krishnamoorthy, Khalifa University, United Arab Emirates
Sze Shin Low, Zhejiang University, China

***Correspondence:**
Saifuddin Nomanbhay
Saifuddin@uniten.edu.my
Pau Loke Show
PauLoke.Show@nottingham.edu.my

Specialty section:
This article was submitted to Bioenergy and Biofuels, a section of the journal Frontiers in Energy Research

Received: *02 September 2021*
Accepted: *23 September 2021*
Published: *05 October 2021*

Citation:
Chia SR, Nomanbhay S, Ong MY, Chew KW, Khoo KS, Karimi-Maleh H and Show PL (2021) Recent Development of Renewable Diesel Production Using Bimetallic Catalysts. Front. Energy Res. 9:769485. doi: 10.3389/fenrg.2021.769485

INTRODUCTION

Increment of population, industrial activities and hazardous gas emissions has urged the world to explore potential solution in shifting main energy sources to renewable energy due to the huge energy demand (Mofijur et al., 2013a; Peter et al., 2021). The introduction of renewable diesel (RD) as fossil fuel replacement is attractive due to its similarity of chemical structure with petroleum diesel. RD is producible using biodiesel feedstocks such as microalgae, date seeds, *Jatropha curcas* and lignocellulosic biomass (Mofijur et al., 2013b; Bharath et al., 2021; Low et al., 2021; Oladipupo Kareem et al., 2021). However, the production often involves catalytic processes that are governed by catalysts.

Noble metal catalysts such as Pd and Pt are applied due to high selectivity to deoxygenation reaction, but their expensive and scarcity have limited their availability for commercial scale of RD production. The rapid deactivation of pure Pd catalysts hinders the practical application in conversion process (Cheah et al., 2020). Hence, an efficient and cost-effective catalyst leading to the high yield of end products with long lifespan and reusability is utmost important in the current industries.

The combination of noble metals with low-cost metals forms bimetallic catalysts that can enhance the catalytic properties of catalysts during the conversion process. Such catalysts are relatively cheaper with promising catalyst efficiency. Bimetallic catalysts are prominent catalysts as high selectivity, activity and stability are observed to yield high hydrocarbons content and purity (Malins, 2021). The synergistic effects between two metals are the major factor controlling the catalyst's efficiencies, which mainly depends on the types of metals.

Numerous reviews have discussed about the recent development of RD processes and Ni-based catalysts in producing RD, but less reviews highlighted the comprehensive mechanisms of bimetallic catalysts in current RD development even technical investigation on bimetallic catalysts are plenty. The aim of this mini review is to highlight the current status of bimetallic catalysts in RD production with their respective interaction with and without support, revealing the suitability of bimetallic catalysts in RD production from recent studies.

RENEWABLE DIESEL PRODUCTION TECHNOLOGIES

The production of RD is achievable through thermochemical processes and biochemical process. Vegetable oil and animal fats are subjected to hydroprocessing or pyrolysis while lignocellulosic biomass undergo pyrolysis, Fischer-Tropsch (FT) process, biological conversion of sugars (i Nogué et al., 2018; Okeke et al., 2020). Among the technologies, hydroprocessing is performed directly on natural triglycerides to obtain RD, which involved a series of complex reactions. Major reactions produce the hydrocarbons, C_{15}–C_{18} are hydrodeoxygenation (HDO), decarboxylation and decarbonylation, depending on the type of catalysts and reaction conditions (Veriansyah et al., 2012). It was reported that the sonochemically treated catalysts have better triglycerides conversion compared to conventional synthesized catalyst and high selectivity of diesel range hydrocarbons was observed (Ameen et al., 2017). Hydroprocessing allows fuel with lower NO_x emissions, better oxidation stability and higher energy density as compared to the transesterification of fatty acid methyl esters (Šimáček et al., 2010).

Besides, the pyrolysis of feedstocks produces bio-oil, biochar, and non-condensable gases, which bio-oil requires upgrading to become RD (Bharath et al., 2020a; Bharath et al., 2020b). The bio-oil can be upgraded through HDO, catalytic cracking and supercritical fluids to overcome the limitations of bio-oils as hydrocarbon fuel. However, each process possesses particular constraint, such as shorter catalyst lifespan for catalytic cracking, high hydrogen pressure requirement for HDO and high cost of solvent for supercritical fluids (Panwar and Paul, 2021).

On the other hand, the syngas obtained from gasification of lignocellulosic biomass is subjected to FT process to obtain RD. The optimization of gasifying agent to biomass ratio is important to attain optimum yield of RD production and overall energy consumption (Im-orb et al., 2015). Conversion of sugars to RD requires the assistance of microorganisms such as oleaginous yeast to produce lipid while feeding on the provided lignocellulosic sugars. The work of i Nogué et al. (2018) presented biological-catalytical hybrid process to yield 31 yeast strains using corn stover hydrolysate. The produced lipids undergo mild acid treatment and extraction, hydrogenation and isomerization to convert into RD blendstocks from *R. toruloides* as a suitable strain (i Nogué et al., 2018). Generally, catalysts are involved and aid in the accomplishment of the RD production.

BIMETALLIC CATALYSTS FOR RENEWABLE DIESEL PRODUCTION

Monometallic or bimetallic catalysts can be used to speed up reaction rate and maximize yield. As how its named, monometallic catalysts consist only single type of metal and usually act as the parent metal for bimetallic catalyst. The common types used are Ni, Pd, Pt, Rh, Co, Fe, and Ru. Specific catalysts are required to boost the reaction activity or negative output may observe if inappropriate catalysts are used. Undesired side reaction that influences main reaction pathway due to unsuitable catalyst has to be avoided such that Ni leads to methanation in FT process (Martinelli et al., 2020). Therefore, bimetallic catalysts are introduced to overcome such issue and enhance the efficiency in catalytic processes.

Bimetallic catalysts with two metal elements exhibit distinct properties from their respective parent monometallic for physical, chemical, electronic, and photonic properties (Suryawanshi et al., 2018). Compared to monometallic catalysts, they are advantageous due to synergistic effect, morphostructures, and their performances varied with the synthesis method (De et al., 2016). Besides, the distinctive and new properties may generate in bimetallic catalysts despite the combined properties of respective monometallic catalysts. The electronic configuration, oxidation state, surface composition etc, of bimetallic catalysts have distinguished their uniqueness and benefits over monometallic catalysts as reported in literatures (Alshammari et al., 2016). Robustness of bimetallic catalysts is being studied intensively to discover their applications not only in energy production, but environmental remediation and biomedical as well (Al-Haddad et al., 2020). The wide application of bimetallic catalysts in various fields show the potential beneath and more studies are required to commercialize the usage of bimetallic catalysts in RD production.

Synergistic Enhancement

Bimetallic catalysts are known for their synergistic effect that leads by combinations of various metals to a new feature of catalyst. The synergistic enhancement often categorized into geometric (ensemble) and ligand (electronic) effects. When the second metal (which added afterwards) modifies the electronic configuration of first metal, ligand effects occurred (Yang and Koel, 2018). This phenomenon occurs due to the changes on the electronic environment of metals, leading by the formation of heteroatoms. The altered electronic environment subsequently modifies the electronic configurations of metals and hence, the chemical properties of catalysts.

As the geometry of bimetallic catalysts are commonly differed from their parent metals, the distinction properties such as average metal-metal bond length change, change in surface bond lengths and angles are often observed (De et al., 2016; Li and Tsang, 2018). Types of geometric structures for bimetallic nanoparticles are known as core-shell, Janus, crown-jewel, alloyed and hollow structures (Alshammari et al., 2016). In additional, the induction of lattice distortion, expansion or compression caused by alloying metals with dissimilar sizes often observed in core-shell structures (Li and Tsang, 2018). The main application of crown-jewel structure is to jewel the atoms of expensive metals at the crown of low-cost metals for using precious metals effectively. For Janus or metals with side-by-side structures, the presence of both metals on the metal surface are attractive compared to other structures. Janus structure is achievable through seed-mediated growth and three types of shapes can be generated by optimizing the experimental condition (Lyu et al., 2021). Hollow structure outstands other structures due to its high surface to volume ratio while the two metals in alloyed structure is homogenously distributed, produced under cautious monitored reaction kinetics (Alshammari et al., 2016).

The synergistic effect of bimetallic catalyst is the key factor in controlling the catalytic reactivity of the catalysts. The fundamental of the enhanced effect can be explained by the d-band theory, where the energy of adsorbate binds to the metal surface is depending on the electronic structure of surface mostly (De et al., 2016; Lee et al., 2021). Formation of bonding (d–σ) and anti-bonding (d–σ)* is obtained through the hybridization of metal d-band with bonding orbital (σ) of the adsorbate. In bimetallic system, the extension of filling for (d-σ)* state is subjected to the electronic structure, like surface density of state for the metals on the surface when the state of (d–σ) is full. Higher catalyst activities can be generated through weaker binding, resulted by destabilization of metal-adsorbate interaction as the filling of (d–σ)* state is increased (De et al., 2016).

Synthesis Methods

Bimetallic catalysts are synthesized through impregnation, strong electrostatic adsorption, colloidal synthesis etc (Zhong and Regalbuto, 2013; Cho and Regalbuto, 2015; De Coster and Poelman, 2021). Optimization of synthesis methods is required to maximize catalytic activity as it is the key factor in manipulating catalytic properties of bimetallic catalysts.

Impregnation is reported as a simple and established technique to synthesize heterogeneous bimetallic catalysts. It is classified into incipient wetness and wet impregnation to synthesize supported catalysts. The volume of metallic solution is equal to pore volume of support for incipient wetness while higher volume of metallic solution is required in wet impregnation (Alshammari et al., 2016). Incipient wetness tends to produce poor metal dispersion with agglomerated and bigger alloyed particles that has weak metals' contact (Cho and Regalbuto, 2015). Strong electrostatic adsorption is advantageous as catalysts with smaller metal particles and higher dispersion were produced compare to impregnation (Cho and Regalbuto, 2015). Electrostatic interactions are involved in electrostatic adsorption while some system involves both electrostatic and chemical interactions, depending on the type of metal precursor and support used (Ewbank et al., 2014). Core-shell configuration is achievable using sequential electrostatic adsorption where the metal loading of shell is controlled by optimizing the cycles of electrostatic adsorption, showing the flexibility in altering catalyst composition (Cho and Regalbuto, 2015).

Besides, colloidal synthesis was reported to allow specific control on the distribution of metal nanoparticles on support, size distribution and size of particles compare to conventional methods of supported heterogenous catalysts (Quinson et al., 2018b). Optimization of the particles' size is achieved through separating the steps of catalysts preparation and deposition into single stages to prevent the contribution of support on catalysts formation (Quinson et al., 2018a). Enhanced structural and thermal stability was observed in the promoter-rich colloidal bimetallic catalysts via test under 800°C. The obtained result has showed potential in avoiding catalyst deactivation by pre-synthesizing the uniform particles and removing the extra promoter oxides (Escorcia et al., 2020). In electroless deposition, chemical agent is utilized to coat the metal ion or complex on substrate and reduced them chemically (Rao and Trivedi, 2005). This method was claimed to overcome the issues like difficulties in limiting the degree to optimize specific interactions, isolating the bimetallic effects, high energy demand and high waste to product ratios (Gould et al., 2015; Egelske et al., 2020). Past study have reported that higher surface coverages of Ag and Au on Pd particles' surface are achieved and lead to better selectivity of reaction conversion (Zhang et al., 2014). However, the analysis on low and high temperature regimes have indicated the thermal instability of bimetallic catalyst at high temperature (Egelske et al., 2020).

Oxidation-reduction reaction is utilized for bimetallic catalysts with noble metals to reduce the usage of expensive metals and enhance the efficiency of noble metals (Zhao et al., 2020). The surface reaction is controlled to maximize the interactions between two metals. Deposition of the second metal on monometallic parent catalyst is performed through reducing parent catalyst using hydrogen at known temperature, adding pre-dissolved copper solution into the suspension of reduced parent monometallic catalyst, and obtaining synthesized catalyst after stirring and filtration (Epron et al., 2002). Besides, the synthesis of bimetallic nanoparticles is performed *via* top-down (laser ablation) or bottom-up technique (co-reduction, seeded-growth, and anodic dissolution) as illustrated in **Figure 1**. Top-down is a technique that disassemble larger objects while bottom-up is performed by metal cations reduction (Loza et al., 2020). The presence of reducing agent is necessary for the bottom-up method. Co-reduction occurs when metal precursors of both metals are presented and having close reduction potential, leading to alloyed configuration (Bhol et al., 2020). Seeded-growth is performed through sequential reduction for core-shell configuration and anodic dissolution is conducted through the deposition of a metal on another firstly dissolved metal to form hollow configuration. Laser ablation is performed using laser beam on the target immersed in liquid solution to form alloyed configuration, where surface-functionalization and fractionization can be further conducted on well-dispersed bimetallic nano-particles (Zhang et al., 2017; Loza et al., 2020).

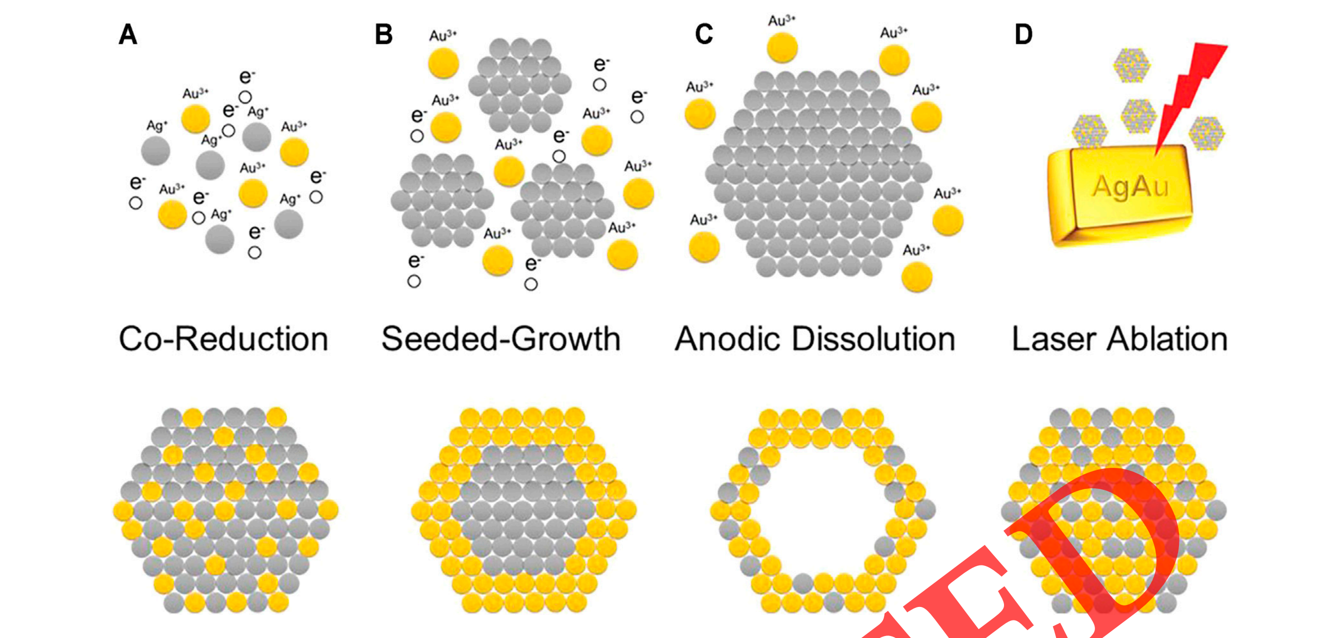

FIGURE 1 | Synthesis methods for bimetallic nanoparticles for various structures. Reprinted from (Loza et al., 2020) with permission from Wiley Online Library.

TABLE 1 | Bimetallic catalysts with supports for RD production.

Type of bimetallic	Type of support	Synthesis method	Application (reaction)	Reference
Pd-Sb	SiO_2	Reduction-oxidation	Dehydrogenation	Ye et al. (2021)
Mo-W	Biochar	Wet impregnation and reduction	Hydrotreatment	Tran et al. (2020)
Co-Mo	AC	Impregnation	Deoxygenation	Gamal et al. (2020)
Ni-Mo	γ-Al_2O_3 or SAPO-11	Incipient wetness	Hydro-process	Lin et al. (2021)
Ir-ReO_x	SiO_2	Sequential impregnation	HDO	Liu et al. (2018)
Pt-MoO_x	ZrO_2	Wet impregnation	HDO	Janampelli and Darbha, (2019)
Ni-La	AC	Wet impregnation	Deoxygenation	Khalit et al. (2020)
Ni-Mo	γ-Al_2O_3	Sonochemical	HDO	Ameen et al. (2019)
Pt-Re	Carbon support	Incipient wetness	Hydro-thermal deoxygenation	Jin and Choi, (2019)
Ni-Mo	SiO_2-Al_2O_3	Impregnation	Hydrotreatment	Malins, (2021)
Pd-Pt	γ-Al_2O_3-H-β	Wet impregnation	Hydrogenation and hydrogenolysis	Palanisamy and Kandasamy, (2020)
CaO-La_2O_3	AC	Impregnation	Deoxygenation	Alsultan et al. (2017)
Mo-Ni	γ-Al_2O_3	Incipient wetness	Catalytic upgrading of pyrolysis oil	Melo et al. (2021)
Pt-WO_x	ZrO_2	Wet impregnation	Deoxygenation	Janampelli and Darbha, (2021)
Ni-Mo	Mesostructured γ-alumina support	Incipient wetness co-impregnation	Continuous hydrotreatment	Afshar Taromi and Kaliaguine, (2018)
Ni-Co	SBA-15	Wet impregnation	Deoxygenation	Kamaruzaman et al. (2020)
Pd-Cu	AC	Incipient wetness	Dehydrogenation	Cheah et al. (2020)

Performances of Bimetallic Catalysts

Bimetallic catalysts can be synthesized into catalysts with and without support. Those without support are rarely applied as unsupported catalysts have lower surface areas compared to supported catalysts. For such reason, most studies utilized supported catalysts in RD production. Yet, the performance of new generation NEBULA unsupported catalysts with high active site density is convincing and has been commercialized due to their outstanding catalytic activity compared to common supported catalysts (Eijsbouts et al., 2007; Burimsitthigul et al., 2021). It was reported that $NiMoS_2$ allowed 95–100% conversion of palmitic and oleic acids through HDO in obtaining high yield and selectivity of C16 and C18 (Yoosuk et al., 2019).

On the other hand, support is used to increase catalytic activity of reactions. Advantages such as higher catalysts' stability was achieved as the metal are well-dispersed on the support, governed by the interaction between metal catalysts and support material (Ferreira-Aparicio et al., 1998). The presence of support is important to reduce cost of precious metal catalysts and allow better metal recovery (Parapat et al., 2014). Reuse of precious bimetallic catalysts with maximised catalysts recovery is achievable using support. However, type of bimetallic catalysts and support influence the synergistic interaction and requires optimization for optimum catalytic properties.

From **Table 1**, bimetallic catalysts in most studies are synthesized through impregnation, either incipient wetness or wet impregnation. Ni-Mo bimetallic catalysts synthesized by deposition-precipitation impregnation are reported to have better performance as higher yield and selectivity to *n*-C18 were obtained compared to incipient wetness and double incipient wetness (Malins, 2021). However, the sonochemical synthesis is claimed to be more effective than impregnation to generate active sites of Mo, enhancing physicochemical properties like higher specific surface area and uniform distribution of metal particles on support's surface (Ameen et al., 2019).

Bimetallic combinations are investigated in HDO, deoxygenation or dehydrogenation reactions. Ni is widely studied as it is comparatively cheaper, yields high hydrocarbon yield and triglycerides conversion by sulfiding itself and other metals with γ-Al_2O_3 as support (Wang et al., 2014). Types of bimetallic combinations and support are key parameters to optimize. It was concluded Ni-Co is more suitable to synthesize with γ-Al_2O_3 compare to SiO_2 as higher conversion and diesel selectivity were obtained (Hari and Yaakob, 2015). The support, γ-Al_2O_3 reported to work better with Ni-Mo than SAPO-11, despite the second metal is unsimilar with the previous work (Lin et al., 2021). Activated carbon (AC), biochar, carbon support in other forms or metals can be utilized as support too.

CONCLUSION

Bimetallic catalysts are proven to be efficient catalyst in RD production with the flexibility, robustness and unique properties that are not possess by monometallic catalysts. Variation of metal combinations with different support favours specific reactions. Exploration of bimetallic catalysts for RD production in more studies is required, to further enhance the catalytic properties and activities in increasing the efficiency of catalyst. Conventional bimetallic catalysts have their advantages, but more studies of novel bimetallic catalysts are required to aid in the improvement of this field. Further investigation is required to fully control the final configuration of bimetallic catalysts through synthesis methods and reduce the possibilities of sites deactivation especially for precious bimetallic catalysts. Expenses on catalysts can be lowered through enhancing the recyclability and stability of catalysts to achieve sustainable, economical, and efficient process in practical application.

AUTHOR CONTRIBUTIONS

SC and SN contributed to conceptualization and visualization. SN, PS and HK-M supervised the progress of manuscript. SC wrote the first draft of manuscript. MO, KC and KK helped review and editing the manuscript. SN provided funding for the manuscript. All the authors contributed to manuscript revision, read, and approved the submitted version.

FUNDING

The authors would like to acknowledge the financial supports from AAIBE Chair of Renewable Energy (ChRE)–UNITEN under project code (202006KETTHA), BOLD 2021 Grant from iRMC–UNITEN under project code (J510050002/2021092), Malaysia Fundamental Research Grant Scheme (FRGS/1/2019/STG05/UNIM/02/2) and the MyPAIR-PHC-Hibiscus Grant (MyPAIR/1/2020/STG05/UNIM/1). The APC was funded by BOLD Refresh Publication Fund 2021 under iRMC, UNITEN (Grant: J5100D4103-BOLDREFRESH2025-CENTER OF EXCELLENCE).

ACKNOWLEDGMENTS

SC would like to acknowledge the post-doctoral fellowship programme and the figure reproduced from the below journal paper with the permission obtained from the rights owner.

REFERENCES

Adira Wan Khalit, W. N., Marliza, T. S., Asikin-Mijan, N., Gamal, M. S., Saiman, M. I., Ibrahim, M. L., et al. (2020). Development of Bimetallic Nickel-Based Catalysts Supported on Activated Carbon for green Fuel Production. *RSC Adv.* 10 (61), 37218–37232. doi:10.1039/d0ra06302a

Afshar Taromi, A., and Kaliaguine, S. (2018). Green Diesel Production via Continuous Hydrotreatment of Triglycerides over Mesostructured γ-alumina Supported NiMo/CoMo Catalysts. *Fuel Process. Tech.* 171, 20–30. doi:10.1016/j.fuproc.2017.10.024

Al-Haddad, J., Alzaabi, F., Pal, P., Rambabu, K., and Banat, F. (2020). Green Synthesis of Bimetallic Copper-Silver Nanoparticles and Their Application in Catalytic and Antibacterial Activities. *Clean. Techn Environ. Pol.* 22 (1), 269–277. doi:10.1007/s10098-019-01765-2

Alshammari, A., Kalevaru, V., and Martin, A. (2016). Bimetallic Catalysts Containing Gold and Palladium for Environmentally Important Reactions. *Catalysts* 6 (7), 97. doi:10.3390/catal6070097

Alsultan, G. A., Asikin-Mijan, N., Lee, H. V., Albazzaz, A. S., and Taufiq-Yap, Y. H. (2017). Deoxygenation of Waste Cooking to Renewable Diesel over walnut Shell-Derived Nanorode Activated Carbon Supported CaO-La 2 O 3 Catalyst. *Energ. Convers. Manag.* 151, 311–323. doi:10.1016/j.enconman.2017.09.001

Ameen, M., Azizan, M. T., Ramli, A., Yusup, S., and Alnarabiji, M. S. (2019). Catalytic Hydrodeoxygenation of Rubber Seed Oil over Sonochemically Synthesized Ni-Mo/γ-Al2O3 Catalyst for green Diesel Production. *Ultrason. Sonochem.* 51, 90–102. doi:10.1016/j.ultsonch.2018.10.011

Ameen, M., Azizan, M. T., Yusup, S., and Ramli, A. (2017). Hydroprocessing of Rubber Seed Oil over Ni-Mo/γ-Al 2 O 3 for the green Diesel Production. *Chem. Eng. Trans.* 61, 1843–1848.

Bharath, G., Hai, A., Rambabu, K., Banat, F., Jayaraman, R., Taher, H., et al. (2020a). Systematic Production and Characterization of Pyrolysis-Oil from Date Tree Wastes for Bio-Fuel Applications. *Biomass and Bioenergy* 135, 105523. doi:10.1016/j.biombioe.2020.105523

Bharath, G., Rambabu, K., Hai, A., Banat, F., Taher, H., Schmidt, J. E., et al. (2020b). Catalytic Hydrodeoxygenation of Biomass-Derived Pyrolysis Oil over Alloyed

Bimetallic Ni3Fe Nanocatalyst for High-Grade Biofuel Production. *Energ. Convers. Manag.* 213, 112859. doi:10.1016/j.enconman.2020.112859

Bharath, G., Rambabu, K., Hai, A., Morajkar, P. P., Salkar, A. V., Hasan, S. W., et al. (2021). Highly Selective Etherification of Fructose and 5-hydroxymethylfurfural over a Novel Pd-Ru/MXene Catalyst for Sustainable Liquid Fuel Production. *Int. J. Energ. Res.* 45 (10), 14680–14691. doi:10.1002/er.6743

Bhol, P., Bhavya, M. B., Swain, S., Saxena, M., and Samal, A. K. (2020). Modern Chemical Routes for the Controlled Synthesis of Anisotropic Bimetallic Nanostructures and Their Application in Catalysis. *Front. Chem.* 8 (357). doi:10.3389/fchem.2020.00357

Burimsitthigul, T., Yoosuk, B., Ngamcharussrivichai, C., and Prasassarakich, P. (2021). Hydrocarbon Biofuel from Hydrotreating of palm Oil over Unsupported Ni-Mo Sulfide Catalysts. *Renew. Energ.* 163, 1648–1659. doi:10.1016/j.renene.2020.10.044

Cheah, K. W., Taylor, M. J., Osatiashtiani, A., Beaumont, S. K., Nowakowski, D. J., Yusup, S., et al. (2020). Monometallic and Bimetallic Catalysts Based on Pd, Cu and Ni for Hydrogen Transfer Deoxygenation of a Prototypical Fatty Acid to Diesel Range Hydrocarbons. *Catal. Today* 355, 882–892. doi:10.1016/j.cattod.2019.03.017

Cho, H.-R., and Regalbuto, J. R. (2015). The Rational Synthesis of Pt-Pd Bimetallic Catalysts by Electrostatic Adsorption. *Catal. Today* 246, 143–153. doi:10.1016/j.cattod.2014.09.029

De Coster, V., and Poelman, H. (2021). Topic Review Catalyst Design via Colloidal Synthesis Subjects: Others| Nanoscience & Nanotechnology| Chemistry, *Phys. View times*, 348.

De, S., Zhang, J., Luque, R., and Yan, N. (2016). Ni-based Bimetallic Heterogeneous Catalysts for Energy and Environmental Applications. *Energy Environ. Sci.* 9 (11), 3314–3347. doi:10.1039/C6EE02002J

Egelske, B. T., Keels, J. M., Monnier, J. R., and Regalbuto, J. R. (2020). An Analysis of Electroless Deposition Derived Ni-Pt Catalysts for the Dry Reforming of Methane. *J. Catal.* 381, 374–384. doi:10.1016/j.jcat.2019.10.035

Eijsbouts, S., Mayo, S. W., and Fujita, K. (2007). Unsupported Transition Metal Sulfide Catalysts: From Fundamentals to Industrial Application. *Appl. Catal. A: Gen.* 322, 58–66. doi:10.1016/j.apcata.2007.01.008

Epron, F., Gauthard, F., and Barbier, J. (2002). Influence of Oxidizing and Reducing Treatments on the Metal–Metal Interactions and on the Activity for Nitrate Reduction of a Pt-Cu Bimetallic Catalyst. *Appl. Catal. A: Gen.* 237 (1), 253–261. doi:10.1016/S0926-860X(02)00331-9

Escorcia, N. J., LiBretto, N. J., Miller, J. T., and Li, C. W. (2020). Colloidal Synthesis of Well-Defined Bimetallic Nanoparticles for Nonoxidative Alkane Dehydrogenation. *ACS Catal.* 10 (17), 9813–9823. doi:10.1021/acscatal.0c01554

Ewbank, J. L., Kovarik, L., Kenvin, C. C., and Sievers, C. (2014). Effect of Preparation Methods on the Performance of Co/Al2O3 Catalysts for Dry Reforming of Methane. *Green. Chem.* 16 (2), 885–896. doi:10.1039/c3gc41782d

Ferreira-Aparicio, P., Guerrero-Ruiz, A., and Rodríguez-Ramos, I. (1998). Comparative Study at Low and Medium Reaction Temperatures of Syngas Production by Methane Reforming with Carbon Dioxide over Silica and Alumina Supported Catalysts. *Appl. Catal. A: Gen.* 170 (1), 177–187. doi:10.1016/s0926-860x(98)00048-9

Gamal, M. S., Asikin-Mijan, N., Khalit, W. N. A. W., Arumugam, M., Izham, S. M., and Taufiq-Yap, Y. H. (2020). Effective Catalytic Deoxygenation of palm Fatty Acid Distillate for green Diesel Production under Hydrogen-free Atmosphere over Bimetallic Catalyst CoMo Supported on Activated Carbon. *Fuel Process. Tech.* 208, 106519. doi:10.1016/j.fuproc.2020.106519

Gould, T. D., Montemore, M. M., Lubers, A. M., Ellis, L. D., Weimer, A. W., Falconer, J. L., et al. (2015). Enhanced Dry Reforming of Methane on Ni and Ni-Pt Catalysts Synthesized by Atomic Layer Deposition. *Appl. Catal. A: Gen.* 492, 107–116. doi:10.1016/j.apcata.2014.11.037

Hari, T. K., and Yaakob, Z. (2015). Production of Diesel Fuel by the Hydrotreatment of Jatropha Oil Derived Fatty Acid Methyl Esters over γ-Al2O3 and SiO2 Supported NiCo Bimetallic Catalysts. *Reac Kinet Mech. Cat* 116 (1), 131–145. doi:10.1007/s11144-015-0874-8

Im-orb, K., Simasatitkul, L., and Arpornwichanop, A. (2015). "Performance Analysis and Optimization of the Biomass Gasification and Fischer-Tropsch Integrated Process for Green Fuel Productions," in *Computer Aided Chemical Engineering*. Editors K. V. Gernaey, J. K. Huusom, and R. Gani (Elsevier), 275–280. doi:10.1016/b978-0-444-63578-5.50041-4

Janampelli, S., and Darbha, S. (2019). Highly Efficient Pt-MoOx/ZrO2 Catalyst for green Diesel Production. *Catal. Commun.* 125, 70–76. doi:10.1016/j.catcom.2019.03.027

Janampelli, S., and Darbha, S. (2021). Selective Deoxygenation of Fatty Acids to Fuel-Range Hydrocarbons over Pt-MOx/ZrO2 (M = Mo and W) Catalysts. *Catal. Today* 375, 174–180. doi:10.1016/j.cattod.2020.04.020

Jin, M., and Choi, M. (2019). Hydrothermal Deoxygenation of Triglycerides over Carbon-Supported Bimetallic PtRe Catalysts without an External Hydrogen Source. *Mol. Catal.* 474, 110419. doi:10.1016/j.mcat.2019.110419

Kamaruzaman, M. F., Taufiq-Yap, Y. H., and Derawi, D. (2020). Green Diesel Production from palm Fatty Acid Distillate over SBA-15-Supported Nickel, Cobalt, and Nickel/cobalt Catalysts. *Biomass and Bioenergy* 134, 105476. doi:10.1016/j.biombioe.2020.105476

Lee, K. R., Yun, D., Park, D. S., Yun, Y. S., Song, C. K., Kim, Y., et al. (2021). *In Situ* manipulation of the D-Band center in Metals for Catalytic Activity in CO Oxidation. *Chem. Commun.* 57 (27), 3403–3406. doi:10.1039/D0CC06979E

Li, M. M.-J., and Tsang, S. C. E. (2018). Bimetallic Catalysts for green Methanol Production *via* CO2 and Renewable Hydrogen: a Mini-Review and Prospects. *Catal. Sci. Technol.* 8 (14), 3450–3464. doi:10.1039/C8CY00304A

Lin, J. K., Lee, C. P., Lin, H. P., Halim, E., and Wang, W. C. (2021). The Production of Hydro-processed Renewable Diesel over the Nonsulfide Catalyst. *Int. J. Energ. Res.* n/a(n/a). doi:10.1002/er.7119

Liu, S., Simonetti, T., Zheng, W., and Saha, B. (2018). Selective Hydrodeoxygenation of Vegetable Oils and Waste Cooking Oils to Green Diesel Using a Silica-Supported Ir-ReO X Bimetallic Catalyst. *ChemSusChem.* 11 (9), 1446–1454. doi:10.1002/cssc.201800321

Low, S. S., Bong, K. X., Mubashir, M., Cheng, C. K., Lam, M. K., Lim, J. W., et al. (2021). Microalgae Cultivation in Palm Oil Mill Effluent (POME) Treatment and Biofuel Production. *Sustainability* 13 (6), 3247. doi:10.3390/su13063247

Loza, K., Heggen, M., and Epple, M. (2020). Synthesis, Structure, Properties, and Applications of Bimetallic Nanoparticles of noble Metals. *Adv. Funct. Mater.* 30 (21), 1909260. doi:10.1002/adfm.201909260

Lyu, Z., Zhu, S., Xu, L., Chen, Z., Zhang, Y., Xie, M., et al. (2021). Kinetically Controlled Synthesis of Pd-Cu Janus Nanocrystals with Enriched Surface Structures and Enhanced Catalytic Activities toward CO2 Reduction. *J. Am. Chem. Soc.* 143 (1), 149–162. doi:10.1021/jacs.0c05408

Malins, K. (2021). Synthesis of Renewable Hydrocarbons from Vegetable Oil Feedstock by Hydrotreatment over Selective Sulfur-free SiO2-Al2O3 Supported Monometallic Pd, Pt, Ru, Ni, Mo and Bimetallic NiMo Catalysts. *Fuel* 285, 119129. doi:10.1016/j.fuel.2020.119129

Martinelli, M., Gnanamani, M. K., LeViness, S., Jacobs, G., and Shafer, W. D. (2020). An Overview of Fischer-Tropsch Synthesis: XtL Processes, Catalysts and Reactors. *Appl. Catal. A: Gen.* 608, 117740. doi:10.1016/j.apcata.2020.117740

Melo, J. A., de Sá, M. S., Moral, A., Bimbela, F., Gandía, L. M., and Wisniewski, A. (2021). Renewable Hydrocarbon Production from Waste Cottonseed Oil Pyrolysis and Catalytic Upgrading of Vapors with Mo-Co and Mo-Ni Catalysts Supported on γ-Al2O3. *Nanomaterials* 11 (7), 1659. doi:10.3390/nano11071659

Mofijur, M., Atabani, A. E., Masjuki, H. H., Kalam, M. A., and Masum, B. M. (2013a). A Study on the Effects of Promising Edible and Non-edible Biodiesel Feedstocks on Engine Performance and Emissions Production: A Comparative Evaluation. *Renew. Sustain. Energ. Rev.* 23, 391–404. doi:10.1016/j.rser.2013.03.009

Mofijur, M., Masjuki, H. H., Kalam, M. A., and Atabani, A. E. (2013b). Evaluation of Biodiesel Blending, Engine Performance and Emissions Characteristics of Jatropha Curcas Methyl Ester: Malaysian Perspective. *Energy* 55, 879–887. doi:10.1016/j.energy.2013.02.059

Okeke, I. J., Sahoo, K., Kaliyan, N., and Mani, S. (2020). Life Cycle Assessment of Renewable Diesel Production via Anaerobic Digestion and Fischer-Tropsch Synthesis from Miscanthus Grown in Strip-Mined Soils. *J. Clean. Prod.* 249, 119358. doi:10.1016/j.jclepro.2019.119358

Oladipupo Kareem, M., Edathil, A. A., Rambabu, K., Bharath, G., Banat, F., Nirmala, G. S., et al. (2021). Extraction, Characterization and Optimization of High Quality Bio-Oil Derived from Waste Date Seeds. *Chem. Eng. Commun.* 208 (6), 801–811. doi:10.1080/00986445.2019.1650034

Palanisamy, S., and Kandasamy, K. (2020). Direct Hydrogenation and Hydrotreating of Neat Vegetal Oil into Renewable Diesel Using Alumina Binder with Zeolite. *Rev. Chim.* 71 (9), 98–112. doi:10.37358/rc.20.9.8321

Panwar, N. L., and Paul, A. S. (2021). An Overview of Recent Development in Bio-Oil Upgrading and Separation Techniques. *Environ. Eng. Res.* 26 (5), 200382–200380. doi:10.4491/eer.2020.382

Parapat, R. Y., Saputra, O. H. I., Ang, A. P., Schwarze, M., and Schomäcker, R. (2014). Support Effect in the Preparation of Supported Metal Catalysts via Microemulsion. *RSC Adv.* 4 (92), 50955–50963. doi:10.1039/c4ra10736e

Peter, A. P., Khoo, K. S., Chew, K. W., Ling, T. C., Ho, S.-H., Chang, J.-S., et al. (2021). Microalgae for Biofuels, Wastewater Treatment and Environmental Monitoring. *Environ. Chem. Lett.* 19 (4), 2891–2904. doi:10.1007/s10311-021-01219-6

Quinson, J., Inaba, M., Neumann, S., Swane, A. A., Bucher, J., Simonsen, S. B., et al. (2018a). Investigating Particle Size Effects in Catalysis by Applying a Size-Controlled and Surfactant-free Synthesis of Colloidal Nanoparticles in Alkaline Ethylene Glycol: Case Study of the Oxygen Reduction Reaction on Pt. *ACS Catal.* 8 (7), 6627–6635. doi:10.1021/acscatal.8b00694

Quinson, J., Neumann, S., Wannmacher, T., Kacenauskaite, L., Inaba, M., Bucher, J., et al. (2018b). Colloids for Catalysts: a Concept for the Preparation of superior Catalysts of Industrial Relevance. *Angew. Chem.* 130 (38), 12518–12521. doi:10.1002/ange.201807450

Rao, C., and Trivedi, D. (2005). Chemical and Electrochemical Depositions of Platinum Group Metals and Their Applications. *Coord. Chem. Rev.* 249 (5), 613–631. doi:10.1016/j.ccr.2004.08.015

Sànchez i Nogué, V., Black, B. A., Kruger, J. S., Singer, C. A., Ramirez, K. J., Reed, M. L., et al. (2018). Integrated Diesel Production from Lignocellulosic Sugarsviaoleaginous Yeast. *Green. Chem.* 20 (18), 4349–4365. doi:10.1039/c8gc01905c

Šimáček, P., Kubička, D., Šebor, G., and Pospíšil, M. (2010). Fuel Properties of Hydroprocessed Rapeseed Oil. *Fuel* 89 (3), 611–615. doi:10.1016/j.fuel.2009.09.017

Suryawanshi, P. L., Polagani, R. K., and Sonawane, S. H. (2018). "Synthesis of Nanomaterials for Fuel Cell Applications," in *Nanomaterials for Green Energy.* Editors B. A. Bhanvase, V. B. Pawade, S.J. Dhoble, S.H. Sonawane, and M. Ashokkumar (Elsevier), 205–226. doi:10.1016/b978-0-12-813731-4.00007-2

Tran, C.-C., Akmach, D., and Kaliaguine, S. (2020). Hydrodeoxygenation of Vegetable Oils over Biochar Supported Bimetallic Carbides for Producing Renewable Diesel under Mild Conditions. *Green. Chem.* 22 (19), 6424–6436. doi:10.1039/d0gc00680g

Veriansyah, B., Han, J. Y., Kim, S. K., Hong, S.-A., Kim, Y. J., Lim, J. S., et al. (2012). Production of Renewable Diesel by Hydroprocessing of Soybean Oil: Effect of Catalysts. *Fuel* 94, 578–585. doi:10.1016/j.fuel.2011.10.057

Wang, C., Liu, Q., Song, J., Li, W., Li, P., Xu, R., et al. (2014). High Quality Diesel-Range Alkanes Production via a Single-step Hydrotreatment of Vegetable Oil over Ni/zeolite Catalyst. *Catal. Today* 234, 153–160. doi:10.1016/j.cattod.2014.02.011

Yang, X., and Koel, B. E. (2018). "Adsorption and Reaction of Unsaturated Hydrocarbons on Sn/Pt Alloys," in *Encyclopedia of Interfacial Chemistry*. Editor K. Wandelt (Oxford: Elsevier), 1–10. doi:10.1016/b978-0-12-409547-2.12802-1

Ye, C., Peng, M., Cui, T., Tang, X., Wang, D., Jiao, M., et al. (2021). Revealing the Surface Atomic Arrangement of noble Metal Alkane Dehydrogenation Catalysts by a Stepwise Reduction-Oxidation Approach. *Nano Res.*, 1–7. doi:10.1007/s12274-021-3636-0

Yoosuk, B., Sanggam, P., Wiengket, S., and Prasassarakich, P. (2019). Hydrodeoxygenation of Oleic Acid and Palmitic Acid to Hydrocarbon-like Biofuel over Unsupported Ni-Mo and Co-mo Sulfide Catalysts. *Renew. Energ.* 139, 1391–1399. doi:10.1016/j.renene.2019.03.030

Zhang, J., Chaker, M., and Ma, D. (2017). Pulsed Laser Ablation Based Synthesis of Colloidal Metal Nanoparticles for Catalytic Applications. *J. Colloid Interf. Sci.* 489, 138–149. doi:10.1016/j.jcis.2016.07.050

Zhang, Y., Diao, W., Williams, C. T., and Monnier, J. R. (2014). Selective Hydrogenation of Acetylene in Excess Ethylene Using Ag- and Au-Pd/SiO2 Bimetallic Catalysts Prepared by Electroless Deposition. *Appl. Catal. A: Gen.* 469, 419–426. doi:10.1016/j.apcata.2013.10.024

Zhao, Q., Wang, C., Wang, H., Wang, J., Tang, Y., Mao, Z., et al. (2020). Synthesis of a High-Performance Low-Platinum PtAg/C Alloyed Oxygen Reduction Catalyst through the Gradual Reduction Method. *New J. Chem.* 44 (9), 3728–3736. doi:10.1039/C9NJ06156H

Zhong, C. J., and Regalbuto, J. R. (2013). "Metal Nanoparticle Synthesis," in *Comprehensive Inorganic Chemistry II*. Editors J. Reedijk and K. Poeppelmeier Second Edition (Amsterdam: Elsevier), 75–102. doi:10.1016/b978-0-08-097774-4.00711-7

Conflict of Interest: The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Publisher's Note: All claims expressed in this article are solely those of the authors and do not necessarily represent those of their affiliated organizations, or those of the publisher, the editors and the reviewers. Any product that may be evaluated in this article, or claim that may be made by its manufacturer, is not guaranteed or endorsed by the publisher.