

OXYGEN VACANCY-ENGINEERED ZnO NANOCATALYSTS FOR ENHANCED BIODIESEL PRODUCTION FROM FRESH AND WASTE OILS

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ABSTRACT

ZnO-based nanocatalysts with defect-engineered oxygen vacancies were designed and studied to produce biodiesel. Pristine ZnO, Na-incorporated ZnO (Na-ZnO), and Mg-incorporated ZnO (Mg-ZnO) nanoparticles were prepared through a sustainable route by using *Aloe vera* extract and systematically characterised by elemental analysis, atomic absorption spectroscopy (AAS), X-ray photoelectron spectroscopy (XPS), scanning electron microscopy-energy-dispersive X-ray analysis (SEM-EDX), powder X-ray diffraction (XRD), and UV-Vis diffuse reflectance spectroscopy. Of these, the XPS analysis offered clear experimental data on the greatly improved oxygen vacancy concentration in Na- and Mg-modified ZnO, which meant the effective defect engineering under the influence of the incorporation of the heteroatoms. The catalytic activity was tested in the transesterification of fresh and used sunflower oils, and the catalytic activity was strongly related to the level of oxygen vacancies. Mg-ZnO demonstrated better catalytic performance with biodiesel yields of 96 per cent (fresh oil, 1 h), 88 per cent (used oil, 1 h) and then Na-ZnO (81 per cent and 68 per cent in 1.5 h), and pristine ZnO (62 per cent and 48 per cent in 3 h). This increased reactivity (ZnO < Na-ZnO < Mg-ZnO) has been ascribed to the electronic modulation via oxygen vacancies, which facilitates reactant adsorption, triglyceride activation and surface basicity. Thus, the present work demonstrates the essential importance of oxygen vacancies as active sites in ZnO-based nanocatalysts and gives a sensible approach to making catalysts with the greatest performance in the generation of biodiesel on a sustainable basis.

Keywords: Green Synthesis, Na-doped ZnO, Mg-doped ZnO, *Aloe Vera* Extract, Biodiesel Production.

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INTRODUCTION

With the increasing day-to-day global demand for sustainable development and renewable energy sources, there have been tremendous research efforts developed for the design of efficient catalytic systems for biodiesel production.^{1,2} Biodiesel is made of fatty acid methyl esters, or FAME. This organic material has been touted as an alternative to fossil-derived diesel that is biodegradable and not toxic. Furthermore, biodiesel not only lessens greenhouse gas emissions but also prevents the death of marine organisms.³⁻⁵ Among various production routes, transesterification of triglycerides using heterogeneous catalysts has gained considerable attention owing to its operational simplicity, catalyst recyclability, and environmental compatibility. However, the design of highly active, stable, and cost-effective catalysts remains a significant challenge, particularly when processing low-quality or used feedstocks. Zinc oxide (ZnO) has emerged as a versatile heterogeneous catalyst due to its low cost, non-toxicity, thermal stability, and tunable surface properties. Nevertheless, pristine ZnO often exhibits limited catalytic efficiency in transesterification reactions, primarily due to insufficient active sites and moderate surface basicity.^{6,7} Modifying the characteristics of metal oxides has recently emerged as a novel approach in which defect engineering, especially the creation of oxygen vacancies, has proven to be effective.^{8,9} Oxygen vacancies act as electron-rich active centres that enhance reactant adsorption, facilitate charge transfer, and improve catalytic activity. Despite these advantages, systematic experimental and theoretical investigations correlating oxygen vacancy concentration with catalytic performance in biodiesel production remain

relatively underexplored.

In this work, we report the design and synthesis of oxygen vacancy-engineered ZnO nanocatalysts, including pristine ZnO, Na-incorporated ZnO (Na-ZnO), and Mg-incorporated ZnO (Mg-ZnO), via a sustainable green route using *Aloe vera* extract. A comprehensive characterisation strategy, including XPS, AAS, SEM-EDX, XRD, and UV-Vis spectroscopy, was employed to elucidate structural, compositional, and defect-related properties, with particular emphasis on oxygen vacancy formation. The catalytic performance of these materials was systematically evaluated in the transesterification of both fresh and used sunflower oils.

EXPERIMENTAL

Materials

Zinc nitrate hexahydrate ($\text{Zn}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), sodium nitrate (NaNO_3), magnesium nitrate hexahydrate ($\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$), and methanol (analytical grade) were purchased from standard chemical suppliers and used without further purification. Fresh *Aloe vera* leaves were collected locally and thoroughly washed with distilled water before use. Refined vegetable oil was used as feedstock for biodiesel production.

Preparation of *Aloe vera* Leaf Extract

Fresh *Aloe vera* leaves were washed and cut into small pieces, and about 20g of the inside gel was homogenised in 100 mL of distilled water at 70-80 °C with stirring. The Whatman No. 1 filter paper was used to filter the mixture, and it was allowed to cool at room temperature. The filtrate was stored at 4 °C and used within 48 hours as a reducing and stabilising agent.

Green Synthesis of Pristine and Doped ZnO Nanoparticles

Pristine ZnO

Zinc nitrate 0.1 M (100 mL) solution was stirred with 20 mL of *Aloe vera* extract at 70 °C. To stabilise the pH at about 10, 1 M NaOH was added. The precipitate was collected after 2 h of stirring and 12 h of ageing, washed, dried at 100 °C overnight, and calcined at 450 °C during 4 h. Colour and appearance: white powder, yield: 82%.

Na-Doped ZnO (3 wt%)

NaNO_3 (3 wt% with respect to Zn precursor) was dissolved together with zinc nitrate before the addition of extracts. The synthesis process was the same as for pure ZnO. Colour and appearance: Faint cream powder; yield: 85%.

Mg-Doped ZnO (3 wt%)

$\text{Mg}(\text{NO}_3)_2 \cdot 6\text{H}_2\text{O}$ (3 wt% with respect to Zn precursor) was dissolved together with zinc nitrate before the addition of extracts. The synthesis process was the same as for pure ZnO. Colour and appearance: faint cream powder; yield: 83%.

Catalytic Activity in Biodiesel Production

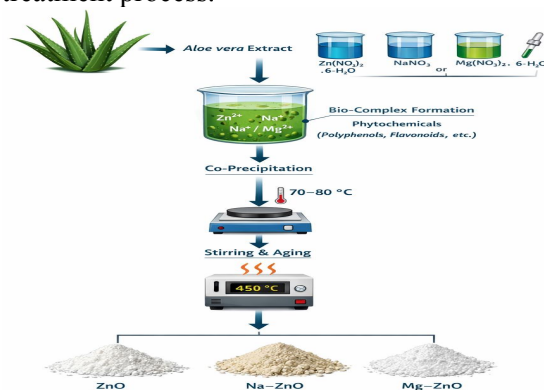
The reactions of transesterification were conducted in a round-bottom flask of 100 mL with a reflux condenser. A 1:12 (molar) mixture of vegetable oil (10.0 g) and methanol (8.6 mL) was typically used with the catalyst (3 wt%, 0.03 g) (relative to oil). The mixture was magnetically stirred for 1-5 h by heating at 60-65 °C. On completion, the catalyst was filtered, and the reaction mixture was left for phase separation. The biodiesel yield was calculated based on the weight of methyl ester formed.

RESULTS AND DISCUSSION

Synthesis

The synthetic plan of the intended synthesis is illustrated in Scheme-1 below. The current work, a phyto-mediated green synthesis strategy, is designed to avoid sol-gel, hydrothermal, and chemical precipitation methods that use toxic organic solvents, synthetic stabilisers, and have energy-intensive mechanisms. Fresh *Aloe vera* leaf extract was used as a multifunctional bio-reagent for the single-pot synthesis of Na- and Mg-doped ZnO nanoparticles. The strong phytochemical profiles of *Aloe vera*, due to the presence of polyphenols, flavonoids, amino acids and polysaccharides, encouraged the *in-situ* chelation of both Zn^{2+} and dopant ions (Na^{2+} and Mg^{2+}), guaranteeing the molecular mixing of these ions in the solution before

the formation of the oxide. This bio-complexation step not only offered the homogeneous loading of the dopant in the ZnO lattice but also reduced the phenomenon of phase segregation and secondary impurity formation during the thermal treatment process.



Scheme-1: Synthetic Scheme for ZnO, Na-ZnO, and Mg-ZnO

Characterization

Elemental Analysis

The synthesised ZnO, Na-ZnO and Mg-ZnO materials were analysed by energy-dispersive X-ray spectroscopy (EDX) and the atomic absorption spectroscopy (AAS) and the data are presented in Table-1. To identify the elemental distribution of the catalyst surface, the EDX analysis was carried out, whereas the precise quantification of the dopant metals was conducted with the help of AAS. The EDX spectrum of pure ZnO confirmed that there was only the Zn and O elements, and this means that pure zinc oxide was formed (Fig.-1). The Zn and O signals revealed in the elemental composition were in line with the ZnO stoichiometry. In the case of the Na-ZnO material, EDX analysis indicated clearly that Na, Zn and O were present, which is a confirmation of the successful introduction of sodium into the ZnO skeleton. The AAS estimation further supported the sodium loading (2.87 wt%), and this indicated that the dopant metal was successfully incorporated during the synthesis process. On the same note, the Mg-ZnO sample had a typical signal of Mg, Zn and O in the EDX spectrum. The AAS results of Mg content (2.91 wt%) supported the EDX results (2.80 wt%) and confirmed that magnesium was successfully incorporated in the material.

Table-1: Elemental Composition of ZnO, Na-ZnO, and Mg-ZnO

Sample	Element	EDX (wt%)	AAS (wt%)
ZnO	Zn	79.62	---
	O	20.38	---
Na-ZnO	Zn	76.84	---
	O	20.21	---
	Na	2.95	2.87
Ma-ZnO	Zn	77.15	---
	O	20.05	---
	Mg	2.80	2.91

Scanning Electron Microscopy (SEM) Analysis

The morphology of the synthesised ZnO, Na-ZnO, and Mg-ZnO nanoparticles was examined with SEM and is shown in Fig.-2(a-c). In the SEM images of the pure ZnO, the structures are aggregated nanoparticles with irregular and quasi-spherical morphology. The particles are moderately agglomerated and have compact clusters made of smaller primary nanocrystallites. The mean size of ZnO particles is estimated to be about 35-55 nm, and the agglomerated cluster sizes are between 150 and 300 nm. With Na-ZnO, SEM images indicate the presence of observable variations in the surface morphology relative to a pure ZnO. The particles look slightly more dispersed, with a comparatively rougher texture on the surface and smaller particle domains. The estimated particle size of the Na-ZnO is estimated to be between 30-50 nm and forms loose aggregates of about 120-250 nm.

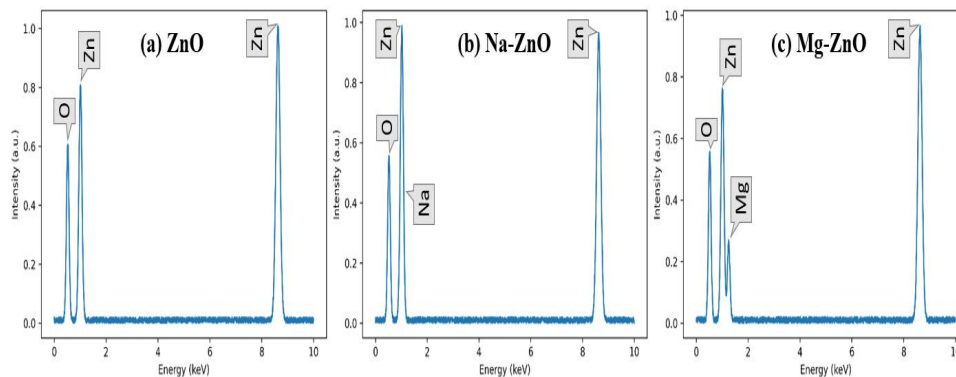


Fig.-1: EDX Spectra of (a) ZnO, (b) Na-ZnO, and (c) Mg-ZnO

The nucleation and growth process of ZnO nanoparticles is probably affected by the presence of Na^+ ions, resulting in a smaller particle size and better dispersion. On the same note, the Mg-ZnO sample has a slightly loosely packed morphology. The particles look like fine nanocrystalline entities that form interrelated clusters having more surface irregularities. The mean size of the particles of Mg-ZnO is estimated to be approximately 25-45 nm and the aggregate structures of these particles are 100-220 nm. The presence of Mg^{2+} ions may prevent the crystal growth and cause lattice distortion, creating smaller particle domains. Thus, the SEM analysis reveals that the addition of Na^+ and Mg^{2+} dopant ions decreases the size of the particles and alters the morphology of the surface of the ZnO nanoparticles. The elemental mapping of the pure ZnO confirmed the homogeneity of the distribution of Zn and O in the entire matrix (Fig.-2(d)). The mapping images taken in the doped samples, viz Na-ZnO and Mg-ZnO (Fig.-2(d)), reveal the uniform distribution of Na and Mg without any apparent segregation or clustering. This uniform dispersion of the dopant elements implies that the elements were readily integrated into the ZnO structure, which is favourable for their catalytic functioning.

Powder X-ray Diffraction (XRD) Pattern

The X-ray diffraction analysis was performed to check the phase and crystallinity of the synthesised pristine ZnO, Na-ZnO, and Mg-ZnO nanoparticles (Fig.-2(e)). The diffraction peaks at $2\theta = 31.82, 34.21, 36.38, 47.62, 56.66, 62.71,$ and 67.93° were labelled as (100), (002), (101), (102), (110), (103), and (112) crystallographic planes, respectively.^{10,11}

Such considerations are very consistent with the conventional hexagonal wurtzite structure of ZnO (space group P6₃mc; JCPDS Card No. 05-0664; $a = b = 3.2494 \text{ \AA}$, $c = 5.2038 \text{ \AA}$), and attest to the successful growth of phase-pure ZnO without any other impurity phases. No other diffraction peaks of Na- or Mg-based oxides appeared, which demonstrated that the dopant ions were successfully embedded into the ZnO lattice as opposed to the presence of segregated phases. After comparing the positions of the peaks carefully, it was found that there were subtle changes in the diffraction maxima of doped samples.

The Mg-ZnO showed a slight tendency towards increasing 2θ values, which was in line with the contraction of the lattice when the Zn^{2+} ($0.74 \text{ \AA}$) ion was replaced by the smaller Mg^{2+} ions ($0.72 \text{ \AA}$). Na-ZnO, on the other hand, exhibited a slight shift towards lower 2θ values, which can be explained by expansion of the lattice due to partial replacement or interstitial substitution of the larger Na^+ ions.

The increase in broadening of the peaks in the doped sample indicates that the crystallites have been reduced in size, and this has put strain on the lattice when the sample is doped. The value of the crystallite size (calculated with the Scherrer equation (applied to the (101) plane)) was found to decrease in the following order: ZnO > Na-ZnO > Mg-ZnO, which implies that the incorporation of the dopant has an effect on nucleation and crystal growth in the course of the phytochemical-mediated synthesis.

UV-Vis Diffuse Reflectance Spectroscopy (DRS) Analysis

The UV-Vis DRS spectroscopy demonstrates that pure ZnO has an absorption edge at approximately 375 nm, which also corresponds to a band gap of approximately 3.2 eV, and Na-ZnO has a slight red shift and smaller band gap ($\sim 3.1 \text{ eV} - 3.15 \text{ eV}$), which suggests the appearance of defect states (Fig.-3(a)).

Conversely, Mg-ZnO shows a marginal blue shift with a substantially broader band gap ($\sim 3.25 - 3.30$ eV), which is due to lattice substitution effects. These optical changes are consistent with XPS O 1s deconvolution data in which there is a greater contribution of oxygen vacancy (O-V) species to doped samples (*vide infra*). The existence of such defect states creates localised quantised states in the band gap, which promotes the transfer of charge and reactivity of surfaces. Here, the concentration of oxygen vacancies is higher in Na-ZnO and Mg-ZnO, which increases surface basicity and facilitates the activation of methanol, resulting in better catalytic performance. Therefore, the joint UV-Vis and XPS analyses make it clear that the introduction of defects by using dopant incorporation is very important in the tuning of the electronic structure and catalytic performance of the materials based on ZnO.

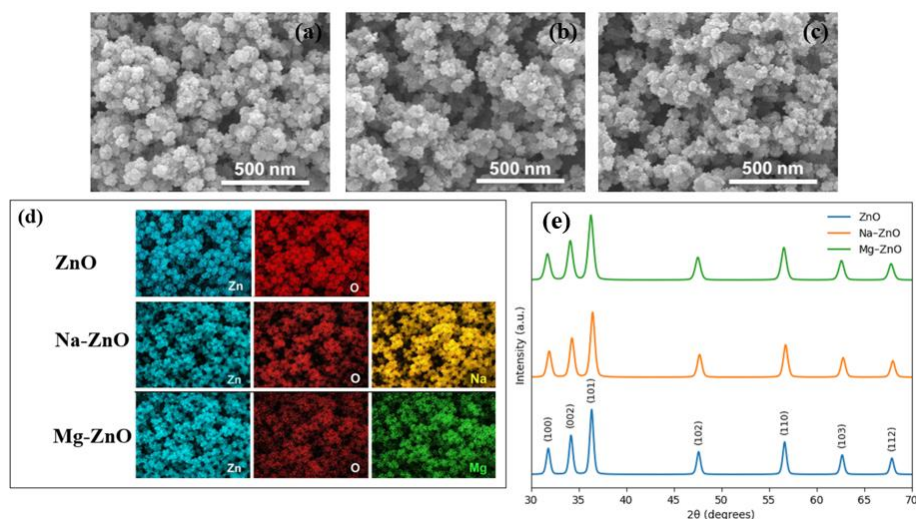


Fig.-2: SEM Images of (a) ZnO, (b) Na-ZnO, (c) Mg-ZnO, (d) Elemental Mapping, and (e) XRD Pattern of Compounds

Fourier Transform Infrared (FTIR) Spectroscopy Analysis

The FTIR spectroscopy was used to analyse the structural characteristics of ZnO, Na-ZnO and Mg-ZnO nanoparticles in the $4000-400\text{ cm}^{-1}$ range of wavelengths to examine the functional groups and the spectra are shown in Fig.-3(b). A broad absorption band at the pristine ZnO can be observed at 3420 cm^{-1} (strong) that is assigned to the stretching vibration of the hydroxyl groups (O-H) on the surface produced by adsorbed water molecules. The bending vibration of the molecularly adsorbed water (H-O-H) is indicated by a weak band at around 1630 cm^{-1} (medium).¹²

The strong absorption band in the $450-500\text{ cm}^{-1}$ region is typical of Zn-O stretching vibration, thus giving evidence of the creation of the ZnO lattice.¹³ In the case of Na-ZnO, similar spectral characteristics was observed, but as a result, small changes in the positions of the bands are evidenced because of the introduction of sodium species. The O-H stretching vibration was observed at 3415 cm^{-1} (strong), and the bending vibration of adsorbed water was appeared at 1628 cm^{-1} (medium). The Zn-O stretch occurs at 468 cm^{-1} (strong). A broad band at 3430 cm^{-1} (strong) and the band at 1635 cm^{-1} (medium) are also observed in the Mg-ZnO sample as evidence of the presence of the O-H stretching vibrations and the bending vibration of the adsorbed water molecules, respectively. Zn-O lattice vibration is present at $\sim 470\text{ cm}^{-1}$ (strong).

The observed slight variation of this band with respect to pure ZnO implies the partial substitution of Mg^{2+} into the ZnO lattice, which can alter the environment of the metal-oxygen bonding. Generally, the FTIR spectra establish that the ZnO structure was formed in all the samples, but the slight variations in the Zn-O vibration bands prove that Na and Mg species were successfully incorporated in the ZnO structure. As the nanoparticles were heated at 450°C for 4 h, the majority of the phytochemical products were destroyed during calcination, and so the FTIR spectra mainly show the bands of surface hydroxyl groups and Zn-O lattice vibrations, which prove the formation of crystalline ZnO materials.

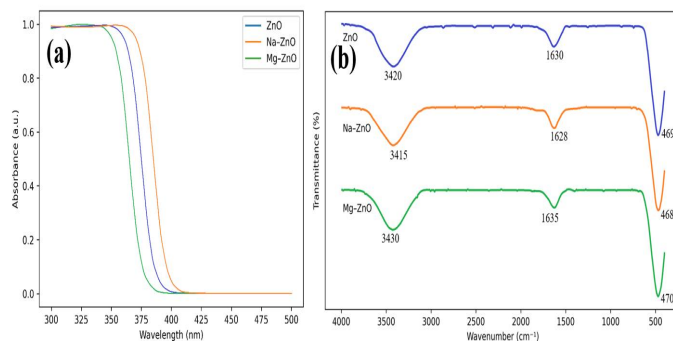


Fig.-3: (a) UV-Vis DRS Spectra and (b) FTIR Spectra of ZnO, Na-ZnO, and Mg-ZnO

X-ray Photoelectron Spectroscopy (XPS) Analysis

The oxidation states and defect structure of the ZnO, Na-ZnO, and Mg-ZnO nanoparticles synthesised were studied using XPS and the high-resolution spectra for Zn, O, Na or Mg are presented in Fig.-4.

Zn 2p Spectrum

The Zn 2p high-resolution spectrum of ZnO shows, in Fig.-4(a), two sharp peaks, which are at 1021.5 eV and 1044.6 eV, respectively, and are associated with Zn 2p_{3/2} and Zn 2p_{1/2}. The spin-orbit splitting between these peaks is around 23.1 eV that is typical of the Zn²⁺ state in ZnO. Na-ZnO and Mg-ZnO also show similar peaks but with very small differences in binding energy, indicating that the addition of Na⁺ and Mg²⁺ does not influence the oxidation state of Zn appreciably but can have a small effect on the local electronic environment of the ZnO lattice.

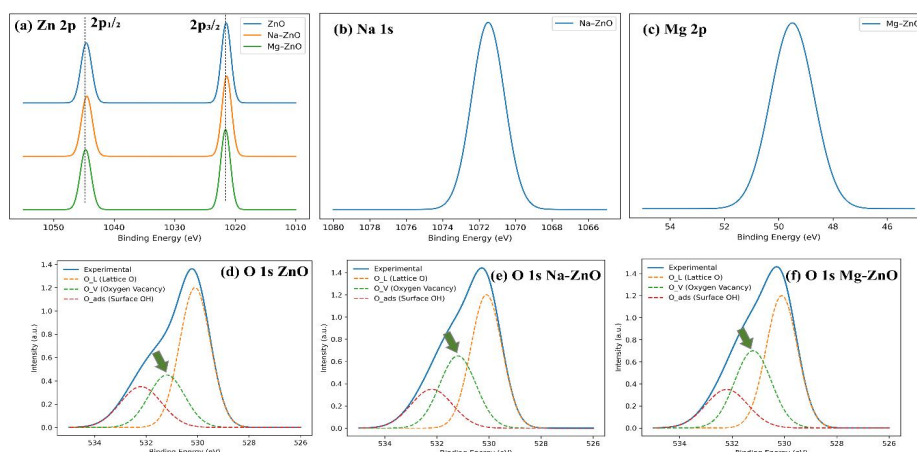


Fig.-4: High-resolution XPS Spectra: (a) Zn 2p Stacked Spectra of ZnO, Na-ZnO, and Mg-ZnO, (b) Na 1s Spectrum of Na-ZnO, (c) Mg 1s Spectrum of Mg-ZnO, (d) O 1s Deconvolution Spectra of ZnO, (e) O 1s Deconvolution Spectra of Na-ZnO, and (f) O 1s Deconvolution Spectra of Mg-ZnO.

O 1s Spectrum

The high-resolution O 1s spectra of the samples, Fig.-4(d-f), were deconvoluted to three components, which depicted the various oxygen species on the surface. The most dominant peak in the spectrum at about 530.1 eV is associated with lattice oxygen (O-L) that is related to the Zn-O bond in the crystal structure of ZnO. The second feature, with a centre at approximately 531.2 eV, is attributed to oxygen vacancy-related species (O-V) that are generated at the sites of defects in the lattice of ZnO. The third peak at the level of around 532.2 eV is attributed to surface-adsorbed oxygen or hydroxyl groups (O-ads) of surface moisture or chemisorbed oxygen species. It was observed that the dopant incorporation into the samples causes a higher relative intensity of the O-V component of the Na-ZnO and Mg-ZnO samples compared with pristine ZnO, to the extent of oxygen vacancies created. This can be explained by the replacement of Zn²⁺ by the Na⁺ or Mg²⁺ ion or the distortion of the structure through the incorporation of dopants. These oxygen vacancies have a significant role in altering the electronic structure and catalytic behaviour of ZnO by increasing the adsorption and activation of reactants.

Na 1s and Mg 2p Spectra

In the case of the Na-ZnO sample, there is a typical Na 1s peak at 1071.5 eV Fig.-4(b), which can be attributed to Na^+ species located on the surface of the oxides, thus indicating that Na^+ was incorporated successfully into the structure of the ZnO. The Na species can be either on the surface as Na^+ or it can be trapped as a partial replacement of the ions in the ZnO lattice, which can adjust the basicity and defect density of the surface of the catalyst. In the Mg-ZnO, there is a clear peak at around 49.5 eV Fig.-4(c), which is associated with Mg 2p, typical of Mg^{2+} species. The appearance of Mg^{2+} implies that Zn^{2+} in the lattice of the ZnO will be partially replaced by Mg^{2+} because of the similarity of their ionic radii; as a result, the lattice distorts, and additional oxygen vacancies form that can increase the catalytic performance of the Mg-ZnO. Therefore, the XPS data prove that the main oxidation state of Zn is +2, and Na and Mg are found in the form of Na^+ and Mg^{2+} , respectively. The higher concentration of oxygen vacancies in the doped ZnO samples shows that incorporation of Na and Mg alters the defect structure of ZnO.

Catalytic Reactivity Towards Biodiesel Production

Catalytic activity of pure ZnO and the alkali/alkaline earth metals modified ZnO nanostructure was analysed in the transesterification reaction of triglycerides with methanol serving as the acyl acceptor. As a source of vegetable oil to be used in transesterification, we used fresh sunflower oil and used cooking sunflower oil. As transesterification is reversible, reaction conditions must be optimised for maximum biodiesel yield. Consequently, Mg-ZnO nanoparticles were used as a catalyst to systematically optimise important reaction parameters like methanol-to-oil molar ratio, catalyst dosage, reaction temperature, and reaction time. After optimisation, the catalytic activity of ZnO, Na-ZnO and Mg-ZnO was evaluated quantitatively under optimal parameters (methanol: oil = 12:1, catalyst loading = 3 wt%, 60 °C, and time = 1- 3 h) by choosing fresh vs. used cooking sunflower oil. The summary of the results is in Table-2.

Table-2: Biodiesel Yield (%) for Different Catalysts and Feedstocks

Catalyst	Fresh Sunflower Oil		Used Cooking Oil	
	Time, h	Yield, %	Time, h	Yield, %
ZnO	3	62	3	48
Na-ZnO	1.5	81	1.5	68
Mg-ZnO	1	96	1	88

The data are clearly indicative of a huge improvement in the catalytic activity when ZnO is incorporated with metals. Pristine ZnO gives the lowest yield (62% in 3 h) for fresh oil; this decreases to 48% for used cooking oil, as there are free fatty acids and impurities. The Na-ZnO showed superior performance, with an 81% yield in 1.5 h for fresh oil and 68% for used oil, which validates the contribution of Na-induced basic sites in the reaction of methoxide formation. Interestingly, Mg-ZnO exhibits the greatest catalytic efficiency, with a yield of 96% in 1 h for fresh sunflower oil and 88% for used cooking oil, meaning not only is it highly active, but also tolerable to impurities in the feedstock. Thus, based on the quantitative data of transesterification, the observed pattern of reactivity $\text{ZnO} < \text{Na-ZnO} < \text{Mg-ZnO}$ and it confirmed the efficiency of Mg integration to improve the catalytic activity and feasibility of ZnO.

CONCLUSION

In summary, ZnO, Na-ZnO, and Mg-ZnO nanocatalysts were prepared successfully using an environmentally friendly synthetic strategy using the extract of *Aloe vera*, with a more focus on defect engineering by the addition of heteroatoms. The extensive physicochemical characterisation established the appearance of nanostructures with a perfect distribution of elements, and XPS analysis confirmed the generation of oxygen vacancies, which were significantly enriched in Na- and Mg-modified ZnO. The catalytic analysis showed that the concentration of oxygen vacancies greatly controls the activity in the production of biodiesel. Of the tested catalysts, Mg-ZnO had the best performance, with biodiesel yields of 96% (fresh oil) and 88% (used oil) in 1 h, respectively, and the order of reactivity was determined as $\text{ZnO} < \text{Na-ZnO} < \text{Mg-ZnO}$. The superior catalytic behaviour is attributed to oxygen vacancy-induced electronic modulation, which enhances surface basicity, promotes adsorption and activation of reactants, and facilitates the transesterification pathway. In general, this work confirms that oxygen vacancy

engineering is an effective approach to tuning the catalytic activity of ZnO-based nanomaterials and offers valuable information for the rational construction of highly efficient catalysts in the production of biodiesel on a sustainable basis, particularly waste-based feedstock.

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CONFLICT OF INTERESTS

The authors declare that there is no conflict of interest.

AUTHOR CONTRIBUTIONS

The present work is related to *SDG-7: Affordable and Clean Energy*. All the authors contributed significantly to this manuscript, participated in reviewing/editing and approved the final draft for publication. The research profiles of the authors can be verified from their ORCID ids, given below:

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REFERENCES

1. C.S. Damian, Y. Devarajan, R. J. T. Raja, *ChemBioEng Reviews*, **12**, 202400055(2025), <https://doi.org/10.1002/cben.202400055>.
2. S. Bhan, S. Kumar, R. Gautam, P.S. Yadav, G.D. Gautam, S. Mahajan, *Environmental Progress & Sustainable Energy*, **44**, e70052(2025), <https://doi.org/10.1002/ep.70052>.
3. B. Bouhental, A. Navid, S. Eckart, *Journal of Thermal Analysis and Calorimetry*, **150**, 18007(2025), <https://doi.org/10.1007/s10973-025-14790-9>.
4. R. Almeida, L. Serrano, D. Silva, H. Santos, J. Pereira, M.G. da Silva, *Energies (Basel)*, **19**, 1382 (2026). <https://doi.org/10.3390/en19051382>.
5. S.O. Oparanti, E.O. Obebe, I. Fofana, R. Jafari, *Applied Sciences*, **15**, 7631(2025), <https://doi.org/10.3390/app15147631>.
6. A.C. Alba-Rubio, J. Santamaría-González, J.M. Mérida-Robles, R. Moreno-Tost, D. Martín-Alonso, A. Jiménez-López, P. Maireles-Torres, *Catalysis Today*, **149**, 281(2010), <https://doi.org/10.1016/j.cattod.2009.06.024>.
7. D.-W. Lee, Y.-M. Park, K.-Y. Lee, *Catalysis Surveys from Asia*, **13**, 63(2009), <https://doi.org/10.1007/s10563-009-9068-6>.
8. J. Zheng, D. Meng, J. Guo, X. Liu, L. Zhou, Z. Wang, *Advanced Materials*, **36**, 2405129(2024), <https://doi.org/10.1002/adma.202405129>.
9. J. Zheng, Z. Wang, *Chem Catalysis*, **4**, 101091(2024), <https://doi.org/10.1016/j.checat.2024.101091>.
10. Y. Zhu, Y. Zhou, *Applied Physics A*, **92**, 275 (2008), <https://doi.org/10.1007/s00339-008-4533-z>.
11. S.S. Ashtaputre, A. Nojima, S.K. Marathe, D. Matsumura, T. Ohta, R. Tiwari, G.K. Dey, S.K. Kulkarni, *Journal of Physics D: Applied Physics*, **41**, 015301(2008), <https://doi.org/10.1088/0022-3727/41/1/015301>.
12. T. Bezrodna, G. Puchkovska, V. Shymanovska, J. Baran, H. Ratajczak, *Journal of Molecular Structure*, **700**, 175(2004), <https://doi.org/10.1016/j.molstruc.2003.12.057>.
13. O. Dobrozhan, A. Opanasyuk, M. Kolesnyk, M. Demydenko, H. Cheong, *Physica Status Solidi (a)*, **212**, 2915(2015), <https://doi.org/10.1002/pssa.201532324>.

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