Research Article

Journal of Environmental Nanotechnology

rGO/PdO Nanocomposites as a Heterogeneous Catalyst for the Oxidative Disproportionation of Benzyl Alcohol

Nandan Singh Karki[1], Manisha Bisht[1*], Ashutosh Pratap Pande[1], Devendra Singh Dhami[2], Rajaram Bal[3], Bhawana Pant[4], Anil Chandra Kothari[4] and Bhagwat Upreti[5]

[1]Department of Chemistry, Moti Ram Babu Ram Government Post Graduate College, Haldwani, UK, India
[2]Department of Chemistry, Soban Singh Jeena University, Almora, UK, India
[3]Light Stock Processing Division, CSIR-Indian Institute of Petroleum, Dehradun, UK, India
[4]Department of Chemistry, Kumaun University, Nainital, UK, India
[5]Chromatography and mass spectrometry, Area and Analytical Science Division, CSIR-Indian Institute of Petroleum, Dehradun, UK, India
Received: 20.08.2025 Accepted: 19.09.2025 Published: 30.09.2025
*manishatanuja@gmail.com

ABSTRACT

This study introduces an innovative approach for the synthesis of a heterogeneous composite catalyst, specifically the reduced graphene oxide/palladium oxide (rGO/PdO) nanocomposite, utilizing a chemical solution method. The synthesis entails the reduction of graphene oxide and palladium chloride ($PdCl_2$) in the presence of sodium borohydride ($NaBH_4$), resulting in the effective immobilization of palladium oxide nanoparticles over the surface of functionalized reduced graphene oxide sheets. The rGO/PdO nanocomposite that comes out of this process has excellent catalytic properties. It is very effective, cheap, reusable, and good for the environment. The oxidative disproportionation of benzyl alcohol was used to test its catalytic performance, and the results were excellent. X-ray diffraction (XRD), Field emission scanning electron microscopy (FESEM), energy-dispersive X-ray spectroscopy (EDX), Fourier-transform infrared spectroscopy (FTIR), and thermogravimetric analysis (TGA) were all used to characterize the synthesized materials fully. GC-MS was used to confirm the catalytic activity further. The results show that the rGO/PdO nanocomposite could be a suitable catalyst for green and long-lasting oxidation processes.

Keywords: rGO/PdO nanocomposite; Heterogeneous catalyst; Disproportionation reaction; Benzyl alcohol.

1. INTRODUCTION

The need for nanotechnology has attracted the focus of researchers in the last few decades to synthesize nanomaterials (Handayani *et al.* 2022; Kumari *et al.* 2020). Graphene and its derivatives, notably graphene oxide (GO) and reduced graphene oxide (rGO), are considered to be excellent materials because graphene and its related carbon nanostructures have exceptional electrical, optical, thermal, mechanical, and chemical capabilities (Balandin *et al.* 2008; Dato *et al.* 2009; Loh *et al.* 2010; Sarkar and Dolui, 2015; Stankovich *et al.* 2006). Among the various allotropic forms of carbon, graphene is a unique allotrope of Carbon obtained from Graphite, distinguished by its inherent properties. It is thus referred to as a "wonder material" (Chakraborty and Hashmi, 2018). In 2004, A. Geim and K. S. Novosel created graphene from 3D graphite, consisting of several layers. They won the Nobel Prize in Physics in 2010 for this work (Geim, 2012; Kumar and Pattammattel, 2017). The graphene discovery was a massive revolution in the research field, due to which A. Geim and K. S. Novoselov stated in their article "The Rise of Graphene," that "Only the very tip of the iceberg has been uncovered so far" (Geim and Novoselov, 2007). Graphene oxide (GO) is the graphene derivative obtained from the graphite powder by using the modified Hummer's method, Torr's method, or Brodie's method (Chen *et al.* 2013; Pedrosa *et al.* 2020; Zaaba *et al.* 2017). The GO bears many oxygen functionalities like epoxy, carboxyl, hydroxyl, and carbonyl groups over the 2D hexagonal graphene surface (Khine *et al.* 2022). When the GO is reduced using various methods, such as chemical, mechanical, thermal, and green approaches, the synthesis of another graphene derivative called rGO occurs, which contains fewer oxygen functionalities than the GO. The π-electron conjugation in GO is partially disrupted by the large number of oxygen functionalities on its surface, rendering it a non-conducting material (Liu *et al.* 2022).

In contrast, the π-electron conjugation in rGO is somewhat restored compared to GO, due to the smaller number of oxygen functionalities present in rGO. From the study of the research society, it was observed that a drastic boost in the value of rGO electrical conductivity occurs when GO is reduced. Because it has a lot of oxygen functionalities, the structures exhibit a hydrophilic nature. However, rGO obtained from GO is

partially hydrophilic because it contains fewer oxygen functionalities than GO. The optical properties as well as electrical conductivity of GO can vary according to the extent of reduction into rGO It is clear from the fact that rGO has a lower optical band gap (0.2–2 eV) than GO (1–3.5 eV)(Merazga *et al.* 2020; Rai *et al.* 2019; Shen *et al.* 2013). Due to large surface area of the graphene and its oxygen containing derivates like GO and rGO they behave as the good matrix to synthesize the composite catalyst by adsorbing the other metal or metal oxide nanoparticle as a catalyst at their surface which makes them novel and superior for various applications like in catalysis, sensors, energy storage, fuel calls and biomedical fields (Aziz *et al.* 2017; de Medeiros *et al.* 2021; Rai *et al.* 2019; Tamang *et al.* 2023; Yoon *et al.* 2015).

Various nanocomposites of rGO/M and rGO/MOX types synthesized in the past few decades exhibited enormous contributions in different fields of science. The CuOxPdOy/rGOc nanocomposite is used for the selective reduction of NO by CO (Nascimento *et al.* 2020). The Pd/rGO nanocomposite exhibited higher hydrogen sorption capacity than Pd nanoparticles (Konda and Chen, 2015). Under ideal conditions, the nitrite content was analyzed using a rGO/PdO modified graphite electrode with a linear range of 10–1500 µM and a limit of detection (3σ) of 10.14 µM(Salagare *et al.* 2022). rGO/Pd/PVP nanocomposite, synthesized by the combination of polyvinylpyrrolidone-stabilized active palladium nanoparticles anchored over the rGO surface, has exceptional catalytic activity during cross-coupling reactions like Heck, Sonogashira, and Suzuki (Elazab and El-Idreesy, 2019). Reduced graphene oxide modified with silver and palladium nanoparticles (Ag/Pd/rGO) was prepared by impregnating Pd and Ag into the rGO platform for electrochemical sensors. Nanocomposite synthesized by anchoring Ag and Pd nanoparticles over the rGO support is used for electrochemical sensors (Leve *et al.* 2024). rGO doped by Pd-PdO behaves as an electrocatalyst for converting nitrate into ammonia (Ebenezer *et al.* 2024). CuxPd1-xO/rGO nanocomposite, synthesized by the accumulation of CuxPd1-xO nanoparticles over the rGO support, behaves as an efficient catalyst for direct C-H bond activation by using alcohol as a carbonyl source (Hu *et al.* 2023). Many rGO/Metal nanocomposite and carbon supported metal nanocomposite were previously used as catalyst for the conversion of benzyl alcohol into benzaldehyde, toluene and benzyl benzoate (Altaee *et al.* 2020; Altaee and Alshamsi, 2020; Sanaa Tareq *et al.* 2018; Tareq *et al.* 2018). but the yield were found very low due to which rGO/PdO was proposed as catalyst for the curiosity of increasing the yield of product because PdO nanoparticles will supposed to enhance the anchoring ability with rGO solid support by which catalytic efficiency would be increased. Based on the literature referenced above, we synthesized rGO/PdO nanocomposites using an in-situ chemical solution method for the Oxidative disproportionation of ethylbenzene, The synergetic interaction between rGO and PdO enhance surface area by supporting tendency of rGO for high PdO loading without compromising dispersion with improved adsorption and stability of PdO as rGO prevents aglomeriation of PdO nanoparticles and create additional active sites along with improve adsorption ability which reflects in the form of better catalytic performance of composite as well as strong ability to adsorb the substrate and for treating as a good heterogeneous catalyst to achieving a good yield compared to previous research in this area . The incorporation of reduced graphene oxide (rGO) is proposed to improve the electron transfer dynamics of PdO nanoparticles by facilitating an efficient medium for redox processes. Consequently, the composite material typically exhibits enhanced catalytic activity, improved selectivity, greater stability, and higher product yield compared to its individual constituents.

2. MATERIALS AND METHODS

Graphite, Conc. Sulphuric acid (H_2SO_4), Potassium permanganate ($KMnO_4$),, Hydrochloric acid (HCl), 30% Hydrogen peroxide (H_2O_2), acetonitrile (ACN), $PdCl_2$, Hydrazine mono hydrate ($NH_2NH_2.H_2O$) are purchased from LobaChemie Pvt. Ltd.

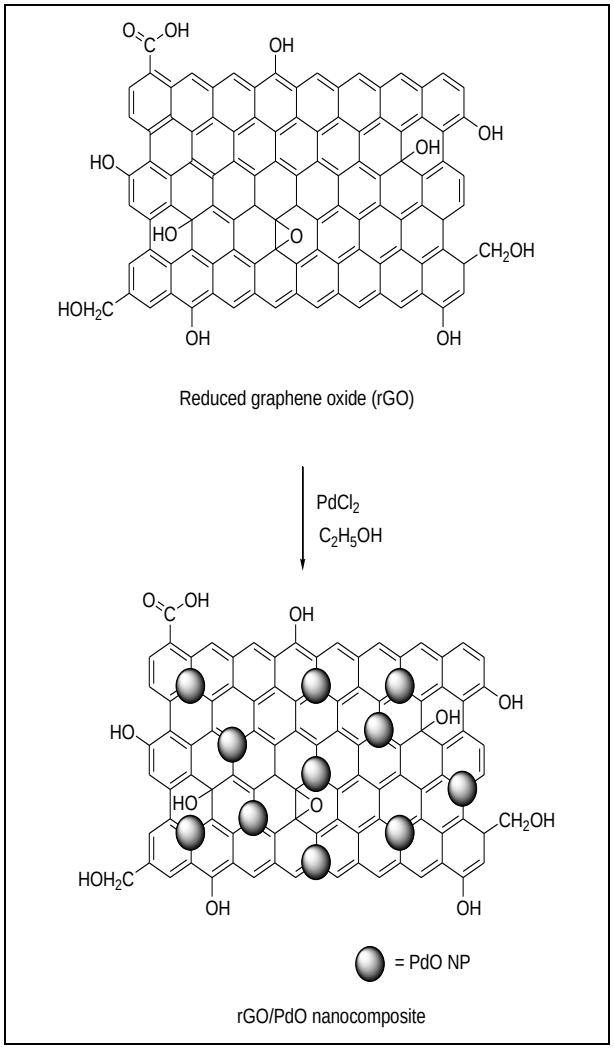
2.1 Synthesis of rGO from Graphite

The Modified Hummers' technique turns Graphite into GO. In this process, 5 g of Graphite was put in a container, and 7.5 mL of concentrated H_2SO_4 was steadily added while keeping the temperature between 0 and 5 ºC. After that, 15 g of $KMnO_4$ was gently added to the reaction mix. For two hours, the mixture was stirred constantly at 5±1 ºC. After that, the reaction mixture was stirred for another half hour until it reached room temperature. Also, the reaction temperature was raised to 98°C by adding 200 mL of deionized water and stirring the reaction mixture constantly for the following 45 minutes. The reaction mixture gave 140 mL of deionised water and 20 mL of 30% H_2O_2, which caused GO to form (a yellow-brown precipitate). The latter was separated using vacuum filtering and rinsed with 100 cc of 5% aqueous HCl. After that, the solid was subsequently dried at 60 oC in a vacuum oven (Chen *et al.* 2013; Karki *et al.* 2023).

Synthesis of rGO from the prepared GO was done by the reduction process using hydrazine hydrate ($N_2H_4 \cdot H_2O$) as reducing agent. For this purpose, GO suspension was first prepared by dissolving 250 mg GO powder in 300 mL of deionized water. Subsequently, 100 µL of $N_2H_4 \cdot H_2O$ was added to the GO suspension, and the resulting solution was stirred for 12 hours. Finally, coloured rGO was obtained. This black-coloured rGO was washed with deionised water and dried at 60 °C (Park *et al.* 2011).

2.2 Synthesis of rGO/PdO Nanocomposite Structure

rGO/PdO nanocomposites are synthesized using the in situ chemical solution method. 30 mL of rGO and ethanol (1µg/mL) are used to dissolve $PdCl_2$ so that their respective molar ratios stay at 1:1. The solution is constantly stirred for one hour to ensure uniform mixing. As an ageing procedure, the final solution is left undisturbed for a full day. The solution is heated to 80 °C for the whole day to extract the dark powder. Several times, DI water is used to wash and filter the powder. A black powder known as rGO/PdO nanocomposite is then produced by annealing the filtered powder at 600ºC to eliminate organic and chloride ion contaminants (Arora *et al.* 2019).



Scheme 1. rGO/PdO nanocomposite synthesis

2.3 Material Characterization

Several analytical approaches are used to characterise the rGO/PdO nanocomposite that was created using the chemical solution process. An Alpha-Bruker FTIR spectrometer is used for FTIR spectral analysis. The produced catalyst's XRD pattern was analysed using the Bruker AXS D8Advance A25-X1-1A2Z2C4B0. An FE-SEM instrument, model JSM-7610F-Plus FESEM, and a DII-29030SCRT Au Sputter Coater are used to analyze composite morphology. Gold is applied to the samples before examination. One analysis method for determining a compound's thermal stability is thermogravimetric analysis (TGA). The Perkin-Elmer thermal analyser is the tool utilised for the current research. The heating rate is 10°C per minute, and the temperature range in nitrogen flow is 75–580 °C. The produced materials' absorption maxima are found using UV-visible spectroscopy. A Shimadzu UV-1900i spectrometer with a wavelength range of 200–800 nm was the tool used for the analysis.

3. RESULT AND DISCUSSION

During this nanocomposite synthesis, the requisite rGO/PdO nanocomposite is prepared by the in situ synthesis and deposition of PdO nanoparticles over the surface of rGO according to the following general representation.

3.1 Analysis of Synthesized rGO/PdO Nanocomposite

3.1.1 X-ray Diffraction Analysis

The phase identification and structural properties of the synthesized rGO/PdO nanocomposite were characterized with Powder X-ray Diffraction (PXRD) in a 2θ range of 10° to 80°, which is presented in Fig. 1. The XRD pattern shows clear diffraction peaks that give information about the various components of the nanocomposite. A typical diffraction peak detected at 2θ=11 is related to the [001] plane of graphene oxide (GO) and usually is indicative of the presence of oxygen-containing functional groups and verifies successful oxidation of Graphite to GO, consistent with previous research (Dat *et al.* 2020; Chen *et al.* 2024; Mangalam *et al.* 2019).In addition, a peak at 2θ = 23.81 belongs to the [002] plane of the reduced graphene oxide (rGO), reflecting the graphitic structure renewal during the reduction process. An intense but broad peak at 2θ = 43.12 with overlapping contributions from the GO and rGO phases also validates the simultaneous existence and structural conversion during synthesis (Chen *et al.* 2024). More importantly,theXRD pattern of the rGO/PdO nanocomposite shows sharp peaks at 2θ = 27.04°, 33.57°, 42.27°, 47.05°, 61.17°, and 73.08°, which are assigned to the crystal planes (100), (101), (110), (111), (103), (200), and (202), respectively (Arora *et al.* 2019; Chen *et al.* 2024). These peaks agree with typical palladium oxide (PdO) patterns, thus confirming the successful synthesis and crystalline structure of PdO nanoparticles integrated in the rGO matrix. The overall diffraction pattern attests to the successful synthesis of the rGO/PdO

nanocomposite. PdO nanoparticles are evenly distributed over the reduced graphene oxide sheets to support the hybrid material's improved crystallinity and possible catalytic activity. From the above discussion it is clearly stablished that all the peaks of XRD spectra of GO and rGO/PdO nanocomposite (Fig. 1) matching with the data of previous literature which confirm the successful synthesis of composite.

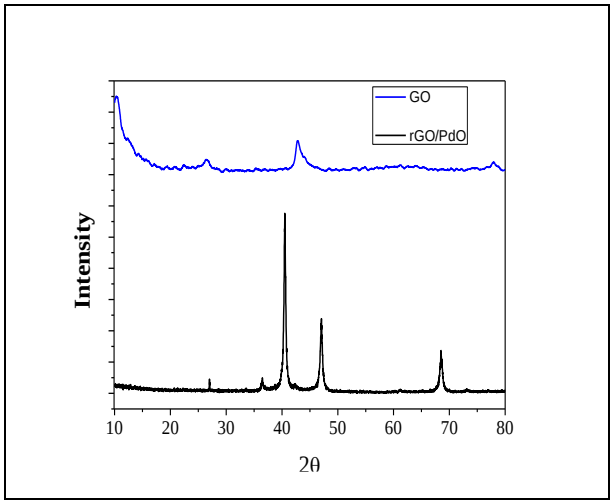


Fig. 1: XRD pattern of GO and rGO/PdO nanocomposite

3.1.2 SEM Interpretation

The SEM images of powdered rGO/PdO are visualized in Fig. 2 (X, Y, Z). The images have a low resolution (1µm) and a magnification of 10 to 25 KX of the surface of the thin film of rGO/PdO nanocomposite. The images show stacked nanosheets of rGO that are randomly mixed and uniformly aggregated on the sample's surface as dark areas. Nonetheless, the mass of PdO nanoparticles within rGO nanosheets is indicated by the bright clusters of blotches in the photos. The wrinkled rGO nanosheets are folded at the edges and uniformly distributed next to the sample's surface, adding a significant amount of surface area to the PdO nanoparticle clusters when the high resolution is increased to 300 nm to 45.00 KX pictures (Jose *et al.* 2021; Rana *et al.* 2019). These SEM images confirm that PdO nanoparticles are evenly distributed by adsorption on the surface of rGO, which will be facile for good catalytic and others applications of the nanocomposite.

The elemental composition of synthesised rGO/PdO nanocomposites was examined using EDX spectroscopy. Palladium (PdO) has been successfully deposited on the surface of reduced graphene oxide (rGO) according to the EDX spectrum of the rGO/PdO nanocomposite (Fig. 3) (Jose *et al.* 2021). The result of EDX may be justified by the fact that due to the polar nature of PdO its deposition on to the rGO surface through ionic or covalent interactions is found high which will provide good catalytic activity.

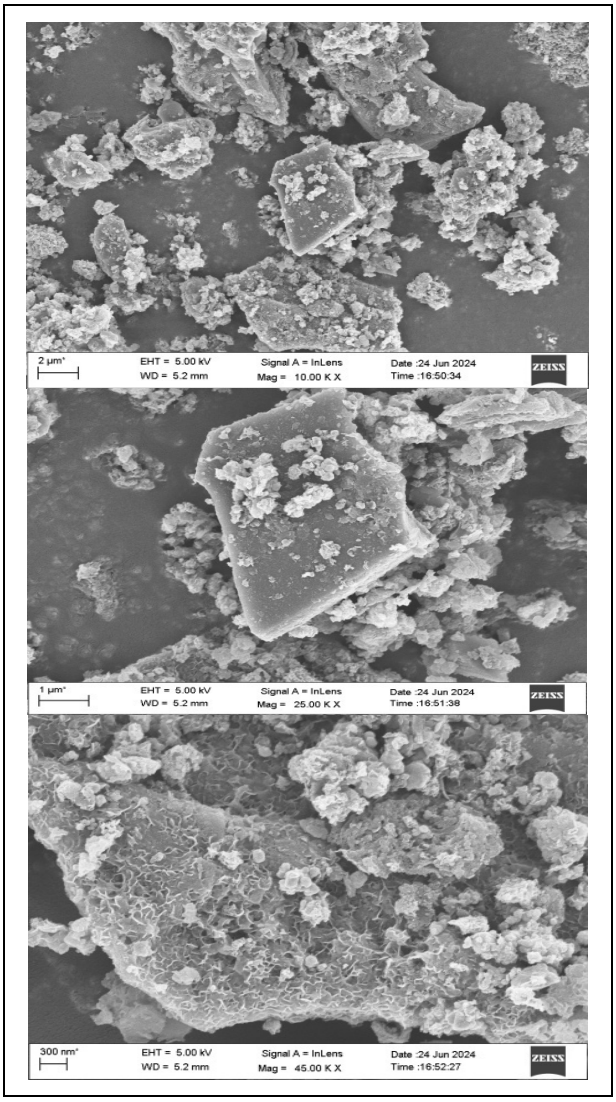


Fig. 2: SEM interpretation to show adsorption of PdO on the surface of reduced graphene oxide

3.1.3 EDX Interpretation

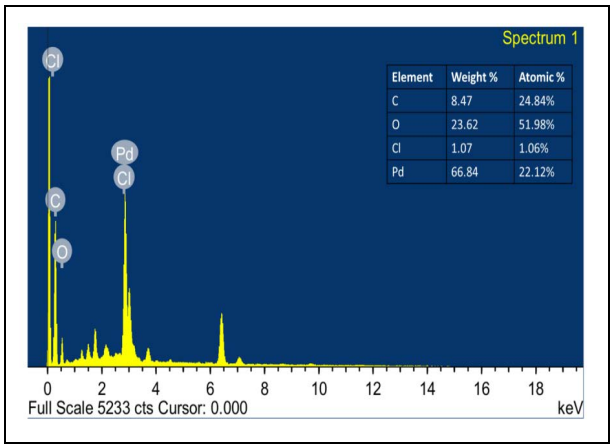


Fig. 3: EDX data to show successful rGO/PdO nanocomposite synthesis

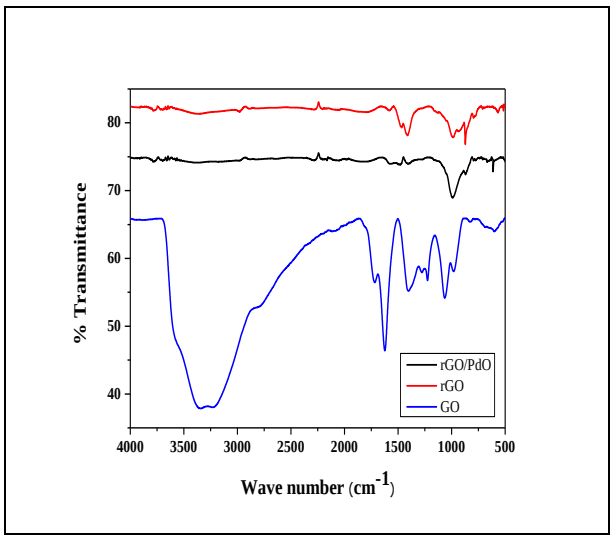


Fig. 4: FTIR spectrum of GO, rGO, and rGO/PdO nanocomposite

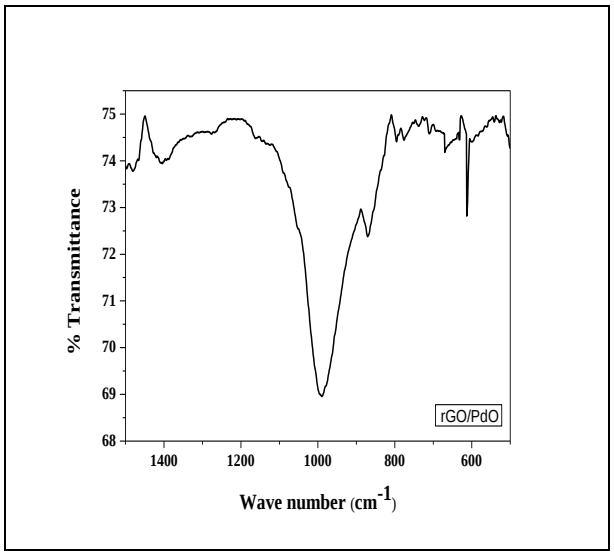


Fig. 5: Magnify FTIR spectrum of rGO/PdO nanocomposite (from 1500 cm^{-1} to 500 cm^{-1})

3.1.4 FTIR Interpretation

The functional groups in the synthesised graphene oxide (GO) and the rGO/PdO nanocomposite were identified using Fourier-transform infrared (FTIR) spectroscopy. The stretching vibrations of the O–H group, the C=O group of carboxylic acids, the tertiary C–OH group, the C–C group, and the C–O group, respectively, were represented by the distinctive peaks in the FTIR spectrum of GO at 3349 cm-1, 1716 cm-1, 1401 cm^{-1}, 1225 cm^{-1}, and 1063 cm^{-1} (S.-Q. Liu *et al.* 2013; Verma *et al.* 2023). Partial reduction of the oxygen-bearing functional groups during the conversion of GO to rGO is indicated by the sharp decline in peak intensities upon synthesis of the rGO/PdO nanocomposite, with certain peaks completely disappearing (Fig. 4). Interestingly, the O-H group's stretching vibration peak moved to a higher wavelength. At 3514 cm^{-1}, it showed up as a weaker peak. Furthermore, the successful synthesis of the rGO/PdO nanocomposite is confirmed by the appearance of peaks at 613 cm^{-1} and 670 cm^{-1}, which correspond to the Pd–O and Pd–C bonds, respectively (Fig. 5). (Arora *et al.* 2019). Further all these observed frequencies in FTIR spectra (Fig. 4 and 5) confirm the successful synthesis of rGO / PdO nanocomposite.

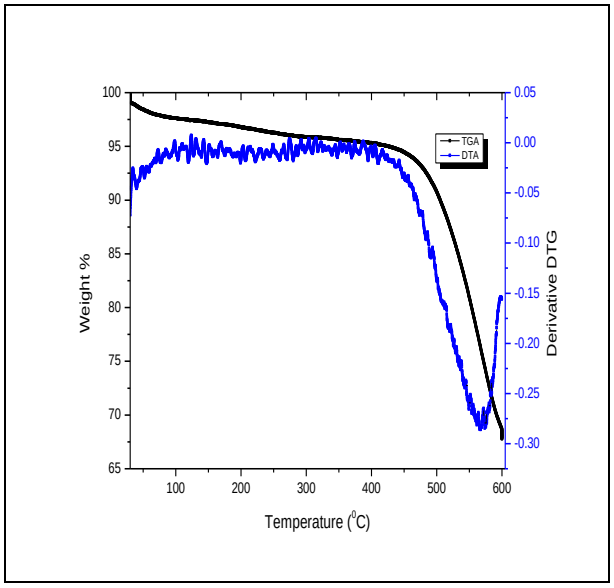


Fig. 6: DTA and TGA spectra to show the stability of rGO/PdO

3.1.5 DTA and TGA Interpretation

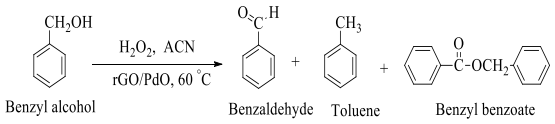
The thermal stability of the synthesised rGO/PdO nanocomposite was assessed by thermogravimetric analysis (TGA). The evaporation of moisture and residual water content is responsible for the slight mass loss of around 3.22% below 200 °C, according to the TGA results in Fig. 6. Oxygen-containing functional groups decompose with a mass loss of about 6% in the 200–500 °C temperature range. Further mass loss results from the pyrolysis of the carbon structure over 500 °C. The rGO/PdO nanocomposite shows a substantially lower mass loss than graphene oxide (GO), according to the TGA measurements, suggesting that it has better heat stability than GO. DTA was used as an additional method to confirm the synthesis of the rGO/PdO nanocomposite. It is quite evident from the above discussion that the synthesized rGO / PdO nanocomposite having good thermal stability.

3.2 Catalytic Activity of rGO/PdO Nanocomposite

3.2.1 Disproportionation of Benzyl Alcohol

The oxidation of benzyl alcohol, catalysed by a rGO/PdO nanocomposite using aqueous 30% H_2O_2 as the oxidant, yielded three oxidation products: benzaldehyde,

toluene, and benzyl benzoate. Others have also found these products (Altaee *et al.* 2020; Altaee and Alshamsi, 2020; Sanaa Tareq *et al.* 2018; Tareq *et al.* 2018).



Scheme 2. Disproportionation of benzyl alcohol catalysed by rGO/PdO nanocomposite at 60 °C

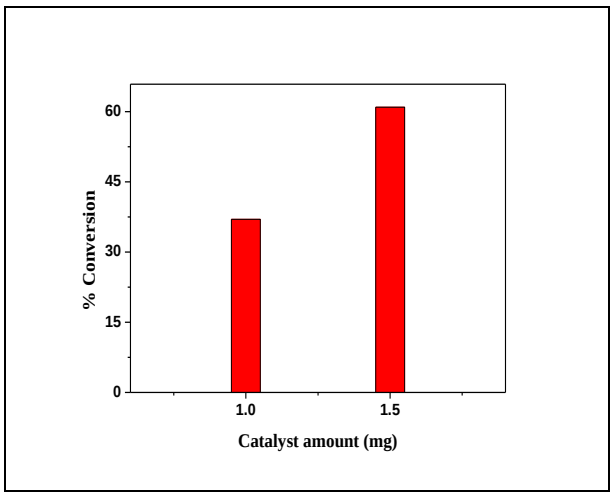


Fig. 7: Effect of catalyst amount on reduction of benzyl alcohol. Reaction condition: 20 µL of benzyl alcohol, 10 µL of hydrogen peroxide, 10 mL of acetonitrile (ACN) at 60 °C

To determine the catalytic activity of the synthesized rGO/PdO nanocomposite, 20 µL of benzyl alcohol was dissolved in 10 mL of acetonitrile (ACN) and added to two individual round-bottom flasks with 0.0010 g and 0.0015 g of the rGO/PdO catalyst, respectively. Afterwards, 10 µL of hydrogen peroxide (H_2O_2) was added to both flasks as an oxidant. Reaction vessels were equipped with reflux condensers and heated on a heating mantle at 60 °C for 30 minutes.

Under such reaction conditions, catalytic oxidation of benzyl alcohol was noted. The efficiency of benzyl alcohol conversion was found to be a function of the catalyst loading: 0.0015 g of the rGO/PdO nanocomposite provided a greater benzyl alcohol conversion of 61%. In comparison, 0.0010 g gave a relatively lower conversion of 37% (entry 1-2, Table 1). These findings reflect that greater amount of the catalyst increase the catalytic activity, presumably owing to the enhanced accessibility of active sites (Fig.7). The selectivity of reaction products has been analyzed as a function of catalytic amount is presented as bar diagram (Fig.8). Table 2 represents the selectivity variation of the various products with the variation of catalytic amount of the rGO/PdO nanocomposite catalyst.

Table 1. Conversion of benzyl alcohol (20µL) using different amounts of rGO/PdO nanocomposite as a catalyst, 10 µL of hydrogen peroxide, and 10 mL of acetonitrile for 30 minutes

Entry No.	Catalyst (g)	Temperature (°C)	Conversion%
1	0.0010	60	37
2	0.0015	60	61
3 1st recyclic	0.0015	60	58
4 2nd recyclic	0.0015	60	55

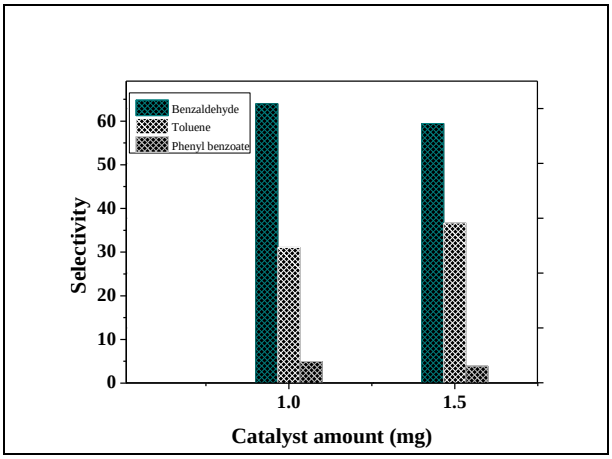


Fig. 8: Bar diagram showing the percentage selectivity of product formation with catalytic amounts

Table 2. Effect of catalytic amount on the conversion and selectivity of the product formed during the oxidation of benzyl alcohol

Entry No.	Catalyst (g)	Temperature (°C)	Time (min)	Conversion (%)	Selectivity		
					Benzaldehyde	Toluene	Benzyl Benzoate
1	0.0010	60	30	37	64	31.08	4.92
2	0.0015	60	30	61	59.44	36.68	3.88

Reaction conditions: 0.0010/0.0015 g catalyst, 60 °C reaction temperature, 30% H_2O_2 concentration, and 30-minute reaction time.

3.3 Test for Recyclability and Heterogeneity of the Reaction

The recyclability of the rGO/PdO nanocomposite catalyst was tested in the oxidation of benzyl alcohol. The catalyst was recovered after each catalytic cycle by filtration from the reaction mixture, washed several times with acetonitrile, and then dried at 120 °C. In the reaction conditions reported in Table 1,

Entry 2, the catalyst demonstrated 58% conversion during the first cycle and 55% conversion during the second cycle, demonstrating good reusability without loss in catalytic activity.

The heterogeneous character of the rGO/PdO nanocomposite catalyst can be confirmed through a hot filtration test. The reaction was terminated after 15 minutes, and the catalyst was separated by filtration. The resulting filtrate was left to further react for another 15 minutes under the same conditions. Gas chromatographic determination showed no additional benzyl alcohol conversion, thus ensuring that the catalytic activity was stopped once the catalyst had been removed. This finding validates the conclusion that the rGO/PdOnanocomposite acts as a bona fide heterogeneous catalyst.

4. CONCLUSION

This paper outlines the synthesis, characterization, and application of rGO/PdO nanocomposites for the catalytic oxidative disproportionation of benzyl alcohol. The PdO nanoparticles were synthesised in situ and affixed to surface-functionalized rGO sheets, yielding a nanocomposite with notable catalytic capabilities. The rGO/PdO nanocomposite serves as an effective and selective oxidative catalyst, facilitating partial oxidation instead of complete oxidation or side reactions. In this catalytic oxidation, the oxidant H_2O_2 functions as a moderate, environmentally friendly oxidant that, under catalytic circumstances, selectively oxidises the alcoholic group to an aldehyde without overoxidation to a carboxylic acid or esterification. Moreover, the catalyst exhibited remarkable recyclability and heterogeneous characteristics, underscoring its promise as a sustainable and economical material within the context of green chemistry. Due to the principle of atom economics, a substantial yield of the primary product was achieved through this procedure.

ACKNOWLEDGMENT

We are thankful to the Indian Institute of Petroleum, Dehradun, Uttarakhand, India, for providing infrastructure and facilities. The authors also wish to appreciate the North East Institute of Science & Technology, Jorhat, Assam, India, for providing some facilities to conduct this work successfully.

FUNDING

This research received no specific grant from any funding agency in the public, commercial, or not-for-profit sectors.

CONFLICTS OF INTEREST

The authors declare that there is no conflict of interest.

COPYRIGHT

This article is an open-access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (http://creativecommons.org/licenses/by/4.0/)



REFERENCES

Altaee, H. and Alshamsi, H. A., Selective oxidation of benzyl alcohol by reduced graphene oxide supported platinum nanoparticles, *J. Phys. Conf. Ser.*, 1664(1), 012074(2020a). https://doi.org/10.1088/1742-6596/1664/1/012074

Altaee, H., Alshamsi, H. A. H. and Joda, B. A., Reduced graphene oxide supported palladium nanoparticles as an efficient catalyst for aerobic oxidation of benzyl alcohol, *AIP Conf. Proc.*, 2290, 030036(2020b). https://doi.org/10.1063/5.0027427

Arora, K., Srivastava, S., Solanki, P. R. and Puri, N. K., Electrochemical Hydrogen Gas Sensing Employing Palladium Oxide/Reduced Graphene Oxide (PdO-rGO) Nanocomposites, *IEEE Sensors J.*, 19(18), 8262–8271 (2019a). https://doi.org/10.1109/JSEN.2019.2918360

Aziz, N. S. A., Azmi, M. K. N. and Hashim, A. M., One-Pot Green Synthesis of Highly Reduced Graphene Oxide Decorated with Silver Nanoparticles, *Sains Malaysiana*, 46(7), 1083–1088(2017). https://doi.org/10.17576/jsm-2017-4607-10

Balandin, A. A., Ghosh, S., Bao, W., Calizo, I., Teweldebrhan, D., Miao, F. and Lau, C. N., Superior Thermal Conductivity of Single-Layer Graphene, *Nano Lett.*, 8(3), 902–907(2008). https://doi.org/10.1021/nl0731872

Chakraborty, M. and Hashmi, M. S. J., Wonder material graphene: properties, synthesis and practical applications, *Adv. Mater. Proc. Technol.*, 4(4), 573–602(2018). https://doi.org/10.1080/2374068X.2018.1484998

Chen, J., Yao, B., Li, C. and Shi, G., An improved Hummers method for eco-friendly synthesi's of graphene oxide, *Carbon.*, 64, 225–229(2013). https://doi.org/10.1016/j.carbon.2013.07.055

Chen, L., Xhang, Z. and Hu, T., A graphene oxide-modified biosensor for non-invasive glucose monitoring in college athletes, *Alexandria Eng. J.*, 95, 321–332(2024). https://doi.org/10.1016/j.aej.2024.03.051

Dat, N. M., Long, P. N. B., Nhi, D. C. U., Minh, N. N., Duy, L. M., Quan, L. N., Nam, H. M., Phong, M. T. and Hieu, N. H., Synthesis of silver/reduced graphene oxide for antibacterial activity and catalytic reduction of organic dyes, *Synth. Met.*, 260, 116260(2020). https://doi.org/10.1016/j.synthmet.2019.116260

Dato, A., Lee, Z., Jeon, K. J., Erni, R., Radmilovic, V., Richardson, T. J. and Frenklach, M., Clean and highly ordered graphene synthesized in the gas phase, *Chem. Commun.*, 40, 6095(2009). https://doi.org/10.1039/b911395a

Ebenezer, J., Lal, A., Velayudham, P., Borenstein, A. and Schechter, A., Laser-Induced Pd-PdO/rGO Catalysts for Enhanced Electrocatalytic Conversion of Nitrate into Ammonia, *ACS Appl. Mater. Interf.*, 16(28), 36433–36443(2024). https://doi.org/10.1021/acsami.4c06378

Elazab, H. A. and El-Idreesy, T. T., Polyvinylpyrrolidone - Reduced Graphene Oxide - Pd Nanoparticles as an Efficient Nanocomposite for Catalysis Applications in Cross-Coupling Reactions, *Bull. Chem. React. Eng. Catal.*, 14(3), 490–501(2019). https://doi.org/10.9767/bcrec.14.3.3461.490-501

Geim, A. K., Graphene prehistory, *Physica Scr.*, T146, 014003(2012). https://doi.org/10.1088/0031-8949/2012/T146/014003

Geim, A., Novoselov, K. The rise of graphene. *Nature Materials* 6, 183–191 (2007). https://doi.org/10.1038/nmat1849

Handayani, M., Suwaji, B. I., Ihsantia Ning Asih, G., Kusumaningsih, T., Kusumastuti, Y., Rochmadi., and Anshori, I., In-situ synthesis of reduced graphene oxide/silver nanoparticles (rGO/AgNPs) nanocomposites for high loading capacity of acetylsalicylic acid, *Nanocomposites*, 8(1), 74–80(2022). https://doi.org/10.1080/20550324.2022.2054210

Hu, Q., Gao, L., Lu, W. and Chen, Y., CuxPd1-xO nanoparticle-reduced graphene oxide nanocomposite catalyzed direct ortho-C–H acylation of 2-aryl pyridines, *Catal. Commun.*, 174, 106591(2023). https://doi.org/10.1016/j.catcom.2022.106591

Jose, J., Jose, S. P., Prasankumar, T., Shaji, S., Pillai, S. and B, S. P., Emerging ternary nanocomposite of rGO draped palladium oxide/polypyrrole for high-performance supercapacitors, *J. Alloys Compd.*, 855, 157481(2021). https://doi.org/10.1016/j.jallcom.2020.157481

Karki, N. S., Bisht, M., Sharma, A., Mudila, H., & Pal, M. K., Performance of rGO/V2O5 as a heterogeneous catalyst for oxidation of methyl phenyl sulfide, *Bulg. Chem. Commun.*, 55, 257–260(2023). https://doi.org/10.34049/bcc.55.A.0039

Khine, Y. Y., Wen, X., Jin, X., Foller, T. and Joshi, R., Functional groups in graphene oxide, *Phys. Chem. Chem. Phys.*, 24(43), 26337–26355(2022). https://doi.org/10.1039/D2CP04082D

Konda, S. K. and Chen, A., One-step synthesis of Pd and reduced graphene oxide nanocomposites for enhanced hydrogen sorption and storage, *Electrochem. Commun.*, 60, 148–152(2015). https://doi.org/10.1016/j.elecom.2015.08.023

Kumar, C. V. and Pattammattel, A., Discovery of graphene and beyond, Introduction to Graphene, *Elsevier Inc.*, 1–15(2017). https://doi.org/10.1016/B978-0-12-813182-4.00001-5

Kumari, S., Sharma, P., Yadav, S., Kumar, J., Vij, A., Rawat, P., Kumar, S., Sinha, C., Bhattacharya, J., Srivastava, C. M. and Majumder, S., A Novel Synthesis of the Graphene Oxide-Silver (GO-Ag) Nanocomposite for Unique Physiochemical Applications, *ACS Omega.*, 5(10), 5041–5047(2020). https://doi.org/10.1021/acsomega.9b03976

Leve, Z., Ross, N., Pokpas, K., Carleschi, E., Doyle, B. P., Sanga, N. A., Mokwebo, K. V. and Iwuoha, E. , Synthesis and Characterization of Palladium/Silver Modified Reduced Graphene Oxide–Nanocomposite Platform for Electrochemical Sensors, *ChemistrySelect*, 9(17), e202400606(2024). https://doi.org/10.1002/slct.202400606

Liu, J., Chen, S., Liu, Y. and Zhao, B., Progress in preparation, characterization, surface functional modification of graphene oxide: A review, *J. Saudi Chem. Soc.*, 26(6), 101560(2022). https://doi.org/10.1016/j.jscs.2022.101560

Liu, S. Q., Xiao, B., Feng, L. R., Zhou, S. S., Chen, Z. G., Liu, C. B., Chen, F., Wu, Z. Y., Xu, N., Oh, W. C. and Meng, Z. D., Graphene oxide enhances the Fenton-like photocatalytic activity of nickel ferrite for degradation of dyes under visible light irradiation, *Carbon*, 64, 197–206(2013). https://doi.org/10.1016/j.carbon.2013.07.052

Loh, K. P., Bao, Q., Eda, G. and Chhowalla, M., Graphene oxide as a chemically tunable platform for optical applications, *Nat. Chem.*, 2(12), 1015–1024(2010). https://doi.org/10.1038/nchem.907

Mangalam, J., Kumar, M., Sharma, M., and Joshi, M., High adsorptivity and visible light-assisted photocatalytic activity of silver/reduced graphene oxide (Ag/rGO) nanocomposite for wastewater treatment, *Nano-Struct. Nano-Objects*, 17, 58–66 (2019). https://doi.org/10.1016/j.nanoso.2018.11.003

Medeiros, A. M. Z. D., Khan, L. U., da Silva, G. H., Ospina, C. A., Alves, O. L., Castro, V. L. D., and Martinez, D. S. T. Graphene oxide-silver nanoparticle hybrid material: an integrated nanosafety study in zebrafish embryos, *Ecotoxicol. Environ. Saf.*, 209, 111776(2021). https://doi.org/10.1016/j.ecoenv.2020.111776

Merazga, A., Al-Zahrani, J., Al-Baradi, A., Omer, B., Badawi, A. and Al-Omairy, S., Optical band-gap of reduced graphene oxide/TiO2 composite and performance of associated dye-sensitized solar cells, *Mater. Sci. Eng. B*, 259, 114581(2020). https://doi.org/10.1016/j.mseb.2020.114581

Nascimento, J. R. D., D'Oliveira, M. R., Veiga, A. G., Chagas, C. A. and Schmal, M., Synthesis of Reduced Graphene Oxide as a Support for Nano Copper and Palladium/Copper Catalysts for Selective NO Reduction by CO, *ACS Omega*., 5(40), 25568–25581(2020). https://doi.org/10.1021/acsomega.0c02417

Park, S., An, J., Potts, J. R., Velamakanni, A., Murali, S. and Ruoff, R. S., Hydrazine-reduction of Graphite- and graphene oxide, Carbon, 49(9), 3019–3023(2011). https://doi.org/10.1016/j.carbon.2011.02.071

Pedrosa, M., Silva, E. S. D., Pastrana-Martínez, L. M., Drazic, G., Falaras, P., Faria, J. L., Figueiredo, J. L., & Silva, A. M. T., Hummers' and Brodie's graphene oxides as photocatalysts for phenol degradation, *J. Colloid Interface Sci.*, 567, 243–255(2020). https://doi.org/10.1016/j.jcis.2020.01.093

Rai, S., Bhujel, R., Biswas, J. and Swain, B. P., Effect of electrolyte on the supercapacitive behaviour of copper oxide/reduced graphene oxide nanocomposite, *Ceram. Int.*, 45(11), 14136–14145(2019). https://doi.org/10.1016/j.ceramint.2019.04.114

Rana, S., Varadwaj, G. B. B. and Jonnalagadda, S. B., Pd nanoparticle supported reduced graphene oxide and its excellent catalytic activity for the Ullmann C–C coupling reaction in a green solvent, *RSC Adv.*, 9(23), 13332–13335(2019). https://doi.org/10.1039/C9RA01715A

Salagare, S., Adarakatti, P. S., Venkataramanappa, Y. and Almalki, A. S. A., Electrochemical nitrite sensing employing palladium oxide–reduced graphene oxide (PdO-RGO) nanocomposites: application to food and environmental samples, *Ionics*, 28(2), 927–938(2022). https://doi.org/10.1007/s11581-021-04355-9

Sarkar, C. and Dolui, S. K., Synthesis of copper oxide/reduced graphene oxide nanocomposite and its enhanced catalytic activity towards reduction of 4-nitrophenol, *RSC Adv.*, 5(75), 60763–60769(2015). https://doi.org/10.1039/C5RA10551J

Shen, Y., Yang, S., Zhou, P., Sun, Q., Wang, P., Wan, L., Li, J., Chen, L., Wang, X., Ding, S. and Zhang, D. W. ,Evolution of the band-gap and optical properties of graphene oxide with controllable reduction level, *Carbon*, 62, 157–164(2013). https://doi.org/10.1016/j.carbon.2013.06.007

Stankovich, S., Dikin, D. A., Dommett, G. H. B., Kohlhaas, K. M., Zimney, E. J., Stach, E. A., Piner, R. D., Nguyen, S. T. and Ruoff, R. S., Graphene-based composite materials, *Nat.*, 442(7100), 282–286(2006). https://doi.org/10.1038/nature04969

Tamang, S., Rai, S., Bhujel, R., Bhattacharyya, N. K., Swain, B. P. and Biswas, J., A concise review on GO, rGO and metal oxide/rGO composites: Fabrication and their supercapacitor and catalytic applications, *J. Alloys Compd.*, 947, 169588(2023). https://doi.org/10.1016/j.jallcom.2023.169588

Tareq, S. S., Saiman, M. I., Yun Hin, T. Y., Abdullah, A. H. and Rashid, U., The Impact of Hydrogen Peroxide as An Oxidant for Solvent-free Liquid Phase Oxidation of Benzyl Alcohol using Au-Pd Supported Carbon and Titanium Catalysts, *Bull. Chem. React. Eng. Catal.*, 13(2), 373–385(2018a). https://doi.org/10.9767/bcrec.13.2.1204.373-385

Tareq, S., Yap, Y. H. T., Saleh, T. A., Abdullah, A. H. Rashid, U. and Saiman, M. I., Synthesis of bimetallic gold-pallidum loaded on carbon as efficient catalysts for the oxidation of benzyl alcohol into benzaldehyde, *J. Mol. Liq.*, 271, 885–891(2018b). https://doi.org/10.1016/j.molliq.2018.09.037

Verma, R., Chauhan, M. S., Pandey, S. and Dandia, A., Reduced graphene Oxide/NiO based nanocomposites for the efficient removal of alizarin dye, indigo dye and reduction of nitro aromatic compounds, *Heliyon*, 9(6), e17162(2023). https://doi.org/10.1016/j.heliyon.2023.e17162

Yoon, Y., Samanta, K., Lee, H., Lee, K., Tiwari, A. P., Lee, J., Yang, J. and Lee, H., Highly Stretchable and Conductive Silver Nanoparticle Embedded Graphene Flake Electrode Prepared by In situ Dual Reduction Reaction, *Sci. Rep.*, 5(1), 14177(2015). https://doi.org/10.1038/srep14177

Zaaba, N. I., Foo, K. L., Hashim, U., Tan, S. J., Liu, W. W. and Voon, C. H., Synthesis of Graphene Oxide using Modified Hummers Method: Solvent Influence, *Proc. Eng.*, 184, 469–477(2017). https://doi.org/10.1016/j.proeng.2017.04.118