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SYNTHESIS, CHARACTERIZATION, AND PHOTOCATALYTIC EFFICIENCY OF A NEW SMART PdO OXIDE NANOMATERIALS FOR USING IN THE RECYCLING AND SUSTAINABLE WASTEWATER TREATMENT

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ABSTRACT. Nanostructured PdO materials with promising catalytic properties were successfully synthesized by the controlled thermal decomposition in air of three Pd(II) complexes containing Pd(II) ion, ofloxacin drug and amino acid. The Pd(II) complexes which were used as precursors were [Pd(OFL)(Gly)]Cl, [Pd(OFL)(Ala)]Cl, and [Pd(OFL)₂]Cl₂, where Gly is glycine amino acid, Ala is alanine amino acid, and OFL is ofloxacin. Structural and morphological properties of the synthesized PdO materials were obtained using FTIR, XRD, SEM, and EDX techniques. The XRD results confirm the tetragonal structure of PdO. The obtained PdO materials were tested as a catalyst for the heterogeneous degradation of H₂O₂ solution. The results revealed that PdO could effectively degrade H₂O₂.

KEY WORDS: PdO, Nanoparticles, Photocatalytic efficiency, Wastewater treatment

INTRODUCTION

Providing a clean environment that is free of any pollutants, toxic and hazardous or otherwise, is an important concern of scientists world-wide and this goal can be achieved with the help of environmentally friendly chemistry using transition metal oxides. These oxides, like RuO₂, Co₃O₄, TiO₂, NiO, PdO, MnO₂, ZnO, In₂O₃, SnO₂, and TiO₂, possess good semiconductor properties, like a significant band gap, as well as transport and optical properties that utilize transition metal oxides for different advanced photocatalytic applications [1-14]. Many pollutants and toxic and hazardous substances, like textile dyes, pesticides, and pharmaceutical drugs, were removed from environments based on photocatalytic degradation in visible light catalyzed by nanostructured transition metal oxides because the metal oxides, in nano-scale ranges, possess high surface areas and improved reactive sites [15-22]. Palladium oxide (PdO) possesses a band gap value equal to 2.2 eV and it considered a p-type semiconductor [23, 24]. Recently, palladium metal (Pd) and its oxide (PdO) have received special attention and extensive investigation due to their unique properties as catalysts because they possess high catalytic potency at low temperatures and low volatility at high temperatures. They have wide applications [25-39] in methane combustion [25-28], carbon monoxide oxidation [29-32], catalyzing several organic conversions and reactions, like reduction reactions, hydrogenations of unsaturated olefins, and carbon-carbon cross-coupling formation [33-35], ethanol oxidation; it decomposes ethanol through decarbonylation and dehydrogenation, releasing CO and H species and environmental redemption applications when incorporating Pd or PdO with TiO₂. This incorporation reduced the band gap of TiO₂. This incorporating material showed extremely high photocatalytic degradation of rhodamine and methylene blue [36-39].

In this work, nanostructured PdO materials were prepared via the controlled thermal decomposition at low temperatures in air of three Pd(II) complexes containing Pd(II) ion,

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ofloxacin drug, and amino acid, and these materials were analyzed for their structural and morphological properties using the Shimadzu FT-IR spectrophotometer, XRD, SEM, and EDX techniques. The three complexes which were used as precursors were complex **I** ([Pd(OFL)(Gly)]Cl), complex **II** ([Pd(OFL)(Ala)]Cl), and complex **III** ([Pd(OFL)₂]Cl₂), where Gly is glycine amino acid, Ala is alanine amino acid, and OFL is ofloxacin. The heterogeneous catalytic degradation of the prepared PdO materials as catalysts toward H₂O₂ was examined at room temperature in water.

EXPERIMENTAL

General

The chemicals were of analytical grades and were bought from BDH (UK) and Sigma-Aldrich (USA) chemical companies. The instruments X'Pert Philips X-ray powder diffractometer and Shimadzu FT-IR spectrophotometer were used to collect the XRD and IR spectra of the PdO materials, respectively. Their XRD spectra were scanned from 2θ of 105° to 20°, where their IR spectra were scanned from wavenumber of 400 cm⁻¹ to 4000 cm⁻¹.

The SEM and EDX profiles for the PdO materials were obtained using the instruments Joel JSM-6390LV scanning electron microscope (SEM) and Noran six 200 energy dispersive X-ray (EDX) analyzer, respectively.

Synthesis of the PdO materials

Three Pd(II) complexes containing Pd(II) ion, ofloxacin drug, and amino acid (glycine or alanine) were synthesized according to the literature method [40]. These complexes are: **I**: [Pd(OFL)(Gly)]Cl, **II**: [Pd(OFL)(Ala)]Cl and **III**: [Pd(OFL)₂]Cl₂.

Complex **I**, [Pd(OFL)(Gly)]Cl was prepared by adding a hot methanolic solution (2 mmol, 40 mL, 0.722 g) of OFL to an aqueous solution (2 mmol, 25 mL, 0.354 g) of PdCl₂ and glycine (2 mmol, 5 mL, 0.150 g). The reaction mixtures were neutralized at pH = 8-9 and then refluxed for 6-7 h at ~70-80 °C. The solution was filtered off and left to slowly evaporate. Then, they were dried in an oven to dispose of the solvent after 6-15 h. Yellow color product was deposited and collected in a glass bottle for the chemical analyses.

Complex **II**, [Pd(OFL)(Ala)]Cl was prepared by adding a hot methanolic solution (2 mmol, 40 mL, 0.722 g) of OFL to an aqueous solution (2 mmol, 25 mL, 0.354 g) of PdCl₂ and alanine (2 mmol, 5 mL, 0.178 g). The reaction mixtures were neutralized at pH = 8-9 and then refluxed for 6-7 h at ~70-80 °C. The solution was filtered off and left to slowly evaporate. Then, it was dried in a drying oven to dispose of the solvent after 6-15 h. Yellowish white color product deposited and was collected in a glass bottle for the chemical analyses.

Complex **III**, [Pd(OFL)₂]Cl₂ was prepared by adding a hot methanolic solution (4 mmol, 40 mL, 1.445 g) of OFL ligand to an aqueous solution (2 mmol, 15 mL, 0.354 g) of PdCl₂. The reaction mixture was neutralized at pH = 8-9 and then refluxed for 6-7 h at ~70-80 °C. The colored solution was filtered off and left to slowly evaporate. Afterwards, it was dried in an oven to dispose of the remaining solvent, and yellowish white color products deposited and were collected in a glass bottle for the chemical analyses.

The Gly in these complexes is glycine amino acid, Ala is alanine amino acid, and OFL is ofloxacin drug. The chemical structures of **I**, **II** and **III** are presented in Figure 1. Nanostructured PdO materials were prepared by the controlled thermal decomposition of **I**, **II** and **III** as precursors in air at temperatures of 600 °C for 3 h using electric furnace. The obtained PdO products were ground into fine powder (2-3 mm), and then characterized by the FTIR, XRD, SEM, and EDX methods.

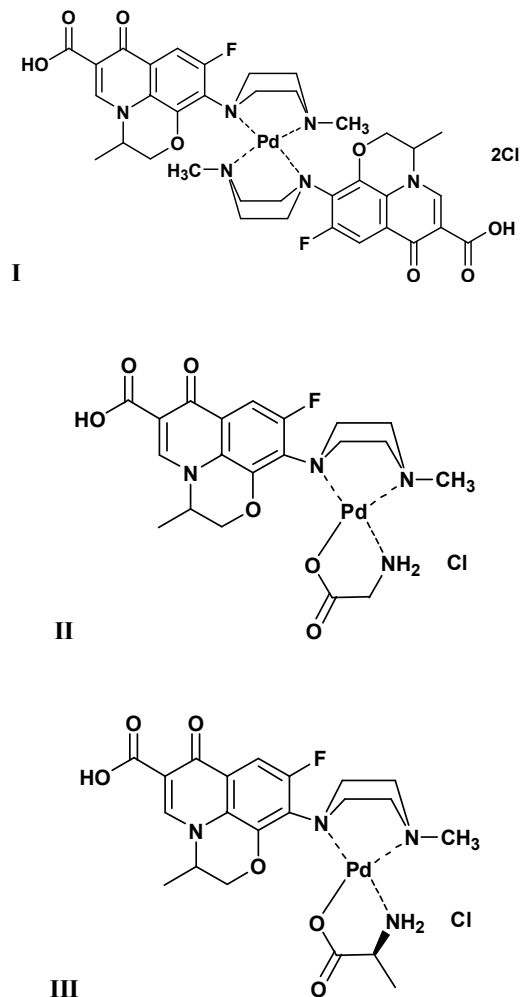


Figure 1. Chemical structures I, II and III.

Catalytic experiment

The catalytic decomposition of H₂O₂ by the synthetic PdO has been observed by titration of the undecomposed H₂O₂ with a standard solution of KMnO₄. The PdO (0.02 g) was mixed with 5 mL of H₂O₂ (0.01 N) in a conical flask under magnetic stirring at room temperature. The decomposition of H₂O₂ was investigated at different times within the range of 10-50 min. Then, a 5-mL aliquot of reaction mixture was titrated with (0.1 N) KMnO₄ in the presence of an acidic H₂SO₄ solution, and the difference in consumed volumes of the KMnO₄ solution before and after the catalytic decomposition was calculated.

RESULTS AND DISCUSSION

Characterization of the PdO materials

The PdO materials were generated from the solid-state thermal decomposition of **I**, **II** and **III** at 600 °C. The composition, crystallinity, and surface morphology of the obtained PdO materials were investigated using XRD, SEM, EDX and FTIR methods. Figure 2 a-c depicts the IR spectra of the prepared PdO materials. Generally, metal oxides showed IR absorption bands in the fingerprint region below 1000 cm^{-1} appeared from inter-atomic vibrations. The prepared PdO materials showed weak bands around 1200 cm^{-1} and 3000 cm^{-1} , which may be assigned to the O–H deformation and stretching vibrations, respectively. These bands arise from the water adsorption on the PdO surface. Bands located at 580 cm^{-1} and 650 cm^{-1} were attributed to the Pd–O stretching vibrations [41]. Peroxo groups stretching vibrations showed that the absorption band appeared at 1365 cm^{-1} [42]. Figure 3 a-c represents the XRD patterns of the prepared PdO materials. These materials showed characteristic diffraction peaks at 2θ values of 71.34° (211), 60.07° (103), 54.71° (112), 42.03° (110), 39.78° (101), and 33.57° (002). These peaks can be indexed to tetragonal PdO (JCPDS Card No. 75–584) [43]. Based on the Debye-Scherrer equation, the average particle size for the PdO materials was estimated to be ~ 40 nm. The XRD spectra of the PdO materials showed some minor peaks, which could be due to the presence of trace of impurities presented in PdO. Figure 4 a-c presents the SEM micrographs of the prepared PdO materials taken with different scales from 1 to 50 μm and various magnifications (1,000x to 20,000x). These micrographs indicate that the particles of PdO were agglomerated with non-defined structural morphology. The non-defined shaped of the particles could be due to the high surface energy of the particles and the strong tendency to form agglomerates.

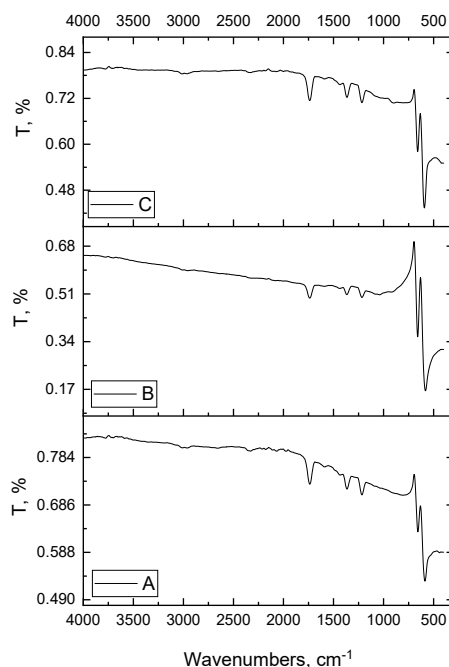


Figure 2. IR spectra of PdO generated from the calcination of **I** (A), **II** (B) and **III** (C) complexes.

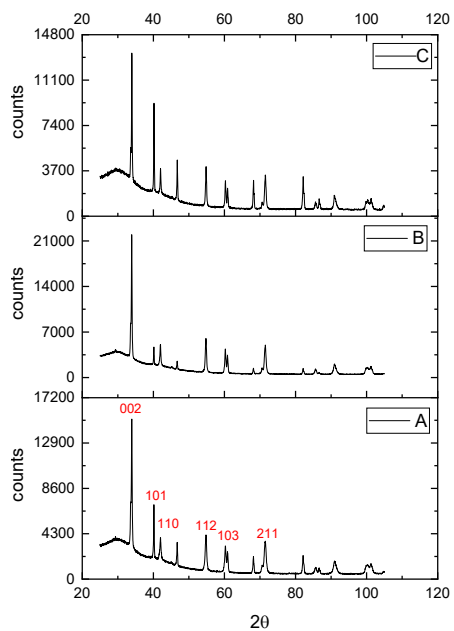


Figure 3. XRD spectra of PdO generated from the calcination of I (A), II (B) and III (C) complexes.

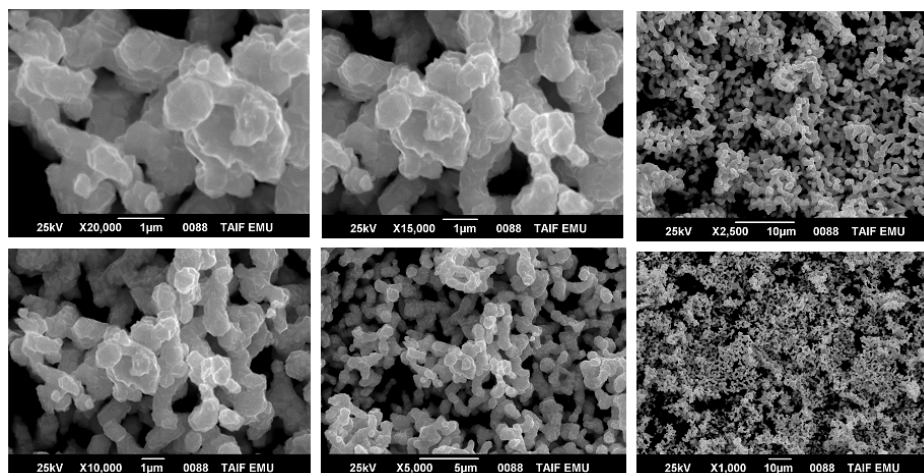


Figure 4a. SEM micrographs of PdO generated from the calcination of I at different magnifications.

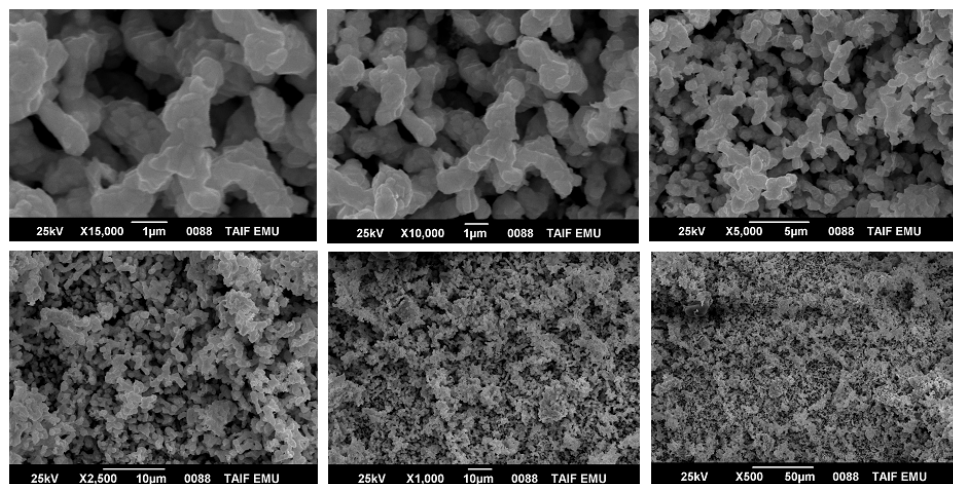


Figure 4b. SEM micrographs of PdO generated from the calcination of **II** at different magnifications.

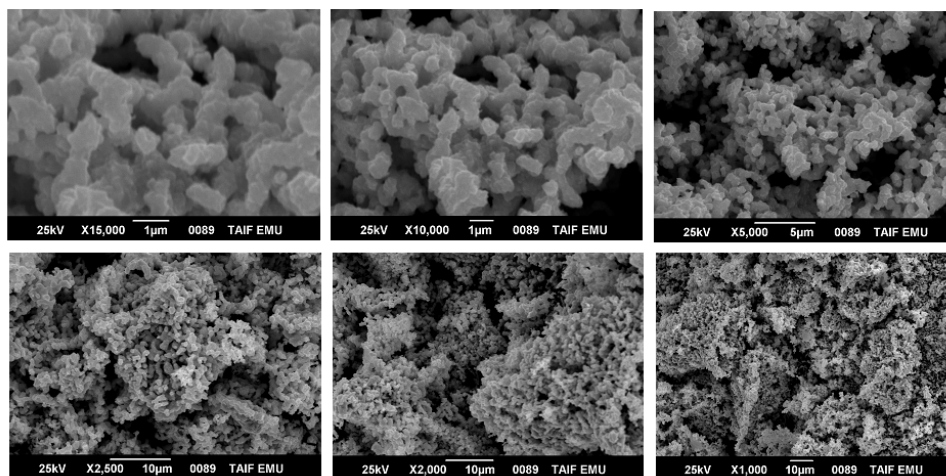


Figure 4c. SEM micrographs of PdO generated from the calcination of **III** at different magnifications.

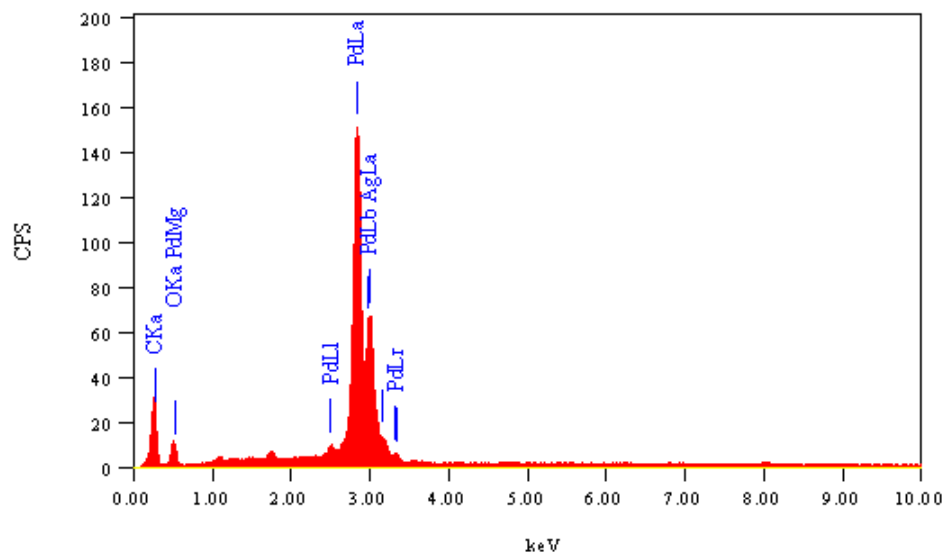


Figure 5a. EDX spectrum of PdO generated from the calcination of **I**.

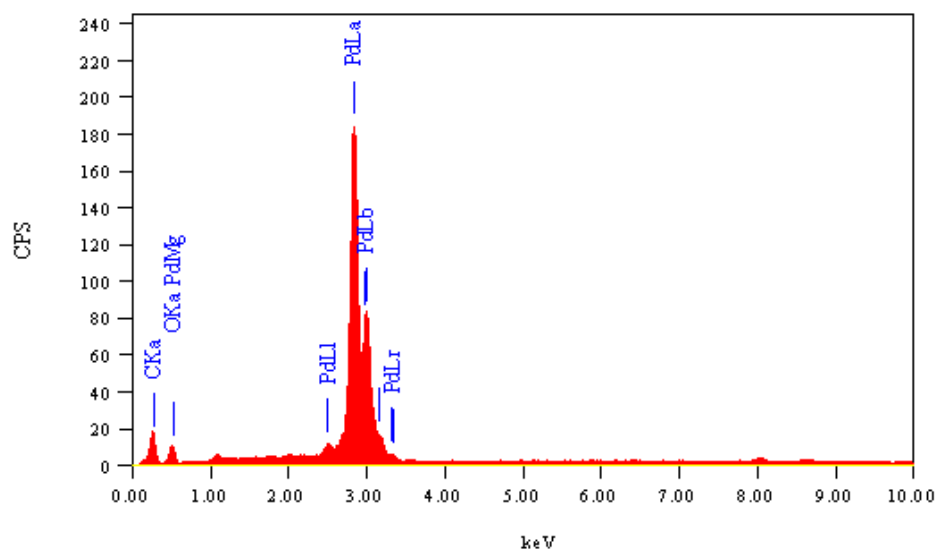


Figure 5b. EDX spectrum of PdO generated from the calcination of **II**.

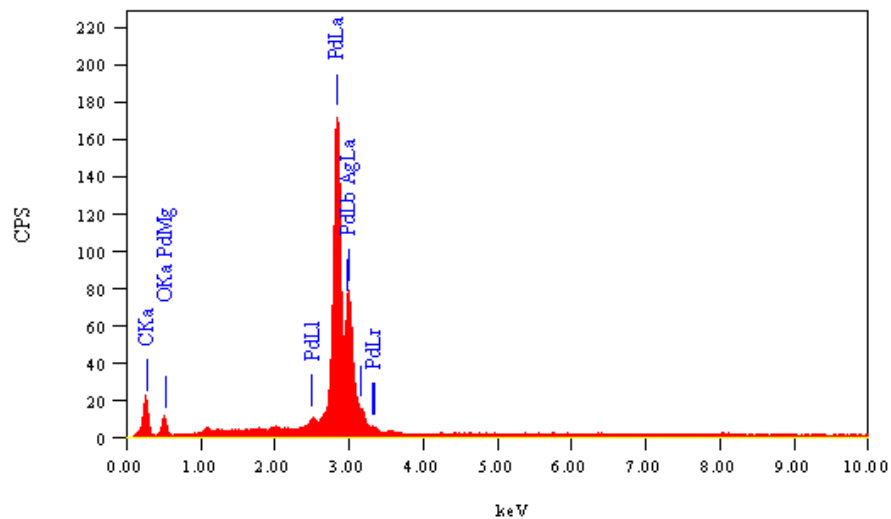


Figure 5c. EDX spectrum of PdO generated from the calcination of **III**.

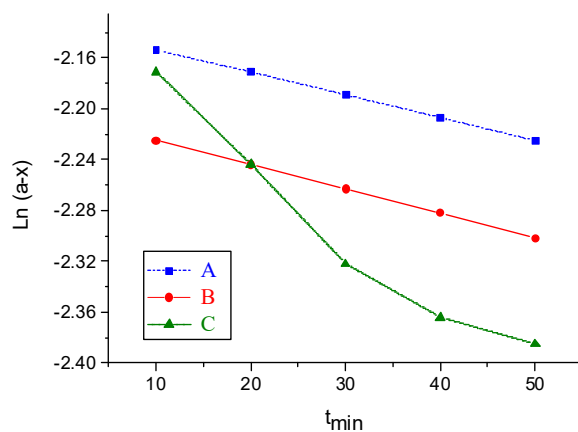


Figure 6. Effect of time (min) on the decomposition of H_2O_2 using PdO prepared from the calcination of **A**; complex **I**, **B**; complex **II**, and **C**; complex **III**.

Elemental analysis of the prepared PdO materials has been verified using the EDX technique, and their EDX spectra are illustrated in Figure 5 a-c. These spectra confirmed the successful preparation of the PdO products by the formation of the major emission energies of palladium and oxygen peaks.

Catalytic activity of the PdO materials

Table 1 lists the catalytic activity data for the decomposition of H_2O_2 at a constant weight of PdO and a constant concentration of H_2O_2 (0.01 N) at room temperature. Figure 6 shows that the rate of decomposition of H_2O_2 increased with time, which after 50 min were $1.8 \times 10^{-3} < 2.0 \times 10^{-3} < 7.8 \times 10^{-3}$ for the synthesized PdO products from the thermal decomposition of **I**, **II** and **III**, respectively. The catalytic decomposition of H_2O_2 tends to be associated with an intermediate radical species, which can bind to the surfaces where H_2O_2 undergoes decomposition [44, 45]. The degree of decomposition of H_2O_2 showed inverse dependent on the surface area, pore volume and mean pore dimensions. The chemical nature of the surface, rather than the porosity characterizations, was the principal factor in enhancing the disproportionation of H_2O_2 on the prepared PdO oxides.

Table 1. Catalytic activity data of the PdO synthesized from the calcination of **I**, **II** and **III**.

PdO synthesized from calcination of I					
Results	t_{\min}				
	10	20	30	40	50
$V_{(\text{KMnO}_4)}$	5.8	5.7	5.6	5.5	5.4
$N_{(\text{H}_2\text{O}_2) a-x}$	0.116	0.114	0.112	0.110	0.108
$\text{Ln}(a-x)$	-2.154	-2.171	-2.189	-2.207	-2.225
K	1.8×10^{-3}				
PdO synthesized from calcination of II					
$V_{(\text{KMnO}_4)}$	5.4	5.3	5.2	5.1	5.0
$N_{(\text{H}_2\text{O}_2) a-x}$	0.108	0.106	0.104	0.102	0.100
$\text{Ln}(a-x)$	-2.225	-2.244	-2.263	-2.282	-2.302
K	2.0×10^{-3}				
PdO synthesized from calcination of III					
$V_{(\text{KMnO}_4)}$	5.7	5.3	4.9	4.7	4.6
$N_{(\text{H}_2\text{O}_2) a-x}$	0.114	0.106	0.098	0.094	0.092
$\text{Ln}(a-x)$	-2.171	-2.244	-2.322	-2.364	-2.385
K	7.8×10^{-3}				

*K (min^{-1}) = rate constant of the H_2O_2 decomposition.

CONCLUSION

In this work, nanostructured PdO oxide nanomaterials were synthesized by the calcination of three Pd(II) complexes. These complexes contained ofloxacin drug, amino acid (alanine or glycine), and Pd(II) ions. The structure and morphology of the synthesized PdO nanomaterials were characterized using FTIR, XRD, SEM, and EDX techniques. The PdO nano oxides were tested as a catalyst for the heterogeneous catalytic activity degradation of H_2O_2 solution at room temperature.

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