

Removal of cyanide in aqueous solution by oxidation with hydrogen peroxide catalyzed by copper oxide

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ABSTRACT

This work is dedicated to the removal of free cyanide from aqueous solution through oxidation with hydrogen peroxide H_2O_2 catalyzed by copper oxide nanoparticles. Effects of initial molar ratio $[H_2O_2]_0/[CN^-]_0$, catalyst dose, temperature, pH and the catalyst stability on cyanide removal have been investigated. The use of copper oxide has improved the reaction rate showing catalytic activity. The cyanide removal efficiency was increased from 60% to 94% by increasing in the dose of catalyst from 0.5 g/L to 5.0 g/L. Increasing the temperature from 20 °C to 35 °C promotes cyanide removal and the four successive times re-use of catalyst shows good stability. Kinetics of cyanide removal was found to be of pseudo-first-order with respect to cyanide. The rate constants have been determined.

Key words | catalytic oxidation, copper oxide nanoparticles, cyanide, hydrogen peroxide, kinetics, stability

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INTRODUCTION

Liquid effluents containing cyanides are generated in some industrial operations such as gold and silver extraction, production of paint, adhesives, surface finishing, plating and electroplating, petro-chemical applications, photography industry, rocket propellant, pharmaceuticals, coal carbonization (Dash *et al.* 2009; Kuyucak & Akcil 2013). Plants, microorganisms and insects can also naturally produce cyanide. Cyanides in all their forms, such as free cyanide, cyanide salts, or metal-cyanide complexes are potentially toxic for aquatic life and human beings (Dash *et al.* 2009; Shen *et al.* 2014). Short-term exposure can cause rapid breathing, tremors, and other neurological effects. Long-term exposure can cause weight loss, thyroid deficiency, and nerve damage. Their toxicity is mainly due to their aptitude to release free cyanides (Kuyucak & Akcil 2013; Uppal

et al. 2016). It is therefore absolutely essential to remove or reduce the concentration of these cyanides' harmful compounds in wastewater at their point source before they are released into the environment.

For the cyanide removal from solution or slurries, different processes are proposed and/or applied (Kuyucak & Akcil 2013). Physicochemical methods such as alkaline chlorination oxidation (Kuyucak & Akcil 2013), oxidation by ozone (Cui *et al.* 2014), oxidation by Caro's acid (Teixeira *et al.* 2013; Hewitt *et al.* 2015), oxidation by oxygen and by hydrogen peroxide (Yeddou *et al.* 2010; Tian *et al.* 2016; Yubo *et al.* 2018), photocatalytic degradation (Raisa *et al.* 2018), electrochemical oxidation (Berenguer *et al.* 2017), adsorption (Arif *et al.* 2019) and biological degradation at low concentrations (Singh & Balomajumder 2016). The

efficiency of these processes depends on the type and concentration of the cyanide species present (Yazici *et al.* 2006).

Considering the disadvantages of conventional chemical treatment methods, the oxidation by hydrogen peroxide can be a good treatment alternative for the complete destruction of cyanide and transformation to a not dangerous form. In presence of hydrogen peroxide, the cyanides are oxidized into cyanates (CNO⁻) or into (CO₃²⁻), when the excess of H₂O₂ is used (Yazici *et al.* 2006). This process can remove the totality of free and non-stable metal complex (WADs) cyanides, it does not enrich the medium with salt and does not produce dangerous products (Yeddou *et al.* 2011). In opposition, this process needs use of a catalyst to increase the rate of cyanides removal.

Soluble copper is frequently used as a catalyst for the oxidation of cyanides by hydrogen peroxide because of its high efficiency. However, it cannot be recovered and it can therefore cause environmental problems as it is a heavy metal. For these reasons, some authors have used copper in a heterogeneous form (Kitis *et al.* 2005; Yeddou *et al.* 2011). Yeddou *et al.* (2011) used copper impregnated carbon and suggest that the catalytic action would be due to the CuO that formed on the surface of the activated carbon.

CuO is well known as excellent adsorbent of several compounds (Zhu *et al.* 2013) and active catalyst in oxidative reactions (Suramwar *et al.* 2012; Li *et al.* 2014). The CuO catalyst may play the critical role of decomposing H₂O₂ and producing free radical species as HO• and HOO•, who have a strong potential of oxidation (Liou & Chen 2009). Copper oxide has been used as adsorbent for adsorption of hydrogen cyanide (HCN) (Yang *et al.* 2015). However, to our knowledge, oxidation of cyanides by hydrogen peroxide in the presence of copper oxide has not been yet investigated.

The present work is carried out to investigate the use of copper (II) oxide nanoparticles for cyanide oxidation in solution by hydrogen peroxide and to evaluate its catalytic activity. Effects of initial molar ratio [H₂O₂]₀/[CN⁻]₀, CuO dose, pH, temperature and catalytic stability of CuO on cyanide removal have been analyzed and studied.

MATERIAL AND METHODS

Chemicals and reagents

Copper (II) oxide nanoparticles (CuO) (Sigma-Aldrich) are used as a catalyst in this work. It has been initially

repeatedly washed with boiling bidistilled water and dried for few hours at 105 °C. The point of zero charge (pH_{zc}) is determined by the mass titration method (Noh & Schwarz 1990). All other used chemicals are analytical reagent grade (Merck, Darmstadt, Germany). Cyanide solutions are prepared with potassium cyanide (KCN) (99%). Hydrogen peroxide H₂O₂ (50 wt.%) is used for their oxidation into cyanates. The adjustment of the pH is carried out by the addition of NaOH (1 N) and HCl (1 N).

Analytical apparatus

The X-ray diffraction (XRD) patterns of CuO are obtained using a diffractometer (Inel cps 120) which is equipped with an iron anticathode ($k = 1.936 \text{ \AA}$) and an ethane ionization curved detector allowing to read angles in the range $2\theta = 5\text{--}125^\circ$. The surface morphologies of the copper oxide are characterized using a scanning electron microscope (SEM) (Philips ESEM XL 30).

Cyanide concentration is analyzed by potentiometric method with a cyanide-specific electrode (Orion 96-06) (Clesceri *et al.* 1998). Cyanate concentration is found out by hydrolyzing it to ammonia at acidic pH (1.5–2.0) and ammonia is measured by the potentiometric method (Clesceri *et al.* 1998). The pH is measured using a standard pH-meter (HI 221, Hanna Instruments, Tanneries, France).

Experimental procedure of cyanide removal

The experiments are performed in a double-walled glass reactor in batch mode with 1 L of cyanide solutions. The reactor is covered with aluminum foils to prevent contact with light, and kept closed with PTFE lid to avoid air penetration. The solution is stirred with a magnetic stirrer. The required amount of copper oxide nanoparticles (CuO) is added. The beginning of the test is considered to occur simultaneously with the injection of hydrogen peroxide. The concentration of cyanide is determined versus time while the tests are performed. The amount of cyanate is analyzed in the end of tests. The tested parameters are the initial molar ratio [H₂O₂]₀/[CN]₀, the CuO dose, the temperature and the catalyst stability. In all experiments, the initial concentration of cyanide and the pH are maintained at 260 mg/L and 11.0, respectively, to be in conditions close to those existing in some local cyanided industrial discharges. Maintaining the pH at the value of 11 also allows avoiding formation of very volatile and dangerous HCN.

RESULTS AND DISCUSSION

Characterization of copper oxide nanoparticles

The pH of zero charge (pH_{zpc}) for copper oxide (CuO) is found to be 6.1. The XRD patterns of CuO (Figure 1) show that the CuO material used has a crystalline structure. It is also illustrated that CuO did not change after four consecutive tests of oxidation with hydrogen peroxide. The SEM image of the CuO (Figure 2) shows a rough surface with pores.

Effect of initial molar ratio [H₂O₂]₀/[CN⁻]₀

The oxidation ability of hydrogen peroxide is examined for initial molar ratios [H₂O₂]₀/[CN⁻]₀ of 1, 3, 5 and 10. (Figure 3) shows the decrease of cyanide concentration caused by the hydrogen peroxide. Initial preliminary tests are carried out with hydrogen peroxide in absence of

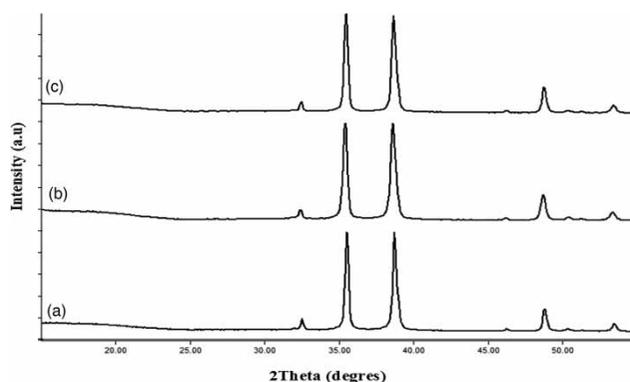


Figure 1 | XRD patterns of (a) CuO, (b) CuO (first use) and (c) CuO (fourth use).

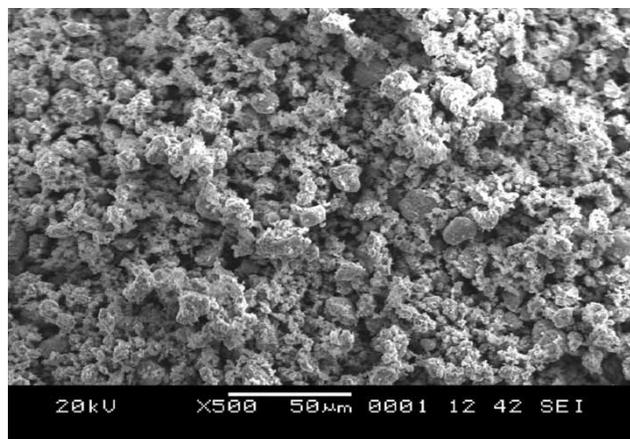


Figure 2 | SEM image of CuO.

catalyst ([CuO] = 0) and also without hydrogen peroxide ([H₂O₂]₀ = 0) in presence of catalyst.

In presence of CuO without peroxide hydrogen and after 40 min, the cyanide concentration decreases from the initial value of 260 mg/L to around 135 mg/L (elimination of 45% of cyanides). The cyanide removal is due to the adsorption on CuO. The amount of removed cyanide by 1 g of copper oxide is 125 mg. Although the adsorption capacity found in our work is very interesting compared to other works (Dash *et al.* 2009), it separates only 52% of the initial cyanides.

In the absence of CuO, the oxidation of cyanide by hydrogen peroxide is very slow compared to the oxidation in the presence of catalyst. For initial molar ratio of 3, in the absence of CuO, only 15% of cyanides are removed during 40 min whereas in the presence of CuO and presence of CuO, more than 63% of cyanides are removed after 15 min. The rate of cyanide removal rises with the increase of molar ratio [H₂O₂]₀/[CN⁻]₀. For molar ratios of 1.0, 3.0, 5.0, and 10.0, the cyanide concentrations reached after 12 min are 164.5, 135.2, 26 and 5.2 mg/L, respectively (corresponding to the removal percentages of 36.7%, 48.0%, 90.0% and 98.0%). These values are interesting compared with those found in other works about oxidation of cyanide by hydrogen peroxide (Kitis *et al.* 2005; Yeddou *et al.* 2010; Chergui *et al.* 2015). The positive effect of increasing the amount of H₂O₂ can be explained by the strong oxidant hydroxyl radicals, which are generated on the surface of the CuO (Suramwar *et al.* 2012; Zhu *et al.* 2013; Li *et al.* 2014).

At the end of the oxidation tests, the concentration of cyanate found shows that 90–95% of cyanides were converted into cyanate which are much less toxic (Kuyucak & Akcil 2013).

Effect of copper oxide dose

Copper oxide dose is an essential parameter that strongly affects the oxidation potential. The results of cyanides removal by hydrogen peroxide for CuO dose ranged between 0 and 10 g/L, an initial cyanide concentration of 260 mg/L and an initial molar ratio [H₂O₂]₀/[CN⁻]₀ of 3 are analyzed. Figure 4 shows that the cyanide removal increases with the increase of the catalyst dose. The cyanide percentage which is reached after 15 min is 8, 63, 78, 94 and 99.9 for a CuO dose of 0, 1, 3, 5 and 10 g/L, respectively. The values of initial rate of cyanide removal (determined from Figure 4) are 0.07, 0.4, 0.6, 0.7, 0.9 and 1.7 mmol/Lmin, respectively. This is due to the high availability of

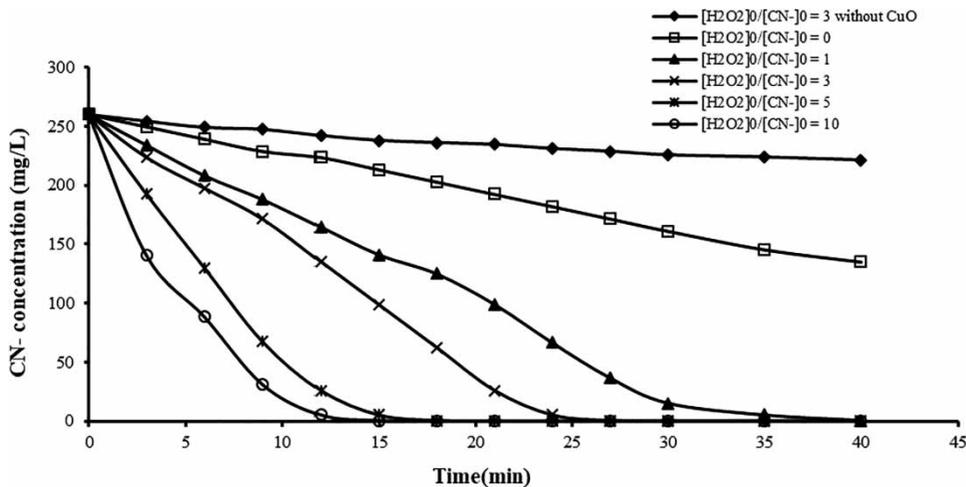


Figure 3 | Effect of initial molar ratio $[H_2O_2]_0/[CN^-]_0$ on the cyanide removal by hydrogen peroxide. CuO (1 g/L), $[CN^-]_0 = 10$ mM (260 mg/L), pH = 11.0, $T = 20^\circ C$.

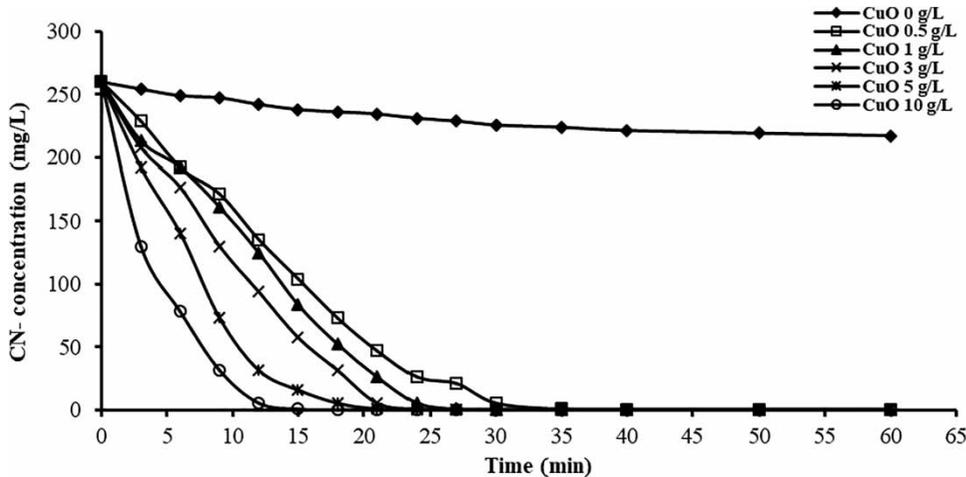
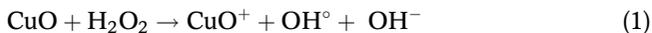


Figure 4 | Effect of CuO dose. $[H_2O_2]_0/[CN^-]_0 = 3$, $[CN^-]_0 = 10$ mM (260 mg/L), $T = 20^\circ C$, pH = 11.0.

very active surface of CuO, which make it possible to produce large quantities of hydroxyl radicals (OH^\cdot) from hydrogen peroxide. The mechanism of radicals' generation can be illustrated by Equation (1).



In a previous study (Kitis *et al.* 2005; Yeddou *et al.* 2010; Chergui *et al.* 2015), authors observed that the increase of the amount of catalyst improve the kinetics of cyanides oxidation by hydrogen peroxide. Yeddou *et al.* (2011) observe, for an initial molar ratio of 3, 260 mg/L of initial cyanide concentration and 10 g/L of copper impregnated activated carbon catalyst, an elimination of more than 90% of cyanides. Chergui *et al.* (2015) removed, in the same

conditions, 81% of cyanides after 450 min of oxidation catalyzed by alumina. Kitis *et al.* (2005) showed that more than 90% of cyanides were removed in 4 h in presence of copper impregnated pumice catalyst with a dose of 3 g/L for a concentration of hydrogen peroxide and cyanide of 150 and 100 mg/L, respectively.

Stability of CuO

Controlling the stability of a catalyst is of crucial importance for retaining process of its properties and activity. This parameter is studied by the re-use of the same sample of CuO four successive times. Before each re-use, the CuO is washed with distilled water and dried for few hours at $80^\circ C$. The results (Figure 5) show that the rate of cyanide

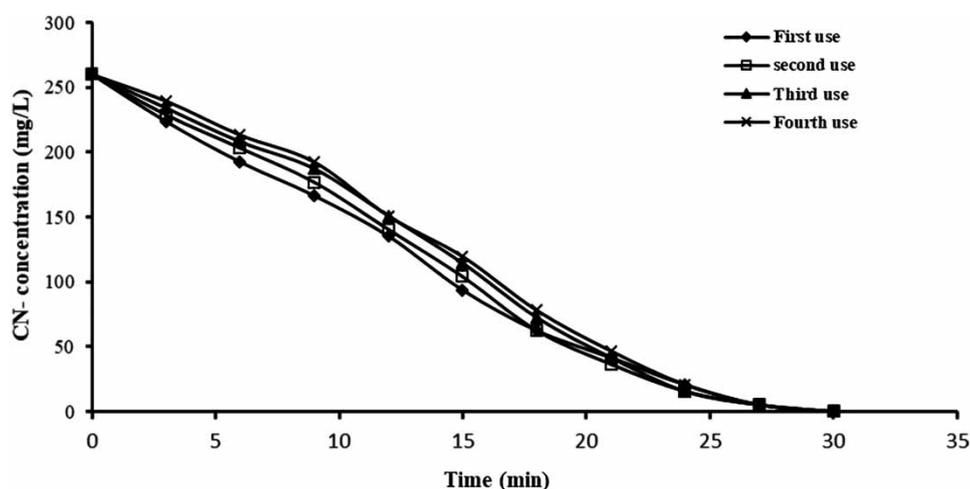


Figure 5 | Re-use of CuO. CuO (1 g/L), [H₂O₂]₀/[CN⁻]₀ = 3, [CN⁻]₀ = 10 mM (260 mg/L), T = 20 °C, pH = 11.0.

removal decreases slightly after each re-use, showing a good stability of catalyst. The same RDX patterns (Figure 1) for fresh CuO and CuO, used four consecutive times, confirm this stability. The stability of catalyst was also studied by the determination the amount of copper leached during the cyanide oxidation. Less than 5.0 mg/L of copper concentration in the solution was found after total elimination of cyanide at pH 11 with catalyst dose of 10 g/L, cyanide concentration of 260 mg/L and initial molar ratios [H₂O₂]₀/[CN⁻]₀ of 10.

Kinetics of removal of cyanide in oxidation by hydrogen peroxide

The kinetic data of cyanide oxidation by hydrogen peroxide catalyzed by CuO are analyzed using the pseudo-first-order (Equations (1) and (2)) and the pseudo-second-order (Equations (3) and (4)) models with respect to cyanide.

Pseudo-first-order model

$$\frac{dC}{dt} = k_{app}C \quad (2)$$

$$\ln \frac{C_0}{C} = k_{app}t \quad (\text{Linear form}) \quad (3)$$

Pseudo-second-order model

$$\frac{dC}{dt} = k_{app}C^2 \quad (4)$$

$$\frac{1}{C} - \frac{1}{C_0} = k_{app}t \quad (\text{Linear form}) \quad (5)$$

where C₀, C, k_{app} are initial cyanide concentration, cyanide concentration at time t and apparent rate constants, respectively.

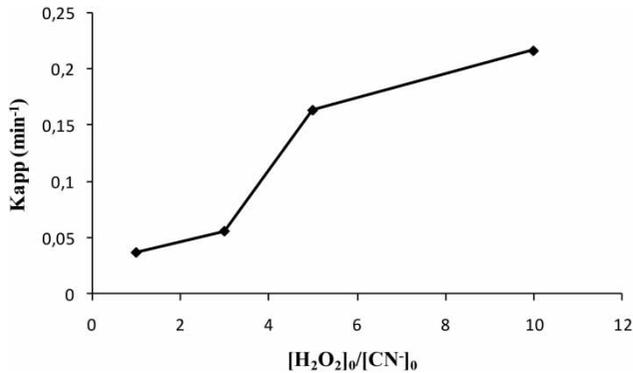
The graphs of ln(C₀/C) and ((1/C) - (1/C₀)) versus time (figures not shown) show that the kinetics data of cyanide oxidation are well fitted by the pseudo-first-order model with high coefficients of determination R² values (>95%). The calculated constants of the two kinetic models along with coefficients of determination R² values are presented in Table 1. It is observed that the apparent rate constants increase with the increase in the concentration of the hydrogen peroxide and the dose of the CuO catalyst. Figure 6 represents the evolution of K_{app} as a function of the initial molar ratios [H₂O₂]₀/[CN⁻]₀; it is shown as a non-linear trend. The reaction mechanism is probably very complex in this case and no precise order with respect to the hydrogen peroxide can be determined, thus confirming a complexity of the oxidation mechanism in the presence of CuO catalyst. This complexity was mentioned by Yeddou *et al.* (2010) and Chergui *et al.* (2015) when using the heterogeneous catalysts copper impregnated activated carbon and activated alumina, respectively.

Effect of temperature and determination of activation energy

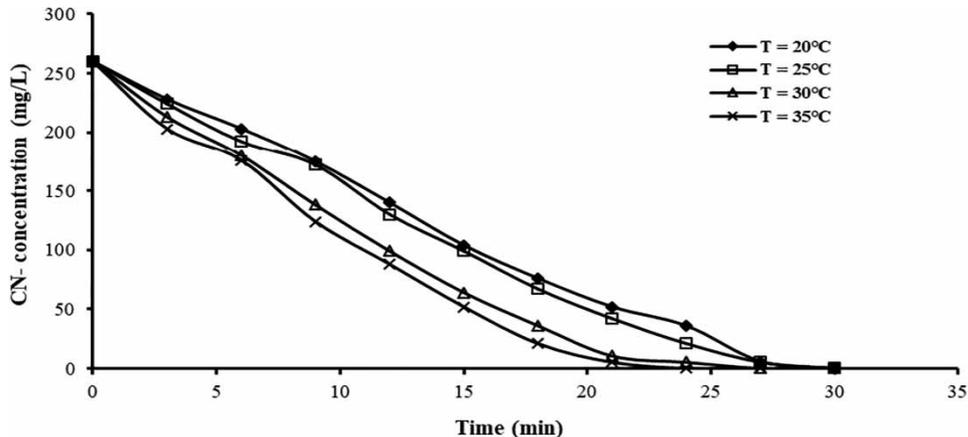
The effect of temperature (Figure 7) is studied for the values of temperatures of 20, 25 and 35 °C, for initial molar ratios [H₂O₂]₀/[CN⁻]₀ equal to 3, for catalyst dose of 1 g/L and an initial cyanide concentration of 260 mg/L. It is observed that the initial rate and the extent of cyanide removal are improved with the increase of temperature.

Table 1 | Kinetic model parameters for cyanide removal in oxidation by hydrogen peroxide, pH = 11.0, [CN⁻]₀ = 10 mM (260 mg/L)

[CuO] (g/L)	[H ₂ O ₂] ₀ /[CN ⁻] ₀	Temperature (°C)	Pseudo-first-order		Pseudo-second-order	
			k ₁ (min ⁻¹)	R ²	K ₂ (L/mmol.min)	R ²
1	3	25	0.081	0.967	0.019	0.671
1	3	30	0.094	0.950	0.031	0.656
1	3	35	0.105	0.952	0.037	0.637
1	1	20	0.037	0.983	0.005	0.935
1	3	20	0.056	0.950	0.012	0.755
1	5	20	0.164	0.916	0.052	0.694
1	10	20	0.217	0.967	0.063	0.778
3	3	20	0.089	0.955	0.017	0.806
5	3	20	0.168	0.942	0.043	0.718
10	3	20	0.225	0.987	0.065	0.825

**Figure 6** | Evolution of apparent rate constants (K_{app}) with initial concentration of hydrogen peroxide in presence of CuO (1 g/L), [CN⁻]₀ = 10 mM (260 mg/L), pH = 11.0, T = 20 °C.

This may be due to the fact that the conversion of H₂O₂ into hydroxyl radicals is accelerated with the increase of temperature.

**Figure 7** | Effect of temperature. CuO (1 g/L), [H₂O₂]₀/[CN⁻]₀ = 3, [CN⁻]₀ = 10 mM (260 mg/L), pH = 11.0.

The apparent activation energy of the cyanide removal by hydrogen peroxide is calculated from the linear form of the Arrhenius (Equation (5))

$$\ln K_{app} = \ln K_0 - E_a/RT \quad (6)$$

where K₀ is the pre-exponential factor and E_a the apparent activation energy (kJ/mol).

After plotting lnK_{app} as a function of 1/T (Figure 8), the value of the apparent activation energy is determined from the slope of regression line. The apparent activation energy is 32.2 kJ/mol for the oxidation in presence of 1 g/L of copper oxide (CuO). In the previous study, Yeddou et al. (2010) found values of 82.7 and 46.2 kJ/mol for the apparent activation energy in the oxidation of 260 mg/L of cyanide by hydrogen peroxide with initial molar ratio [H₂O₂]₀/[CN⁻]₀ equal to 5 in the absence and in the

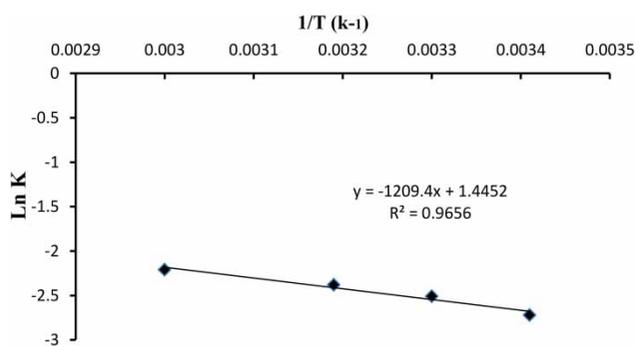


Figure 8 | Validation of the Arrhenius law for cyanide removal by hydrogen peroxide in the presence of CuO.

presence of activated carbon catalyst (10 g/L), respectively. Chergui *et al.* (2015) found a value of 55.7 kJ/mol in presence of 10 g/L of alumina catalyst (Al₂O₃). The CuO, with dose of 1 g/L, reduces significantly the apparent energy, confirming thus its role of catalyst.

CONCLUSIONS

In this study, the oxidation of free cyanide by hydrogen peroxide catalyzed with the copper oxide nanoparticles is discussed. The copper oxide has significantly increased the reaction rate, showing a catalytic activity. This study showed the following conclusions.

- The rate of cyanide removal increases with the initial molar ratio [H₂O₂]₀/[CN⁻]₀ between 1.0 and 10. In all cases, more than 90% of cyanides are removed in 30 min.
- The increase in the concentration of the copper oxide from 1.0 to 10 g/L has a beneficial effect.
- The cyanide kinetics improves with the increase of the temperature between 20 and 35 °C. The apparent activation energy of the cyanide removal by hydrogen peroxide is 32.2 kJ/mol.
- The four successive reuses of catalyst shows a good stability.
- The kinetic study showed that the pseudo-first-order model responds better than the pseudo-second-order for cyanides removal by oxidation with hydrogen peroxide catalyzed by CuO with respect to cyanide.

The proposed CuO catalyst can be a good alternative to the use of homogeneous catalysts, the removal of which after treatment can cause a problem. This catalyst allows removing cyanide with fast kinetic and, at the same time, consumes only hydrogen peroxide as chemical product.

Interesting rates of cyanide removal can be obtained even with small initial molar ratios [H₂O₂]₀/[CN⁻]₀.

REFERENCES

- Arif, H. J., Sheeraz, A. M., Azizullah, C. & Asif, H. K. 2019 Efficient removal of cyanide from industrial effluent using acid treated modified surface activated carbon. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*. DOI: 10.1080/15567036.2019.1568643.
- Berenguer, R., La Rosa-Toro, A., Quijada, C. & Morallón, E. 2017 Electrocatalytic oxidation of cyanide on copper-doped cobalt oxide electrodes. *Applied Catalysis B: Environmental* **207**, 286–296.
- Chergui, S., Yeddou, A. R., Chergui, A., Halet, F., Amaouche, H., Najemi, B. & Ould-Dris, A. 2015 Removal of cyanide in aqueous solution by oxidation with hydrogen peroxide in presence of activated alumina. *Toxicological and Environmental Chemistry* **97** (10), 1289–1295.
- Clesceri, L. S., Greenberg, A. E. & Eaton, A. D. 1998 *Standard Methods for the Examination of Water and Wastewater*, 20th edn. American Public Health Association, Washington, DC, USA.
- Cui, J., Wang, X., Yuan, Y., Guo, X., Gu, X. & Jian, L. 2014 Combined ozone oxidation and biological aerated filter processes for treatment of cyanide containing electroplating wastewater. *Chemical Engineering Journal* **241**, 184–189.
- Dash, R. R., Gaur, A. & Balomajumder, C. 2009 Cyanide in industrial wastewaters and its removal. a review on biotreatment. *Journal of Hazardous Materials* **163** (1), 1–11.
- Hewitt, D. M., Simons, A. M. & Breuer, P. L. 2015 A fundamental investigation of the Caro's acid cyanide destruction process. *Canadian Metallurgical Quarterly* **54** (3), 261–268.
- Kitis, M., Karakaya, E., Yigit, N. O., Civelekoglu, G. & Akcil, A. 2005 Heterogeneous catalytic degradation of cyanide using copper-impregnated pumice and hydrogen peroxide. *Water Research* **39** (8), 1652–1662.
- Kuyucak, N. & Akcil, A. 2013 Cyanide and removal options from effluents in gold mining and metallurgical processes. *Minerals Engineering* **50**, 13–29. <http://dx.doi.org/10.1016/j.mineng.2013.05.027>.
- Li, H., Liao, J. & Zeng, T. 2014 A facile synthesis of CuO nanowires and nanorods, and their catalytic activity in the oxidative degradation of Rhodamine B with hydrogen peroxide. *Catalysis Communications* **46**, 169–173.
- Liou, R. M. & Chen, S. H. 2009 CuO impregnated activated carbon for catalytic wet peroxide oxidation of phenol. *Journal of Hazardous Materials* **172** (1), 498–506.
- Noh, J. S. & Schwarz, J. A. 1990 Effect of HNO₃ treatment on the surface acidity of activated carbons. *Carbon* **28** (5), 675–682.
- Raisa, E. N., Aracely, H., Laura, H., Jorge, L. G., Minerva, V. & Maria, M. 2018 Cyanide degradation in aqueous solution by heterogeneous photocatalysis using boron-doped zinc oxide. *Catalysis Today* **328**, 202–209.
- Shen, J., Zhao, H., Cao, H., Zhang, Y. & Chen, Y. 2014 Removal of total cyanide in coking wastewater during a coagulation

- process: significance of organic polymers. *Journal of Environmental Sciences* **26** (2), 231–239.
- Singh, N. & Balomajumder, C. 2016 Batch growth kinetic studies for elimination of phenol and cyanide using mixed microbial culture. *Journal of Water Process Engineering* **11**, 130–137.
- Suramwar, N. V., Thakare, S. R. & Khaty, N. T. 2012 Synthesis and catalytic properties of nano CuO prepared by soft chemical method. *International Journal of Nano Dimension* **3** (1), 75–80.
- Teixeira, L. A. C., Andia, J. P. M., Yokoyama, L., da Fonseca Araújo, F. V. & Sarmiento, C. M. 2013 Oxidation of cyanide in effluents by Caro's acid. *Minerals Engineering* **45**, 81–87.
- Tian, S., Li, Y., Zeng, H., Guan, W., Wang, Y. & Zhao, X. 2016 Cyanide oxidation by singlet oxygen generated via reaction between H₂O₂ from cathodic reduction and OCl⁻ from anodic oxidation. *Journal of Colloid and Interface Science* **482**, 205–211.
- Uppal, H., Tripathy, S. S., Chawla, S., Sharma, B., Dalai, M. K., Singh, S. P. & Singh, N. 2016 Study of cyanide removal from contaminated water using zinc peroxide nanomaterial. *Journal of Environmental Sciences* **55**, 76–85.
- Yang, M., He, J., Hu, M., Hu, X., Yan, C. & Cheng, Z. 2015 Synthesis of copper oxide nanoparticles and their sensing property to hydrogen cyanide under varied humidity conditions. *Sensors and Actuators B: Chemical* **213**, 59–64.
- Yazici, E. Y., Deveci, H., Alp, İ., Uslu, T. & Celep, O. 2006 Factors affecting decomposition of cyanide by hydrogen peroxide. In: *Proceedings of the 25rd International Mineral Processing Congress*, Istanbul, Turkey.
- Yeddou, A. R., Nadjemi, B., Halet, F., Ould-Dris, A. & Capart, R. 2010 Removal of cyanide in aqueous solution by oxidation with hydrogen peroxide in presence of activated carbon prepared from olive stones. *Minerals Engineering* **23** (1), 32–39.
- Yeddou, A. R., Chergui, S., Chergui, A., Halet, F., Amaouche, H., Nadjemi, B., Ould-Dris, A. & Belkouch, J. 2011 Removal of cyanide in aqueous solution by oxidation with hydrogen peroxide in presence of copper-impregnated activated carbon. *Minerals Engineering* **24** (8), 788–793.
- Yubo, T., Peiwei, H., Lianqi, W., Xiaomeng, Z., Bo, Y., Peng, Q. & Shufeng, Y. 2018 Removal of cyanide adsorbed on pyrite by H₂O₂ oxidation under alkaline conditions. *Journal of Environmental Sciences* **78**, 287–292.
- Zhu, M., Meng, D., Wang, C., Di, J. & Diao, G. 2013 Degradation of methylene blue with H₂O₂ over a cupric oxide nanosheet catalyst. *Chinese Journal of Catalysis* **34** (11), 2125–2129.

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