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Comparative analysis of the environmental impacts of solar photo-Fenton and photocatalysis methods for treatment of phenolic wastewater on life-cycle basis

مقارنة تحليلية للتأثيرات البيئية لطريقة فنتون الضوئية الشمسية و طريقة التحفيز الضوئي لمعالجة مياه الصرف الملوثة بالفينول على أساس دورة الحياة

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KEYWORDS:
Solar photo-Fenton;
photocatalysis;
Phenol;
LCA

الملخص العربي:- فى هذا البحث تمت المقارنة بين الأثر البيئى الناتج عن معالجة مياه الصرف الملوثة بالفينول بطريقة فنتون الضوئية الشمسية وطريقة التحفيز الضوئي الشمسي. النموذج الذى تم دراستة كان 100 م³/يوم من مياه الصرف الصحى الملوثة ب 100 مجم/ لتر من الفينول. تم عمل مقارنة بين كلا من المواد والطاقة المطلوبة لعملية الانشاء والتشغيل لطريقة فنتون الضوئية الشمسية و طريقة التحفيز الضوئي الشمسي. تم استخدام طريقة "Impact 2002" لدراسة التأثيرات البيئية المختلفة. نتائج تقييم الأداء البيئى لطريقتى المعالجة لمياه الصرف الصحى الملوثة بالفينول اظهرت ان طريقة فنتون الضوئية الشمسية أقل ضررا للبيئة من طريقة التحفيز الضوئي الشمسي.

***Abstract*— This research aims to compare the environmental performance of two methods for phenolic wastewater treatment. The two methods are solar photo-Fenton and solar photocatalysis by TiO_2. A case study of 100 m^3/d of wastewater contaminated with 100 mg/l of phenol was considered, whereas the functional unit was one cubic meter of treated wastewater. The life cycle inventory included the materials and energy required in both construction and operating phases. The effects of the by-products from phenol oxidation have been considered. The method "Impact 2002" was employed to calculate the different impacts of the two methods. The results showed that solar photo-Fenton is causing less environmental impacts due to the lower effects of its chemical reagents.**

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I. INTRODUCTION

PHENOL is a very harmful and toxic material that is resulted from a lot of industries as plastics, pharmaceuticals, paint, and textiles. Biological treatment was not an effective method for phenolic wastewater treatment. Accordingly, chemical treatment methods were considered in recent studies. It is worthy to note that the phenol removal by using chemical methods was the main indicator of the treatment performance, whereas, the trade-offs for other environmental impacts resulted from chemical methods were not considered in the literature.

Life cycle assessment (LCA) is a universal technique for determination of specific environmental impacts from the start of the treatment process to the end (i.e. cradle to grave) [1][2]. LCA could be utilized as a decision-making tool for waste management because it offers elaborate insights into the environmental impacts of different alternatives including the contribution of all incorporated activities [3].

Consequently, this study aims to investigate and compare the environmental impacts of two common chemical methods for phenolic waste treatment (i.e. photo-Fenton and photocatalysis) [4]–[6]. The calculation of the environmental impacts on different categories was performed on life cycle assessment (LCA) basis [7]. The determination and interpretation of the environmental impacts was carried out using Simapro 7 software. The database Ecoinvent 2 was used to identify the contribution of materials and processes to the environmental impacts and comparing them with each other [8].

II. Methodology

A. Goal and scope

This research aims to study and compare the environmental impacts of solar photo-Fenton and TiO_2 photocatalysis. As shown in Table 1, the used reactor in the solar photo-Fenton method is compound parabolic collectors 700m and the time of reaction is 80 min [9]. In solar photocatalysis, the used reactor is composed of compound parabolic collectors of 2060 m length and the time of reaction is 250 min [10]. In solar photo-Fenton method, the percentage of phenol removal was 99%, whereas in solar photocatalysis it was 80%.

TABLE I
THE TWO TECHNOLOGIES FOR PHENOLIC WASTEWATER TREATMENT

technology	Reactor	Time of reaction (min)	Percentage of phenol removal	Reference
Solar photo-Fenton	Compound parabolic collectors 700 m	80	99%	[9]
Solar photocatalysis by TiO_2	Compound parabolic collectors 2060 m	250	80%	[10]

B. Reactors

Photo-Fenton and photocatalysis processes reactors as illustrated in Fig. 1 [10].

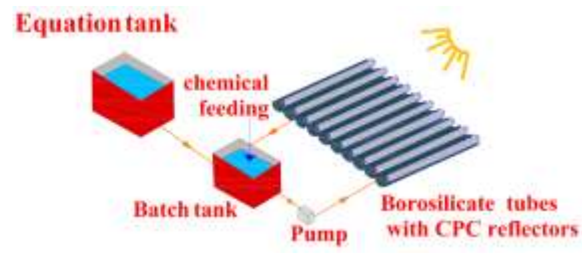


Fig. 1. Photo-Fenton and photocatalysis processes reactors.

C. Life cycle inventory

The functional unit which used in the two methods was 1 m^3 of the phenol solution with a concentration of 100 mg/l. The construction and operation phases were taken into account. The study boundary included the equalization tank, treatment reactor, chemicals addition, energy consumption, the remaining transformation products, sludge in the effluent, and the emitted CO_2 which is emitted due to the oxidation of phenol. The different inputs, outputs, and energy forms are illustrated in Fig. 2 [9],[10]. The life span of the reactors has been assumed as 20 years includes equalization and chemical feeding tanks. The life cycle inventories have been estimated based on the hydraulic designs of all reactors, which have been provided the reactor sizing, and the amounts of materials needed in the construction phase. A summary of the inventories of the two methods of treatment is illustrated in Table II [9],[10].

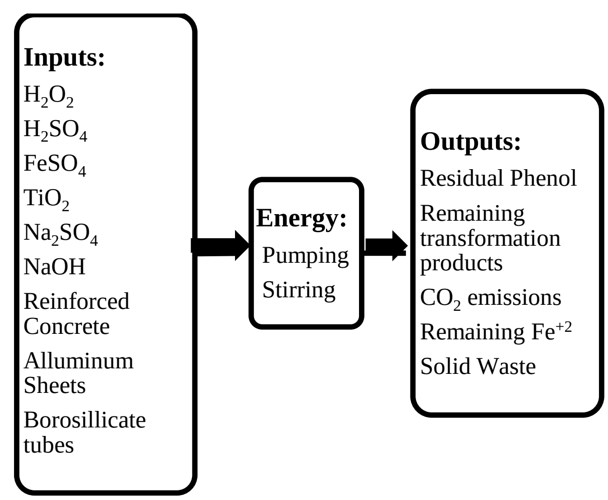


Fig. 2. Life cycle inventory

TABLE II
LIFE CYCLE INVENTORY

materials	UNIT	Solar Photocatalysis By TiO_2	Solar Photo-Fenton
Inputs:			
Hydrogen peroxide	kg	-	1.5
Sulfuric acid	gm	0.3	45
Ferrous sulphate	gm	-	490
Titanium dioxide	kg	0.4	-
Sodium hydroxide	gm	0.3	50
Reinforced-Concrete	gm	17	17
Glass tube, borosillicate	gm	1.25	0.45
aluminum sheets	gm	0.2	0.06
Process:			
mixing	kw	0.38	0.13
pump	kw	6.6	2.2
outputs:			
Fe^{+2}	gm	-	10
Phenol	gm	20	0.2
CO_2	gm	60	80
Catechol	gm	7	8
Hydroquinone	gm	2	2.5
Formic acid	gm	32	40
Benzoquinone	gm	3	4

Mixing is consumed by $E = G^2 \mu V T$

Where E: the energy consumption, G: the average velocity gradient inside the tank, V: the tank volume, and T: the retention time of wastewater.

The friction head loss in the tubes calculated by

$$Q = 0.355\ C\ D^{0.63}\ A\ \left[\frac{H_f}{L}\right]^{0.54}$$

and The bending head loss was calculated by

$$H_b = \frac{L}{10} \times k_b \frac{v^2}{2\,g}$$

and the consumed energy calculated by

$$E = \frac{\gamma\ Q\ H_t\ T}{75\ \eta_1\ \eta_2} \times \frac{745.7\ \text{Watt}}{1\ \text{Horse Power}}$$

Where Q: flow rate inside the tubes, C: the friction coefficient of glass, D: the diameter of the pipes, A: the cross-sectional area of the pipes, H_f: the friction head loss, L: the length of the pipes, H_b: the bending head loss, v: the water velocity inside the pipes, g: the acceleration due to the gravity, γ: the specific weight of water, H_t: total losses (H_f+ H_b), and η_i: operation coefficients.

D. Phenol transformation

The phenol is transformed to catechol and hydroquinone [10],[11]. Then, hydroquinone and catechol are transformed into other components [12]. Some of these components were transformed into water and carbon dioxide so they weren't assumed as emissions because water and carbon dioxide have no impacts in the Ecoinvent database.

E. LCA method

The environmental impacts were calculated using IMPACT 2002 method [13]. The categories impacts as carcinogenic, Non-carcinogenic, respiratory inorganics, Ionizing radiation, ozone layer depletion, respiratory organics, Aquatic ecotoxicity, Terrestrial ecotoxicity, Terrestrial acid and land occupation, aquatic acidification, aquatic eutrophication, global warming, non-renewable energy, Mineral extraction was calculated using the Ecoinvent 2.2 database [14]. The SimaPro® 7.1 software was used to analyze the impacts.

III. RESULTS AND DISCUSSION

A. Comparison of methods

Table 3 shows the environmental impacts of solar photo-Fenton and TiO_2 photocatalysis. A comparison by simapro7 between the environmental impacts of solar photo-Fenton and TiO_2 photocatalysis are shown in Fig.4 (a) and Fig.4 (b). The TiO_2 photocatalysis process causes a lot of harmful environmental emissions so solar photo-Fenton is better to the environment than TiO_2 photocatalysis. In TiO_2 photocatalysis method, the results of carcinogenic, respiratory organics, aquatic eutrophication, Mineral extraction categories are lower than their results in solar photo-Fenton but the results from other categories as Non-carcinogenic, respiratory inorganics, Ionizing radiation, ozone layer depletion, Aquatic ecotoxicity, terrestrial ecotoxicity, Terrestrial acid and land occupation, aquatic acidification, global warming, non-renewable energy are higher in TiO_2 photocatalysis process. So, solar photo-Fenton process is better in phenolic wastewater treatment. The same results were shown in single score impacts comparison by EDIP 2003 as in Fig. 5.

TABLE III
ENVIRONMENTAL IMPACTS OF DIFFERENT TECHNOLOGIES

Impact category	UNIT	Photo-Fenton	Photo-catalysis
carcinogens	kg C_2H_2Cl eq	0.707	0.0247
Non-carcinogens	kg C_2H_2Cl eq	0.0344	0.035
respiratory inorganics	kg $PM_{2.5}$ eq	0.00145	0.00251
Ionizing radiation	Bq C-14 eq	404	1.06E3
Ozone layer depletion	kg CFC-11 eq	7.64E-7	1.82E-6
respiratory organics	kg C_2H_4 eq	0.0014	0.000931
Aquatic ecotoxicity	kg TEG water	982	1.93E3
Terrestrial ecotoxicity	kg TEG soil	21.2	26.6
Terrestrial acid	kg SO_2 eq	0.0283	0.0553
land occupation	M_2org.arable	0.0932	0.256
aquatic acidification	Kg SO_2.eq	0.01	0.0204
aquatic eutrophication	Kg PO_4 p-lim	0.000174	0.000146
global warming	Kg CO_2.eq	2.4	3.03
non-renewable energy	MJ primary	72.7	127
Mineral extraction	MJ surplus	0.0596	0.031

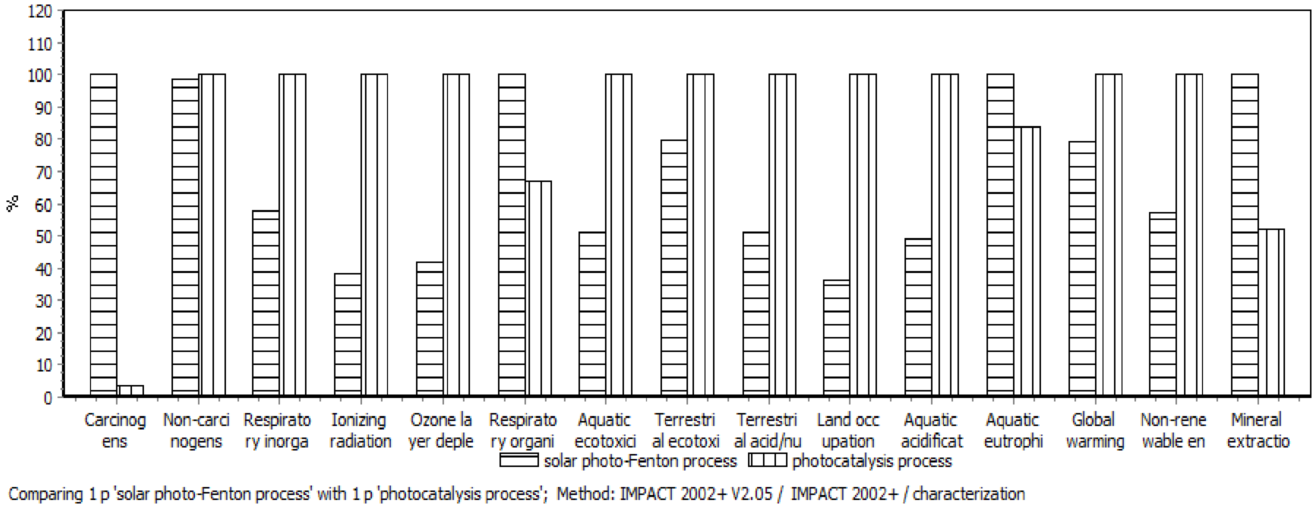


Fig. 4. Comparison between solar photo-Fenton process and photocatalysis process; (a) characterization,

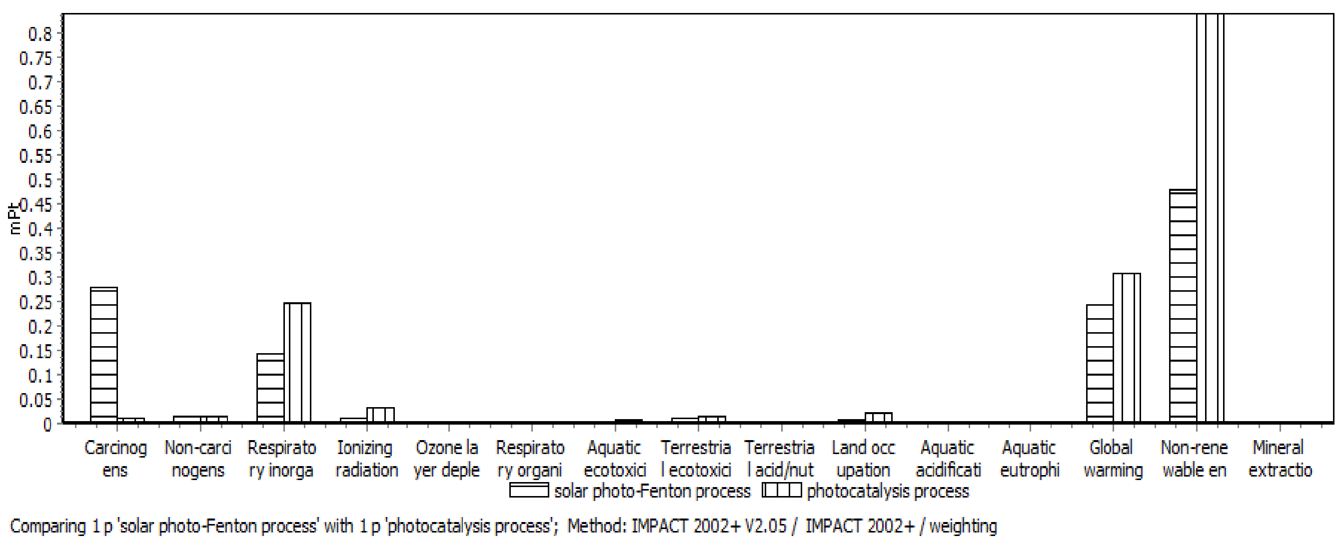


Fig. 4. Comparison between solar photo-Fenton process and photocatalysis process; (b) weighting

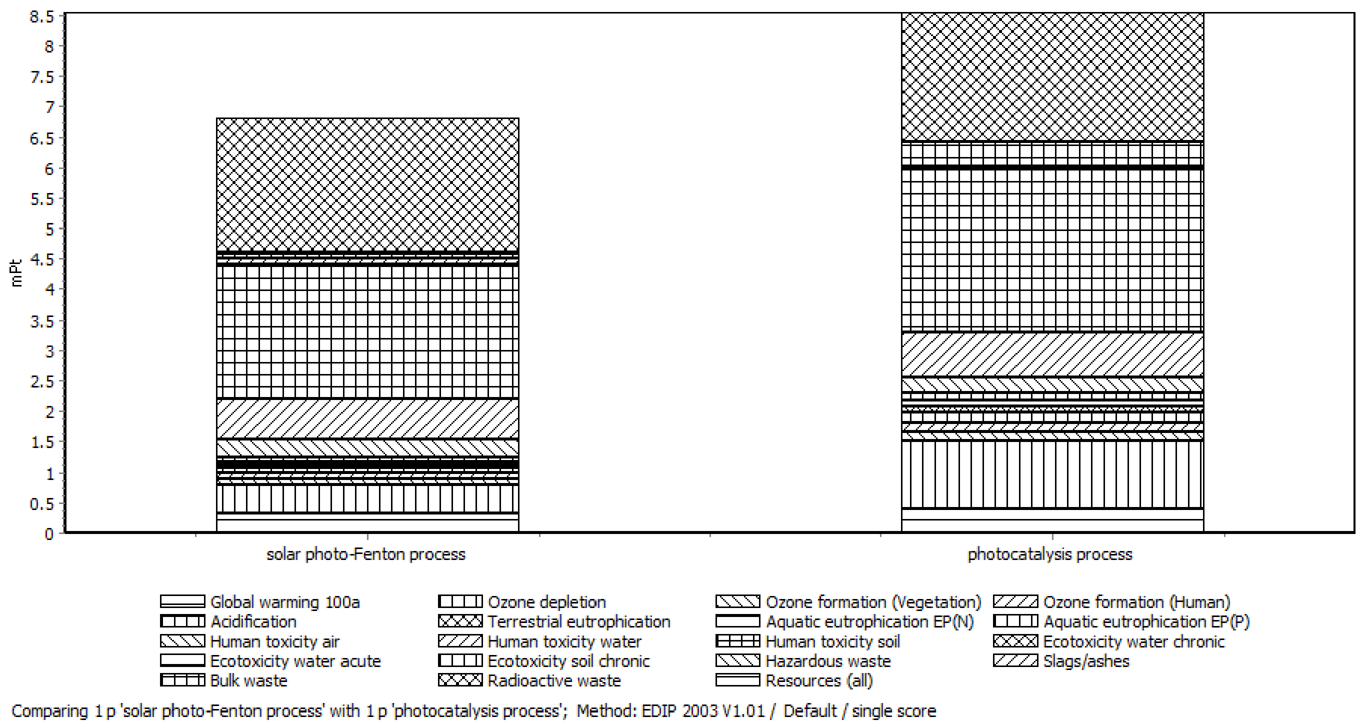


Fig. 5. Single score impacts by EDIP 2003

B. Interpretation of result

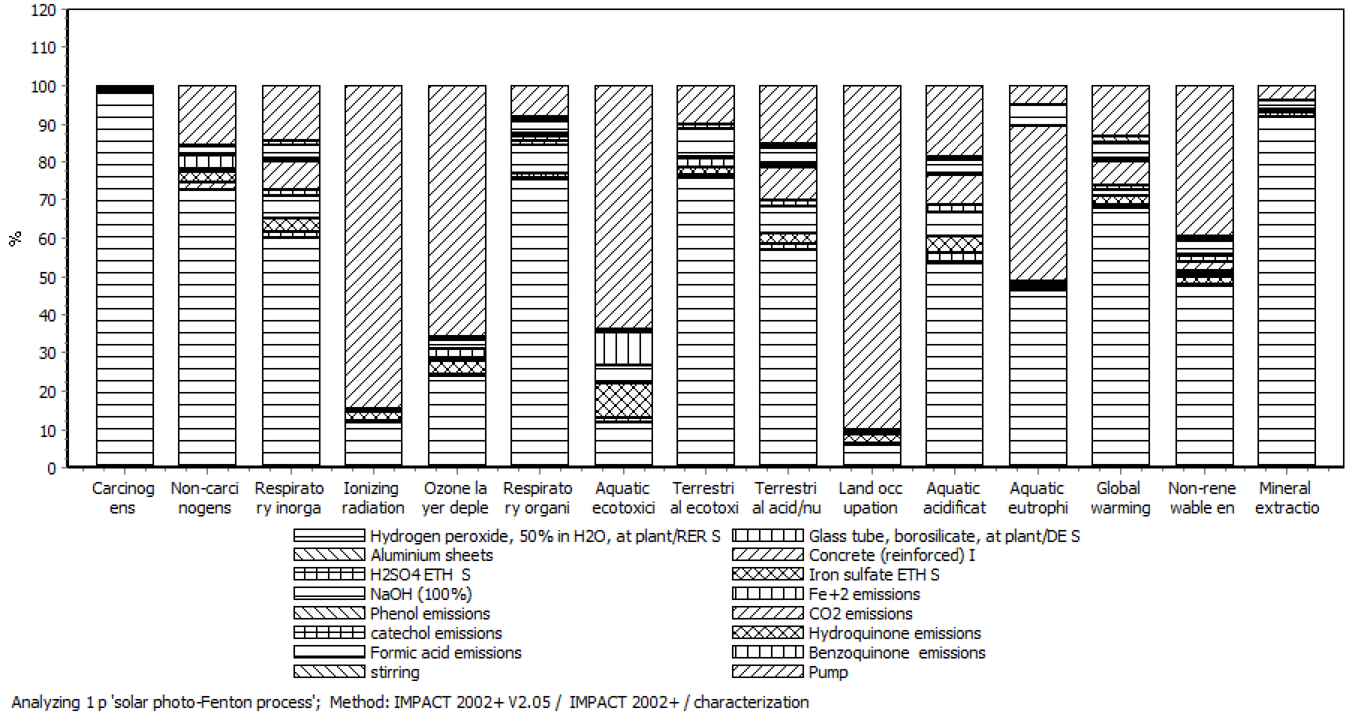
1) Solar Photo-Fenton

The Photo-Fenton process is the most eco-friendly process because of using solar radiation as an energy source. And its high performance for removal of phenol leads to lower emissions in the effluent. Electricity caused most impact categories as shown in Fig.6 (a) [9].

2) TiO_2 photocatalysis

TiO_2 is the main responsible for most impact categories [15]. TiO_2 causes more than 75% to the results of carcinogens, Non-carcinogens, Respiratory inorganics, Respiratory organics, Terrestrial ecotoxicity, Terrestrial acid, Aquatic acidification and Mineral extraction. The residual phenol is the main contributor to Ionizing radiation, Ozone layer depletion, Aquatic ecotoxicity, and land occupation. Other materials contribute to impact categories but with insignificant percentage, as shown in Fig.6 (b) [10].

(a)



(b)

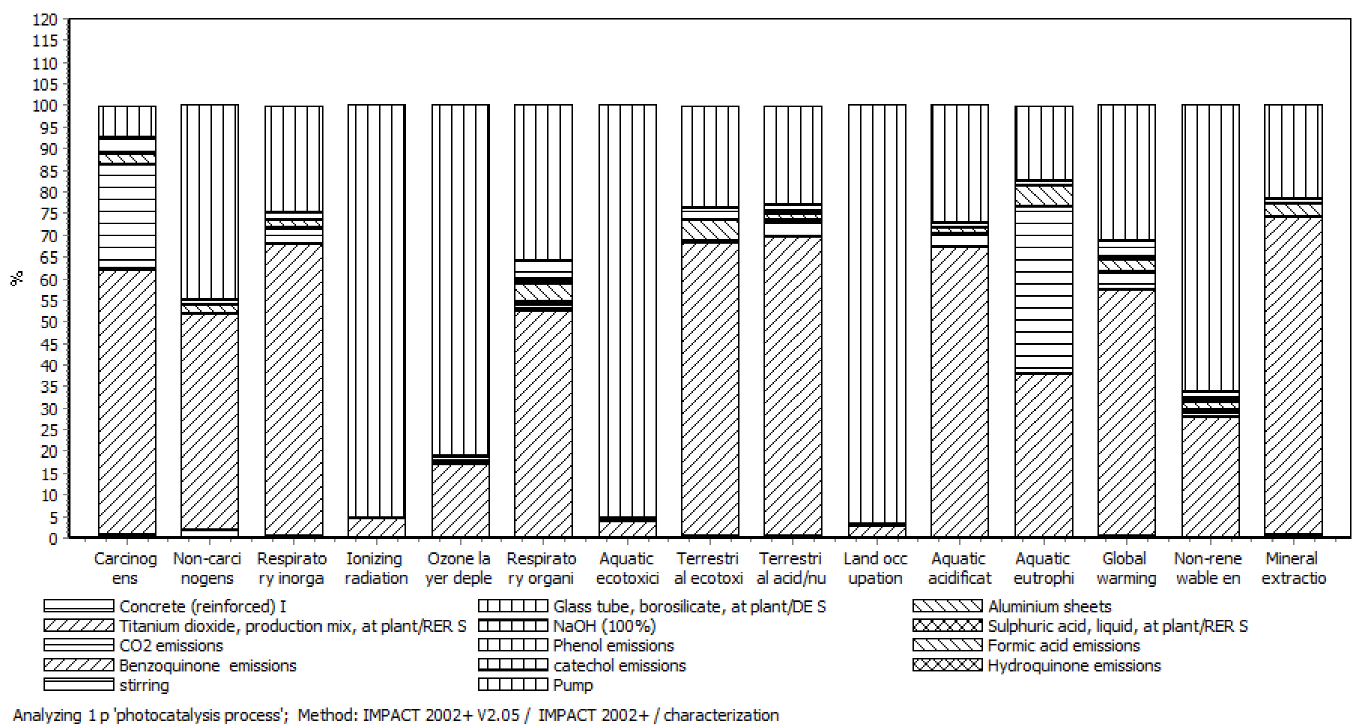


Fig.6 Contribution of inventory in environmental impacts (a) photo-Fenton (b)Photocatalysis

IV. Conclusion

The goal of this research is to study and interpret the environmental impacts of two methods for the treatment of phenolic wastewater. The two methods of treatment are solar photo-Fenton and solar photocatalysis using TiO_2. The solar photo-Fenton process was an eco-friendly method because it caused low harmful environmental impacts per all categories of the IMPACT 2002 method. In TiO_2 photocatalysis method, TiO_2 increased the potentials of carcinogens, Non-carcinogens, Respiratory inorganics, Respiratory organics, Terrestrial ecotoxicity, Terrestrial acid, Aquatic acidification, and Mineral extraction. Eco-friendly materials should be used to reach an eco-friendly performance of chemical treatment methods of phenolic wastewater.

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