Journal of Environmental Chemical Engineering 4 (2016) 719–732

Contents lists available at ScienceDirect

Journal of Environmental Chemical Engineering

journal homepage: www.elsevier.com/locate/jece

Photochemical degradation of an actual slaughterhouse wastewater by continuous UV/H_2O_2 photoreactor with recycle

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ARTICLE INFO

Article history:
Received 20 July 2015
Received in revised form 6 November 2015
Accepted 7 December 2015
Available online 10 December 2015

Keywords:
Slaughterhouse wastewater
Advanced oxidation processes
Recycle effect
UV/H_2O_2
Central composite design
Experimental design

ABSTRACT

Slaughterhouse wastewater is treated using the UV/H_2O_2 process in a continuous photoreactor with recycle, in which the effect of the recycle ratio (the ratio of recycle flow rate to the main feed flow rate) on the photoreactor efficiency is investigated. A four-factor, five-level central composite design along with response surface methodology is used to maximize the total organic carbon removal from an actual slaughterhouse wastewater and minimize the H_2O_2 residual in the effluent. The effects of the flow rate and the influent concentrations of total organic carbon and H_2O_2 on the photodegradation of the actual slaughterhouse wastewater are also investigated. Statistical models are developed to predict both the total organic carbon removal and the H_2O_2 residual as response variables. The recycle ratio is found to be significant in minimizing the H_2O_2 residual and the cross-factor interactions of recycle ratio with other variables demonstrate a significant effect on both total organic carbon removal and H_2O_2 residual. A maximum total organic carbon removal of 81% and a minimum H_2O_2 residual of less than 2% are found at optimum operating conditions of 24 mg/L influent total organic carbon, 860 mg/L influent H_2O_2 concentration, 15 mL/min flow rate, and 0.18 recycle ratio. The model is validated under optimal operating conditions based on the experimental design results. The good agreement between model predictions and experimental values indicates that the proposed model could successfully describe the photochemical treatment of actual slaughterhouse wastewater by the continuous UV/H_2O_2 process with recycle and its applicability as a post-treatment method.

1. Introduction

The global production of beef, pork, and poultry meat has been doubled in the past decade and is projected to steadily grow until 2050. Furthermore, the number of slaughterhouse facilities are increasing, which results in an expected higher volume of slaughterhouse wastewater (SWW) to be treated. The SWW is typically assessed in terms of bulk parameters because of the diverse pollutant loads in the SWW derived from the type and number of animals slaughtered that fluctuate amid the meat industry [1]. SWW usually contain high levels of organics and nutrients, expressed as bulk components such as biochemical oxygen demand (BOD), chemical oxygen demand (COD), and total organic carbon (TOC). Thus, SWW is considered detrimental worldwide, and on-site treatment would be the best option to treat and disinfect the effluents to be discharged safely into receiving waters [1–5].

Advanced oxidation processes (AOPs) are becoming an attractive alternative over conventional treatment and a complimentary treatment option, as either pretreatment or post-treatment, to current biological processes for SWW treatment [3–9]. Furthermore, AOPs may inactivate microorganisms without adding additional chemicals to the SWW, avoiding the formation of hazardous by-products [6–10].

Several AOPs have been tested for SWW treatment including ozonation, gamma radiation, and UV/H_2O_2 [5–12]. However, the UV/H_2O_2 process has been found to be more efficient for SWW treatment. The UV/H_2O_2 process is five times faster in inactivation and inhibition of microorganisms as well as in degrading aromatic compounds than those of other technologies. Removal efficiencies of up to 97, 95, and 75% could be achieved by the UV/H_2O_2 process for COD, BOD, and TOC, respectively [3–9]. Thus, AOPs might be considered to enhance the SWW quality for water reuse purposes.

On the other hand, AOPs are considered multifactor systems due to the interaction of several parameters including organics

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http://dx.doi.org/10.1016/j.jece.2015.12.009
2213-3437/

Nomenclature

c	Residual term
C_{H2O2in}	Hydrogen peroxide concentration in the influent
C_{H2O2M}	Hydrogen peroxide concentration entering the photoreactor
$C_{H2O2out}$	Hydrogen peroxide concentration in the effluent
C_{SWWin}	Slaughterhouse wastewater concentration in the influent
C_{SWWM}	Slaughterhouse wastewater concentration entering the photoreactor
C_{SWWout}	Slaughterhouse wastewater concentration in the effluent
D	Desirability objective function
d_i	Response range i
d_1	Total organic carbon removal response range
d_2	H_2O_2 residual response range
df	Degrees of freedom
E	Einstein unit
F-value	Fisher's exact test value
k	Number of factors
n	Number of responses in the measure
p-value	Probability value
Q	Flow rate
r	Recycle ratio
R^2	Coefficient of determination
TOC_{in}	Influent TOC concentration
X_i	Independent variable i
X_j	Independent variable j
X_1	Influent concentration of TOC
X_2	Influent H_2O_2 concentration
X_3	Flow rate
X_4	Recycle ratio
Y	Predicted response
Y_1	Total organic carbon removal
Y_2	H_2O_2 residual

Greek letters

α	Significance level
β_o	Constant coefficient of the statistical model
β_i	Linear coefficients of the statistical model
β_{ii}	Quadratic coefficients of the statistical model
β_{ij}	Interaction coefficients of the statistical model

Acronyms

3D	Three-dimensional
2D	Two-dimensional
ANOVA	Analysis of variance
AOP	Advanced oxidation process
BOD	Biochemical oxygen demand
CCD	Central composite design
CI	Confidence intervals
COD	Chemical oxygen demand
DOE	Design of experiments
DW	Distilled water
LVREA	Local volumetric rate of energy absorption
OMAFRA	Ontario Ministry of Agricultural and Rural Affairs
RSM	Response surface methodology
SS	Sum of squares
SWW	Slaughterhouse wastewater
TOC	Total organic carbon
UV	Ultraviolet light

concentration, light source intensity, oxidant concentration, reaction time, pH, and output power. Therefore, the characterization of such systems requires the consideration of cross-factor and single-factor effects using the design of experiments (DOE) to identify those factors that influence the multivariable system [13].

The optimization of parameters by conventional methods needs time, materials, and a large number of experiments. On the other hand, parameters such as H_2O_2 residuals, known to be toxic to microorganisms in biological post-treatment, and recycle ratio, known as the ratio of recycle flow rate to the main feed flow rate, are not widely investigated. Moreover, conventional methods fail to consider the combined effects of all the factors involved. Therefore, a DOE is used to overcome the limitations of conventional methods and consequently optimize the factors involved. Conversely, the response surface methodology (RSM) has been recognized to be statistically reliable to analyze multifactor systems in chemical treatment processes. RSM considers cross-factor interactions to attain optimal responses using the minimum number of experiments [13–15].

In this study, the effects of the recycle ratio, the flow rate, and the influent concentrations of TOC and H_2O_2, and their interactions on the photochemical treatment of SWW in a UV/H_2O_2 photoreactor with recycle were investigated to evaluate its feasibility as a post-treatment method. The DOE was used to optimize the photochemical treatment of the SWW using UV/H_2O_2 process in a continuous photoreactor with recycle by maximizing the TOC removal and minimizing the H_2O_2 residual in the effluent. The optimal parametric values for the DOE were obtained using a central composite design (CCD) using four factors at five levels combined with RSM. Statistical models were also developed to predict both percent TOC removal and H_2O_2 residual as response variables by the UV/H_2O_2 process. As a final point, the statistical models were validated by an additional set of experiments carried out at optimum conditions according to the DOE results.

2. Materials and methods

2.1. Materials

Actual SWW samples were taken from selected provincially licensed meat-processing plants directly from their source in Ontario, Canada, at the time of the study [16]. SWW samples had an average TOC concentration of 862 mg/L. Table 1 shows the overall SWW characteristics from the selected provincially licensed meat processing plants [5]. Three out of ten sample sites were used in this study due to the TOC low range of the slaughterhouse wastewater effluents obtained from the meat-processing plants (11–94 mg/L). Distilled water (DW) was used to dilute SWW samples in order to adjust the influent TOC concentrations to different CCD levels accordingly. A hydrogen peroxide solution (30% w/w) was purchased from Sigma-Aldrich and used as received.

Table 1
Characteristics of the actual slaughterhouse wastewater from selected provincially licensed meat processing plants along with study range values and detection limits.

Parameter	Range	Mean	Study range	Detection limits
BOD (mg/L)	37.95–8,231	2,649	37.95–339.5	0.000–10,000
COD (mg/L)	87.23–14,256	5,577	87.23–780.4	0.000–15,000
TN (mg/L)	6.120–339.2	156.4	6.120–54.74	0.100–25,000
TOC (mg/L)	10.51–1,718	86.21	10.51–94.01	0.100–25,000
TP (mg/L)	2.570–77.31	4.281	2.570–22.98	0.020–125.00
TSS (mg/L)	0.390–738.0	309.2	0.390–103.5	0.000–750.00
pH	6.0–7.1	6.9	6.8–7.0	4.0–10