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Slaughterhouse Wastewater Characterization and Treatment: An Economic and Public Health Necessity of the Meat Processing Industry in Ontario, Canada

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Abstract

The characteristics of the slaughterhouse effluents and current wastewater treatment practices in the province of Ontario, Canada are analyzed. Meat processing plants are found to produce large amounts of wastewater due to the slaughtering process and cleaning of their facilities. Furthermore, the composition of the wastewater varies according to the type and number of animals slaughtered and the water requirements of the process. However, the slaughterhouse wastewater usually contains high levels of organics and nutrients. Several slaughterhouses in Ontario discharge their wastewater into the municipal sewer system after primary pretreatment at the meat processing plant. Therefore, due to the high-strength characteristics of the slaughterhouse effluents, an extensive treatment for a safe discharge into the environment is required. Thus, the combination of biological processes and advanced oxidation technologies for slaughterhouse wastewater treatment is evaluated in this study. Results show that the application of combined biological and advanced oxidation processes is recommended for on-site slaughterhouse wastewater treatment.

Keywords

Slaughterhouse Wastewater, Anaerobic Digestion, Activated Sludge, Advanced Oxidation Processes

1. Introduction

The treatment of water and wastewater has become crucial due to the continuous growth of world population

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and the pollution of freshwater because of not adequately treated wastewater discharged into environment, especially in developing countries [1]. Besides, the decreasing availability of freshwater has redirected the objectives in the area of wastewater treatment to recycling and reuse. Nevertheless, diverse techniques are adopted for water and wastewater treatment depending on the differences in geographic location, financial resources, living standards, and life quality in different countries, as well as the characteristics of the wastewater effluents and pollutants [2].

The meat processing industry produces large volumes of Slaughterhouse Wastewater (SWW) from the slaughtering of animals and cleaning of the slaughterhouse facilities. Up to 24% of the water used in the food and beverage industry is from the meat processing [3]. Slaughterhouses and Meat Processing Plants (MPPs) are part of a large industry worldwide, where the composition of the wastewater depends on the diverse practices in the slaughtering process. Consequently, SWW requires significant treatment for a safe and sustainable release to the environment [1].

According to Mittal [4], slaughterhouses in Ontario, Canada, typically discharge the SWW into the municipal sewer system after a preliminary treatment. Thus, slaughterhouses commonly pay surcharges, penalties, or fines to dispose their effluents into receiving municipal wastewater treatment plants. Moreover, there are currently 134 MPPs in Ontario that can process 100 - 200 animals per month. Approximately 53% of Ontario's slaughterhouses do not treat their wastewater on-site before disposal. Dissolved Air Flotation (DAF) or aeration is the typical method of preliminary treatment with 16% of Ontario's slaughterhouses using it at their facilities. The rest of slaughterhouses (31%) use passive methods such as lagoons or storage tanks to settle solids (**Figure 1**) [1].

Direct discharge of untreated slaughterhouse effluents to a water body is not practical due to the high organic load of the SWW. Therefore, appropriated disposal and treatment is required. It may be also stated that in terms of operation and economics, it is beneficial to implement combined processes for the management of slaughterhouse effluents since it couples the benefit of different technologies to improve high strength industrial wastewater treatment [5].

Advantages of the combined processes include potential energy recovery from the conversion of organic pollutants into biogas with high overall treatment efficiency [5]. However, SWWs may contain toxic and non-biodegradable organic substances which make biological treatment alone insufficient [1]. Thus, Advanced Oxidation Processes (AOPs) are used to improve the bio-treatability of wastewaters containing non-biodegradable organics, which are toxic to common microorganisms. AOPs are becoming an attractive alternative to conventional treatment methods and a complimentary treatment option to biological processes in SWW treatment. Furthermore, AOPs can inactivate microorganisms for disinfection while avoiding the formation of hazardous by-products [6].

This study aims to identify the characteristics of the slaughterhouse wastewater in Ontario, Canada and discuss possible treatment alternatives to minimize the impact of the discharge of these wastewaters to the environment, and to optimize processes for organics and nutrient removal, including combined biological treatment

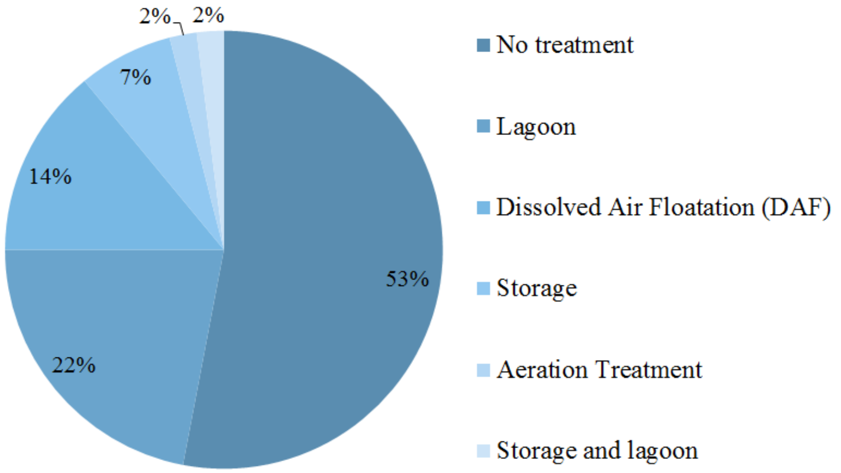

Figure 1. Slaughterhouse wastewater treatment systems in Ontario.

and AOPs for water reuse. Consequently, the effects of the influent concentration of TOC, flow rate, pH, H_2O_2 dosage, and their interactions on the overall treatment efficiency of the combined anaerobic-aerobic and UV/ H_2O_2 process and the effluent H_2O_2 residual concentration were investigated using the Design of Experiments (DOE) to optimize the combined processes in continuous mode at laboratory scale for SWW treatment. Statistical models were also developed to predict the percent TOC removal and the effluent concentration of H_2O_2 as response variables. The statistical models were validated by an additional set of experiments at the optimum conditions in line with 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 [7]. A 30% w/w hydrogen peroxide solution was purchased from Sigma-Aldrich, whereas NaOH (99%) and H_2SO_4 (99%) were obtained from EMD Millipore for pH adjustment.

2.2. Slaughterhouse Wastewater Characteristics

The main source of SWW is the feces, urine, blood, lint, fat, carcasses, and non-digested food in the intestines of the slaughtered animals, the production leftovers, and the cleaning of the facilities [8]. The SWW composition varies according to the industrial process and water demand. Nevertheless, they usually contain high levels of organics and nutrients, typically measured as biochemical oxygen demand (BOD), chemical oxygen demand (COD), total organic carbon (TOC), total suspended solids (TSS), total nitrogen (TN), and phosphorus (TP).

Slaughterhouse effluents are considered detrimental worldwide due to its complex composition of fats, proteins, and fibers, as well as the presence of organics, nutrients, pathogenic and non-pathogenic microorganisms, detergents and disinfectants used for cleaning activities, and pharmaceuticals for veterinary purposes [9]. Therefore, the treatment and disposal of wastewater from slaughterhouses and meat processing plants are an economic and public health necessity [10]. **Table 1** attempts to summarize the typical characteristics of the slaughterhouse effluents in Ontario, Canada. The SWW features and common ranges are listed as BOD, COD, TOC, TSS, TN, and pH.

2.3. Experimental Setup and Procedure

An anaerobic baffled reactor (ABR), followed by an aerobic activated sludge (AS) reactor, and a UV/H_2O_2 photoreactor, operated in continuous mode, were used in a combined system at the laboratory scale for SWW treatment. The schematic diagram of the experimental setup for the combined ABR-AS-UV/H_2O_2 processes is illustrated in **Figure 2**.

Table 1. Common characteristics of slaughterhouse wastewater.

Parameter	Range	Average
BOD (mg/L)	610 - 4635	1209
Ca (mg/L)	32 - 316	67
COD (mg/L)	1250 - 15,900	4221
K (mg/L)	0.01 - 100	90
Na (mg/L)	62 - 833	621
Pb (mg/L)	0.21 - 34	4
TN (mg/L)	50 - 841	427
TOC (mg/L)	100 - 1200	546
TP (mg/L)	25 - 200	50
TSS (mg/L)	300 - 2800	1164
pH	4.90 - 8.10	6.95

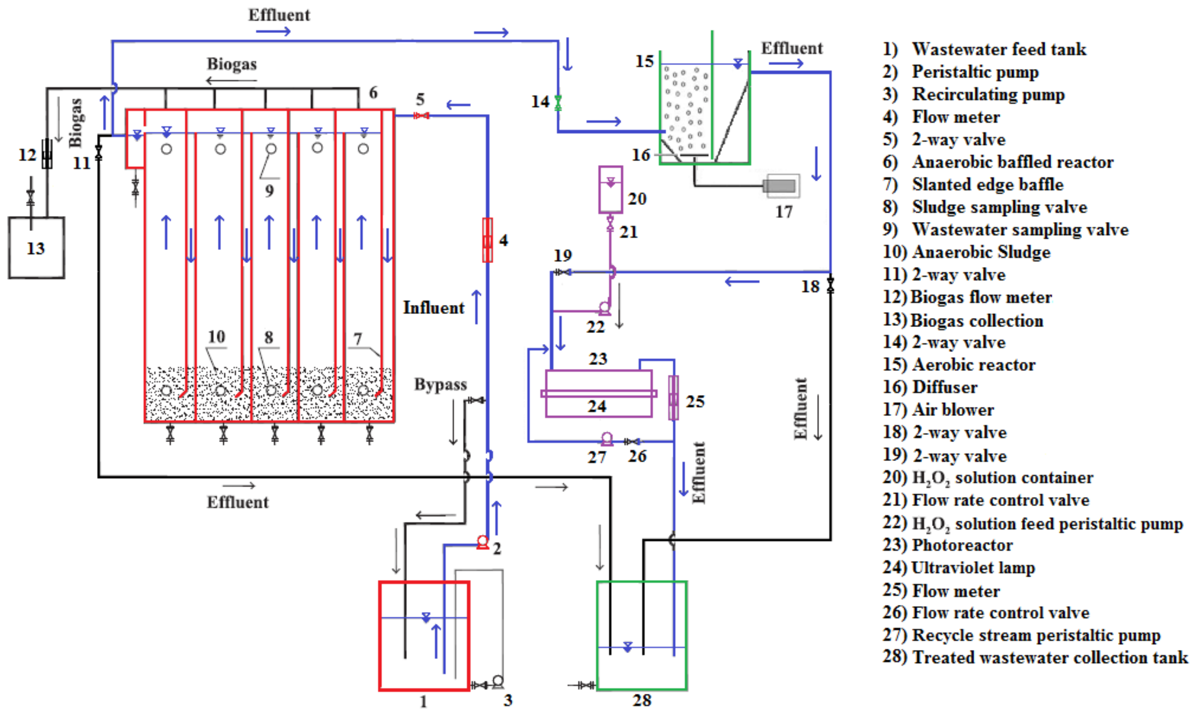

Figure 2. Schematic diagram of the combined anaerobic, aerobic and UV/H_2O_2 processes for the treatment of SWW.

The 50 L combined ABR-AS-UV/H_2O_2system consisted of a 36-L ABR with five equal-volume chambers integrated with individual headspaces, biogas collection piping, and a 13-L aerobic AS reactor with a monitored air flow rate, and a 1-L photoreactor with recycle and uniform light distribution. A 45˚ slanted-edge baffle within each ABR chamber permits the down- and up-flow of the SWW, providing effective mixing and contact time between the SWW and the biomass. The AS air flow rate was set at 2 L/min to guarantee nitrifying bacteria growth and dissolved oxygen (DO) concentrations over 2.0 mg/L.

Anaerobic and aerobic sludge seeds were loaded into the anaerobic and aerobic bioreactors, respectively. The inoculum was acclimatized in two months by feeding the actual SWW continuously into the reactors at a constant flow rate (75 mL/min) while gradually increasing its concentration.

The stainless steel cylindrical photoreactor (Barrier SL-1S-Siemens Inc., Markham, ON) had an external diameter of 8 cm and a length of 34 cm with a 2.5 cm diameter UV-C lamp and output power of 6 W with 254 nm wavelength was inserted into the center of the photoreactor. A quartz sleeve covered the UV-C lamp to protect the lamp from fouling and maintain a uniform UV radiation emission.

TOC concentrations were analyzed for each sample using an automated TOC analyzer (Teledyne Tekmar Apollo 9000, Mason, OH). Temperature and pH were measured daily using a pH meter with atemperature probe (Thermo Scientific Orion 230A+, Ottawa, ON). The H_2O_2 residuals were measured with a UV-Visible Spectrophotometer (Ultrospec 1100 pro-Amersham Biosciences, Amersham, UK) at 454 nm using neocuproine and copper [11]. All experiments were repeated in triplicates, and the average values were reported. Furthermore, three replicates were made for each analytical measurement.

2.4. Experimental Design and Optimization

A four-factor along with five-level CCD in conjunction with RSM was used to maximize percent TOC removal and minimize percent H_2O_2 residuals in the effluent. The influent concentration of TOC (X_1), flow rate (X_2), H_2O_2 dosage (X_3), and pH (X_4) were used as independent factors in the DOE; whereas, the percent TOC removal (Y_1) and H_2O_2 residual (Y_2) were considered process responses. Thus, each factor was coded at five levels, from −2 to +2, as shown in **Table 2**. Previous studies [1] [7] [11] [12] were used to determine and select the critical ranges of the factors.

Equation (1) was used to predict the model responses as a quadratic model and estimate the parametrical

Table 2. Independent variables with coded levels based on a four-factor, five level CCD.

Independent variable	Symbol	Coded levels				
		−2	−1	0	1	2
TOC_{in} (mg/L)	X_1	50	450	850	1250	1650
Flow rate (mL/min)	X_2	15	45	75	105	135
$H_2O_{2,in}$ (mg/L)	X_3	100	300	500	700	900
pH	X_4	3	5	7	9	11

coefficients by correlating dependent and independent variables using the least-squares regression [11]:

$$Y = \beta_o + \sum_{i=1}^{k}\beta_i X_i + \sum_{i=1}^{k}\beta_{ii} X_i^2 + \sum_{i=1}^{k-1}\sum_{j=2}^{k}\beta_{ij} X_i X_j + c \quad (1)$$

where β_o, β_i, β_{ii}, and β_{ij} are the constant, linear, quadratic, and cross-factor interaction coefficients, respectively; X_i and X_j represent the independent variables; Y_i is the predicted response; and c and k are the residual term and the number of factors, respectively.

The Design-Expert 9.0.4.1 statistical software was employed for graphical and regression analysis to estimate the coefficients of the response functions. The significance of the independent variables, factor interactions, and model equations were examined by analysis of variance (ANOVA) at 95% confidence intervals (CI).

Three-dimensional (3D) surfaces and two-dimensional (2D) contour plots were obtained while keeping another factor constant in the quadratic models. Experiments were carried out to validate the statistical models for maximum percent TOC removal and minimum H_2O_2 residual.

Optimal operating conditions were estimated using the numerical optimization method built in the software. Lastly, an additional experimental run was carried out to validate the predicted optimal conditions for both response functions, the percent removal of TOC, and H_2O_2 residual.

The desirability multiple response method was used to combine the desirable ranges for each response to obtaining a simultaneous objective function that represents the geometric mean of all transformed responses as shown in Equation (2) [13]:

$$D = \left(d_1 \times d_2 \times \cdots \times d_n\right)^{1/n} = \left(\prod_{i-1}^{n} d_i\right)^{1/n} \quad (2)$$

where D, d_i, and n are the desirability objective function, each response range, and the number of responses, respectively. If any of the analyzed responses is found to be outside of their desirability range, the overall desirability function becomes zero. Therefore, for a simultaneous optimization, each response is required to be assigned low and high values for optimization. In this case, the percent removal of TOC (d_1) is maximized while the H_2O_2 residual (d_2) is minimized.

3. Results and Discussion

3.1. Experimental Design and Statistical Analysis

Table 3 portrays the four-factor, five-level CCD with observed and predicted values for both percent TOC removal and H_2O_2 residual by the developed quadratic models related to the combined ABR-AS-UV/H_2O_2 system in a continuous photoreactor for SWW treatment.

RSM was employed for parameter estimation, indicating the relationship between the input factors and the responses, as shown in Equation (2). Thus, to predict the response functions for percent TOC removal and H_2O_2 residual, the second-order polynomial Equations (3) and (4) were developed, respectively:

$$\begin{aligned} Y_1 = {} & 86.67 - 4.96X_1 - 0.59X_2 - 0.91X_3 - 1.82X_4 - 0.47X_1X_2 - 1.26X_1X_3 - 0.31X_1X_4 + 0.82X_2X_3 \\ & + 0.33X_2X_4 - 3.17X_3X_4 + 0.93X_1^2 - 0.02X_2^2 - 1.06X_3^2 - 1.88X_4^2 \end{aligned} \quad (3)$$

$$\begin{aligned} Y_2 = {} & 1.75 - 0.01X_1 + 0.17X_2 + 0.09X_3 + 0.05X_4 - 0.02X_1X_2 - 0.03X_1X_3 - 0.09X_1X_4 - 0.02X_2X_3 \\ & + 0.09X_2X_4 + 0.04X_3X_4 + 0.05X_1^2 - 0.01X_2^2 + 0.03X_3^2 + 0.04X_4^2 \end{aligned} \quad (4)$$

Table 3. Four-factor, five-level CCD with observed and predicted percent TOC removal and H_2O_2 residual.

Run	Independent coded variables				TOC removal (%)		H_2O_2 residual (%)	
	X_1	X_2	X_3	X_4	Observed	Predicted	Observed	Predicted
1	450	45	300	5	88.74	88.85	1.51	1.53
2	1250	45	300	5	83.11	83.01	1.78	1.78
3	450	105	300	5	86.64	86.33	1.74	1.77
4	1250	105	300	5	78.42	78.60	1.92	1.94
5	450	45	700	5	94.16	94.26	1.72	1.74
6	1250	45	700	5	83.29	83.37	1.84	1.87
7	450	105	700	5	95.51	95.01	1.91	1.91
8	1250	105	700	5	82.58	82.24	1.93	1.95
9	450	45	300	9	91.32	91.53	1.56	1.55
10	1250	45	300	9	84.25	84.46	1.42	1.46
11	450	105	300	9	90.68	90.31	2.14	2.15
12	1250	105	300	9	81.58	81.35	1.98	1.97
13	450	45	700	9	84.72	84.25	1.90	1.92
14	1250	45	700	9	71.97	72.14	1.71	1.69
15	450	105	700	9	86.34	86.30	2.42	2.44
16	1250	105	700	9	72.71	72.31	2.11	2.13
17	50	75	500	7	99.89	100.32	2.01	1.98
18	1650	75	500	7	80.48	80.48	1.95	1.93
19	850	15	500	7	88.15	87.78	1.39	1.37
20	850	135	500	7	84.63	85.42	2.08	2.05
21	850	75	100	7	84.31	84.24	1.71	1.69
22	850	75	900	7	80.11	80.60	2.09	2.06
23	850	75	500	3	82.62	82.79	1.84	1.80
24	850	75	500	11	75.28	75.53	2.01	2.00
25	850	75	500	7	86.85	86.67	1.73	1.75
26	850	75	500	7	85.95	86.67	1.73	1.75
27	850	75	500	7	86.81	86.67	1.75	1.75
28	850	75	500	7	86.30	86.67	1.76	1.75
29	850	75	500	7	87.53	86.67	1.78	1.75
30	850	75	500	7	86.60	86.67	1.75	1.75

Negative coefficients for the model components X_1, X_2, X_3, X_4, X_1X_2, X_1X_3, X_1X_4, X_3X_4, X_2^2, X_3^2, and X_4^2 in Y_1 and X_1, X_1X_2, X_1X_3, X_1X_4, X_2X_3, and X_2^2 in Y_2, indicate unfavorable effects on the percent TOC removal and the H_2O_2 residual, respectively. Whereas, positive coefficients for X_2X_3, X_2X_4, and X_1^2 in Y_1 and X_2, X_3, X_4, X_2X_4, X_3X_4, X_1^2, X_3^2, and X_4^2 in Y_2 indicate favorable effects on the percent TOC removal and the H_2O_2 residual, respectively. Since the coefficients with values close to zero represent lower relative intensity, X_2^2 do not intensely affect the TOC removal while X_1, X_1X_2, X_2X_3, and X_2^2 do not intensely affect H_2O_2 residual.

Although this evaluation provides a rapid analysis of the parametrical effect on the response variables, ANOVA with 95% CI was also applied to evaluate the statistical significance of the developed quadratic models for the percent TOC removal and the H_2O_2 residual. Thus, the statistical significance of each factor coefficient, as shown in Equations (3) and (4), was determined by the Fisher's (*F*) exact test, comparing probability (*p*) values greater than *F*. Consequently, the model *F*-values of 287.69 and 116.90 for TOC removal and H_2O_2 residual, respectively, imply the models are significant.

Besides, small probability values ($p < 0.05$) indicate significant model terms, which confirm the accuracy of the developed models to predict the response functions. Conversely, *p*-values > 0.10 indicate the model terms are not significant, in this case, X_2^2 is not significant for both TOC removal and H_2O_2 residual. If the quadratic effect is not significant, then the optimal levels of the parameter are in the extremes of the experimental region [14].

The goodness of fit of the developed models was validated by the determination coefficient (R^2) and the adjusted R^2 that ensures an adequate variation of the quadratic model to the experimental values. The values of R^2 and adjusted R^2 were found to be 0.9963 and 0.9928 for the percent TOC removal and 0.9909 and 0.9824 for the H_2O_2 residual, respectively, representing an adequate model's significance.

Moreover, the adequate precision for the percent TOC removal and H_2O_2 residual models were found to be 77.49 and 51.54, respectively (**Table 4**). Since both values were greater than 4.00, the model can be used to navigate the CCD design space [15]. The lack of fit was calculated to assess how well the model fits the data. The lack of fit *p*-values of the percent TOC removal and the H_2O_2 residual were found to be 0.6059 and 0.1145, respectively. A not significant lack of fit ($p > 0.10$) indicates that the model fits the data well.

On the other hand, the assumption of the constant variance was verified by plotting the internally studentized residual versus predicted values (**Figure 3(a)** and **Figure 3(b)**). The studentized residuals were found dividing the residuals by their standard deviations showing a randomly scattered pattern within the outlier detection limits –3 and +3. Therefore, model predictions, described in Equations (3) and (4), for both the percent TOC removal and the H_2O_2 residual, respectively, are satisfactory.

Moreover, the normal probability plot of residuals, shown in **Figure 4(a)** and **Figure 4(b)** for the TOC removal

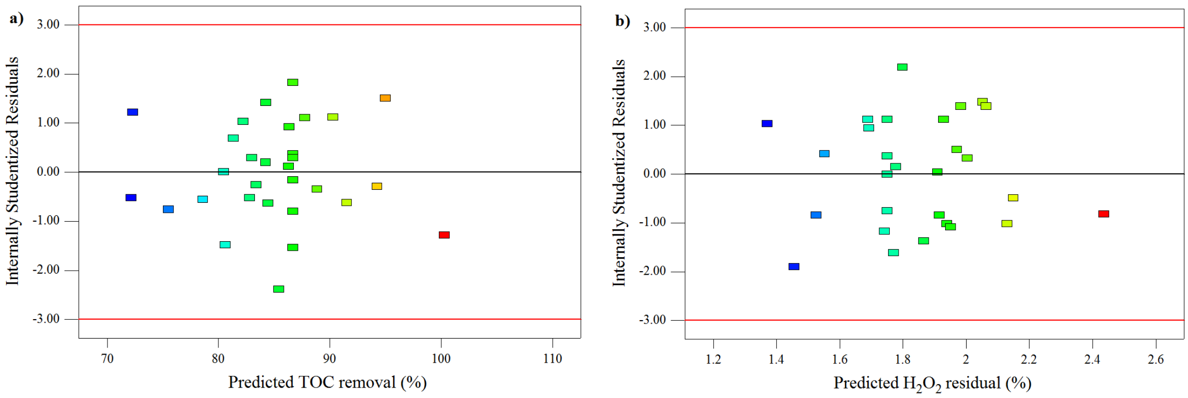

Figure 3. Internally studentized residuals versus predicted values for (a) percent TOC removal and (b) H_2O_2 residual.

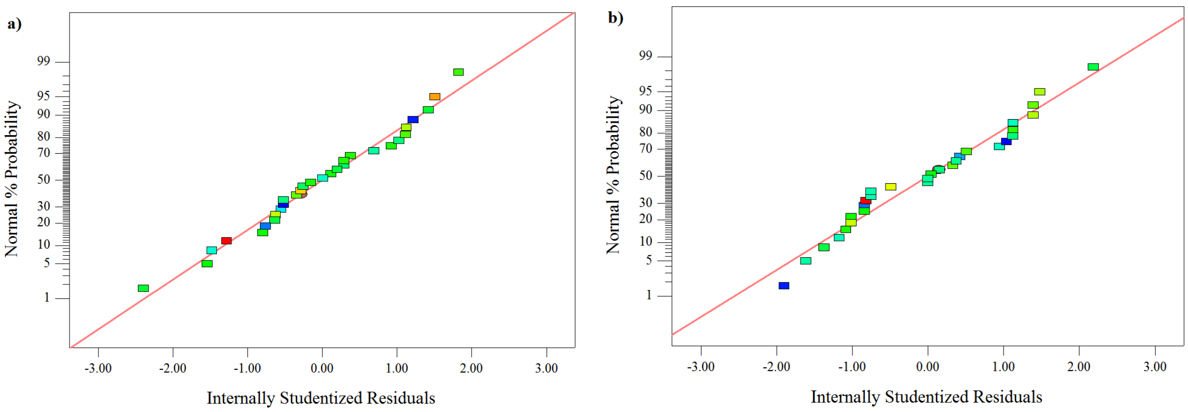

Figure 4. Internally studentized residuals versus normal probability for (a) percent TOC removal and (b) H_2O_2 residual.

and the H_2O_2 residual, respectively, showed a straight line pattern followed by the points on the plot, not an S-shaped curve. Consequently, a transformation of the response is not required because of the normal distribution of the residuals [11].

The correlation between the observed and predicted values is shown in **Figure 5(a)** and **Figure 5(b)** for the TOC removal and the H_2O_2 residual, respectively. As a result, minor discrepancies are represented by a straight line trend, which indicates a good agreement between observed and predicted values. Hence, the quadratic model predictions for both percent TOC removal and H_2O_2 residual responses are satisfactory.

3.2. Individual and Cross-Factor Interaction Effects of Model Parameters

The significance of each model factor was also evaluated using the F-exact test and p-values for each factor including linear, quadratic, and cross-factor interaction. All four independent variables including influent TOC (X_1), flow rate (X_2), H_2O_2 dosage (X_3), and pH (X_4) have a significant effect on both responses since their p- values are lower than 0.05. Besides, the cross-factor interactions of all model parameters, including the influent TOC concentration and flow rate (X_1X_2), influent TOC concentration and H_2O_2 dosage (X_1X_3), influent TOC concentration and pH (X_1X_4), flow rate and H_2O_2 dosage (X_2X_3), flow rate and pH (X_2X_4), and H_2O_2 dosage and pH (X_3X_4) showed a significant effect on both TOC removal and H_2O_2 residual. The cross-factor interaction effects with the highest significance as per their p-values < 0.0001 are illustrated in **Figure 6**.

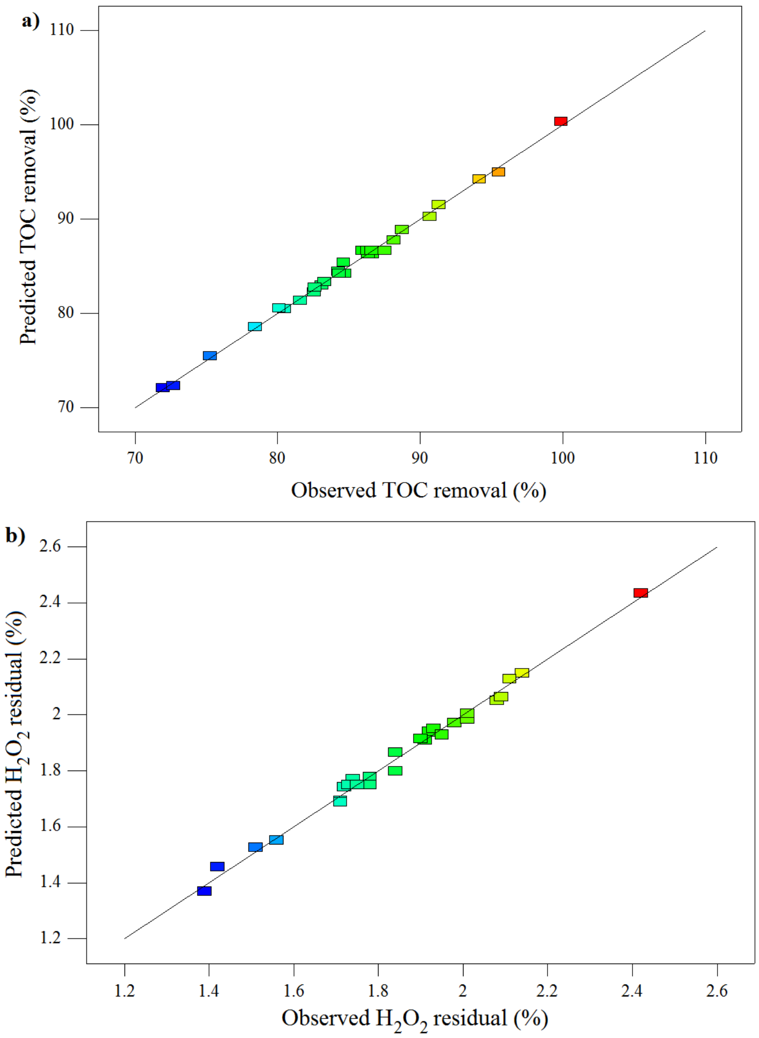

Figure 5. Observed experimental data versus predicted values for (a) percent TOC removal and (b) H_2O_2 residual.

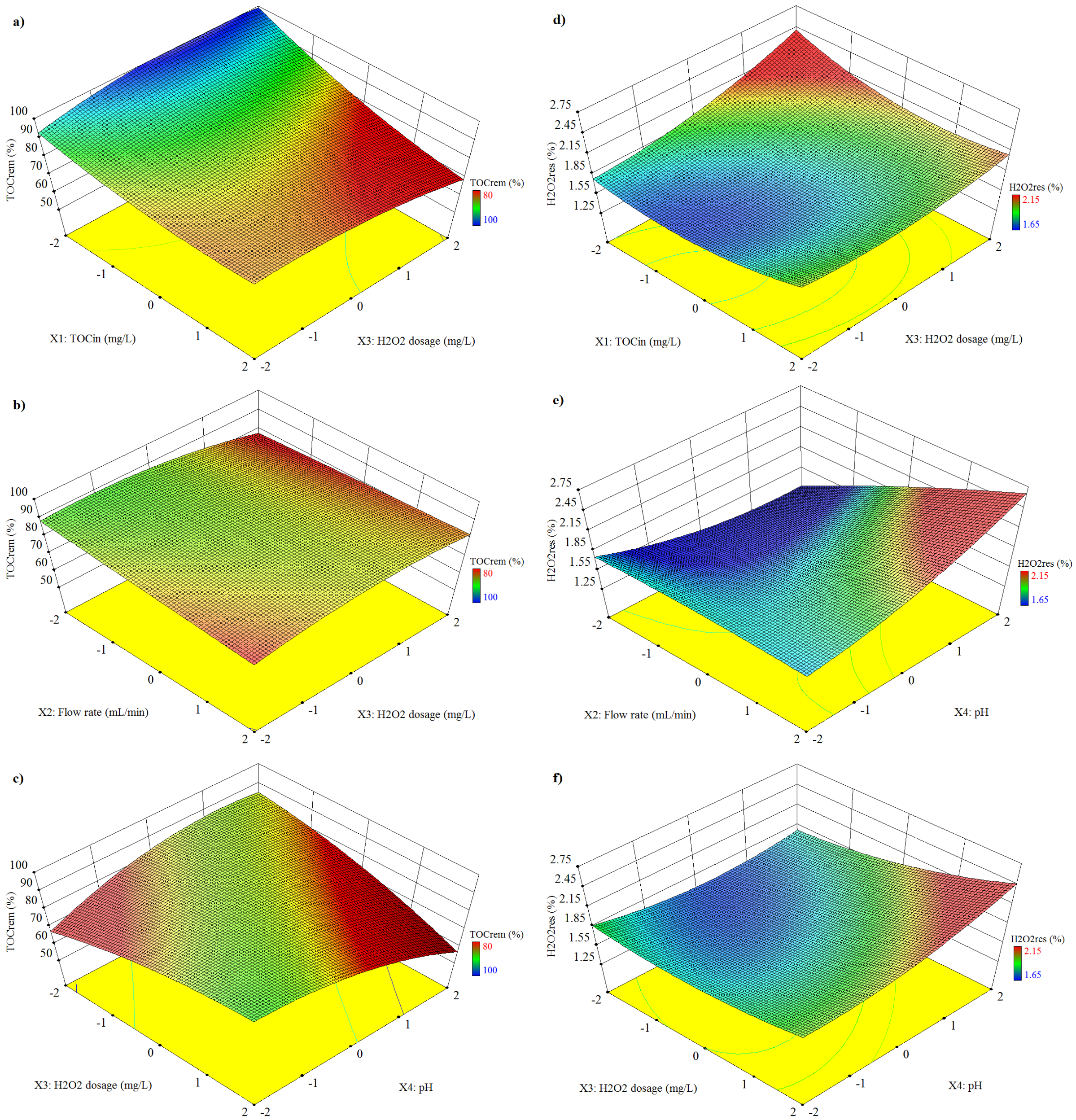

Figure 6. 3D surfaces and 2D plots of the interaction effects of: (a) influent TOC concentration and H_2O_2 dosage (X_1X_3), (b) flow rate and H_2O_2 dosage (X_2X_3), and (c) H_2O_2 dosage and pH (X_3X_4) on the TOC removal; and (d) influent TOC concentration and H_2O_2 dosage (X_1X_3), (e) flow rate and pH (X_2X_4), and (f) H_2O_2 dosage and pH (X_3X_4) on H_2O_2 residual.

3.3. Optimization of Operating Conditions

The RSM was used to calculate the optimum conditions for the four independent variables to get maximum percent TOC removal and minimum H_2O_2 residual. Equations (3) and (4) were defined as objective functions for percent TOC removal and H_2O_2 residual, respectively, and the independent factors in their range were used as model constraints. Thus, the following optimum conditions to reach a maximum TOC removal of 98.9% and minimum H_2O_2 residual of 1.4% were found: influent TOC of 50 mg/L, flow rate of 15 mL/min, H_2O_2 dosage of 344 mg/L, and pH of 7.2. The obtained optimal operating conditions were used in an additional run to validate the predicted values. Obtaining a TOC removal of 97.8% and H_2O_2 residual of 1.3% were obtained experimentally, confirming the reliability of the model since the values are within the 95% CI.

Table 4. ANOVA of the prediction results for the percent TOC and H_2O_2 residual by quadratic modeling.

Source	Sum of squares	df^a	Mean square	F value[b]	p-value (Prob. > F)[c]	Remark
$TOC_{removal}$ model	1064.8	14	76.057	287.69	<0.0001	Significant
X_1	590.24	1	590.24	2232.6	<0.0001	Significant
X_2	8.3308	1	8.3308	31.512	<0.0001	Significant
X_3	19.911	1	19.911	75.313	<0.0001	Significant
X_4	79.061	1	79.061	299.05	<0.0001	Significant
X_1X_2	3.5721	1	3.5721	13.512	0.0022	Significant
X_1X_3	25.402	1	25.402	96.083	<0.0001	Significant
X_1X_4	1.5006	1	1.5006	5.6762	0.0309	Significant
X_2X_3	10.726	1	10.726	40.570	<0.0001	Significant
X_2X_4	1.6900	1	1.6900	6.3925	0.0232	Significant
X_3X_4	160.78	1	160.78	608.17	<0.0001	Significant
X_1^2	23.766	1	23.766	89.894	<0.0001	Significant
X_2^2	0.0088	1	0.0088	0.0333	0.8576	Not significant
X_3^2	30.989	1	30.989	117.22	<0.0001	Significant
X_4^2	96.729	1	96.729	365.88	<0.0001	Significant
Residual	3.9656	15	0.2644			
Lack of Fit	2.5139	10	0.2514	0.86581	0.6059	Not significant
Pure error	1.4517	5	0.2903			
Corrected total SS^d	1068.8	29				
R^2	0.9963					
Adjusted R^2	0.9928					
Adequate Precision	77.489					
$H_2O_{2,residual}$ model	1.3975	14	0.0998	116.90	<0.0001	Significant
X_1	0.0045	1	0.0045	5.3139	0.0359	Significant
X_2	0.6970	1	0.6970	816.27	<0.0001	Significant
X_3	0.2109	1	0.2109	247.03	<0.0001	Significant
X_4	0.0630	1	0.0630	73.824	<0.0001	Significant
X_1X_2	0.0068	1	0.0068	7.9709	0.0128	Significant
X_1X_3	0.0163	1	0.0163	19.038	0.0006	Significant
X_1X_4	0.1208	1	0.1208	141.42	<0.0001	Significant
X_2X_3	0.0060	1	0.0060	7.0340	0.0181	Significant
X_2X_4	0.1243	1	0.1243	145.52	<0.0001	Significant
X_3X_4	0.0218	1	0.0218	25.479	0.0001	Significant
X_1^2	0.0729	1	0.0729	85.402	<0.0001	Significant
X_2^2	0.0026	1	0.0026	3.0146	0.1030	Not significant
X_3^2	0.0273	1	0.0273	32.000	<0.0001	Significant
X_4^2	0.0392	1	0.0392	45.927	<0.0001	Significant
Residual	0.0128	15	0.0009			
Lack of Fit	0.0110	10	0.0011	3.0579	0.1145	Not significant
Pure error	0.0018	5	0.0004			
Corrected total SS^d	1.4103	29				
R^2	0.9909					
Adjusted R^2	0.9824					
Adequate Precision	51.542					

[a]Degrees of freedom (*df*). [b]Fisher's (*F*) exact test value. [c]A probability value (p) < 0.05 is considered to be significant, a p-value > 0.10 is considered not significant. [d]Total sum of squares corrected for the mean.

4. Conclusion

The interaction effects of the influent TOC concentration, flow rate, H_2O_2 dosage, and pH had a significant effect on both TOC removal and H_2O_2 residual. Optimum conditions were found for each variable to achieve maximum TOC removal with minimum H_2O_2 residual. The developed mathematical models provided a comprehensive exploration of the cross-factor interactive effects of the independent variables on the responses. The proposed models explaining the treatment of SWW by the continuous ABR-AS-UV/H_2O_2 system were found suitable for future studies on reactor design, modeling, and scale-up.

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References

[1] Bustillo-Lecompte, C.F. and Mehrvar, M. (2015) Slaughterhouse Wastewater Characteristics, Treatment, and Management in the Meat Processing Industry: A Review on Trends and Advances. *Journal of Environmental Management*, **161**, 287-302. http://dx.doi.org/10.1016/j.jenvman.2015.07.008

[2] Daigger, G.T. (2009) Evolving Urban Water and Residuals Management Paradigms: Water Reclamation and Reuse, Decentralization, and Resource Recovery. *Water Environment Research*, **81**, 809-823. http://dx.doi.org/10.2175/106143009X425898

[3] Gerbens-Leenes, P.W., Mekonnen, M.M. and Hoekstra, A.Y. (2013) The Water Footprint of Poultry, Pork and Beef: A Comparative Study in Different Countries and Production Systems. *Water Resources and Industry*, **1-2**, 25-36. http://dx.doi.org/10.1016/j.wri.2013.03.001

[4] Mittal, G.S. (2006) Treatment of Wastewater from Abattoirs before Land Application—A Review. *Bioresource Technology*, **97**, 1119-1135. http://dx.doi.org/10.1016/j.biortech.2004.11.021

[5] Bustillo-Lecompte, C.F., Mehrvar, M. and Quiñones-Bolaños, E. (2014) Cost-Effectiveness Analysis of TOC Removal from Slaughterhouse Wastewater Using Combined Anaerobic-Aerobic and UV/H_2O_2 Processes. *Journal of Environmental Management*, **134**, 145-152. http://dx.doi.org/10.1016/j.jenvman.2013.12.035

[6] Barrera, M., Mehrvar, M., Gilbride, K., McCarthy, L., Laursen, A., Bostan, V. and Pushchak, R. (2012) Photolytic Treatment of Organic Constituents and Bacterial Pathogens in Secondary Effluent of Synthetic Slaughterhouse Wastewater. *Chemical Engineering Research and Design*, **90**, 1335-1350. http://dx.doi.org/10.1016/j.cherd.2011.11.018

[7] OMAFRA (2015) Provincially Licensed Meat Plants in Ontario. Ontario Ministry of Agricultural and Rural Affairs (OMAFRA). http://www.omafra.gov.on.ca/english/food/inspection/maps/TblAllAbattoirs.htm

[8] Bustillo-Lecompte, C.F., Mehrvar, M. and Quiñones-Bolaños, E. (2013) Combined Anaerobic-Aerobic and UV/H_2O_2 Processes for the Treatment of Synthetic Slaughterhouse Wastewater. *Journal of Environmental Science and Health, Part A: Toxic/Hazardous Substances and Environmental Engineering*, **48**, 1122-1135. http://dx.doi.org/10.1080/10934529.2013.774662

[9] Tritt, W.P. and Schuchardt, F. (1992) Materials Flow and Possibilities of Treating Liquid and Solid Wastes from Slaughterhouses in Germany. A Review. *Bioresource Technology*, **41**, 235-245. http://dx.doi.org/10.1016/0960-8524(92)90008-L

[10] Debik, E. and Coskun, T. (2009) Use of the Static Granular Bed Reactor (SGBR) with Anaerobic Sludge to Treat Poultry Slaughterhouse Wastewater and Kinetic Modeling. *Bioresource Technology*, **100**, 2777-2782. http://dx.doi.org/10.1016/j.biortech.2008.12.058

[11] Bustillo-Lecompte, C.F., Ghafoori, S. and Mehrvar, M. (2016) Photochemical Degradation of an Actual Slaughterhouse Wastewater by Continuous UV/H_2O_2 Photoreactor with Recycle. *Journal of Environmental Chemical Engineering*, **4**, 719-732. http://dx.doi.org/10.1016/j.jece.2015.12.009

[12] Bustillo-Lecompte, C.F., Knight, M. and Mehrvar, M. (2015) Assessing the Performance of UV/H_2O_2as a Pretreatment Process in TOC Removal of an Actual Petroleum Refinery Wastewater and its Inhibitory Effects on Activated Sludge. *Canadian Journal of ChemicalEngineering*, **93**, 798-807. http://dx.doi.org/10.1002/cjce.22180

[13] Myers, R.H., Montgomery, D.C., Vining, G.G., Borror, C.M. and Kowalski, S.M. (2004) Response Surface Methodology: A Retrospective and Literature Survey. *Journal of Quality Technology*, **36**, 53-77.

[14] Botha, G.E., Oliveira, J.C. and Ahrné, L. (2012) Quality Optimisation of Combined Osmotic Dehydration and Micro-

wave Assisted Air Drying of Pineapple using Constant Power Emission. *Food and Bioproducts Processing*, **90**, 171-179. http://dx.doi.org/10.1016/j.fbp.2011.02.006

[15] Ghafoori, S., Mehrvar, M. and Chan, P.K. (2012) Free-Radical-Induced Degradation of Aqueous Polyethylene Oxide by UV/H_2O_2: Experimental Design, Reaction Mechanisms, and Kinetic Modeling. *Industrial and Engineering Chemistry Research*, **51**, 14980-14993. http://dx.doi.org/10.1016/j.fbp.2011.02.006