Final Report

AMPC
AUSTRALIAN MEAT PROCESSOR CORPORATION

Treating Tannery Effluent

Removal of persistent organics from tannery effluent

Project Code
2022-1058

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Date Submitted
5/12/2022

Published by
AMPC

Date Published
5/12/2022

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1.0 Executive Summary

The overall objective of this project was to develop a pilot scale system capable of oxidising persistent organic compounds (POC's) in the wastewater from the Casino Hide Tanner. Ozone was chosen as an appropriate oxidising agent and a series of laboratory trials were conducted to obtain the appropriate treatment conditions for a larger scale application. We also tested the effects of adding Fenton's reagents (hydrogen peroxide) on the ozone treatment efficiency. Two pilot scale systems were then tested on site, one relied on a dissolved ozone delivery method (venturi injection), and the second used a direct ozone delivery approach (blower). The outcomes of the pilot trials allowed us to make recommendations for future implementation of the ozone treatment system.

The laboratory trials demonstrated that removal of a test POC compound (4-chloro-3-methylphenol) from wastewater was at least 70% within 2-3 hours. Fenton's reagent did improve POC removal but only by 10%. When we normalise the % removal data to account for reaction time and ozone dose, the degradation rates of the test POC in the ozone only and ozone plus Fenton's treatments were similar, ~120 mg POC $g^{-} O_3 h^{-1}$.

In the field trials, the addition of ozone via a venturi system achieved a 33% removal of the test POC within 24 h, this equated to a removal rate of 7.5 mg POC $g^{-} O_3 h^{-1}$. The large difference in removal rate between the field and lab trials is due to the high ozone dose to treatment volume ratio lab trial (0.5 g h^{-1} for 4 L in the lab vs 5 g h^{-1} for 400 L in the field). In addition, the field trial used wastewater with a much higher organic load than in the lab trials.

The addition of Fenton's reagent increased the removal of the test POC to 70% in the venturi injection trial and almost doubled the removal rate (13 mg POC $g^{-} O_3 h^{-1}$). Note that the presence of solids in the wastewater resulted in frequent pump blockages that were a persistent issue. Future pilot systems using an ozone delivery system will need a more solids friendly pump.

The addition of ozone via the blower system was not as effective as the venturi system. When ozone was used alone, the removal of the test POC was 36% with a removal rate of only 4 mg POC $g^{-} O_3 h^{-1}$. With Fenton's reagent present, the removal of the test POC was 55% and the removal rate was 5.3 mg POC $g^{-} O_3 h^{-1}$. The reduced removal rate with the blower system was caused by the large loss of ozone from the tank reactor. Future pilot systems relying on a direct delivery approach would require a better diffusion system and a potentially more powerful blower,

Based on the pilot scale results we were able to design an optimised ozone/Fenton's system for further testing. The new system would be based on a 20 g h^{-1} ozone unit, a venturi-based delivery system, and Fenton's reagents (0.125 mM Fe^{2+} and 50 mM of H_2O_2). With this system we estimate that it would be possible to remove > 90% of the POC's from 1500 L of tannery wastewater in 24 h. The running cost of this treatment would be ~ $40. Without the Fenton's reagents we could treat 670 L of wastewater in 24 h for < $10.

The next phase of this work is to install the new pilot scale unit and test it onsite using 1000 L of wastewater. If the results match what we have predicted then we could increase the treatment volume. Note that we already have the 20 g h^{-1} ozone unit for the next phase of the work, however a new pump would be required.

2.0 Introduction

During tannery wastewater treatment, dissolved air flotation (DAF) is used to remove solids while the clarified wastewater is applied to land. However both the solid and liquid streams from DAF contain persistent organic compounds (POC's) which are used during the tanning process to prevent fungal and other microbial growth on leather products. If POC's can be removed from wastewater prior to DAF treatment, then the cost of landfill disposal would decrease significantly, and the potential contamination of water bodies from land application of liquid waste disposal could be alleviated.

An effective means of degrading POC's into more benign compounds is the use of advanced oxidation procedures (AOP's) such as ultraviolet (UV) oxidation, and the Fenton process (addition of hydrogen peroxide – H_2O_2, and iron – Fe^{2+}) (Lofrano *et al.*, 2013). The high turbidity of tannery wastewater may exclude UV treatment, and Fenton's reagents can be a major cost barrier, particularly H_2O_2. Another approach for POC degradation is to use ozone (O_3) (Pera-Titus *et al.*, 2004; Malik *et al.*, 2020), a powerful oxidising agent that can be produced onsite relatively cheaply. Ozone is known to degrade phenolic compounds (Benitez *et al.*, 2000), but studies to date have focussed at the degradation of pure POC's rather than POC's in a wastewater environment. Mixed wastewater has a much higher organic load than pure compound so it is expected that the efficiency of POC breakdown will be much lower. In this case it may be possible to hybridise the oxidation process, for instance by combining O_3 oxidation and the Fenton reaction. (Asaithambi, Sajjadi and Aziz, 2017). The Fenton reaction is essentially an oxidation reaction in which H_2O_2 forms highly reactive OH* radicals in the presence of Fe^{2+} (Babuponnusami and Muthukumar, 2014). Again, the combination of O_3 oxidation and the Fenton reaction has only been applied to pure POC's (e.g. phenolic compounds), not mixed wastewater (Esplugas *et al.*, 2002).

In addition to the choice of AOP, the delivery method into the wastewater stream is important from both an efficiency and operational perspective. For example, O_3 can be delivered to the wastewater stream via dissolution in water, or through direct injection. The dissolution option involves drawing O_3 into a water stream with a venturi and delivering that water stream into the wastewater holding tank. Venturi injection allows O_3 to dissolve in the delivery water giving it excellent contact with the organic material in the wastewater. However, the delivery water must be relatively free of solids to avoid clogging of either the pump or venturi orifice. Direct injection involves pumping O_3 into the wastewater tank. While this technique avoids issues of clogging, the transfer of O_3 into the liquid phase is low, hence the efficiency of degradation can be compromised.

The aim of this study is to test the suitability of O_3 oxidation as a means for degrading POC's in tannery wastewater. In addition, we also assessed the degradation of POC's with a combination of O_3 and the Fenton reaction, and compared dissolved and direct techniques for O_3 delivery. We also calculated the costs associated with running the tested treatment system.

3.0 Project Objectives

3.1 Optimise the operational conditions for a pilot scale AOP degradation system for tannery waste liquids

3.1.1 Establish basic ozone treatment conditions

3.1.2 Combine ozone treatment with Fenton's oxidation reaction

3.2 Construct and test a pilot scale system for AOP degradation of waste liquids prior to the precipitation stage

3.2.1 Use of dissolved ozone

3.2.2 Direct ozone delivery

3.2.3 Determine operating costs

4.0 Methodology

4.1 Optimisation trials (Objectives 3.1.1 and 3.1.2)

4.1.1 Establish basic ozone treatment conditions

The initial proposal to AMPC was predicated on the use of UV on the tannery wastewater to break down POC's. However, the transmissivity of UV light in the wastewater was negligible at the wavelengths of interest, i.e. below 300 nm, likely due to the presence of coloured organic compounds and solids. The total absorption of UV means it cannot penetrate the waste solution, hence we moved to an alternative oxidation procedure, namely ozone (O_3) treatment.

To assess O_3 treatment efficiency it was first necessary to select a test POC and establish a rapid method for the determination of this test POC in liquid wastes. For this project we selected 4-chloro-3-methylphenol as the test POC, this is a white solid with a phenolic odour and a molecular weight of 142.6 g mol^{-1} which melts at 64.2ºC and decomposes at approximately 240ºC. It has a solubility in water which varies from 3.3 g L^{-1} at pH 5 to 4.2 g L^{-1} at pH 9. It is highly soluble in organic solvents such as hexane, ethanol, dichloromethane, and acetone. Due to its low molecular weight we focussed on a gas chromatographic method. Pure 4-chloro-3-methylphenol (Sigma-Aldrich) was purchased and a series of standards were prepared in ethanol. Pure compound, which is relatively insoluble, was first dissolved in water with the assistance of the surfactant TritonX (1 g L^{-1}). The developed method relies on gas chromatography with a flame ionization detector (GCFID). The method takes 30 minutes per sample with a retention time of 19.75 minutes. A linear response was found with a limit of detection of approximately 50 µg L^{-1} (50 ppb). To extract the 4-chloro-3-methylphenol, a 50 mL of sample was partitioned against dichloromethane (DCM) and salted with a saturated $CaCl_2$ solution to drive the compound into the organic phase. The DCM solutions were taken to dryness on a rotary evaporator, made up quantitatively with 10 mL of ethanol, and analysed via GCFID against standards of known POC concentration. The same procedure was followed for wastewater samples.

In the initial trials, the quantitative breakdown of the pure POC test compound with O_3 was measured using a small 1 g h^{-1} O_3 generator using bottled O_2 (Fig. 1). An example of the degradation of the test POC is shown in Fig. 2 where the concentration of the test POC at an O_3 dose rate of 0.5 g h^{-1} is plotted against reaction time. The removal of the pure test POC was 95%.

Figure 1. Lab setup showing ozone generator (left), reaction chamber (centre), and residual ozone trap (right).

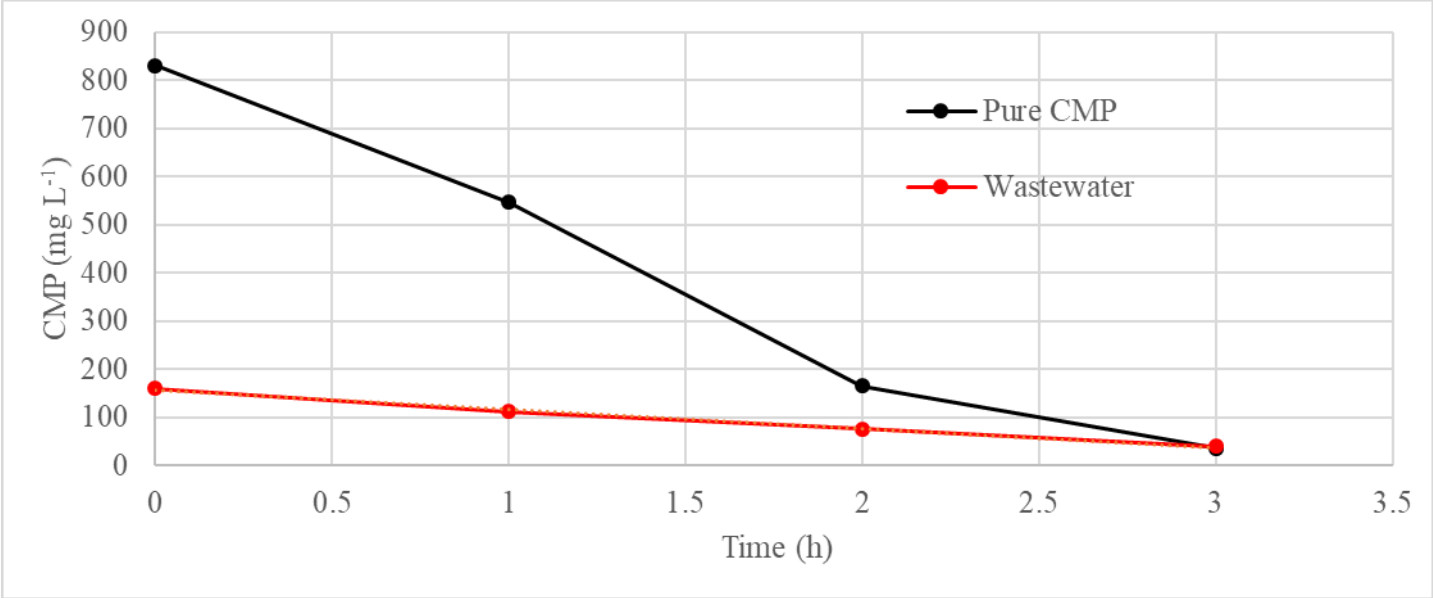

Figure 2. Concentration of the pure test POC 4-chloro-3-methylphenol (CMP) and CMP in tannery wastewater over time at an O_3 dose rate of 0.5 g h^{-}.

Following the pure test POC degradation trial, a similar experiment was performed using tannery wastewater from the balance tank at the Casino Hide Tanners. A 1 L wastewater sample was treated with O_3 (0.5 g h^{-}) and concentration of the test POC was measured every hour for 3 hours. Degradation of POC was high (75% removal in 3 h – Fig. 2), however there was a noticeable loss of O_3 from the reactor, prompting the use of a taller reaction vessel.

A second series of experiments was carried out using a new reactor column. The column was 90 mm (Φ) x 640 mm (height) and holds 4 L of liquid, allowing for greater contact time between O_3 and the wastewater (Fig. 3). The liquid sample was agitated using a magnetic stirrer and the O_3 was introduced using a sintered glass bubbler. For this experiment we used a series of O_3 dose rates (0.4, 0.5, 0.65, and 0.75 g h^{-1}) over a 3 h incubation period. Results are presented in Section 5.

Figure 3. Modified lab setup showing elongated reaction chamber.

4.1.2 Combine ozone treatment with Fenton's oxidation reaction

While O_3 treatment can breakdown POC's, the process is inefficient due to large losses of gas from the incubation vessel. To improve POC breakdown without increasing the incubation time we tested the effects of Fentons' reagent (Fe^{+2} and H_2O_2) in combination with O_3 on the degradation of POC. The O_3 dose rate was fixed at 0.5 g h^{-1} as this was the most efficient delivery rate from the previous experiment. From the literature an Fe^{+2} concentration of 2 mM was chosen, this was kept constant through all the experiments. The concentrations of H_2O_2 tested were 1, 10, 50, and 100 mM. In addition an experiment at 50 mM H_2O_2 without O_3 was also performed. All experiments were run over 3 h.

4.2 Construct and test a pilot scale system for AOP degradation of waste liquids prior to the precipitation stage

4.2.1 Use of dissolved ozone

In the first field trial O_3 was delivered to the wastewater through a venturi system. Wastewater from the main drainage sump was manually added to a 1 m^3 holding tank and then recirculated at 140 L min^{-1} via an external pump (Fig. 4). A venturi draws O_3 from an Oxyzone 5 g hr^{-1} generator, mixed with the recirculating wastewater, and returned to the holding tank via a 4.8 m reaction column (50 mm PVC pipe). Wastewater samples were collected prior to the treated wastewater returning to the holding tank.

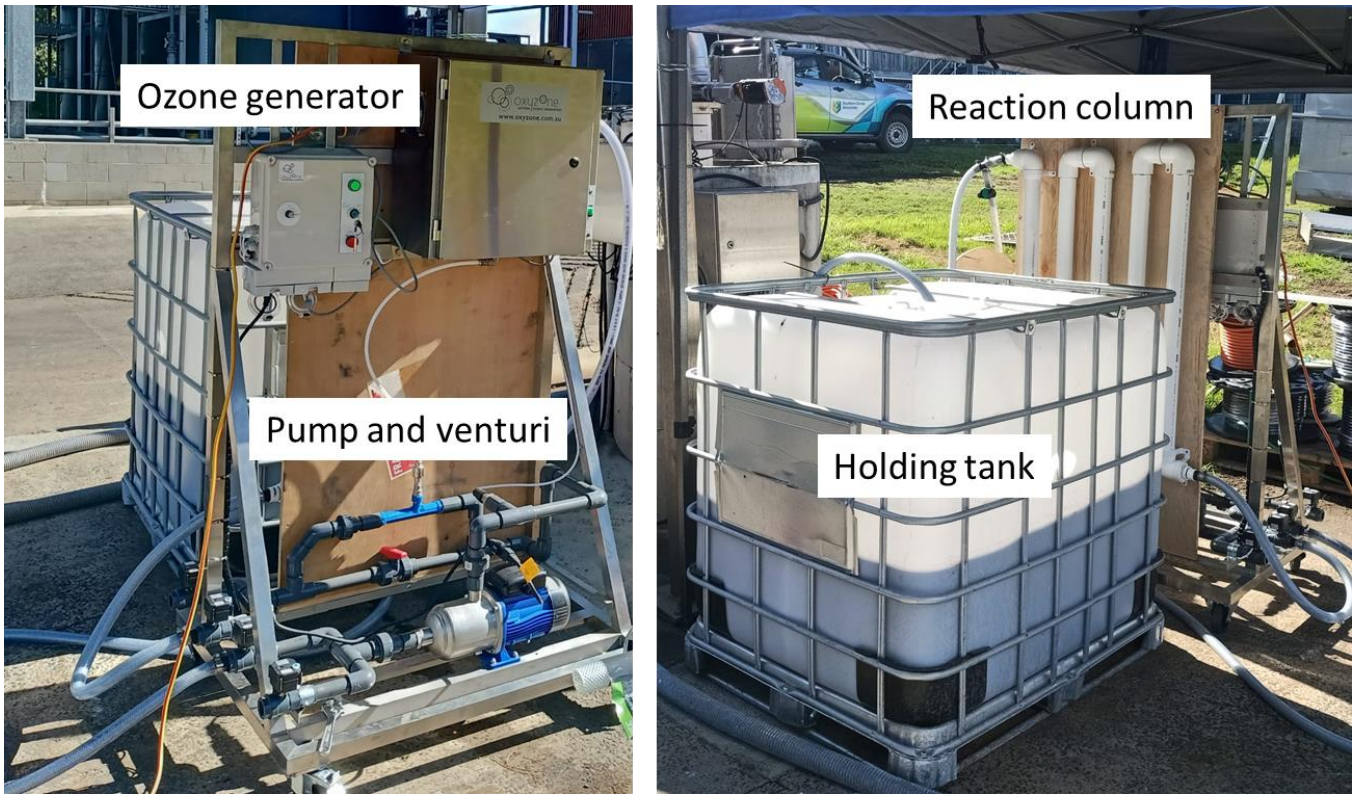

Figure 4. Pilot venturi reactor system set up at Casino Hide Tanners.

The following series of trials were carried out:

Table 1. Details of the field-based trials using venturi dissolved O_3 delivery. Concentrations of the Fenton's reagents are also shown.

Treatment	Volume (L)	Time (h)	O_3 conc (g h^{-1})	H_2O_2 (mM)	Fe^{2+} (mM)
O_3	400	24	5	-	-
O_3 + Fenton's	400	24	5	50	0.25
O_3 + Fenton's	400	24	5	50	0.5
O_3 + Fenton's	400	24	-	50	0.125
O_3 + Fenton's	400	24	5	50	0.125
O_3 + Fenton's	400	24	5	70	0.125

Due the high solids content of the wastewater, persistent pump blockages were encountered. Attempts were made to screen the wastewater prior to the experiments, however it seems that small particle coagulate over time eventually leading to pump blockages. Replacing the pump with a more suitable option was considered, however the orifice on the venturi (6 mm) would then be prone to blockage. It was decided that a more suitable approach may be to add the O_3 directly to the holding tank rather than trying to dissolve it in liquid first. This was the same approach used for the 4 L lab trials.

4.2.2 Direct ozone delivery

A new delivery system was commissioned which uses a side channel air blower to deliver O_3 rather than liquid. The O_3 system was also upgraded to a 20 g h^{-1} generator. The system still uses a venturi to draw the ozone from the generator, but it is not subject to clogging (Fig. 5). This new system ensures that the solids content of the wastewater is not an obstacle for treatment. However, the dilution of O_3 with air has implications for treatment efficiency, and for foaming. To increase contact time we used 700 L rather than 400 L.

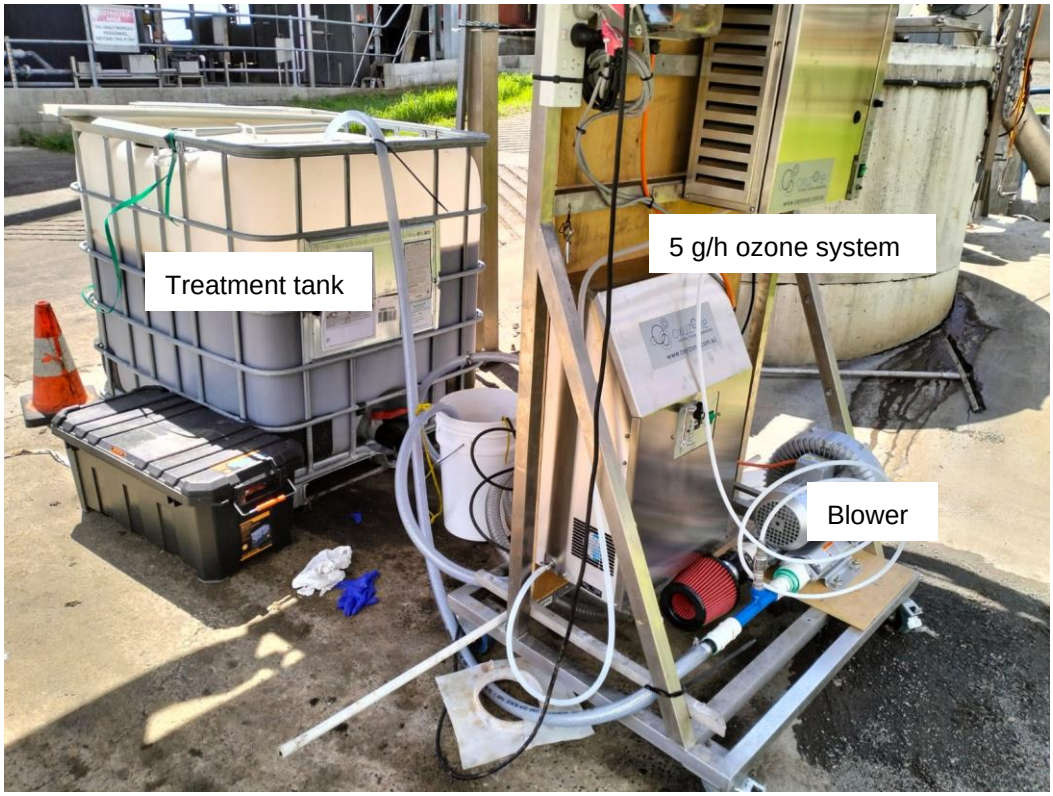

Figure 5. Pilot blower reactor system set up at Casino Hide Tanners.

The following series of trials were carried out with the direct delivery unit:

Table 2. Details of the field-based trials using direct O_3 delivery. Concentrations of the Fenton's reagents are also shown.

Treatment	Volume (L)	Time (h)	O_3 conc (g h^{-1})	H_2O_2 (mM)	Fe^{2+} (µM)
O_3	700	24	20	-	-
O_3	700	24	20	-	-
O_3 + Fenton's	700	24	20	50	0.5
O_3 + Fenton's	700	24	20	50	0.5

4.2.3 Determine operating costs

For this calculation we simply multiplied the operating hours of the O_3 generation system, pump or blower, by their power consumption. The cost of chemicals was also factored in. Any scale up system can use the equipment already purchased for the pilot trials so there is no need to calculate additional capital costs. Personnel operating costs have also not been included.

5.0 Project Outcomes

5.1 Optimisation trials (Objectives 3.1.1 and 3.1.2)

5.1.1 Establish basic ozone treatment conditions

After establishing that O_3 was effective at degrading the pure test POC, we moved on to test the applicability of O_3 on wastewater in a lab scale 4 L trial. Ozone degraded POC in tannery wastewater and removal efficiency was 75% within 3 h of treatment at a dose rate of 0.5 g h^{-1}. This was slower than the pure compound trial at the same O_3 dose rate (Fig. 2) most likely due to the presence of other organic compounds in the tannery waste which are consuming O_3. Higher O_3 dose rates did not have a linear increase on POC degradation because there was a significant loss of O_3 from the small reactor vessel. Hence another set of experiments was performed using a modified reactor set up.

For the modified lab reactor, all O_3 dose rates showed a reduction in wastewater POC concentration over time (Fig. 6) with the quickest consumption of test POC measured at the highest dose rate (0.75g h^{-1}). However, at the two highest dose rates there was a notable discharge of O_3, indicating that the contact time could be improved. At a dose rate of 0.4 g h^{-1}, 42% of the POC in 4 L of wastewater was consumed in 3 hr, whereas at 0.75 g h^{-1} 70% of the test POC was consumed within 2 hr (Fig. 6). Because different O_3 doses, reactor volumes, and treatment times were used, it can be difficult to compare POC removal between different experiments. To make this comparison easier we calculated a POC consumption rate which accounts for different experimental conditions, units are mg POC g^{-} O_3 h^{-1}. At the highest O_3 dose rate the consumption of POC was 121 mg POC g^{-} O_3 h^{-1} (Fig. 6)

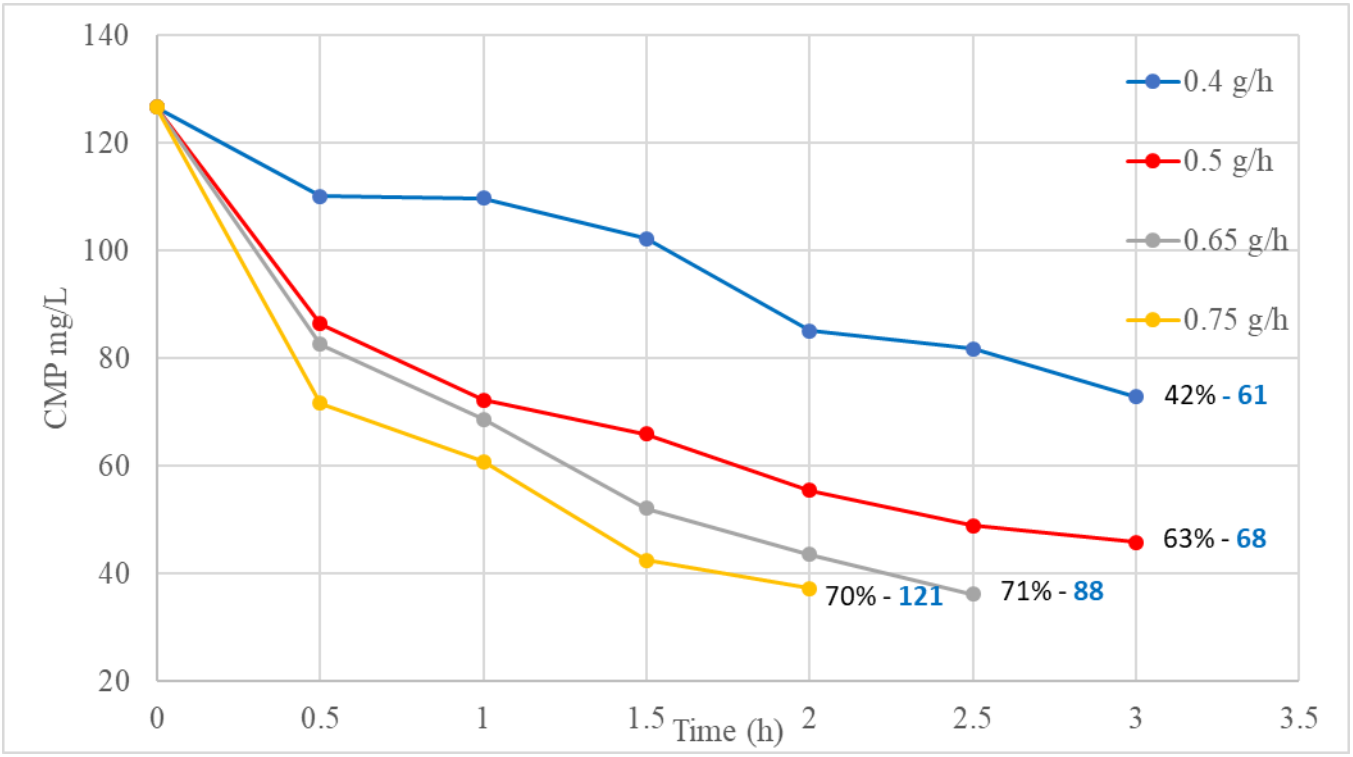

Figure 6. Degradation of the test POC 4-chloro-3-methylphenol (CMP) in 4 L tannery wastewater at different O_3 dosing rates of 0.4, 0.5, 0.65, and 0.75 g h^{-1} over 3 h. Percent reduction is also shown in units of mg POC g^{-} O_3 h^{-1} (bold blue numbers).

5.1.2 Combined ozone treatment with Fenton's oxidation reaction

The Fenton's reagent alone (50 mM H_2O_2) showed a 37% reduction of test POC over three hours, roughly half of the removal achieved with the 0.5 g h^{-1} O_3 dose (Fig. 7). This rules out the use of the Fenton's reaction as a replacement for O_3. When Fenton's reagent and O_3 were combined, no increase in test POC removal was found at a H_2O_2 dose concentration of 1 mM compared to the 0.5 g h^{-1} O_3 dose (Fig. 7). However at 10, 50 and 100 mM of H_2O_2 the removal of test POC was generally faster with a lower final concentration (Fig. 7). At the highest H_2O_2 dose rate (100 mM) there was a 10% improvement in the overall removal of test POC relative to the O_3 only treatment. At this highest H_2O_2 dose rate the consumption of test POC was 84 mg POC g^{-} O_3 h^{-1}, which was higher than the consumption rate with the 0.5 g h^{-1} O_3 alone dose rate (72 mg POC g^{-} O_3 h^{-1}, note that if we calculate this at 2 h the removal rate is around 120 mg POC g^{-} O_3 h^{-1}). Interestingly, the effect of combining Fenton's reagent and O_3 was not additive. In other words, the % removal with the combined O_3 and Fenton's reagent (67%) was less than would ne expected if we were to add the individual consumption rates together (43% and 63% for the 50 mM Fenton's only and 0.5 g h^{-} O_3 only treatments respectively).

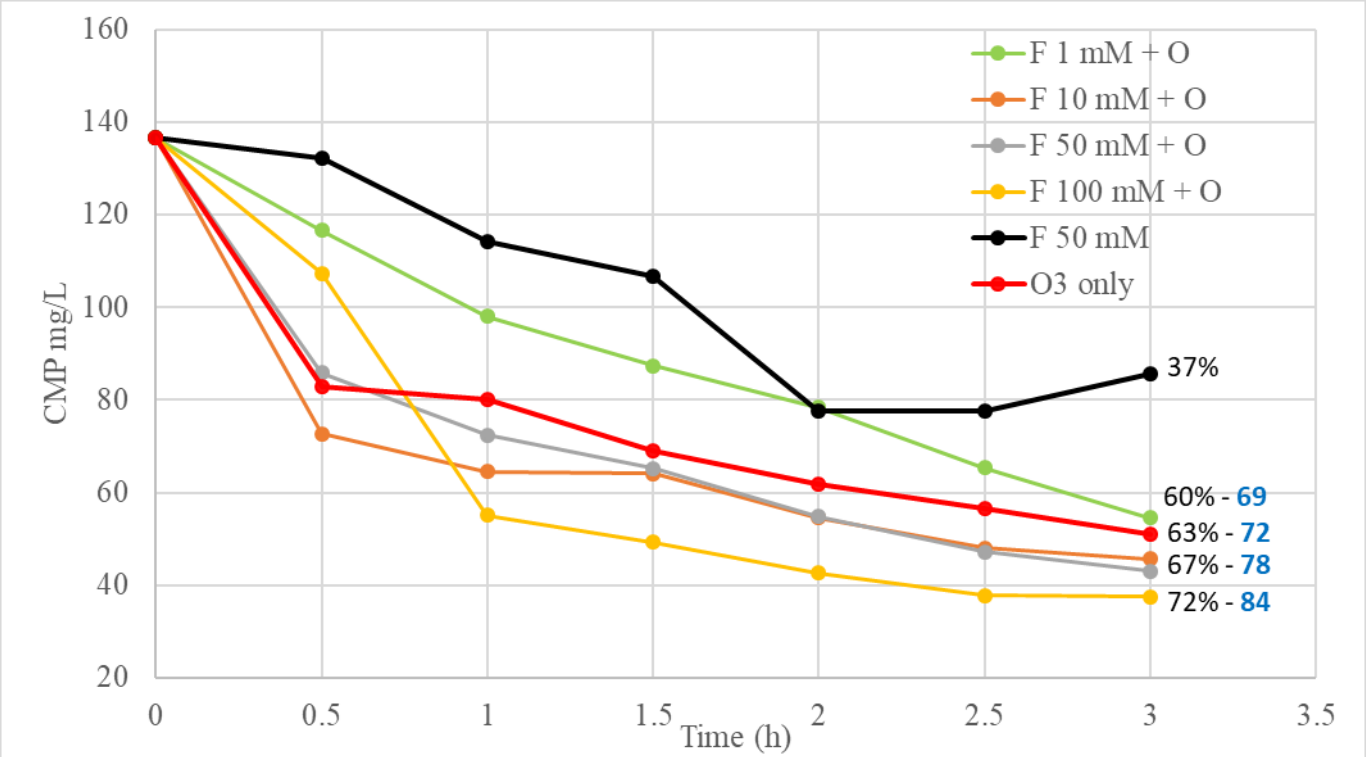

Figure 7. Degradation of the test POC 4-chloro-3-methylphenol (CMP) in 4 L tannery wastewater at different H_2O_2 dosing rates (1, 10, 50, and 100 mM) over 3 h. The O_3 dosing rate was 0.5 g h^{-1} and the Fe^{2+} concentration was kept constant at 2 mM. A Fenton's only (50 mM) and O_3 only treatment (0.5 g h^{-1}) are also shown. Percent reduction is also shown as well as the POC consumption rate, in units of mg POC g^{-} O_3 h^{-1} (bold blue numbers).

5.2 Construct and test a pilot scale system for AOP degradation of waste liquids prior to the precipitation stage

5.2.1 Use of dissolved ozone

Without Fenton's reagent we were able to achieve 33% removal of POC over 24 h, however the removal rate (7.5 mg POC g^{-} O_3 h^{-1}) was much lower than in the lab-based trials. This is because the O_3 dose in the lab trial, per L of wastewater, was much higher than for the field trial (0.5 g h^{-1} for 4 L vs 5 g h^{-1} for 400 L). In addition, for the lab trials the wastewater was collected from the balance tank where the COD was less than half the COD in the main sump, which is where wastewater was drawn for the field trials. The higher organic load would undoubtedly consume O_3.

With the addition of Fenton's reagent we observed an increase in the percent removal of test POC. Maximum removal was 76% (13.4 mg POC g^{-} O_3 h^{-1}) at a dose rate of 0.125 mM Fe^{2+} and 50 mM of H_2O_2. The combination treatment system appears to be at least additive in that the % removal with O_3 + Fenton's (75%) was higher than the sum of individual % removals (33.5% for O_3 only and 32% for Fenton's only).

Table 3. Results of the field trials using a venturi delivery system and a 5 g h^{-1} O_3 generator. Fenton's reagents were also added. Maximum POC removal was observed at a Fenton's dose rate of 0.125 mM Fe^{2+} and 50 mM of H_2O_2.

Treatment	Volume (L)	Time (h)	O_3 conc (g h^{-1})	H_2O_2 (mM)	Fe^{2+} (mM)	% rem	mg POC g^{-} O_3 h^{-1}
O_3	400	24	5	-	-	33.5	7.5
O_3 + Fenton's	400	24	5	50	0.25	39.8	9.0
O_3 + Fenton's	400	24	5	50	0.50	47.9	11.5
Fenton's only	400	24	-	50	0.125	32.3	-
O_3 + Fenton's	400	24	5	50	0.125	75.9	13.4
O_3 + Fenton's	400	24	5	70	0.125	70.8	13.1

In addition to the test The test POC accounts for about 5% of the total carbon content of the wastewater, and yet the total organic carbon removal was well over 20% for all treatments (Fig. 8). The carbon removal data in Fig. 8 also show that the highest removal was achieved at an Fe^{2+} dose of 125 mM, in line with the POC removal data.

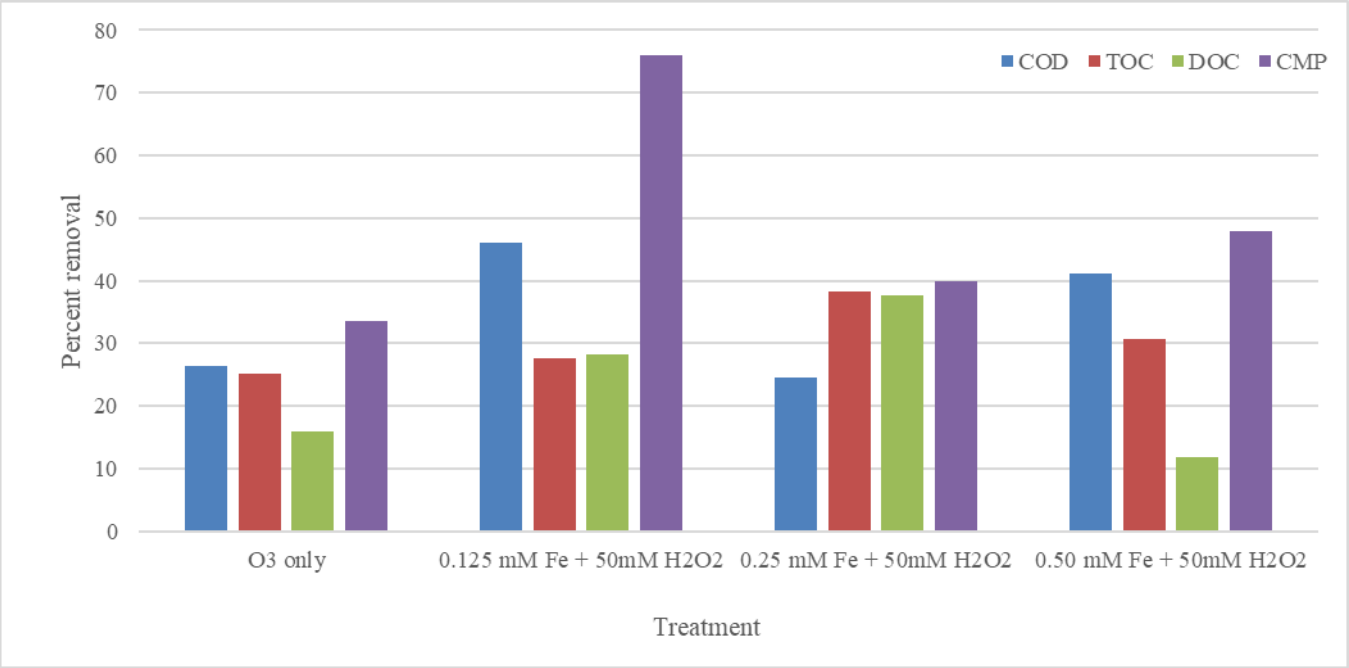

Figure 8. Removal of COD, TOC (total organic carbon), DOC (dissolved organic carbon), and the test POC 4-chloro-3-methylphenol (CMP) in the venturi delivery trials.

5.2.2 Direct ozone delivery

For the direct delivery trials the percent reduction of the test POC was similar to the venturi trials, however a larger O_3 unit was used. As such, the test POC removal rate was lower (~4 mg POC g^{-} O_3 h^{-1}) using direct delivery compared to the venturi system. The addition of Fenton's reagents did increase the percent removal compared to O_3 only, but there was only a small increase in the test POC removal rate (~5.3 mg POC g^{-} O_3 h^{-1}).

Table 4. Results of the field trials using a direct delivery system and a 20 g h^{-1} O_3 generator. Fenton's reagents were also added. Maximum POC removal was observed when Fenton's reagents were added.

Treatment	Volume (L)	Time (h)	O_3 conc (g h^{-1})	H_2O_2 (mM)	Fe^{2+} (mM)	% rem	mg POC g^{-} O_3 h^{-1}
O_3	700	24	20	-	-	35	3.8
O_3	700	24	20	-	-	38	4.4
O_3 + Fenton's	700	24	20	50	0.5	50	5.5
O_3 + Fenton's	700	24	20	50	0.5	60	5.1

5.2.3 Determine operating costs

Operating costs are presented in the Discussion (Table 5).

6.0 Discussion

Our results clearly demonstrate that O_3 is a highly effective oxidising agent for degrading POC's in tannery wastewater. However the very high organic load in the wastewater means that much of the O_3 is directed towards the oxidation of other organic material (Fig. 8). Nevertheless, we were still able to remove appreciable POC from the wastewater.

Overall the venturi delivery system showed much higher rates of POC breakdown than the direct delivery system. The direct delivery approach is advantageous compared to the venturi system because there are no issues with clogging of pumps, so it can be used on wastewater with a high solids content. However there is more loss of O_3 from the direct delivery system. In order to improve the direct delivery system we would recommend using fine ceramic diffusers and a tall reaction column. However this would require an increase in the pressure of the blower which would in turn require more air to be pushed through the system, diluting the O_3 and reducing its effectiveness.

The addition of Fenton's reagent is clearly beneficial for POC breakdown, almost doubling the percent removal compared to O_3 only in both the venturi delivery and direct delivery trials. There appear to be optimal concentrations of Fe^{2+} and H_2O_2 at which POC breakdown is maximised. Based on the trials we performed we selected 0.125 mM of Fe^{2+} and 50 mM of H_2O_2 to maximise POC breakdown.

While the venturi system is prone to clogging, we recommend using a pump with a rotor more appropriate for high solids content wastewater. The size of the venturi can also be increased to avoid clogging. Ultimately the choice of the delivery system comes down to the POC removal rate. In order to summarise our findings and guide decisions on the implementation of a full-scale system we have constructed a table of potential treatment options (Table 5). The table presents the treatment conditions and the volume of wastewater (L) that could achieve > 90% POC removal under these conditions in 24 h. We also provide an estimate of the power and chemical costs required to achieve this treatment.

With pure O_3 and a venturi delivery we estimate that we can remove >90% of the test POC from 670 L of wastewater. A similar removal can be achieved with Fenton's reagents alone (646 L). Combining O_3 with Fenton's we calculate that the test POC can be removed from ~1500 L of wastewater in 24 h (highlighted row in Table 5). This is more than the combined individual removal based on O_3 and Fenton's, suggesting that there are synergies when the two techniques are combined. In terms of the operating costs, assuming the cost of electricity is 20c per KWh, the total cost of treating 1500 L of wastewater with the combined O_3 and Fenton's approach would be under $40.

Table 5. Calculated volume of wastewater that could be treated to > 90% for POC in 24 h under the given conditions. The power and chemical costs for this treatment are also provided

Treatment	O_3 conc (g h^{-1})	H_2O_2 (mM)	Fe^{2+} (mM)	L in 24 h	Power ($)	Chem ($)
Mixed tank	-	50	0.125	**646**	4.6	29.7
Venturi	20	-	-	**670**	7.7	0.0
Venturi	20	50	0.25	**796**	7.7	29.8
Venturi	20	50	0.5	**957**	7.7	30.1
Venturi	20	50	0.125	**1519**	7.7	29.8
Venturi	20	75	0.125	**1417**	7.7	44.6
Blower	20	-	-	**244**	9.4	0.0
Blower	20	-	-	**271**	9.4	0.0
Blower	20	50	0.5	**355**	9.4	29.8
Blower	20	50	0.5	**423**	9.4	29.8

7.0 Conclusions / Recommendations

We recommend setting up and testing the system highlighted in Table 5. This would involve purchase of a more appropriate pump and a larger venturi. The existing 20 g h^{-1} O_3 unit could be used for this trial and initially we would recommend testing it on 1000 L. If the removal rate matches what we have predicted in Table 5 then we would recommend increasing the volume of the treatment tank.

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