Renovation of waste water for direct reuse in an abattoir

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Abstract

Tertiary treatment methods were tested on secondary effluent from an abattoir biological waste-water treatment plant with the purpose of renovating it for reuse in the abattoir. The colour and dissolved organic matter could be removed to such an extent that the water would comply with water of "insignificant health risk" (Department of Health). The treatment process sequence proven to be effective in upgrading this water to "insignificant health risk" standard was coagulation with a polymer blend, separation, ozonation, filtration and activated carbon filtration. The development of biologically activated carbon in practice was accepted as inevitable and desirable for optimum water quality, but not tested. A deciding factor in the selection of an appropriate treatment was that the final water would also have acceptable corrosion properties.

Introduction

Because of present and projected water shortages in South Africa (Die Departement van Waterwese, 1984), the Johannesburg Abattoir has been looking at minimising their freshwater usage. The water demand was reduced significantly by optimising water usage in the abattoir. The next phase would be to renovate and reuse the effluent.

The Johannesburg Abattoir employs biological purification to treat its waste water. This reduces the municipal effluent disposal charges. An added advantage is that single-cell organisms for which an economic application exists are harvested. This secondary treatment process removes 90% to 95% of all the organic matter from the primary effluent (Pretorius et al., 1995). The secondary effluent contains colour, suspended matter and micro-organisms that makes it unsuitable for direct reuse. Further treatment by tertiary processes could renovate it to an acceptable quality for selected applications in the abattoir.

Water quality required

Less than half of the average water demand (Van Heerden, 1995) in an abattoir is applied to processes that bring it into direct contact with products for human consumption. The balance of the water demand could be satisfied with effluent that has been renovated to comply with certain minimum health, aesthetic and economic criteria (Cowan and Steenveld, 1990).

The Department of Health proposed a three-tiered drinking water quality guideline (Pieterse, 1989) which included these limits. This guideline grades water quality into "no health risk", "insignificant" and "low health risk" categories depending on frequency of use. The renovated water could be of "insignificant health risk" quality while water complying with "no health risk" quality criteria should be supplied to the rest of the abattoir.

The Department of Health guideline stipulates permissable levels of indicator organisms which can be reached with disinfection (White, 1992). Dissolved organic matter (DOM) present in water to be disinfected can seriously hamper disinfection

efficiency, increase disinfectant demand (Rogers et al., 1987) and can lead to the formation of carcinogenic chlorinated organics (Vik et al., 1985). DOM can also be the cause of colour, odour and regrowth of organisms in a distribution system (Funke, 1969). DOM should therefore be removed to levels specified by the Departmental guideline for health and aesthetic reasons (Krenkel and Novotny, 1980).

Economic criteria require that maintenance costs should be minimised (Cowan and Steenveld, 1990). The effects of orrosion and aggressive water on equipment and pipes can be controlled by maintaining a calcium carbonate precipitation potential and limiting chloride and sulphate ions (Benefield et al., 1982).

Present water quality

Most suspended solids and biodegradable organic matter are removed during the single-cell production process (Pretorius et al., 1995). The DOM in this secondary effluent would be similar (Rebhun et al., 1969) to that found in secondary treated domestic effluents. This DOM is detectable by colour, taste and odour and the composition and characteristics are similar (Narkis and Rebhun, 1983) to DOM found in coloured surface water streams. On average 45% of DOM in secondary treated domestic sewage would be humic matter (Manka et al., 1974) whereas about 50% would be humic matter in surface water (Sierka et al., 1989). Humic matter is characterised (Christman and Ghassemi, 1966) by an unsaturated structure which is the cause of colour.

Possible treatment alternatives

Because of the possible effect of DOM on the health and aesthetic quality of the reused water, the removal of DOM was identified as a priority. Humic matter makes up the bulk of the DOM. The various methods of removal of humic matter are: chemical coagulation and separation (Edzwald et al., 1977; Grozes et al., 1995); oxidation (Edwards et al., 1994); adsorption onto activated carbon (Weber and Jodellah, 1985; Sierka et al., 1989); membrane processes like reverse osmosis, ultra- and nanofiltraton (Juby and Botha, 1994; Tan and Amy, 1991); and combinations of these (Weber and Jodellah, 1985).

Coagulation is a popular treatment method and its effectiveness has been proved in coloured surface water (Christman and

Ghassemi, 1966). Ozonation in combination with activated carbon (Harrington and DiGiano, 1989) as well as biologically activated carbon is a cost-effective treatment alternative (Juby and Botha, 1994; DiGiano et al., 1982). Juby and Botha (1994) have found nanofiltration effective for both colour and organic matter removal, although it was a more expensive treatment alternative (Tan and Amy, 1991).

Coagulation of humic matter generally involves complexing and precipitation with a polymer (Edzwald et al., 1987). Metal salts form polymeric hydrolysis intermediates when added to water (Semmens and Field, 1980). Organic polyelectrolytes (Dempsey et al., 1985) and pre-formed metal polymers such as polyaluminium chloride (Edwards et al., 1994; Grozes et al., 1995) can have a greater charge neutralisation capacity than these hydrolysis intermediates. Commercial blends of polymetal compounds and organic polyelectrolytes can combine the effect of higher charge densities and optimum length for very effective contaminant removal in specific waters (Kerdachi et al., 1994).

Humic matter stability in water is due to negative charge density (Manka et al., 1974) provided by unprotonated phenol and carboxylic functional groups (Sierka et al., 1989). This charge density is reduced when the pH is reduced (Kuo and Amy, 1988). The stability of the humic matter is reduced, reducing effective coagulant dosage at pH of around 5 (Qureshi and Malmberg, 1985; Amirtharajah et al., 1993). However, decreasing the pH below 4.5 would result in charge reversal (Stephenson and Duff, 1996) and increasing stability.

Removal of DOM by complete oxidation to CO_2 with prolonged ozonation (Constantine, 1982; Chang and Singer, 1991) would generally be uneconomical. Oxidation with lower ozone dosages would decrease the degree of unsaturation of the humic matter (Owen et al., 1995; Kuo and Amy, 1988) by oxidising the double bonds in chromophores and destroying colour. Smaller entities with aldehyde, ketone and carboxylic acid functional groups (Eaton, 1995; Sierka et al., 1989) are the products of this reaction. Turbidity is often increased after ozonation. This can be due to humic matter that adsorbs on and stabilises colloidal matter being oxidised and removed (Edwards et al., 1994).

These products of ozonation are generally more biodegradable than humic matter and would lead to bio-growth on granular activated carbon (Symons, 1980). Optimal use of ozone and activated carbon for removal of organic matter would be in combining an ozonation step to remove colour and increase biodegradability, and fixed bed activated carbon adsorption on which biological activation is promoted (Constantine, 1982).

Objectives

The purpose of this research was to establish which combination of tertiary treatment processes would produce a stable, reusable water of "insignificant health risk" quality from the secondary treated waste water from an abattoir. In order to achieve this the following objectives were formulated:

A comparison of the effectiveness of colour removal by:
- Different chemical coagulants at different pHs.
- Coagulation followed by various combinations of tertiary treatment processes

The final water produced by these treatment processes would be checked for compliance with the "insignificant health risk" quality guideline and guidelines for corrosion control.

Methods

Sample collection and testing

Twenty-five litre samples of secondary effluent from Johannesburg Abattoir were collected every second to third day during the experimental period. The samples were preserved at 4°C between test runs, but allowed to reach ambient temperatures before any experiments were performed. The samples were shaken before aliquots for experimental procedures were drawn. Each sample of raw water was tested for total dissolved solids (TDS), chloride, sulphate, total alkalinity, total hardness, turbidity, colour, dissolved organic carbon (DOC), and total heterotrophic plate counts were performed.

Comparison of coagulants for colour removal

Initially a range of metal salt and polyelectrolyte coagulant blends were screened for their ability to remove colour. Of these, aluminium sulphate $(Al_2(SO_4)_3.18H_2O)$, ferric chloride $(FeCl_3.6H_2O)$ and a polyaluminium chloride and polyamine blend (PACl-Blend - NCP:Chloorkop) gave the best results. These were used for comparison of colour removal. Testing consisted of varying the chemical dosage without adjusting pH, and varying pH while keeping dosages constant as shown in Table 1.

For the varying pH testing, pH was adjusted with 5 N H_2SO_4 or 0.25 N NaOH solutions prior to coagulant addition and recorded after flocculation. Loewenthal et al. (1986) advised that the individual concentrations of chloride and sulphate concentrations should not exceed 50 mg/ℓ each to limit corrosion. Polyamine products often have health limitations for use in drinking water (Mallevaille et al., 1984). Comparing the colour removal at varying pH was therefore performed at:

100 mg/ℓ $Al_2(SO_4)_3.18H_2O$ to limit increase in sulphate concentration to 43 mg/ℓ

120 mg/ℓ ferric chloride to limit increase in chloride concentration to 47 mg/ℓ.

60 mg/ℓ PACl-Blend due to a health limitation on dosing of 66 mg/ℓ.

To identify the coagulant that gave consistently the best results for colour removal at these dosages, the mean and standard deviation (Wine, 1964) was calculated for percentage removal obtained at constant pH for aluminium sulphate (100 mg/ℓ), ferric chloride (120 mg/ℓ) and PACl-Blend (60 mg/ℓ).

Coagulation was performed with the jar test method as recommended by Dental et al., 1988 and Lai et al., 1975. The best results were obtained by rapid mixing for 2 min. at 295 r·min⁻¹ (G-value of 199.5 s⁻¹) after coagulant addition, followed by 20 min at 50 r·min⁻¹ (G-value of 12.6 s⁻¹). 500 mℓ samples to 1 ℓ round glass beakers were used and the G-values were obtained using calibration of G in round beakers by Botha (1995). After 20 min settling, samples of supernatant were drawn for pH and colour measurement.

Corrosivity

Stabilisation dosage requirements were calculated for coagulant dosages and pH, using the Stasoft computer program (Loewenthal et al., 1988). The corrosivity according to the Larson index:

$$\frac{Cl^- + SO_4^{2-}}{Alkalinity}$$ (Loewenthal et al., 1986) was calculated using the theoretical alkalinity given by Stasoft in each case. Loewenthal et al. (1986) recommended that this value should be less than 0.2.

TABLE 1 DETERMINATION OF BEST COAGULANT FOR COLOUR REMOVAL				
Coagulant	Dosage	Metal ion	Counter ion	pH
Varying dosage				
Aluminium sulphate	30 - 400 mg/ℓ	0.1 - 1.8 mmol/ℓ	13 - 173 mg/ℓ SO_4^{2-}	7.6
Ferric chloride	30- 400 mg/ℓ	0.11 - 2,2 mmol/ℓ	12 - 157 mg/ℓ Cl^-	7.6
U 3500	30 - 120		1 - 6 mg/ℓ Cl	7.6
Varying pH				
Alum	100 mg/ℓ	0.3 mmol/ℓ	43 mg/ℓ SO_4^{2-}	4 - 7.6
Ferric chloride	120 mg/ℓ	0.4 mmol/ℓ	47 mg/ℓ Cl^-	4 - 7.6
PACl-Blend	60 mg/ℓ		2 mg/ℓ Cl	4 - 7.6

Ozonation

Ozone was generated with an LN 103 ozone generator (Ozonia, Switzerland) with oxygen as a feed gas. The ozone generator was calibrated by bubbling ozone through a diffuser at the bottom of a 75 mm dia. contact column containing 1 ℓ of a 2% potassium iodide (KI) solution. Ozone dosage was varied according to the time of ozonation at constant voltage and gas flow. After each time period, the KI solution was transferred and titrated to a clear endpoint using 0.1 N sodium thiosulphate ($Na_2S_2O_3.5H_2O$) with starch as indicator as was described by Toerien, (1988) and Razumovski and Zaikov (1984), thereby measuring the amount of ozone transferred during each time interval. The ozone production rate was determined from these data.

The ozone demand of water (National Institute for Water Research, 1981) is defined as the amount of ozone consumed before an ozone residual is observed for a given time period. The readily oxidisable organic matter in water will deplete ozone (Venosa and Meckes, 1983; Rice and Bollyky, 1981) and constitute this demand. Since the unsaturated bonds on humic matter would be preferred sites for ozone attack, the demand would also represent the amount of ozone needed for colour removal (Grasso and Weber, 1988). Ozone demand was determined by applying ozone to distilled water and the sample at increasing dosages and measuring the ozone in the off-gas by the same method described above. The ozone demand of the sample and contact system would be the mass of ozone applied minus the mass of ozone in off-gas per litre of sample.

The relationship between ozone absorbed and colour removal was determined by measuring the percentage colour removal while increasing applied ozone doses. Absorbed ozone was determined in the same manner as described for ozone demand.

Table 2 shows applied ozone dosages employed to obtain these relationships.

Activated carbon adsorption for colour removal

Granules of activated carbon type PHO 12/40 were supplied by Montan (Johannesburg) and added to 150 mℓ aliquots of treated secondary effluent water and shaken over a period of 12 h to

TABLE 2 OZONE COMBINATIONS		
Sample	Applied ozone dosage	Relationship
Distilled water	0 -80 mg/ℓ	Reference curve
Secondary effluent	0 - 80 mg/ℓ	Ozone demand curve
Flocculated secondary effluent	0 - 60 mg/ℓ	Ozone demand curve
Secondary effluent	0 - 20 mg/ℓ	Colour removal curve

TABLE 3 ACTIVATED CARBON ADSORPTION FOR COLOUR REMOVAL	
Sample	Activated carbon added
Flocculated secondary effluent	50 -1000 mg/150 mℓ
Flocculated and ozonated secondary effluent	50 - 1000 mg/150 mℓ

compare the effect of ozonation on the removal of colour by adsorption. Amounts added are shown in Table 3.

Comparison with guideline

The most effective treatment sequence was performed on a sample of secondary effluent and the product water quality after each treatment step was analysed for TDS, chloride, sulphate, alkalinity, hardness, pH, turbidity, colour and DOC. These were compared to the guidelines for health, aesthetic and economic criteria.

Analysis methods

- Organic matter removal with coagulation was measured by colour removal as was mentioned by Edwards and Amirtharajah (1985) and Van Breemen et al. (1979). This relationship between colour and COD removal was confirmed in this study.
- DOC was measured by Rand Water Scientific Services.
- Samples were corrected to pH 7 and centrifuged before colour measurement (Crowther and Evans, 1981) with a Merck

TABLE 4
SECONDARY EFFLUENT QUALITY COMPARED TO REQUIREMENTS FOR WATER OF NO AND INSIGNIFICANT HEALTH RISKS

Parameter	Secondary effluent	No health risk	Insignificant health risk
TDS (mg/ℓ)	664 - 1000	470	2000
Alkalinity (mg/ℓ CaCO$_3$)	300 - 500		
Larson-index	0.49		
Chloride (mg/ℓ)	100 - 120	250	600
Sulphate (mg/ℓ)	35	200	600
Hardness-mg/ℓ (CaCO$_3$)	120	20-300	650
pH	7.65 - 7.8		5.5-9.3
Turbidity (NTU)	2.7 - 5.2 (29)	1	5
Colour (Hazen)	176 - 220	20	20
DOC (mg/ℓ)	91	5	10
Standard plate count (cfu/100mℓ)	2 X 10^6	<100	<1000

Spectroquant photometer SQ118 (E. Merck, Darmstadt), relating it to Hazen units. TDS was determined gravimetrically on the centrifuged samples (*Standard Methods*, 1989).

- Samples were filtered through Whatman 4 filter papers before turbidity measurements. The nephelometric turbidity (Dental et al., 1988) was measured with a Hach turbidimeter model 2100 A (Hach, USA.).

- Total hardness was determined as in *Standard Methods* (1989) method No. 2340C, alkalinity by method 2320, chloride with method 4500-Cl B and standard plate count with method 9215 B.

Results and discussion

Sample collection and testing

The secondary effluent quality is compared to water of "no" and insignificant health risk in Table 4.

The TDS, chloride, sulphate, hardness and pH of the secondary effluent water were all within the limits of water quality of "insignificant health risk" (Pieterse, 1989). The chloride concentration is double the recommended 50 mg/ℓ and the Larson index was calculated to average around 0.43, which is higher than the recommended 0.2 (Loewenthal et al., 1986). The turbidity was mostly within the limit as well, apart from days when anaerobic conditions developed in the secondary clarifier. Turbidity levels up to 29 NTU were recorded. These conditions can be prevented with better operation of the biological plant. The colour, dissolved organic carbon (DOC) and microbiological quality (total heterotrophic plate count) of the secondary effluent did not comply with the requirement for water of insignificant health risk.

Comparison of coagulants for colour removal

Varying dosage

In Fig. 1 the three best coagulants were compared for colour removal at different dosages. No adjustments for pH were made.

Dosages of 120 mg/ PACl-Blend gave far superior colour removal (±68%) than similar dosages of alum and ferric chloride (±30%). To obtain 68% colour removal with alum and ferric
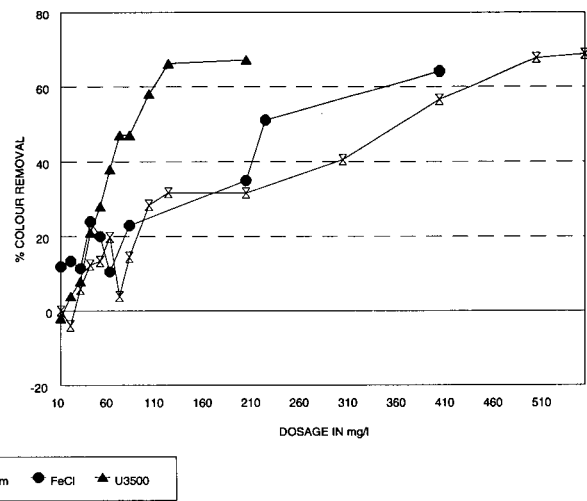

Figure 1
Comparison of colour removal with increasing dosages of three coagulants

chloride dosages of 400 mg/ℓ are needed. At these dosages pH was reduced to 6.

Big increases in colour removal were obtained with small increases in PACl-Blend addition, while increase in colour removal was more gradual with alum and ferric chloride. The fact that these two coagulants gave similar removal of colour was confirmed by plotting the percentage removals by alum and ferric chloride at selected dosages against each other. A straight line with a gradient of 1 was obtained with r^2 = 0.97.

The amount of coagulant added would be proportional to the amount of reaction sites on the organic matter (Amirtharajah et al., 1993, Vik et al., 1985). The charge density provided by the polyaluminium chloride and polyamine blend, PACl-Blend, is high (Dempsey et al., 1985), therefore less is needed to reach the optimum charge addition than with ferric chloride or alum. Secondly, different fractions of the humic matter could be more amenable to removal by different coagulants (Randtke and McCarty, 1979). A blend like PACl-Blend could therefore be more effective for colour removal. The pH was reduced when

ferric chloride and alum were used due to depletion of hydroxide to form hydrolysis intermediates and hydroxide precipitate (Hong-Xiao and Stumm, 1987). This reduction in pH could play a role in the increase in colour removal obtained at higher dosages of metal salts.

Corrosion requirements limit the dosages of alum and ferric chloride to 100 mg/ℓ and 120 mg/ℓ respectively and health requirements limit the PACl-Blend addition to 60 mg/ℓ. The mean and standard deviation (σ) for removals obtained at these dosages at pH 7.6 was calculated and is reported in Table 5.

TABLE 5
MEAN AND STANDARD DEVIATION OF COLOUR REMOVAL WITH 3 COAGULANTS

Alum at 100 mg/ℓ	Mean- 26.2% σ - 3.8 %
Ferric chloride at 120 mg/ℓ	Mean - 25.5 % σ - 13.2 %
PACl-Blend at 60 mg/ℓ	Mean - 37.6% σ - 2.7 %

PACl-Blend at 60 mg/ℓ gave better colour removal than alum at 100 mg/ℓ and ferric chloride at 120 mg/ℓ. The difference between colour removal obtained with alum and ferric chloride is marginal. The length and charge distribution of the hydrolysis intermediates-metal species formed with metal coagulants (Stephenson and Duff, 1996) would be determined by pH and would not necessarily always be consistent or optimum. This would explain high variability in results obtained with colour removal with ferric chloride.

Varying pH

The influence of pH on the efficiency of colour removal is compared for the three coagulants at constant dosages in Fig. 2.

Better removal was obtained with 60 mg/ℓ PACl-Blend than with 100 mg/ℓ alum or 120 mg/ℓ ferric chloride at all pH values. Similar removal efficiencies were again obtained with alum and ferric chloride. Colour removal was at least 20% higher at pH of around 5 than at pH 7.6 for all three coagulants. Optimum removal under pH conditions of around 5 was found by several authors like Edzwald et al. (1977), Narkis and Rebhun (1983) and Christman and Ghassemi (1966) and is explained by the destabilising effect of reducing pH on organic matter (Kuo and Amy, 1988).

Corrosivity

The Larson index increased from 0.49 to 0.5 with the dosage of 60 mg/ℓ PACl-Blend. The Larson index, after restabilisation with lime, of a water treated with 400 mg/ℓ ferric chloride was 1.4 and 400 mg/ℓ alum was 1.1. Dosages of alum and ferric chloride to these levels is not recommended.

The buffer capacity of the secondary effluent was high (alkalinity - Table 4) and added to the stability of the humic matter (Moyers and Wu, 1985). The amount of hydrochloric or sulphuric acid added to obtain a pH of 5 in the secondary effluent increased the chloride or sulphate ion concentrations to 300 mg/ℓ and 400 mg/ℓ respectively. This would increase the Larson index of the water to 0.75. The adjustment of the pH to 5 for optimum colour removal is not recommended.

At 60 mg/ℓ PACl-Blend the water still contained 62.4% of the original colour and organic matter and needed to be treated with further processes before complying with the "insignificant health risk standard".
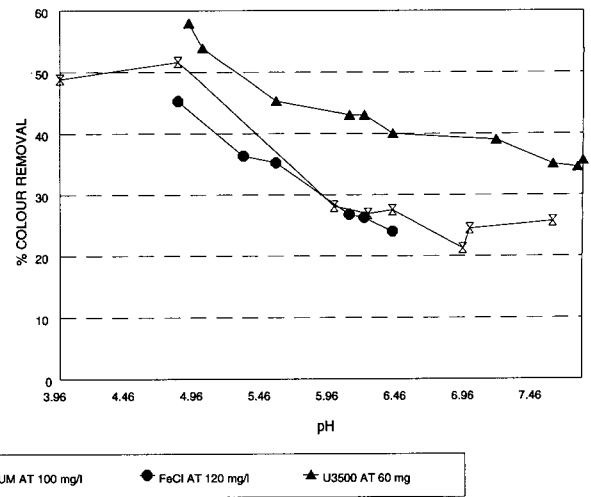
Figure 2
Comparison of the influence of pH on colour removal between three coagulants

Ozonation

An average of 5.86 mg ozone/minute was generated with the ozone generator at 0.5 A and 0.7 bar oxygen pressure. This value was used to determine applied ozone dosage for ozone demand and colour removal.

Ozone demand

The ozone demand of secondary effluent and secondary effluent coagulated with 60 mg/ℓ PACl-Blend can be seen in Fig. 3.

The influence of the amount of dead space in the ozone transfer system on the apparent ozone absorbed by the water is represented by the first straight-line portion where all three curves coincide. The ozone demand was about 8 mg/ℓ (A) for secondary effluent and 5.5 mg/ℓ (B) for flocculated water as shown in Fig. 3. Coagulation would reduce ozone dose. Another advantage is that it may absorb variations in raw water quality, avoiding continual adjustment of ozone dose.

Ozone absorbed and colour removal: Relationship

The reduction of colour from secondary effluent with ozone was non-linear (Juby and Botha, 1994), with significant reductions at low ozone dosages. The removal values were fitted to a power curve with the following formula: $y = 23.6 \, x^{0.43}$ $r^2 = 0.989$. The observed values are plotted with this curve in Fig. 4.

Fitting the colour removal efficiency to a theoretical formula would enable predictions to be made on the ozone dose necessary should the colour in the secondary effluent vary. The colour reduction rate decreases with higher dosages until a certain refractory fraction of colour will remain (Tan and Amy, 1991).

Colour removal with adsorption on activated carbon

In Fig. 5 the colour reduction in coagulated and ozonated secondary effluent by adsorption on increasing dosages of activated carbon is shown.

The colour removal in the flocculated sample was increased from 40% to 64% by the maximum activated carbon added. The carbon probably reached its adsorption capacity for the coloured humic matter around the dosage of 400 mg/150 mℓ. Colour removal from the ozonated water was increased from 77% to 81% by the maximum activated carbon added. The gradient of this curve shows that the adsorption capacity for colour from this water is very low. PHO 12/40 is a coconut-based activated carbon
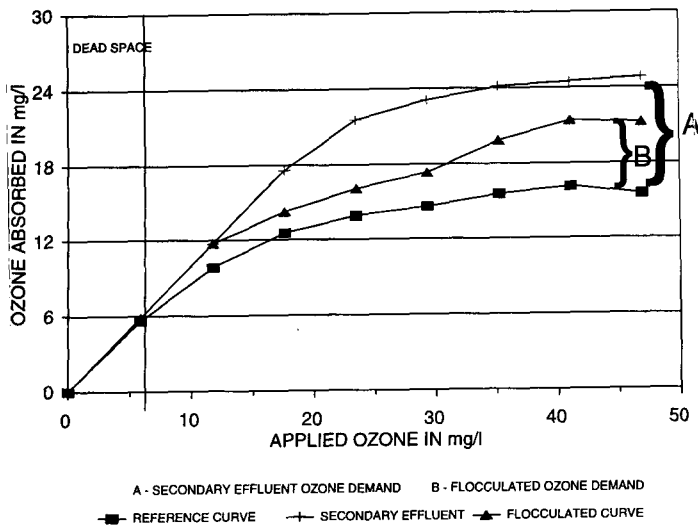
A - SECONDARY EFFLUENT OZONE DEMAND   B - FLOCCULATED OZONE DEMAND
-■- REFERENCE CURVE   -+- SECONDARY EFFLUENT -▲- FLOCCULATED CURVE

Figure 3
Reference and ozone demand curves for secondary effluent
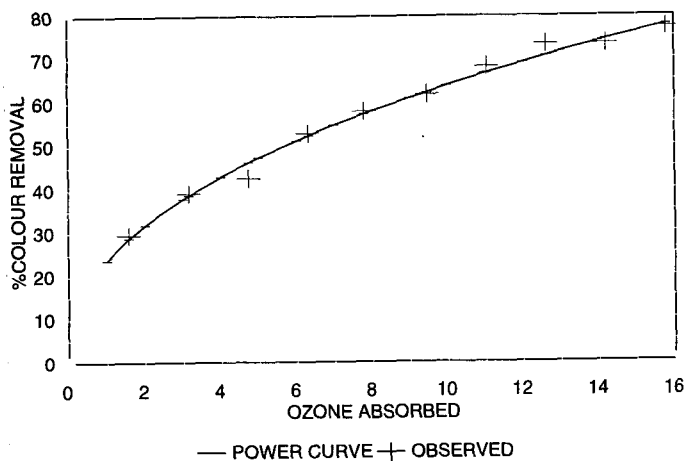and effluent flocculated with 60 mg/ℓ PACl-Blend

— POWER CURVE -+- OBSERVED

Figure 4
Theoretical and actual reduction in colour with increase in
ozone absorbed in secondary effluent

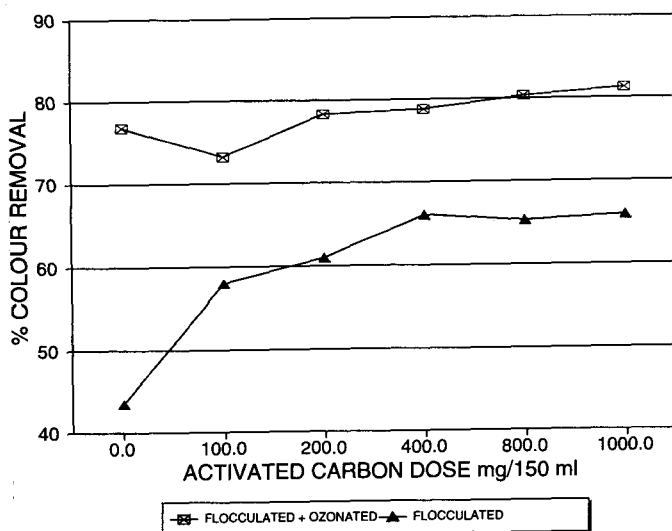-☒- FLOCCULATED + OZONATED-▲- FLOCCULATED

Figure 5
Comparison of colour removal with carbon adsorption of
flocculated and flocculated plus ozonated secondary effluent

with a small pore size and low capacity for adsorption of humic matter. Colour removal could possibly be improved using a peat-, wood- or bitumin-coal-based activated carbon (Nel, 1996).

Comparative removal

Coagulation with 60 mg/ℓ, PACl-Blend, ozonation at 5.5 mg/ℓ followed by filtration and contacting activated carbon at 6.7 mg/ℓ for 12 h was performed on a sample of secondary effluent. The influence of each treatment step on the water quality is compared to guideline values in Table 6.

The TDS, alkalinity, hardness and sulphate concentrations were not altered during any of the treatment processes. A slight increase in chloride-ion concentration was due to the addition of PACl-Blend which releases a small amount of counter ions. Although the Larson index was still outside specification, the treatment process did not increase it significantly (by only 0.01).

The dosage of 60 mg/ℓ PACl-Blend reduced turbidity from 5.2 NTU to 3.6 NTU (by 30%). Small pin flocs appeared in the coagulated sample after ozonation. This could be due to colloidal matter losing their stability due to oxidation of absorbed humic matter (Grasso and Weber, 1988; Edwards et al., 1994). It could also be due to polymerisation of organic matter which could bridge colloidal particles (Chang and Singer, 1991). After filtration removed the pin flocs, the turbidity was improved from 3.6 NTU to 1.9 NTU. Therefore, filtration should be performed after ozonation.

DOC was reduced by 16% to 76 mg/ℓ by coagulation. Ozonation and filtration reduced the DOC by 29% to 50 mg/ℓ. This removal is probably due to destabilisation of organic colloids, pin-floc formation and subsequent removal with filtration and not to complete oxidation to CO_2. McCarthy and Smith (1974) and Edwards et al. (1994) reported that significant fractions of organic matter would be removed only when very high ozone dosages and long reaction periods are employed.

DOC removal with activated carbon adsorption was measured for the maximum dosage. The DOC was reduced to 38 mg/ℓ (by another 13% to 58%). The total DOC removal with this dosage of activated carbon was 61% when coagulated but un-ozonated water was used. This clearly shows that the oxidation products of humic matter (low molecular weight and polar) are not adsorbed well (Symons, 1980). These smaller entities may be more biodegradable than humic matter (Weber, 1984).

The biodegradability of the organic matter and the development of BAC was not examined in this study, but the dosage ratio in this experiment of about 0.8 mg O_3/mg DOC may have to be increased to the recommended 1 to 2 mg ozone/mg TOC which was reported (Juby and Botha, 1994; Goel et al., 1995) to be necessary to increase biodegradability of humic matter. Increasing the biodegradability of the DOC may theoretically promote the formation of BAC which could theoretically increase DOC removal (Juby and Botha, 1994).

Colour was reduced to 110 Hazen with coagulation. Ozonation reduced this colour to 41 Hazen and adsorption to 33 Hazen. This is still higher than the recommended 20 Hazen. Colour may be reduced further if BAC develops.

Bacteria reduction was 50% after flocculation and

TABLE 6
THE WATER QUALITY PRODUCED BY THE SELECTED TREATMENT PROCESSES, TO GUIDELINES FOR
***INSIGNIFICANT HEALTH RISK* AND CORROSION**

	Guideline values	Secondary effluent	PACl-Blend 60 mg/ℓ+settle	Ozonation 5.5 mg/ℓ+filter	Activated carbon
TDS (mg/ℓ)	2000	664	664	664	664
Alkalinity (mg/ℓ CaCO$_3$)		300	300	300	300
Larson-index	0.2	0.49	0.5	0.5	0.5
Chloride (mg/ℓ)	600	110	112	112	112
Sulphate	600	35	35	35	35
Hardness (mg/ℓ CaCO$_3$)	200	120	120	120	120
pH	5.5-9.3	7.65	7.65	7.8	7.5
Turbidity (NTU)	5	5.2	3.6	1.9	1.9
Colour (Hazen)	20	176	110	41	33
DOC (mg/ℓ)	10	91	76	50	38
Standard plate count (cfu/100 mℓ)	1 000	2 000 000	1 000 000	50 000	N/A

95.26% after ozonation. Ozonation was not employed as a disinfection step. Bacteria levels could increase in the final water if BAC develops. A terminal disinfection step is necessary.

Conclusion

Comparison between aluminium sulphate, ferric chloride and PACl-Blend as coagulants for colour removal showed that PACl-Blend resulted in a better colour removal at half the dosages of the other two coagulants (Table 5). Furthermore, PACl-Blend does not impact on the pH of the water (Table 6) and releases significantly lower amounts of counter ions than alum and ferric chloride (Table 1). The colour removal could be doubled by increasing the dosage of the PACl-blend to 120 mg/ℓ which is outside the health limit. Coagulation with PACl-Blend at 60 mg/ℓ and settlement should be an initial treatment step. Either ferric chloride or alum could be used as a second choice since their performance was similar.

Reducing the coagulating pH from 7.6 to 5 increased colour removal by 20% at the same dosages of coagulant. The buffer capacity of the secondary effluent was very high and high acid dosages were needed to achieve this pH reduction. This increased the chloride and sulphate ion concentration to 3 or 4 times the recommended values for corrosion control. Adjusting the pH to optimise coagulation is not advisable.

Ozonation and filtration improved colour and organic matter removal to levels attained by very high dosages of coagulants or better. The relationship defined in this study could be used in practice to adjust ozone dosages for variations in colour of the secondary effluent. DOM was also reduced after filtration. The chemical quality of the water was not affected by ozonation. Ozonation and filtration should be included in the treatment sequence to reduce colour and organic material and to increase the biodegradability of the DOM.

Activated carbon adsorption was slightly less effective in DOM removal after ozonation than after just flocculation. However, colour removal was better with the ozonation step included. DOM levels could possibly be reduced to within the guideline values if BAC is allowed to develop.

The tertiary treatment recommended to renovate the secondary effluent from Johannesburg Abattoir to comply with water quality of "insignificant health risk" should consist of:

- Coagulation with 60 mg/ℓ PACl-Blend and flocculation at ambient pH
- Settlement
- Ozonation at 5.5 mg/ℓ (or higher to increase biodegradability)
- Filtration
- Activated carbon adsorption with provision for biologically activated carbon to develop
- Disinfection.

Recommendations

The formation of BAC after ozonation and the efficiency of removal of DOC and colour should be investigated.

The ammonia concentration was low during these experiments, but is known to vary and could impact adversely on chlorination. The efficiency of post-chlorination for disinfection should be investigated due to the very high chlorine demand.

Acknowledgements

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Appendix

The following results were obtained from the tertiary effluent treatment plant built at the Johannesburg Abattoir as a result of the investigative work reported in this publication: This plant consists of coagulation and settling, followed by ozonation, sand filtration, activated carbon filtration and chlorination.

TABLE 1
AVERAGE VALUES OF PARAMETERS ANALYSED FOR ON SAMPLES FROM THE EFFLUENT RECLAMATION PLANT AT THE JOHANNESBURG ABATTOIR FROM 7 JANUARY 1997 TO 14 MAY 1997

Parameter	Secondary effluent	Coagulation-Ferric chloride and settling	Ozone	Sand filtration	Activatd carbon filtration	Final effluent
Conductivity in mS/m	82					122
Ammonia in mg/l						38
Chloride in mg/l						270
pH	7.2					7.3
Turbidity in NTU		37.8	20	9.9	12.9	2.3
Colour - Hazen		56	48	42		38
DOC in mg/l	32	27	19.5	18	15.8	18.2
UV absorbance @ 254 nm	1.45	0.94	0.73	0.56	0.41	0.307
Plate count cfu/100 ml					5800 - 4.3 x 10⁶	60 - 3000