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# Treatment of grease filter washwater by chemical coagulation

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Ghaly, A.E., Snow, A. and Faber, B.E. 2006. **Treatment of grease filter washwater by chemical coagulation.** Canadian Biosystems Engineering/Le génie des biosystèmes au Canada **48**: 6.13 - 6.22. The treatment of grease filter washwater by chemical coagulation and sedimentation was investigated. Aluminum sulfate, ferrous sulfate, and ferric chloride were used as coagulation agents. Pollutant removal efficiency was measured in terms of total solids, pH, and optical density. Aluminum sulfate was the most effective coagulating agent. It reduced the total solids of the wastewater by 90% (compared to 88 and 28% for ferric chloride and ferrous sulfate, respectively), produced wastewater with the second highest pH (4.15 compared to 6.43 and 2.31 for ferrous sulfate and ferric chloride, respectively) and produced the clearest wastewater with an optical density of 0.194 (compared to 0.456 and 1.985 for ferric chloride and ferrous sulfate, respectively). The influence of temperature (10-40°C) and pH (7-11) on the efficiency of the coagulation/sedimentation process was then determined using aluminum sulfate at a dosage of 2.0 g/L. The results indicated that there was no benefit in varying the temperature and/or pH of the medium. The process was found to be effective at room temperature and a pH of 9.5 (pH of raw wastewater). The process successfully recovered over 80% recyclable water (20% sludge and fat). The quality of the purified water was comparable to that of drinking water. The sludge contained high concentrations of heavy metals and was not suitable for utilization. **Keywords:** pH, temperature, washwater, grease filter, coagulation, sedimentation, aluminum sulfate, ferrous sulfate, ferric chloride.

Le traitement des eaux de lavage graisseuses filtrées par coagulation chimique et par sédimentation a été étudié. Le trisulfate d'aluminium, le sulfate ferreux et le chlorure ferrique ont été utilisés comme agents coagulants. L'efficacité d'extraction des matières polluantes a été mesurée en termes de solides totaux, de pH et de turbidité. Le trisulfate d'aluminium s'est révélé être l'agent coagulant le plus efficace. Il a permis une réduction des solides totaux des eaux de lavage de 90% (comparé à 88 et 28% respectivement pour le chlorure ferrique et le sulfate ferreux), produit une eau de lavage traitée présentant la deuxième valeur de pH la plus élevée (4,15 comparativement à 6,43 et 2,31 respectivement pour le sulfate ferreux et le chlorure ferrique) et a permis d'obtenir une eau ayant la plus faible turbidité à 0,194 (comparativement à 0,456 et 1,985 respectivement pour le chlorure ferrique et le sulfate ferreux). L'influence de la température (10 - 40°C) et du pH (7-11) sur l'efficacité du processus de coagulation/sédimentation a été déterminée en utilisant le trisulfate d'aluminium à un dosage de 2,0 g/L. Les résultats ont indiqué qu'il n'y avait pas d'avantage à varier la température et ou le pH du médium. Le processus était efficace à la température de la pièce et à un pH de 9.5 (correspondant au pH de l'eau de lavage non traité). Le processus a permis de recycler plus de 80% de l'eau brute (20% de boue et gras). La qualité de l'eau purifiée était comparable à celle de l'eau potable. La boue obtenue contenait de fortes concentrations de métaux lourds ce qui la rend indésirable pour

utilisation subséquente. **Mots clés:** pH, température, eau de lavage, filtre à gras, coagulation, sédimentation, trisulfate d'aluminium, sulfate ferreux, chlorure ferrique.

## INTRODUCTION

The food service industry in Canada accounts for 39.6% of the total food dollar spent by consumers, tourists, businesses, institutions, and government (CRFA 2004). The total size of the food service industry in Canada was estimated at 15.347 billion dollars in 2003, which represented 4% of the country's gross domestic product (Statistics Canada 2004; CRFA 2004). Growth over the period of 1997-2003 was reported at 20.53% (Statistics Canada 2004). Factors driving the growth of the food service industry include: (a) the gain in Canadian population, (b) rapid growth in the fast food service sector, (c) impact of working women and two income families, (d) the desire to save time, and (e) conflict over food choices.

Food processing operations utilize significant quantities of water and discharge large volumes of effluents, which represent one of the largest sources of pollution in Canadian waters (Environment Canada 2004a). Wastewaters from food plants, restaurants, and hospitals contain a wide variety of chemical, biological, and physical constituents such as fat, meat, bone scraps, animal or fish entrails and excreta, blood and dairy wastes, pulp and peels of vegetable origin, and detergents from washing. Their compositions and contamination loads vary greatly from one operation to another (Environment Canada 2004b). Generally, food processing wastewaters share several characteristics: (a) they are much higher in strength than domestic wastewaters, (b) they contain high concentrations of fats, oils, and greases (FOG), soaps, and waxes, (c) they are readily biodegradable and usually contain a sufficient amount of nutrients such as nitrogen and phosphorous which are required for biological treatment, (d) they contain proteinaceous material which deaminates to form large concentrations of ammonia in the wastewater, and (e) they contain heavy metals (lead, zinc, cadmium, silver, antimony, etc.), synthetic non-biodegradable organics, phthalates, pesticides (Dieldrin, Lindane, etc.), toluene, benzene, PAHs, acids, dioxins, furans, halogen compounds, and pathogenic materials all of which are objectionable features of these wastes (Environment Canada 2004a). The high concentrations of these biodegradable materials in liquid wastes from food processing operations have a number of negative impacts on the quality of the aquatic environment including: (a) increases in nutrient levels, which

**Table 1. Wash water characteristics and environmental limits for different disposal alternatives.**

Component	Wash-water* (mg/L)	Disposal			
		Sanitary sewer <sup>†a</sup> (mg/L)	Storm sewer <sup>‡b</sup> (µg/L)		Land <sup>cd</sup> (mg/kg)
			Freshwater	Marine	
Aluminum	150	50	5-100		
Antimony	5	5			
Arsenic	1	1	5	12.5	12
Barium		5			750
Beryllium		5			
Bismuth		5			
Cadmium	1	0.1	0.017	0.12	14
Chlorides	1500	1500			
Chromium (total)	5	4			64
Trivalent chromium			8.9	56	
Hexavalent chromium			1.0	1.5	
Cobalt	5	5			20
Copper	3	1	2.4		63
Cyanide		2	5		0.9
Fluorides		10			
Iron		50	300		
Lead	5	2	1-7		70
Manganese	5	5			
Mercury		0.1	0.1		6.6
Molybdenum	5	5	73		
Nickel	3	2			
Phosphorus	1100	30			
Sulphates	1500	1500			
Sulfide		2			
Selenium	5	5	1.0		1.6
Silver	5	2	0.1		
Tin	5	5			
Vanadium	3				130
Zinc		3	30		200
BOD	15000	300			
COD	60000	1000			
Total solids	22775	350			
pH	10	5.5-9.5	6.5-9.0	7.0-8.7	

\* Filter washwater obtained from Enviro Clean Ltd.

† Sanitary sewer is a sewer for the collection and transmission of domestic, commercial, and industrial wastewaters.

‡ Storm sewer is a sewer and all related structures designed exclusively for the collection and transmission of uncontaminated storm water and drainage from land.

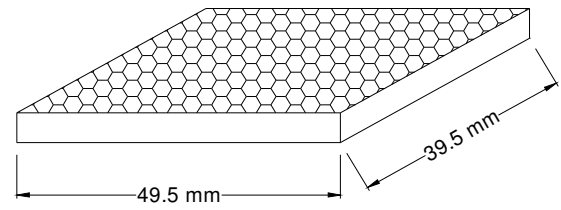
<sup>a</sup> Service Nova Scotia and Municipal Relations (2004)

<sup>b</sup> CCME (2002a)

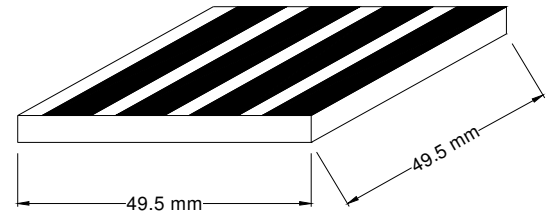
<sup>c</sup> CCME (2002b)

<sup>d</sup> Nova Scotia Department of Environment and Labor (2004)

over-stimulate the growth of algae and other aquatic plants (blooms), (b) depletion of dissolved oxygen resulting from decaying organic wastes, and (c) habitat destruction resulting from increased sedimentation and chemical toxicity. Wastewater effluents can, therefore, render water unfit for domestic,



(a) screen filter



(b) vertical baffle filter

**Fig. 1. Types of grease filters used in fume hoods.**

recreational, and industrial use (Conway and Ross 1980; Besselieve and Schwartz 1976; Patterson 1975; Besselieve 1952; Environment Canada 2004b).

An example of these wastewaters is grease filter washwater. At every cooking facility (restaurants, hospitals, and university kitchens), there is a fume hood which collects the grease before exhausting air into the atmosphere. The filters (Fig. 1) in the fume hood must be cleaned periodically. A typical washing cycle consists of placing one filter at a time on a washing rack constructed of wood. The operator then manually sprays on a cleaning solution of diatomite (#1046) and caustic potash (45% KOH) in and around the filter on each side. A high pressure spray nozzle directs high temperature (72°C) water onto the screen. The hot washwater, which contains cleaning solution and grease particles, enters a drain basin where it is then pumped into a holding tank to allow for cooling. The washwater is fairly high in heavy metal content and pH and cannot be discharged directly to sewers or on land. Table 1 shows the composition of the washwater produced and environmental limits for different disposal alternatives.

Currently, there are three alternatives for disposal of wastewater: (a) discharging to storm sewers, (b) discharging to sanitary sewers, and (c) discharging on land. Since storm sewer waters are released directly to streams, rivers, and oceans, discharging to storm systems would have serious consequences for the aquatic environment as these pollutants could be toxic to marine life and the organic material in the wastewater would begin to decompose, depleting the water body of oxygen. Discharging wastewater to sanitary sewers has several disadvantages as FOG may: (a) clog sewers, pumps, screens, air diffusers, clarifier feedwells, and raleways, (b) hinder

**Table 2. Examples of prosecuted environmental (food waste) offences in Canada (Environment Canada 2003, 2004a; Nova Scotia Department of Environment 1992).**

Year	Act	Defendant	Offence	Fine (Can\$)
2004	Fisheries Act section 36 (3)	Poultry processing plant	illegal discharge of poultry liquid effluent	30,000
2004	Fisheries Act section 36 (3)	Potato processing plant	illegal discharge of effluent (potato leachate)	30,000
2003	Canadian Environmental Protection Act section 125 (1) Fisheries Act section 36 (1) (b)	Fish processing plant	illegal ocean disposal of fish offal	1,750
2003	Canadian Environmental Protection Act section 124 (1)	Fish processing plant	illegal dumping of fish waste	10,000
2001	Canadian Environmental Protection Act section 124 (1) (b)	Fish processing plant	illegal discharge of fish offal	10,000
2000	Fisheries Act section 36 (3)	Meat and poultry processing plant	illegal discharge of meat and poultry liquid effluent	100,000
1992	Environmental Protection Act S.23 (1)	Seafood processing plant	unlawful discharge of material into environment	15,000
1991	General Litter Abatement Regs S.8 (2)	Food processing plant	failure to clean up property within 15 m of food concession	300
1991	General Litter Abatement Regs S.5 (SOT)	Fruit farm	unlawful discharge of litter into the environment	250
1989	Water Act	Food processing plant	unlawful discharge of contaminant	4,000

oxygen transfer in aerobic biological treatment processes, and (c) slow the rate of biodegradation (Green and Kramer 1979). Discharging the material onto land may lead to contamination of the groundwater and destruction of wildlife habitats. Environmental laws in Canada are becoming more and more stringent. Current laws state that if an industrial plant discharges pollutants in excess of established provincial or federal standards, it will be heavily fined (Department of Justice 2004a, 2004b; Legislative Council 2004). Examples of prosecuted environmental offences and convictions in Canada are presented in Table 2. The development of a process that can make productive use of the waste is needed. The objective of this study was to evaluate the chemical treatment of grease filter washwater using three different coagulating agents: aluminum sulfate, ferrous sulfate, and ferric chloride.

## MATERIALS and METHODS

### Experimental design

Two sets of experiments were performed in this study. First, preliminary coagulation/sedimentation experiments were conducted using three common coagulants (aluminum sulfate, ferrous sulfate, and ferric chloride). The tests for each coagulant were conducted at various concentrations (1.0, 1.5, 2.0, 2.5, and 3.0 g/L). These concentrations were within the range reported in the literature. By comparing the total solids reduction and the optical density of the liquid, an optimum concentration was

determined for each individual chemical. The total solids reduction and the clarity (optical density) of the treated waste were then compared to determine the most effective coagulating agent. In the second set of experiments, the most effective coagulant was used to determine the influence of temperature and pH on the efficiency of the coagulation/sedimentation process.

### Experimental protocol

The raw wastewater used in this study was a grease filter washwater obtained from Enviro Clean Ltd. located in Waverly, Nova Scotia. The washwater was first mixed to ensure a homogeneous sample. A one-liter volume was drawn into a beaker and placed on a magnetic stirrer. The proper amount of chemical coagulant for the particular treatment was measured on an analytical balance and added to the wastewater, which was allowed to mix for a period of ten minutes to ensure that the coagulant was completely dissolved. The mixture was then transferred to 1000-mL graduated cylinders where sedimentation took place. Complete settling was achieved when the clear volume became constant which took about 6 hours. Samples of the treated wastewater were taken at the completion of the sedimentation process and placed into 100-mL beakers. The treated wastewater was then analyzed for pH, total solids, and optical density. Once sedimentation was complete (6 hours), the graduated cylinders were washed and prepared for the next set of experiments.

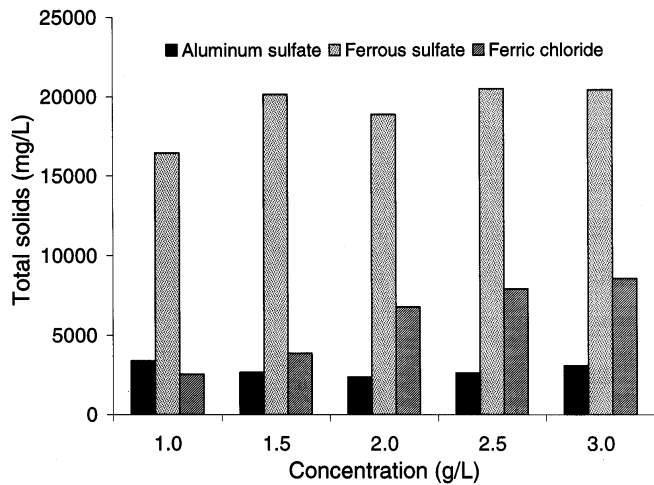


Fig. 2. The total solids of the treated portion of the treated wastewater.

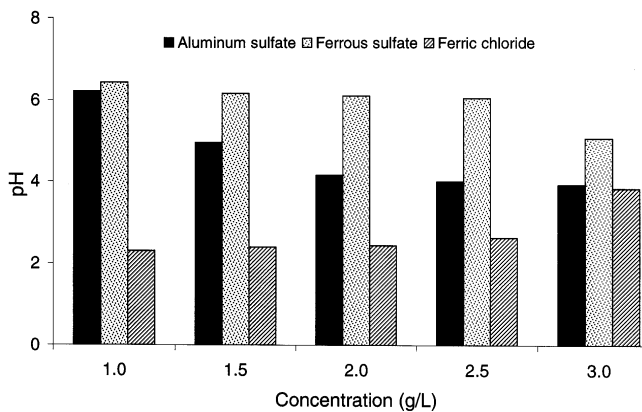


Fig. 3. The pH of the treated portion of the treated wastewater.

### Experimental analyses

The total solids analysis of the liquid sample was determined according to the Standards Methods for the Examination of Water and Wastewater (APHA 1989). A convection oven (Isotemp, model 630F, Fisher Scientific Ltd., Pittsburgh, PA) was used. An analytical balance (Delta range, model PM4600, Mettler Instruments, Greifensee, Switzerland) was used for all determination of mass throughout the experiments. The pH of the samples was determined using a pH meter (Fisher Accumet, model 905MP, Fisher Scientific Ltd., Pittsburgh, PA). The optical density of the samples was determined using a spectrometer (Milton Roy Spectronic, model 1201, Fisher Scientific Ltd., Pittsburgh, PA) at a wavelength setting of 484 nm.

## RESULTS and DISCUSSIONS

### Preliminary experiments

The total solids, pH, and optical density results of the coagulation/sedimentation experiments are presented in Figs. 2 -4.

**Total solids** The total solids of the raw wastewater was 22,775 mg/L. The total solids of the treated wastewater was

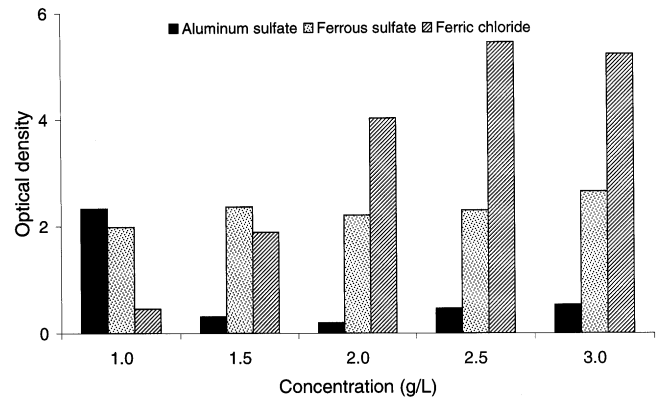


Fig. 4. The optical density of the liquid portion of the treated wastewater.

substantially lower than the raw wastewater for all chemical coagulants. The highest solids removal efficiency of 89.6% was achieved at a concentration of 2.0 g/L of aluminum sulfate, followed by that of 88.8% at a concentration of 1.0 g/L of ferric chloride and that of 27.8% at a concentration of 1.0 g/L of ferrous sulfate as shown in Table 3.

Generally, the total solids of the liquid portion of the treated wastewater increased with increasing chemical concentration for ferrous sulfate (from 16450 to 20413 mg/L) and ferric chloride (from 2548 to 8578 mg/L) whereas for aluminum sulfate the total solids of the liquid portion of the treated wastewater initially decreased (from 3385 to 2358 mg/L) and then increased (from 2358 to 3088 mg/L) when the concentration was increased above 2 g/L. Increasing the coagulant concentration from 1.0 to 3.0 g/L increased the total solids of the treated wastewater by 1.5, 24.1, and 236.7% for aluminum sulfate, ferrous sulfate, and ferric chloride, respectively. The relationship between the total solids ( $TS$ ) of the wastewater and the chemical concentration of aluminum sulfate ( $C_{AS}$ ), ferrous sulfate ( $C_{FS}$ ), and ferric chloride ( $C_{FC}$ ) is described by Eqs. 1-3.

$$TS = 6974.8 - 5174.7C_{AS} + 1739.7C_{AS}^2 - 148.67C_{AS}^3 \quad R^2 = 0.99 \quad (1)$$

$$TS = -2485.8 + 31400C_{FS} - 14481C_{FS}^2 + 2192.7C_{FS}^3 \quad R^2 = 0.81 \quad (2)$$

$$TS = 5078.4 - 8628C_{FC} + 7417.4C_{FC}^2 - 1386.7C_{FC}^3 \quad R^2 = 0.98 \quad (3)$$

where:

- $TS$  = total solids (mg/L),
- $C_{AS}$  = concentration of aluminum sulfate (g/L),
- $C_{FS}$  = concentration of ferrous sulfate (g/L), and
- $C_{FC}$  = concentration of ferric chloride (g/L).

Sievers et al. (1994) conducted a coagulation settling experiment on three types of dilute manure wastewaters (cattle, swine, and poultry). At concentrations of 300 to 450 mg/L, ferric chloride removed 60 to 70% of the volatile solids from the cattle and swine wastewaters and 30% of the volatile solids from poultry wastewater. Liu and Lien (2001) reported that at a pH of  $6.0 \pm 0.1$  and an aluminum sulfate concentration of 70 mg/L, 85.9% of suspended solids (SS) was removed from bakery wastewater. When the aluminum sulfate concentration was increased to 100 mg/L, 95.3% of SS was removed. When

**Table 3. Solids removal efficiency, when initial total solids content of raw wastewater was 22725 mg/L, using aluminum sulfate, ferrous sulfate, and ferric chloride.**

Chemical concentration (g/L)	Aluminum sulfate		Ferrous sulfate		Ferric chloride	
	Final total solids (mg/L)	Reduction (%)	Final total solids (mg/L)	Reduction (%)	Final total solids (mg/L)	Reduction (%)
1.0	3385	85.1	16450	27.8	2548	88.8
1.5	2650	88.4	20138	11.6	3878	83.0
2.0	2358	89.7	18875	17.1	6800	70.1
2.5	2613	88.5	20475	10.1	7933	65.2
3.0	3088	86.4	20413	10.4	8578	62.2

The values are the average of 3 replicates (CV=1.2-6.1%).

ferric chloride was used as the coagulant at a concentration of 90 mg/L, up to 99.1% of SS was removed from the wastewater. Rusten et al. (1990) reported that when ferric chloride was applied to dairy wastewater at dosages ranging from 50 to 200 g/m<sup>3</sup>, the maximum removal efficiencies in terms of total chemical oxygen demand ranged from 52 to 73%. Schneider et al. (1995) used ferric chloride in the coagulation-flocculation treatment of soybean effluent. At a pH of 4.5 and a ferric chloride concentration of 200 to 300 mg/L, 83% of suspended solids and 28% of chemical oxygen demand were removed from the wastewater. The solid removal efficiencies obtained with ferric chloride and aluminum sulfate are comparable to these reported values.

**pH** The initial pH of the raw wastewater was 9.50. Generally, the pH of the wastewater decreased with increasing chemical concentration for aluminum sulfate and ferrous sulfate, whereas for ferric chloride the pH increased as chemical concentration increased. Increasing the chemical concentration from 1.0 to 3.0 g/L changed the pH of the wastewater from 6.2 to 3.9, from 6.4 to 5.1, and from 2.3 to 3.8 for aluminum sulfate, ferrous sulfate, and ferric chloride, respectively. The pH of the treated wastewater was substantially lower than the initial pH for all chemical coagulants (3.8 for aluminum sulfate, 4.1 for ferrous sulfate, and 2.2 for ferric chloride). Aluminum sulfate and ferrous sulfate exhibited the largest reduction in pH (5.6 and 4.4, respectively) at a chemical concentration of 3.0 g/L, whereas ferric chloride had the largest reduction in pH (7.2) at a chemical concentration of 1.0 g/L as shown in Table 4. The relationship between the pH of the washwater and the chemical concentration of aluminum sulfate, ferrous sulfate, and ferric chloride is described by Eqs. 4-6.

$$pH = 11.506 - 7.445C_{AS} + 2.42C_{AS}^2 - 0.26C_{AS}^3 \quad R^2 = 0.99 \quad (4)$$

$$pH = 0.528 - 7.5395C_{FS} + 4.2257C_{FS}^2 - 0.7733C_{FS}^3 \quad R^2 = 0.99 \quad (5)$$

$$pH = -0.668 + 5.8248C_{FC} - 3.5629C_{FC}^2 + 0.7067C_{FC}^3 \quad R^2 = 0.99 \quad (6)$$

where:  $pH$  = negative  $\log_{10}$  of  $[H^+]$  ions.

**Table 4. pH reduction, when initial pH of raw wastewater was 9.5, using aluminum sulfate, ferrous sulfate, and ferric chloride.**

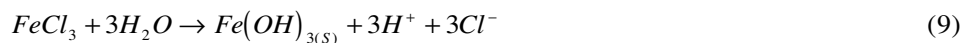
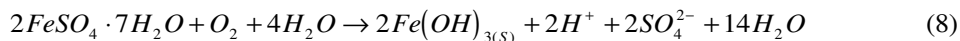
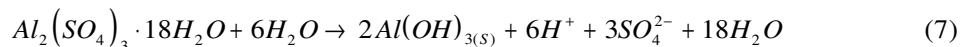
Chemical concentration (g/L)	Aluminum sulfate		Ferrous sulfate		Ferric chloride	
	Final pH	Reduction	Final pH	Reduction	Final pH	Reduction
1.0	6.2	3.3	6.4	3.1	2.3	7.2
1.5	5.0	4.5	6.2	3.3	2.4	7.1
2.0	4.1	5.3	6.1	3.4	2.4	7.1
2.5	4.0	5.5	6.1	3.4	2.6	6.9
3.0	3.9	5.6	5.1	4.4	3.8	5.7

The values are the average of 3 replicates (CV=1.1-4.9%).

Song et al. (2004) reported that an increase in coagulant concentration was associated with a decrease in pH of tannery wastewater. The initial pH of the wastewater was 9.2, and upon addition of either 100 mg/L of aluminum sulfate or 100 mg/L of ferric chloride, the pH of the solution decreased to 8.9. The maximum rate of pH reduction occurred with a coagulant concentration in the range of 500-900 mg/L which produced a final pH of 6.6 and 5.7 for aluminum sulfate and ferric chloride, respectively. In this study, the final pH of the washwater after the addition of 3 g/L aluminum sulfate and ferric chloride was 3.9 and 3.8, respectively.

A decrease in solution pH occurred because aluminum sulfate and iron salts (ferrous sulfate and ferric chloride) consume alkalinity as reported by Droste (1997) and Song et al. (2004). Alkalinity is defined as the quantity of ions in water that will react to neutralize hydrogen or the ability of water to neutralize acids. The ions that constitute alkalinity are primarily hydroxide (OH<sup>-</sup>), carbonate (CO<sub>3</sub><sup>2-</sup>), and bicarbonate (HCO<sub>3</sub><sup>-</sup>), and their presence in solution depends on pH. At a pH of 8.3-12.8, all of the hydroxide ions and half of the carbonate ions react to neutralize acid, and at a pH of 4.5-8.3, half of the carbonate ions and all of the bicarbonate ions are consumed by the acid (Peavy et al. 1985).

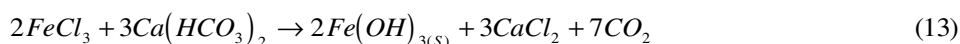
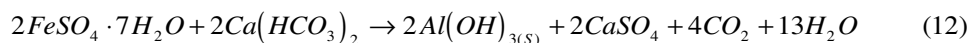
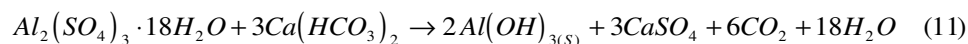
In this study, the initial pH of the wastewater was 9.50. The Fe<sup>3+</sup> or Al<sup>3+</sup> ions react with the OH<sup>-</sup> ions in the wastewater and precipitate in the form of iron or aluminum hydroxides. Reactions of aluminum sulfate (Al<sub>2</sub>(SO<sub>4</sub>)<sub>3</sub>·18H<sub>2</sub>O), ferrous sulfate (FeSO<sub>4</sub>·7H<sub>2</sub>O), and ferric chloride (FeCl<sub>3</sub>) in water are shown in Eqs. 7-9 (Droste 1997).



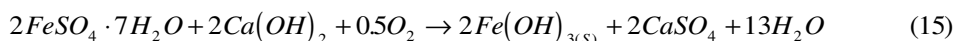
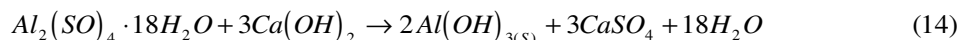
If natural alkalinity is present, then the hydrogen ions interact with the bicarbonate ions as:



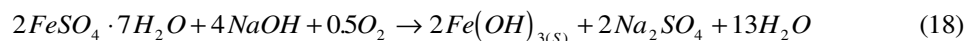
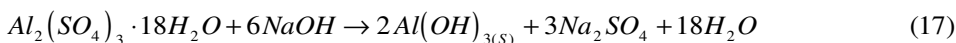
Equations 7- 9 can, therefore, be written as:



If natural alkalinity is insufficient, hydrated lime (Ca(OH)<sub>2</sub>) or caustic soda (NaOH) can be added and Eqs. 7- 9 become:



or



The pH of the treated wastewater can have serious impacts on the receiving environment. In aquatic ecosystems, the pH of marine and fresh waters should fall within the range of 7.0-8.7 and 6.5-9.0, respectively (CCME 2002b). A fluctuation in pH within the range of 6.5 to 9.0 is harmless to most fish and other aquatic life. However, as the pH continues to rise above 9.0, it begins to adversely affect most aquatic species, and a pH in the range of 11.0-11.5 is lethal to all species of fish (EPA 2003). On the other hand, a decrease in pH is also detrimental to the aquatic ecosystem. When pH falls within the range of 5.0-6.0, rainbow trout, salmonids and molluscs become rare, the rate of organic matter decomposition declines because the fungi and bacteria responsible for degradation are not acid tolerant, and most green algae, diatoms, snails, and phytoplankton disappear (EPA 2003). Bamber (1987, 1990) reported that at a pH below 7, four species of bivalves exhibited reduced growth and shell size, weight loss, and suppressed feeding. As the pH of the aquatic environment continues to decrease, the biodiversity of the ecosystem continues to decline, fish population numbers diminish, and some aquatic species are completely eliminated

from the water body. Generally, the young of most species are more sensitive to environmental conditions than adults. Most fish eggs will not hatch when the pH of the surrounding environment reaches 5.0. Acidic waters also affect other aquatic animals such as frogs, toads, and salamanders who often exhibit stunted growth at low pH (EPA 2003). Changes in water chemistry may also occur as a result of a decrease in pH. At low pH, aluminum is released from soils into lakes and streams, and as the pH of the water body decreases, aluminum levels increase leading to weight loss, stunted growth, and death of fish. Phosphates can also be complexed to the mobilized aluminum resulting in a decrease in the primary production of aquatic plants. Phosphate is a limiting nutrient for plants and when bound to aluminum it is not readily available for uptake (EPA 2003). Therefore, when selecting a coagulant for solids removal, the final pH of the wastewater should be considered if the final product is to be disposed into water bodies.

**Optical density** The optical density initially decreased from 2.332 to 0.194 and then increased from 0.194 to 0.526 with increasing aluminum sulfate

concentrations while it increased from 1.985 to 2.650 and from 0.456 to 5.209 with increasing ferrous sulfate and ferric chloride concentrations, respectively (Fig. 3). The relationship between the optical density (OD) and the chemical concentration of aluminum sulfate, ferrous sulfate, and ferric chloride is described by Eqs. 20-22.

$$OD = 15.582 - 21.608C_{AS} + 9.7523C_{AS}^2 - 1.408C_{AS}^3 \quad R^2 = 0.99 \quad (20)$$

$$OD = -1.3846 + 5.9985C_{FS} - 3.152C_{FS}^2 + 0.534C_{FS}^3 \quad R^2 = 0.96 \quad (21)$$

$$OD = 4.065 - 10.344C_{FC} + 8.3043C_{FC}^2 - 1.5767C_{FC}^3 \quad R^2 = 0.99 \quad (22)$$

where: OD = optical density at 484 nm.

The optical density of the treated washwater can be used to determine the optimum dosage of the respective chemical coagulant because the lower the optical density, the clearer the liquid and the better suited it will be for reuse or disposal into water bodies. The optical density results indicated that the optimum dosage for ferrous sulfate and ferric chloride was 1.0 g/L while for aluminum sulfate the optimum dosage was 2.0 g/L. The optical density of each chemical coagulant

**Table 5. Total solids, optical density, and pH values at optimum chemical concentrations of aluminum sulfate, ferrous sulfate, and ferric chloride starting with waste water as an opaque liquid with total solids of 22775 mg/L and pH of 9.5.**

Parameter	Optimum dosage (g/L)	Total solids (mg/L)	Optical density (at 484 nm)	pH
Aluminum sulfate	2	2358	0.194	4.2
Ferrous sulfate	1	16450	1.985	6.4
Ferric chloride	1	2548	0.456	2.3

These values are the average of 3 replicates (CV=2.5-6.1%)

**Table 6. Effect of temperature on the coagulation process using aluminum sulfate.**

Temperature (°C)	Observed effect
10	<ul style="list-style-type: none"> <li>• very fine precipitate was formed in the mixture</li> <li>• precipitate did not settle at all</li> </ul>
20	<ul style="list-style-type: none"> <li>• very dense, sponge-like precipitate formed immediately</li> <li>• precipitate settled very rapidly</li> <li>• resulting liquid portion was clear</li> </ul>
30	<ul style="list-style-type: none"> <li>• white chunky precipitate formed immediately</li> <li>• precipitate did not settle initially</li> <li>• precipitate eventually settled to the bottom</li> <li>• liquid portion was very cloudy</li> </ul>
40	<ul style="list-style-type: none"> <li>• white, fine precipitate formed immediately</li> <li>• within about 2 min most of the precipitate rose to the surface</li> <li>• some precipitate settled to the bottom</li> <li>• resulting liquid portion cloudy</li> </ul>

followed the same trend as the total solids content. The relationship between the total solids and optical density of aluminum sulfate ( $OD_{AS}$ ), ferrous sulfate ( $OD_{FS}$ ) and ferric chloride ( $OD_{FC}$ ) is, therefore, described by Eqs. 23-25.

$$OD_{AS} = -4.3509 + 0.0018TS \quad R^2 = 0.70 \quad (23)$$

$$OD_{FS} = 0.0132 + 0.0001TS \quad R^2 = 0.70 \quad (24)$$

$$OD_{FC} = -1.4744 + 0.0008TS \quad R^2 = 0.98 \quad (25)$$

Sievers et al. (1994) reported a similar linear relationship between the concentration of volatile solids (VS) and turbidity for samples of manure wastewaters. Song et al. (2004) reported that when aluminum sulfate and ferric chloride were used as coagulating agents at a concentration of 800 mg/L and a pH of 7.5, the average removal efficiencies from tannery wastewater in terms of color were 86% for aluminum sulfate and 85% for ferric chloride, respectively.

Mutlu et al. (2002) found that increasing the concentration of either aluminum sulfate or ferric chloride decreased the average color and optical density (OD) of the wastewater. They reported that at a coagulant dosage of 250 mg/L, the average

removal efficiency in terms of color on effluent from a baker's yeast plant were 10% for both aluminum sulfate and ferric chloride. When the aluminum sulfate dosage was increased to 2000 and 4000 mg/L, the removal efficiencies in terms of color and OD were 47 and 60% and 81 and 88%, respectively. When the dosage of ferric chloride was increased to 2000 and 4000 mg/L, the average removal efficiencies in terms of color and OD were 22 and 28% and 80 and 50%, respectively.

In this study, increasing the dosage of the chemical coagulants, not only increased the total solids of the treated washwater, but also increased the color intensity. These findings are in direct conflict with the results of research conducted by Mutlu et al. (2002) and Song et al. (2004). The increase in total solids and color intensity of the treated wastewater can be explained by examining the mechanisms of coagulation. According to Droste (1997), coagulation is the process of adding chemical reagents or coagulants to water or wastewater to destabilize colloidal particles and allow them to agglomerate with other suspended materials forming larger, more readily settled particles. Colloidal particles are negatively charged and upon addition of either aluminum sulfate or iron salts to wastewater, the  $Fe^{3+}$  or  $Al^{3+}$  ions are attracted to these particles. At the point of complete charge neutralization, the colloids begin to agglomerate due to collisions between particles. If excess coagulant is added to the wastewater, the result is excess adsorption of  $Fe^{3+}$  or  $Al^{3+}$  ions, reversal of the net charge on the colloidal particles (from negative to positive), and particle restabilization. The result of particle restabilization by charge reversal allows greater amounts of smaller particles to remain in solution, thus increasing the total solids as well as the color intensity of the wastewater.

Schafran and Tekleab (2000) conducted a study examining the use of coagulation as a means of removing TBT (tributyltin) from shipyard wastewaters and found that when aluminum sulfate was applied to the washwater at concentrations of 60 and 240 mg/L, the percent reductions in TBT were 98 and 75%, respectively. Increasing the coagulant dose produced results that were counter intuitive with lower TBT removal occurring with increasing coagulant dose. The researchers attributed this finding to particle restabilization by charge reversal.

### Selection of coagulant

The total solids, optical density, and pH values observed at the optimum concentration for each chemical coagulant are presented in Table 5. Aluminum sulfate was the most effective coagulating agent. It reduced the total solids of the wastewater by 90% (compared to 88 and 28% for ferric chloride and ferrous sulfate, respectively), produced the second highest pH (4.15 compared to 6.43 and 2.31 for ferrous sulfate and ferric chloride, respectively) and produced the clearest wastewater with an optical density of 0.194 (compared to 0.456 and 1.985 for ferric chloride and ferrous sulfate, respectively).

### Process optimization

The effects of temperature (10-40°C) and pH (7-11) on the coagulation process using aluminum sulfate were investigated.

**Table 7. Effect of initial pH on the coagulation process using aluminum sulfate.**

pH (before addition of chemical)	Observed effect
7	<ul style="list-style-type: none"> <li>• fine precipitate was formed immediately</li> <li>• much of the precipitate rose to the top</li> </ul>
10	<ul style="list-style-type: none"> <li>• very dense, sponge-like precipitate formed immediately</li> <li>• precipitate settled very rapidly</li> <li>• resulting liquid portion was clear</li> </ul>
11	<ul style="list-style-type: none"> <li>• precipitate formed immediately</li> <li>• some precipitate rose to the top and some settled</li> <li>• liquid portion was very cloudy</li> </ul>

**Table 8. Characteristics of sludge, fat, and water layers obtained after treatment.**

Component	Washwater (mg/kg)	Sludge (mg/kg)	Treated water (mg/L)	Tap water (mg/L)
Aluminum	700	10500	0.06	207
Ammonia (as N)	--	--	7.00	0.14
Alkalinity (as CaCO <sub>3</sub> )	--	--	156	33
Antimony	<2	<2	0.003	<2
Arsenic	<2	<2	<0.002	<2
Barium	5.0	10	0.015	6.6
Beryllium	<5.0	<5	<0.005	<5
Bicarbonate	--	--	156	33
Boron	5.0	6.0	0.15	<5
Cadmium	<0.3	<0.3	0.0009	0.3
Calcium	--	--	17.1	17.9
Carbonate (as CaCO <sub>3</sub> )	--	--	0	0
Chloride	--	--	109	11.6
Chromium	2.0	3.0	0.0009	3.0
Cobalt	<1	<1	0.002	<1
Color	--	--	120 TCU	4 TCU
Copper	4.0	7.0	0.033	7.4
Hardness (as CaCO <sub>3</sub> )	--	--	50.9	46.8
Iron	252	415	<0.01	1770
Lead	1.8	2.9	0.0005	5.5
Magnesium	--	--	2.0	0.5
Manganese	8.0	14.0	2.5	19.1
Molybdenum	<2	<2	<0.002	<2
Nickel	3.0	3.0	0.036	<2
Nitrate and Nitrite (as N)	--	--	<0.05	<0.05
Ortho-phosphorus	--	--	0.03	0.02
Potassium	--	--	860	1.0
Reactive Silica	--	--	26.0	2.5
Selenium	<2	<2	<0.002	<2
Silver	--	--	<0.0005	--
Sodium	--	--	148	4.4
Strontium	<5	<5	<0.024	<5
Sulfate	--	--	1110	10
Thallium	<0.1	<0.1	<0.0001	<0.1
Tin	<2	<2	<0.002	<11
TOC	--	--	241	2.2
Turbidity	--	--	8.06 NTU	0.56 NTU
Uranium	<0.1	0.1	<0.0001	<0.1
Vanadium	<2	<2	<0.002	<2
Zinc	385	502	6.4	582.8
pH	--	--	6.3	7.3

The results are shown in Tables 6 and 7. The results indicated that there was no benefit in varying the temperature and/or pH of the medium. The sedimentation process was actually found to be effective at room temperature and a pH of 10 (pH of raw wastewater). Droste (1997) found that aluminum sulfate coagulation was most efficient over a temperature range of 5-20°C. Narasiah et al. (1994) reported that seasonal temperature variations in domestic wastewater did not have a detrimental effect on the coagulation process. However, Hodgson et al. (1997) reported that the coagulation efficiency of kraft mill effluent decrease slightly at elevated temperatures (40°C), which could be due to the nature of the wastewater used in their study.

According to Droste (1997), the pH is a critical factor affecting the efficiency of coagulation. Aluminum salts work best over a pH range of 5.5-6.3. Song et al. (2004) reported that when aluminum sulfate was used as the coagulating agent for the treatment of tannery wastewater, pollutant removal efficiency in terms of COD was most effective at a pH of 6.5-7.5. Ho and Tan (1989) reported that the optimum pH range for coagulation of palm oil mill effluent was 5.9-6.0 when aluminum sulfate was used as the coagulant. Liu and Lien (2001) stated that the optimum pH for coagulation of bakery wastewater with aluminum sulfate was 6.0. Dovletoglou et al. (2002) conducted an experiment to determine the effect of pH adjustment prior to coagulant addition on paint industry wastewater and reported an optimum pH range of 9.5-11.0.

The results obtained from this study showed that there was no need for temperature or pH adjustment of the wastewater. However, because these coagulants reduce the pH of the wastewater, the addition of an alkaline agent such as hydrated lime or caustic soda may be required before final disposal into water bodies or reuse for washing the grease filters.

**Characteristics of supernatant and sludge**

Table 8 shows some characteristics of the liquid and sludge portions obtained from the process. The liquid portion was more than 80% of the total volume and had a water quality comparable to or better than that of drinking water. The sludge portion was less than 20% of the original volume of the wastewater. It, however, contained high concentrations of heavy metals and was not suitable for bioconversion to value added products. Dewatering of the sludge using vacuum filtration reduced its volume to 0.8% of the original volume of the wastewater which could significantly lower the cost of disposal associated with transportation. As a result, about 99.2% of the water could, therefore, be recycled.



## CONCLUSIONS

Aluminum sulfate (at a dosage of 2 g/L) was found to be the most effective coagulant. The average removal efficiency in terms of total solids was 90% and the pH and optical density of the treated wastewater were 4.15 and 0.194. The results indicated that there was no benefit in varying the temperature and/or pH of the medium. The process was found to be effective at room temperature and a pH of 9.5 (pH of raw wastewater). The process successfully recovered over 80% recyclable water and 20% sludge from the grease filter washwater. The quality of the liquid portion was comparable to that of drinking water. The sludge, however, contained high concentrations of heavy metals and was not suitable for bioconversion to value added products.

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