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Evaluation of chemical coagulation–flocculation aids for the removal of suspended solids and phosphorus from intensive recirculating aquaculture effluent discharge

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Abstract

An evaluation of two commonly used coagulation–flocculation aids (alum and ferric chloride) was conducted for the supernatant overflow from settling cones used to treat the effluent from microscreen filters in an intensive recirculating aquaculture system. In addition to determining the effectiveness of these aids in removing both suspended solids and phosphorus, a systematic testing of the variables normally encountered in the coagulation–flocculation process was performed. Tests were carried out to evaluate the dosages and conditions (mixing and flocculation stirring speeds, durations, and settling times) required to achieve optimum waste capture. The orthophosphate removal efficiency for alum and ferric chloride were 89 and 93%, respectively, at a dosage of 90 mg/l. Optimum turbidity removal was achieved with a 60 mg/l dosage for both alum and ferric chloride. Both alum and ferric chloride demonstrated excellent removal of suspended solids from initial TSS values of approximately 100–10 mg/l at a dosage of 90 mg/l. Flocculation and mixing speed played only a minor role in the removal efficiencies for both orthophosphates and suspended solids. Both coagulation–flocculation aids also exhibited excellent settling characteristics, with the majority of the floc quickly settling out in the first 5 min.

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1. Introduction

Phosphorus is one of the most scrutinized nutrients discharged by aquaculture systems, due to its eutrifying impact on freshwater systems. Phosphorus is often the limiting nutrient in natural ecosystems, and excessive algae blooms can occur if discharge concentrations exceed the absorption capacity of the receiving body of water. The potential impact of phosphorus on the environment and discharge limitations imposed by both state and federal regulatory agencies has stimulated research on ways to reduce phosphorus in discharges from recirculating aquaculture systems. Much of the work in this area has been to decrease the phosphorus input in the feed or increasing the dietary phosphorus availability. Until recently, few attempts have been made to reduce the phosphorus levels in the effluent water from recirculating aquaculture systems (Heinen et al., 1996; Adler et al., 1996, 2000). Recirculating aquaculture systems, however, provide opportunities for excellent phosphorus control, because through their design and operation, they provide a concentrated waste stream that can be treated more economically. In contrast, for systems such as raceways, equivalent treatment of the effluent flow stream would be extremely difficult both from an engineering and economic viewpoint.

Several chemical and biological processes have been investigated for the removal of phosphorus from aquaculture effluent water. Adler and Sibrell (2003) investigated the use of neutralized acid mine drainage to reduce the loss of soluble P from agricultural fields and animal wastewater. A biological means of phosphate removal has been demonstrated by Barak and van Rijn (2000), who demonstrated that some denitrifiers were capable of phosphate uptake in excess of their metabolic requirements. Kioussis et al. (1999) developed a polymeric hydrogel, which decreased phosphorus in aquaculture wastewater effluents by more than 99% to less than 0.01 ppm. However, it has been determined that the majority of the phosphorus discharged from intensive aquaculture systems (50–85%) is contained in the filterable or settleable solids fraction (Bergheim et al., 1993; Heinen et al., 1996). Thus any mechanism that could enhance solids removal would also contribute to a reduction in the overall level of phosphorus discharge. Coagulation and flocculation processes with agents such as alum or ferric chloride are standard techniques in the wastewater industry for removal of suspended solids. However these agents have not been extensively applied in the aquaculture industry because of the dilute nature of most aquaculture wastes. The increased use of recirculating systems makes this option more attractive.

Over the past several years, The Conservation Funds Freshwater Institute has demonstrated several technologies and strategies to manage and/or reduce the wastes generated during aquaculture production, including improved feed and feeding strategies (Tsukuda et al., 2000), technologies to minimize water use and concentrate waste streams (Timmons and Summerfelt, 1997; Summerfelt et al., 2000) and overall waste management and treatment reviews (Summerfelt, 1998; Summerfelt, et al.,

1999; Ebeling and Summerfelt, 2002). Future research at the Freshwater Institute will include the application of microfiltration technology using semi-permeable membranes and the construction of a demonstration pilot-scale compost facility.

The objectives of this research were the evaluation of several commonly used coagulation–flocculation aids used in the drinking and wastewater treatment industry, i.e. alum and ferric chloride. In addition to determining their effectiveness in removing both suspended solids and phosphorus, a systematic evaluation of the variables encountered in the coagulation–flocculation process (mixing and flocculation stirring speeds and durations, and settling times) was conducted.

2. Background

One of the most commonly used methods for the removal of suspended solids in drinking water is the addition of coagulant and flocculation aids, such as alum, ferric chloride, and long chain polymers (AWWA, 1997). Coagulation is the process of decreasing or neutralizing the electric charge on suspended particles or zeta potential. Similar electric charges on small particles in water cause the particles to naturally repel each other and hold the small, colloidal particles apart and keep them in suspension. The coagulation/flocculation process neutralizes or reduces the negative charge on the particles. This allows the van der Waals force of attraction to encourage initial aggregation of colloidal and fine suspended materials to form microfloc. Flocculation is the process of bringing together the microfloc particles to form large agglomerations by physically mixing or through the binding action of flocculants, such as long chain polymers. A classical coagulation/flocculation unit process (Metcalf and Eddy, 1991) consists of three separate steps (Fig. 1):

- 1) Rapid or flash mixing: the suitable chemicals (coagulants/flocculants and if required pH adjusters) are added to the wastewater stream, which is stirred and intensively mixed at high speed.

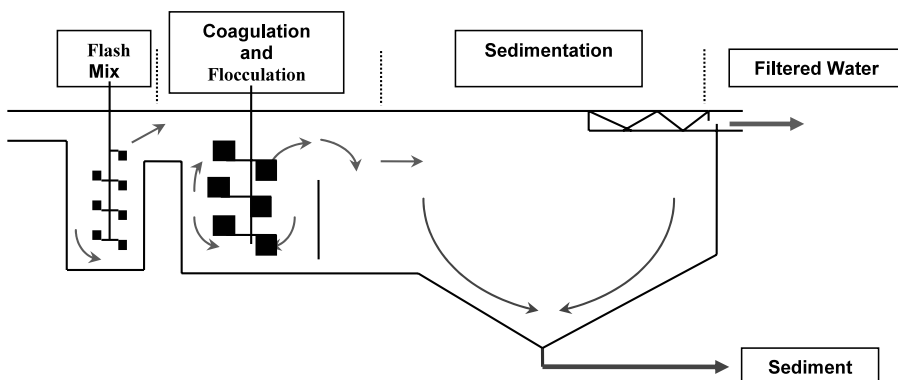


Fig. 1. The coagulation/flocculation unit process.

- 2) Slow mixing (coagulation and flocculation): the wastewater is only moderately stirred in order to form large flocs, which are easily settled out.
- 3) Sedimentation: the floc formed during flocculation is allowed to settle out and is separated from the effluent stream.

Numerous substances have been used as coagulant and flocculation aids, including alum [$\text{Al}_2(\text{SO}_4)_3 \cdot 18\text{H}_2\text{O}$], ferric chloride [$\text{FeCl}_3 \cdot 6\text{H}_2\text{O}$], ferric sulfate [$\text{Fe}_2(\text{SO}_4)_3$], ferrous sulfate [$\text{FeSO}_4 \cdot 7\text{H}_2\text{O}$] and lime [$\text{Ca}(\text{OH})_2$] (Metcalf and Eddy, 1991). Several of the problems with chemical precipitation are that the volume of sludge is increased and the resulting sludge may have poor settling and dewatering characteristics. In addition, metal salts used as coagulation aids consume alkalinity and can depress the pH of the effluent water. The following factors should be taken into consideration in selecting the most appropriate coagulant/flocculant aid:

- Effectiveness in removing phosphorus.
- Cost and reliability of supply.
- Sludge considerations, both volume and characteristics.
- Compatibility with other upstream or downstream treatment processes.
- Environmental effects.
- Labor and equipment requirements for storage, feeding and handling.

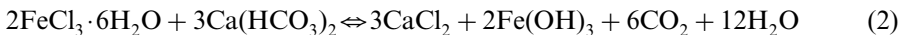
Aluminum sulfate (alum) is the most commonly used coagulant and is easy to handle and apply and produces less sludge than lime. Its primary disadvantage is that it is most effective over a limited pH range of 6.5–7.5. Ferric chloride is also a commonly used coagulant and is effective over a wider pH range of 4–11. The ferric hydroxide floc is also heavier than the alum floc, improving its settling characteristics, and reducing the size of the clarifier. Neither ferric sulfate nor ferrous sulfate is as commonly used today, but ferric sulfate is slowly replacing ferric chloride because it is easier to store and handle. Lime is commonly used and is effective, but is quite pH dependent and produces a large quantity of sludge requiring disposal.

When alum is added to a wastewater, the following reaction takes place:



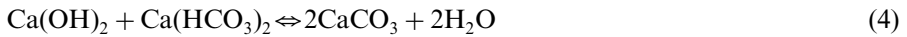
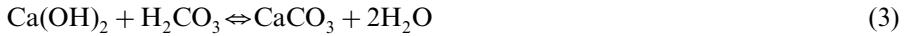
The insoluble aluminum hydroxide, $\text{Al}(\text{OH})_3$, is a gelatinous floc that settles slowly through the wastewater, sweeping out the suspended material. Alkalinity is required for the reaction and if not available, must be added at the rate of 0.45 mg/l as CaCO_3 for every 1 mg/l alum.

Similarly, for ferric chloride:

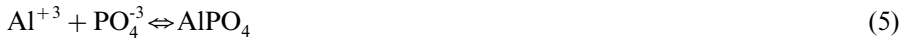


The insoluble ferric hydroxide, $\text{Fe}(\text{OH})_3$, is also a gelatinous floc that settles through the wastewater, sweeping out the suspended material. Alkalinity is required for the reaction and if not available, must be added at the rate of 0.55 mg/l CaCO_3 for every 1 mg/l ferric chloride.

When lime is added as a precipitant, the following reactions can occur:



In addition, both aluminum and iron salts can also be used for the chemical precipitation of phosphorus. The basic reactions involved are:



When lime is used, both the calcium and the hydroxide react with the orthophosphorus to form an insoluble hydroxyapatite:



The above equations are the simplest forms of the reaction (Metcalf and Eddy, 1991). Due to the many other competing reactions, the effects of alkalinity, pH, trace elements, and other compounds in the wastewater, the actual chemical dosage required to remove a given quantity of phosphorus is usually established on the basis of bench-scale test or sometimes pilot-scale tests.

Mixing disperses precipitating agents, coagulants and coagulant aids throughout the wastewater to ensure the most rapid precipitation reactions and subsequent settling of precipitates possible. For engineering design, the degree of mixing is dependent upon the amount of energy supplied, the mixing residence time, and the related turbulence effect, which depends on the size and shape of the mixing tank. Mixing can be subdivided into two types, flash or rapid mixing of chemicals and continuous mixing in reactors or holding tanks. Both are employed during the coagulation/flocculation process. In flash or rapid mixing, the principal objective is to mix completely one substance in another, i.e. alum in wastewater. In continuous mixing, the principal objective is to maintain the contents of a reactor in a completely mixed state that promotes aggregation of particles, i.e. flocculation. The power input per unit volume of liquid can be used as a rough measure of mixing effectiveness (Metcalf and Eddy, 1991). The following equation is normally used to estimate the velocity gradients in coagulation tanks and used for the design and operation of mixing systems (Metcalf and Eddy, 1991):

$$G = [\text{P}/\mu\text{V}]^{1/2} \quad (8)$$

where, G, mean velocity gradient (per s); P, power applied (W) or (ft lb/s); μ , dynamic viscosity (N s/m^2) or (lb s/ft^2); V, tank volume (m^3) or (ft^3).

The actual values for G are usually provided by the equipment manufacturers, although they can be estimated from the area of the paddle, fluid density, and paddle velocity in the fluid. Rapid or flash mixing residence times typically range from 30 s to 2 min, with 1 min being the most common. The intensity and duration of the mixing of the coagulants must be controlled to prevent the breakup of the microfloc, or uneven dosing of coagulant. Typical velocity gradient values for rapid mixing range from $G = 250$ to 1500 per s (Metcalf and Eddy, 1991). Flocculation mixing is

much slower to allow maximum interaction of the floc to aggregate together. Typical values of the velocity gradient for flocculation range from 20 to 80 per s, with a retention time of 20–30 min (Metcalf and Eddy, 1991).

3. Material and methods

The coagulation–flocculation tests were carried out following the standard practice for coagulation–flocculation testing of wastewater to evaluate the chemicals, dosages, and conditions required to achieve optimum results (ASTM, 1995). Samples for jar tests were taken directly from the supernatant overflow from three cone-bottomed settling tanks receiving the backwash water from several rotating microscreen filters used for suspended solids removal in two commercial size recirculating production systems growing arctic charr. The first of these is a pilot-scale partial-reuse system consisting of three 3.66×1.1 m deep circular ‘Cornell-type’ dual-drain culture tanks with a maximum feed loading rate of 45–50 kg of feed per day (Summerfelt et al., in press). The second system is a fully-recirculating system consisting of a 150 m^3 circular production tank with a maximum daily feed rate of 200 kg of feed per day (Summerfelt et al., in press). Water quality characteristics of the supernatant overflow are summarized in Table 1. Because of the excess alkalinity of the water at this location, no alkalinity additions were required in conjunction with alum and ferric chloride treatments.

3.1. Jar tests

For over 50 years, the jar test has been the standard technique used to optimize the addition of coagulants and flocculants used in the wastewater and drinking water

Table 1
Water quality characteristics of supernatant from settling cones.

Parameter	Mean	S.D.	Range
pH	7.14	0.17	6.72–7.29
Temperature (°C)	19.0	0.9	18–20
Alkalinity (mg/l)	278	19	245–303
Turbidity (FTU)	99.2	39.2	35–147
TP (mg/l-P)	9.6	6.2	2.7–20.4
SRP (mg/l-P)	4.1	2.2	2.1–7.9
TSS (mg/l)	77.7	16.7	49–105
TVS (mg/l)	73.4	19.3	43.9–96.8
TN (mg/l-N)	23.3	24.3	6–26.4
TAN (mg/l-N)	9.1	4.6	3.3–17.9
NO ₂ (mg/l-N)	0.10	0.04	0.06–0.18
NO ₃ (mg/l-N)	13.1	4.0	7.2–20.4
CBOD ₅ (mg/l)	189	107	51–340

Number of sample = 9.

treatment industry. The Standard Practice for Coagulation–Flocculation Jar Test of Water, ASTM D 2035, was first approved in 1980 and reapproved in 1999 (ASTM, 1995). The scope of this practice “covers a general procedure for the evaluation of a treatment to reduce dissolved, suspended, colloidal, and nonsettleable matter from water by chemical coagulation–flocculation, followed by gravity settling.” This standard was utilized to provide a technique to systematically evaluate the variables normally encountered in the coagulation–flocculation process.

Since coagulant interactions are very complex, laboratory studies are used to determine the optimal dosage, duration, and intensity of mixing and flocculation. The coagulation–flocculation process consists of three distinct steps. First, the coagulant is added to the effluent water and a rapid and high intensity mixing is initiated. The objective is to obtain complete mixing of the coagulant with the wastewater to maximize the effectiveness of destabilization of colloidal particles and initiate coagulation. Critical parameters for this step are the duration and the intensity (velocity gradient, G) or speed of mixing. The velocity gradient is a measure of the mixing energy and can be determined for a specific piece of equipment or specified in the engineering design analysis. Second, the suspension is slowly stirred to increase contact between coagulating particles and to facilitate the development of large flocs. Again, the flocculation duration and intensity are critical parameters. For example too high intensity can break up the aggregate floc. Third, mixing is terminated and the floc is allowed to settle.

A standard jar test apparatus, the Phipps & Bird Six-Paddle Stirrer with Illuminated Base (Fig. 2) was employed for the tests, with six 2-l square B-Ker² Plexiglas jars, sometimes called Gator Jars. The jars are provided with a sampling port, 10 cm below the water line, which allows for repetitive sampling with minimal impact on the test. By measuring the turbidity of samples taken during the settling

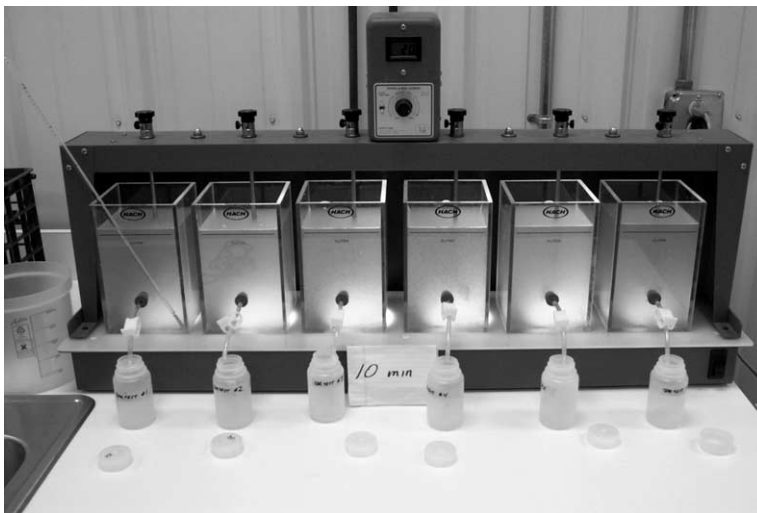


Fig. 2. Phipps and Bird Six-paddle stirrer with illuminated base.

cycle, a settling velocity distribution curve can be plotted. This type of jar has several advantages over the more traditional 1-l circular jars, including a larger volume for reduced errors in mixing and a larger volume of supernatant for analysis. In addition, the square walls reduce water rotation making baffles or stators, unnecessary. Finally, the thick Plexiglas walls offer sufficient thermal insulation to minimize temperature changes during the testing period. The six flat paddles are all driven by a single variable speed motor from 0 to 300 rpm. Velocity gradient curves (G, per s) versus agitator paddle speed (rpm) are provided by the manufacturer (Fig. 3). An illuminated base helps observation of the floc formation and settling characteristics.

Stock solutions of the coagulants and flocculants were used to improve the ease of handling and measuring, and ensure good mixing in the jars. Simple dilutions of alum and ferric chloride with distilled water to a 0.2% solution by weight were employed. Normally, the actual test procedures are representative of an existing treatment system, for example a wastewater treatment plant’s mixing, flocculation and settling tanks, in terms of the duration of mixing and flocculation and the velocity gradients, as well as settling time employed. In contrast, in this engineering design study (and in future work), a wide range of chemicals, dosages and conditions (mixing and flocculation stirring speeds and durations, and settling times) were

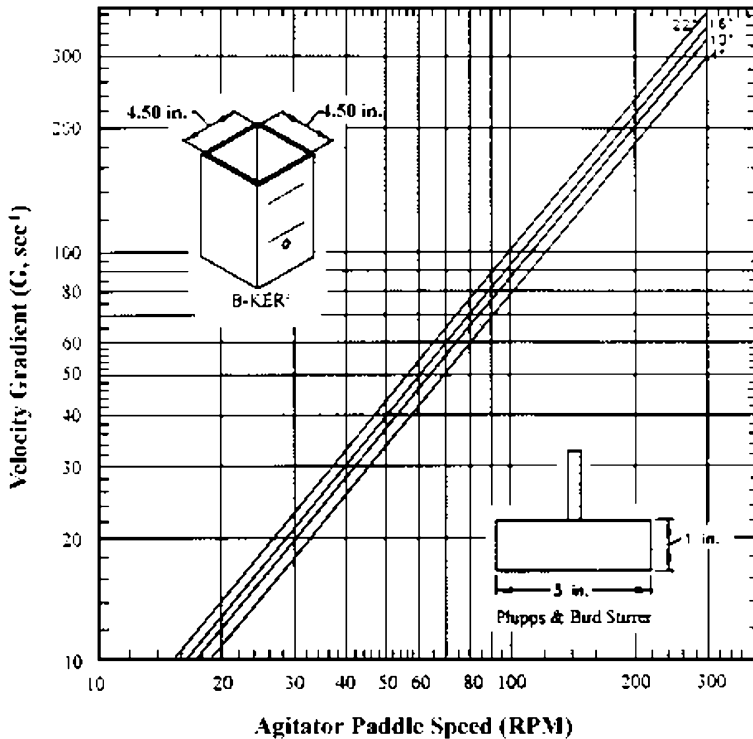


Fig. 3. Velocity gradient curves (G, per s) vs. agitator paddle speed (rpm).

examined to achieve optimum removal of suspended solids and phosphorus. Based on these tests, recommendations can then be made as to the engineering design and operation of both a pilot scale study and large-scale treatment systems.

For each jar test, the following procedure was followed (ASTM, 1995). Each jar was filled with 2 l of sample measured with a graduated cylinder, and the initial temperature recorded. The coagulant or flocculant dose destined for each jar was carefully measured into 150 ml beakers and then distilled water was added to yield equal volumes in all the beakers. The multiple stirrer speed was set to the ‘flash mix’ value (75, 150, 225, or 300 rpm) and the test solutions added. After the predetermined ‘flash mix’ duration, the mixing speed was reduced to the flocculation or ‘slow mix’ value (10, 20, 30, or 40 rpm) for a specified duration. After this time period, the paddles were withdrawn and the floc allowed to settle for specified time (0, 5, 10, 15, 20, 30, or 45 min). Samples were then withdrawn from the sampling ports located 10 cm below the water level for analysis. A baseline set of mixing and flocculation speeds and durations were used for comparison purposes. These were 150 rpm for 1 min mixing, 20 rpm for 20 min flocculation, and a settling time of 30 min.

3.2. Analysis

For all of the jar tests, pH, turbidity, and Soluble Reactive Phosphorus (SRP, orthophosphate) were measured. For the purpose of comparing the effect of various operating parameters such as mixing and flocculation speed, turbidity was used as an indicator of suspended solids and orthophosphate for phosphorus content. In addition, for several of the tests total phosphorus (TP), total dissolved phosphorus (TDP), total suspended solids (TSS), total volatile solids (TVS), total ammonia nitrogen (TAN), and nitrate-nitrogen (NO_3^- -N) were determined. Table 2 shows the methods used for each analysis. When appropriate, reagent standards and blanks were analyzed along with the samples to ensure quality control. The phosphorus percent removal data was fitted to a three parameter sigmoidal curve for statistical comparison, using a *t*-test of the parameters assuming unequal variance. The

Table 2
Laboratory methods used for analysis via a Hach DR/2000 colorimeter

Parameter	Method/Range
Alkalinity ^a	Standard Methods 2320 B
Nitrogen–ammonia ^b	Hach Method 8038 Nessler Method 0–2.50 mg/l NH_3 -N
Nitrogen–nitrate	Hach Method 8039 Cadmium Reduction Method 0.0–30.0 mg/l NO_3^- -N
Phosphorus, reactive ^b	Hach Method 8048 (orthophosphate) 0–2.50 mg/l PO_4^{3-}
Total suspended solids ^a	Standard Methods 2540D
Total phosphorus ^b	Hach Method 8190 (Acid Persulfate Digestion) 0.00–3.50 mg/l PO_4^{3-}
Turbidity ^a	Hach Method 8237 0–450 FTU (Formazin Turbidity Units)

^a Adapted from Standard Methods for the examination of water and wastewater (APHA, 1989).

^b USEPA approved for reporting.

normalized turbidity data was fitted to a three parameter exponential decay for statistical comparison, using a *t*-test of the parameters assuming unequal variance.

4. Results and discussion

4.1. Comparison of alum and ferric chloride

The two coagulant aids, alum and ferric chloride, were tested. Fig. 4 and Table 3 shows a comparison of the effectiveness of alum and ferric chloride in removing orthophosphate and turbidity for the thickening tank supernatant. For orthophosphate percent removal, no significant difference was seen between the alum and ferric chloride ($\alpha = 0.01$). The normalized turbidity data suggests a significant difference at the lower dosages of the two coagulant aids. Although these differences were statistically significant, in practice these lower dosages would not normally be utilized. At concentrations above 90 mg/l, orthophosphate concentrations were reduced to about 0.3 mg/l-P for both alum and ferric chloride. At concentrations of 60 mg/l, the turbidity approached its lowest value. The results show that both coagulants had similar effects despite the different species involved. A comparison of the molecular weights of these compounds indicates that the ferric chloride should be slightly more effective on a weight basis, given its lower formula weight. However, this difference was not observed in these tests.

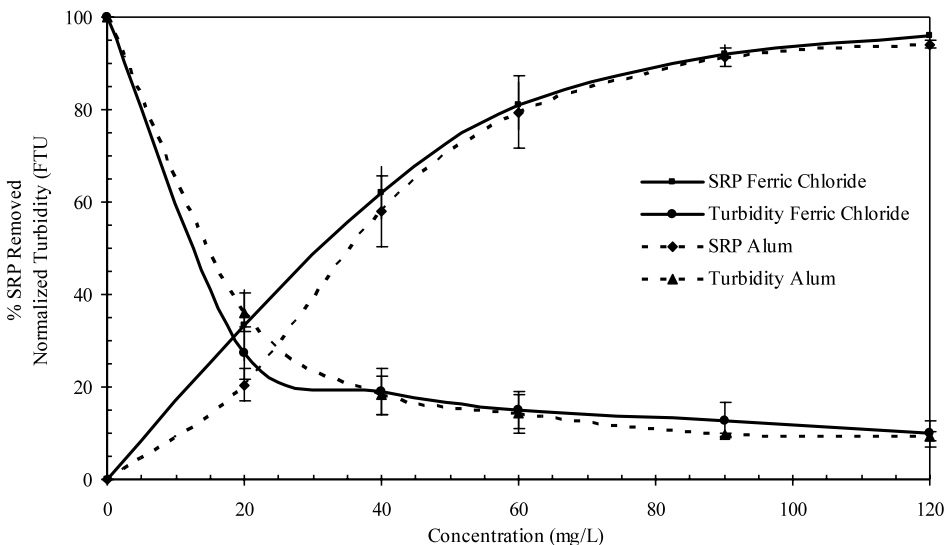


Fig. 4. Comparison of alum and ferric chloride on the percent removal of orthophosphate and normalized turbidity at standard conditions (150 rpm mixing speed, 1 min, 20 rpm flocculation, 20 and 30 min settling time).

Table 3

Removal of orthophosphate and turbidity by alum and ferric chloride at standard conditions (150 rpm mixing speed, 1 min, 20 rpm flocculation, 20 and 30 min settling time)

Dosage (mg/l)	Alum SRP ^a (mg/l-P)	Ferric chloride SRP ^a (mg/l-P)	Alum turbidity (FTU)	Ferric chloride turbidity (FTU)
Raw water	4.22	4.18	137	155
0	3.67	3.93	113	132
20	2.92	2.63	41	36
40	1.53	1.50	20	25
60	0.73	0.76	16	20
90	0.31	0.32	11	17
120	0.21	0.16	11	13

^a Means of four jar tests.

4.2. Effect of mixing intensity

Since there was no practical difference between the two coagulation agents, a series of tests were conducted with alum to examine the effect of the initial mixing intensity (paddle speed or velocity gradient) and the flocculation intensity on the removal efficiency of suspended solids and orthophosphate. The results of these jar tests using alum are shown in Figs. 5 and 6 and in Table 4, over a range of dosages from 0 to 120 mg/l for mixing speeds of 75, 150, 225 and 350 rpm. As can be seen in Tables 4 and 5 for the Raw Water, the effluent varied slightly from day to day due to changes in feed addition, biomass, makeup water addition, etc. Therefore the results in Figs. 5 and 6 are expressed in terms of percent removed to minimize the effect of different initial starting concentrations of orthophosphate and turbidities (although normally very small, see Table 1).

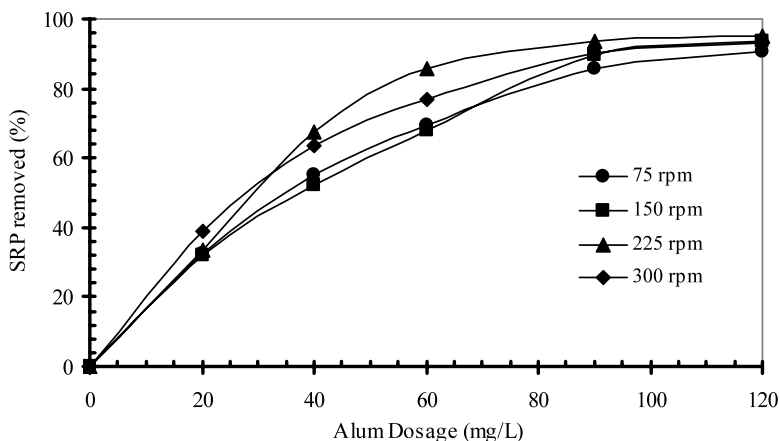


Fig. 5. Effect of mixing intensity and alum dosage on the percent removal of orthophosphate using standard jar test with 1 min mixing time, 20 rpm flocculation for 20 and 30 min settling time.

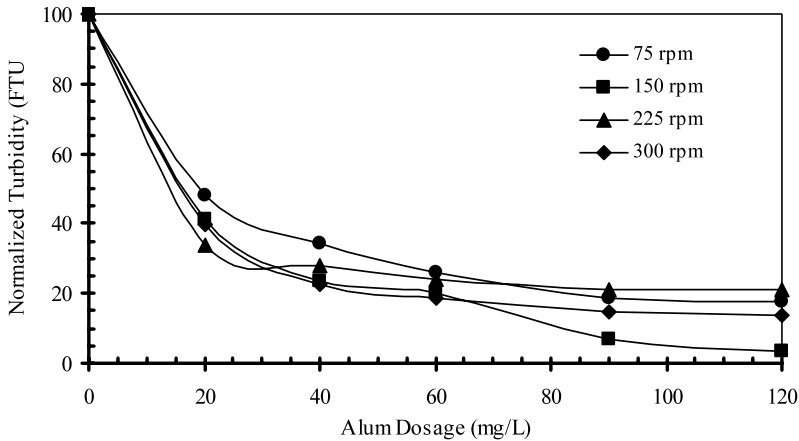


Fig. 6. Effect of mixing intensity and alum dosage on normalized turbidity using standard jar test with 1 min mixing time, 20 rpm flocculation for 20 and 30 min settling time.

For the removal of orthophosphorus, no significant difference was seen between the mixing speeds ($\alpha = 0.01$). For the normalized turbidity data, a significant difference was seen for mixing speeds of 150 rpm and 225 rpm and 225 and 300 rpm ($\alpha = 0.01$). The lower mixing speed may improve the removal of turbidity at lower concentrations, due to reduced shearing of the floc during initial formation.

4.3. Effect of flocculation intensity

Figs. 7 and 8 and Table 5 show the effect of flocculation speed on removal of orthophosphorus and normalized turbidity as a function of alum dosage. Similar to previous results, no significant difference was seen between the mixing speeds in the removal of phosphorus ($\alpha = 0.01$). But for the normalized turbidity data, a significant difference was seen for flocculation speeds of 10 rpm and 40 rpm ($\alpha = 0.01$). The lower mixing speed may improve the removal of turbidity at lower concentrations of alum due to reduced shearing during the flocculation phase.

4.4. Effect of flocculation mixing time

Fig. 9 and Table 6 show the effect of flocculation mixing time on the percent removal of orthophosphate and normalized turbidity at an alum dosage of 60 mg/l. Flocculation mixing times of 0, 5, 10, 15, 20, 25, and 30 min were used. As can be seen from the curves in Fig. 9, after the first 5 min, there is very little change in the concentration of both orthophosphate removal percentage and normalized turbidity.

Table 4
Effect of mixing intensity on soluble reactive phosphorus and turbidity, mixing time of 60 s, flocculation for 20 min at 20 rpm and 30 min settling time

Alum dosage (mg/l)	75 rpm		150 rpm		225 rpm		300 rpm	
	Turbidity (FTU)	SRP (mg/l-P)	Turbidity (FTU)	SRP (mg/l-P)	Turbidity (FTU)	SRP (mg/l-P)	Turbidity (FTU)	SRP (mg/l-P)
Raw water	110	3.84	146	3.91	80	3.16	128	3.84
0	96	3.81	90	3.62	71	2.70	101	3.84
20	46	2.57	37	2.45	24	1.79	40	2.35
40	33	1.71	21	1.73	20	0.88	23	1.39
60	25	1.17	18	1.16	17	0.39	19	0.89
90	18	0.55	6	0.38	15	0.17	15	0.38
120	17	0.36	3	0.23	15	0.13	14	0.26

Table 5
Effect of flocculation intensity on soluble reactive phosphorus and turbidity, mixing time of 60 s at 150 rpm, flocculation for 20 and 30 min settling time

Alum dosage (mg/l)	10 rpm		20 rpm		30 rpm		40 rpm	
	Turbidity (FTU)	SRP (mg/l-P)	Turbidity (FTU)	SRP (mg/l-P)	Turbidity (FTU)	SRP (mg/l-P)	Turbidity (FTU)	SRP (mg/l-P)
Raw water	128	4.27	127	4.36	120	4.40	118	4.30
0	121	3.97	113	3.94	100	3.91	98	3.81
20	58	3.32	46	3.13	34	3.16	28	2.70
40	23	2.12	21	1.82	12	1.66	12	1.61
60	14	1.09	14	0.75	10	0.68	10	0.65
90	9	0.39	11	0.33	11	0.36	13	0.44
120	11	0.29	12	0.28	11	0.28	12	0.39

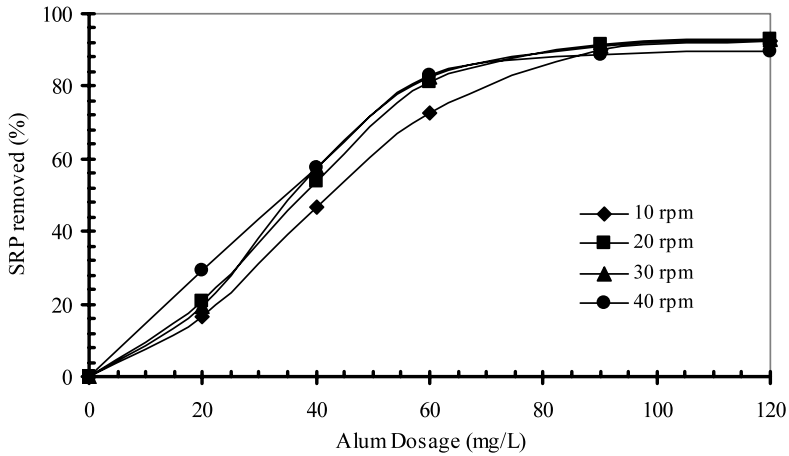


Fig. 7. Effect of flocculation intensity and alum dosage on the percent removal of orthophosphate using standard jar test with 150 rpm mixing speed for 1 min, flocculation time of 20 and 30 min settling time.

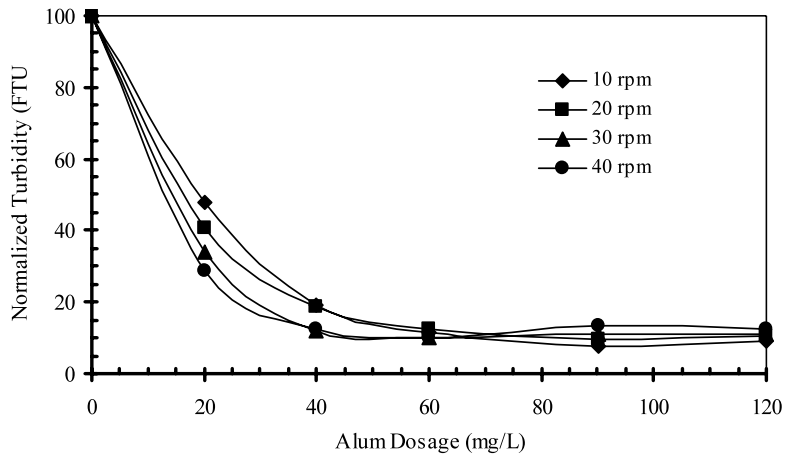


Fig. 8. Effect of flocculation intensity and alum dosage on normalized turbidity removal using standard jar test with 150 rpm mixing speed for 1 min, flocculation time of 20 and 30 min settling time.

4.5. Effect of settling time

The effect of settling time on removal efficiencies was also examined. A standardized set of mixing and flocculation speeds and durations were used for comparison purposes. These were 150 rpm for 1 min mixing, 20 rpm for 20 min flocculation, and a settling time of 5, 10, 15, 20, 30 and 45 min. Fig. 10 and Table 6 show the effect of settling time on the removal of soluble reactive phosphorus and turbidity with ferric chloride. As both curves show, the floc quickly settles out within the first 5 min, with little change in final values after 10 min.

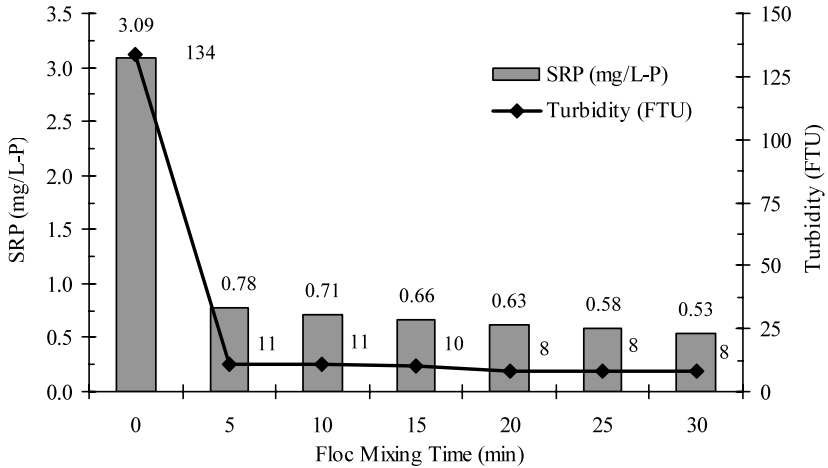


Fig. 9. Effect of flocculation mixing time on the percent removal of orthophosphate and normalized turbidity using standard jar test with 150 rpm mixing speed for 1 min, flocculation speed of 20 rpm, and 30 min settling time at 60 mg/l alum concentration.

Table 6

Effect of flocculation mixing time and flocculation settling time on soluble reactive phosphorus and turbidity, mixing time of 60 s at 150 rpm, flocculation at 20 rpm and variable mixing and settling times

Flocculation mixing time ^a			Flocculation settling time ^b			
Mixing time	Turbidity (FTU)	SRP (mg/l-P)	Time (min)	Turbidity (FTU)	SRP (mg/l-P)	TSS (mg/l)
Raw water	134	3.09	0	89	1.87	90.5
0	11	0.78	5	22	0.28	19.1
5	11	0.71	10	15	0.14	10.2
10	10	0.66	15	14	0.11	8.0
15	8	0.63	20	14	0.10	6.9
20	8	0.58	30	14	0.08	7.2
25	8	0.53	45	13	0.08	8.2

^a Alum as coagulation agent, flocculation settling time of 30 min.

^b Ferric Chloride as coagulation agent, flocculation mixing time of 20 min.

4.6. Water quality characteristics

Table 7 presents additional water quality parameters measured as a function of dosage for alum and ferric chloride. In both cases, the pH drops as expected from near neutral to slightly acidic as alkalinity is consumed, but not enough to impair discharge. Alkalinity is consumed for both coagulation/flocculation aids as predicted, with a significantly higher demand with ferric chloride. The excellent relationship between turbidity and TSS is clearly evident for both alum and ferric chloride. Since TAN is a dissolved nutrient and not chemically reactive with either alum or ferric chloride, very little effect is observed.

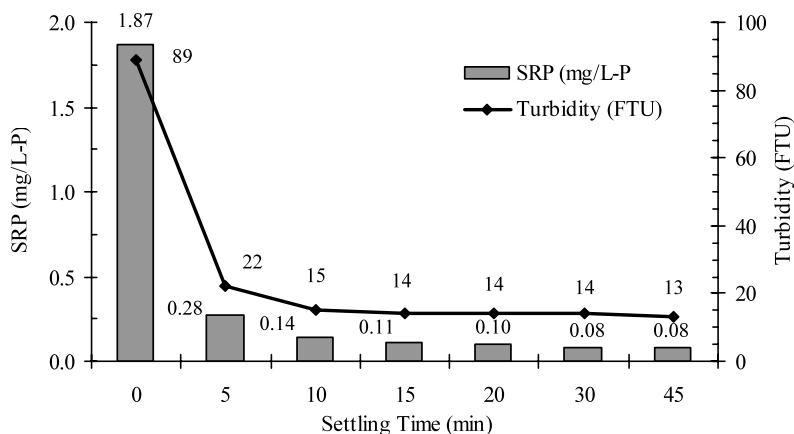


Fig. 10. Effect of settling time on the percent removal of orthophosphate and normalized turbidity using standard jar test with 150 rpm mixing speed for 1 min, flocculation speed of 20 rpm for 20 min, and variable settling times at 60 mg/l ferric chloride concentration.

5. Conclusions

An evaluation of two commonly used coagulation–flocculation aids (alum and ferric chloride) was conducted for the supernatant overflow from microscreen filters in an intensive recirculating aquaculture system using standard jar test procedures. The orthophosphate removal efficiency for alum and ferric chloride were 89 and 93%, respectively, at a dosage of 90 mg/l with final concentrations of SRP approaching 0.3 mg/l-P. Optimal turbidity removal was achieved with a 60 mg/l dosage for both alum and ferric chloride. Both alum and ferric chloride demonstrated excellent removal of suspended solids from initial TSS values of approximately 100–10 mg/l at a dosage of 90 mg/l. Flocculation and mixing speed played only a minor role in the removal efficiencies for both orthophosphates and suspended solids. Both coagulation–flocculation aids also exhibit excellent settling characteristics, with the majority of the floc quickly settling out in the first 5 min.

It is important that mixing and flocculation speeds and time be determined by jar test for each effluent, but good results were obtained for this aquaculture effluent with a mixing speed of 150 rpm for 1 min, 20 rpm flocculation speed for 10 min and a settling time of 10–20 min. Based on these initial studies and for this supernatant, for maximum orthophosphate removal the concentrations of both alum and ferric chloride applied should be greater than 90 mg/l. For maximum turbidity removal, a dosage of 60 mg/l or more of both alum and ferric chloride is required. Future studies will include additional tests with varying mixing, flocculation, and settling times at various dosages for other potential coagulation/flocculation aids, including the use of acid mine drainage sludge. In addition, sludge volumes will be estimated and economic costs estimated.

Table 7

Water quality characteristics for alum and ferric chloride at a mixing time of 60 s at 150 rpm, flocculation for 20 min at 20 rpm and 30 min settling time

Alum dosage (mg/l)	pH	Turbidity (FTU)	Alkalinity (mg/l)	TP (mg/l-P)	SRP (mg/l-P)	TSS (mg/l)	TVS (mg/l)	TAN (mg/l-N)
Raw water	7.11	152	317		5.7	94.2	94.2	11.0
0	7.08	128	317	6.2	5.0	74.8	74.8	9.4
30	7.06	40	307	4.0	3.8	31.6	28.6	8.2
60	6.93	16	298	1.8	1.6	7.0	5.1	8.9
90	6.89	13	289	0.8	0.6	5.6	4.7	8.3
120	6.84	12	267	0.5	0.3	5.1	4.7	8.4
150	6.73	12	262	0.4	0.2	5.0	4.3	9.2
<i>Ferric chloride dosage (mg/l)</i>								
Raw water	7.22	131	322	5.1	4.8	87.5	87.5	8.3
0	7.23	110	300	4.5	4.4	65.7	65.0	5.7
30	7.14	29	281	2.9	2.5	20.4	17.7	4.9
60	7.03	15	268	1.5	1.0	12.5	11.7	4.2
90	6.90	13	253	0.8	0.3	11.6	9.5	4.8
120	6.80	10	232	0.5	0.2	6.1	6.1	5.0
150	6.68	9	183	0.8	0.1	4.1	3.9	5.0

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