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The cost and effectiveness of solids thickening technologies for treating backwash and recovering nutrients from intensive aquaculture systems

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ABSTRACT

The cost and effectiveness of three solids thickening processes, i.e., gravity thickening settlers (GTS), inclined belt filters (IBF), geotextile bag filters (GBF), were individually evaluated with the biosolids backwash produced in intensive aquaculture systems equipped with microscreen drum filters and radial-flow settlers. The IBF produced the cleanest discharge and highest treatment efficiencies, likely reflecting the rapid efficiency with which solids are separated from wastewater. The GBF was the least effective process, i.e., GBF leachate contained the highest concentrations of TP, TN, and cBOD. However, GBF was most effective for sludge volume reduction. Capital cost estimates for an IBF were more than twice that of GTS and GBF of similar treatment capacity. The GTS had the lowest capital and annual operating cost estimates. The estimated annual operating cost of the GBF was orders of magnitude higher than the IBF and GTS, due to the high cost to replace bags.

1. Introduction

1.1. Background

Solids produced in water recirculating systems for fish culture are comprised of a dilute mixture of uneaten feed, fish feces, and biological floc that either grows in the water column or is shed from nitrification reactors or other vessel/pipe surfaces (Cripps and Bergheim, 2000). Rotating microscreen drum filters and gravity settling units are the most typical methods used to remove these biosolids from fish culture process water in recirculating systems. In our experience, the backwash and underflow generated by these removal mechanisms typically results in a backwash (i.e., waste stream) with a total suspended solids (TSS) concentration of 1000–2000 mg/L (0.1–0.2 % solids). However, drum filter backwash alone may contain only 200–400 mg/L TSS. Rapid separation of these biosolids from water is necessary for efficient capture of TSS and carbonaceous biochemical oxygen demand ($cBOD_5$), as well as to reduce leaching of dissolved nitrogen (primarily as ammonia) and phosphorus (primarily as phosphate). The corollary also holds true as fresh fecal matter and waste feed will immediately begin to leach dissolved nutrients and $cBOD_5$ if they are stored within the water for hours or days. For example, Chen et al. (1993) reported that 30–40% of the TSS generated in a recirculating aquaculture system can decay if they are filtered and stored in a plastic-bead filter between 24 h backwash cycles. Similarly, Stewart et al. (2006) found that biosolids stored in a quiescent sedimentation tank would leach and release 35% of total phosphorus (TP), 35% of ortho-phosphate, 61% of total kjeldahl nitrogen (TKN), 24% of total ammonia nitrogen (TAN), and 50% of total organic carbon (TOC) in the first 24 h. Piedecausa et al. (2009) determined that, at a temperature of 15 °C, all of the TAN leached from gilt-head sea bream (*Sparus aurata*) and European sea bass (*Dicentrarchus labrax*) fecal pellets in less than 30 min. Further, the researchers found that leaching was faster for smaller particles, and the fastest leaching rate occurs in the first few minutes, according to first-order kinetics (Piedecausa et al., 2009).

Effective reduction in overall sludge volume into a form practical for storage, off-site hauling, composting, or land application for nutrient reuse and can significantly mitigate waste handling and disposal costs (Metcalf and Eddy, 1991; Summerfelt and Vinci, 2008). Consequently, backwash flows must be dewatered from initial concentrations of <0.1–0.2% solids to concentrations of >5–10% solids to achieve at least a 50–100 fold decrease in biosolids volume. Gravity thickening settlers (GTS) are the simplest and most commonly used technology for dewatering biosolids from intensive fish culture facilities (Henderson and Bromage 1988; Bergheim et al. 1993, 1998; Chen et al. 1997, 2002; Brazil and Summerfelt, 2006; Sindilariu et al., 2009), but constructed wetlands (Summerfelt et al., 1999; Comeau et al., 2001), inclined belt filters (IBF; Ebeling et al., 2006) and geotextile bag filters (GBF; Sharrer et al., 2009) are also used. Septic tanks, which are similar to GTS, are another commonly applied and practical option

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for treating backwash flows from recirculating systems at smaller fish farms (Summerfelt and Penne, 2007). Application of these technologies can differ widely in terms of solids and nutrient capture, footprint requirements, as well as capital and operating costs.

1.2. Gravity thickening settlers

Municipal and industrial wastewater treatment facilities commonly use GTS – also called circular, center-feed sedimentation basins or radial-flow settlers – for sedimentation of liquids containing high concentrations of suspended solids with relatively low specific-gravity, such as slow-settling microbiological solids produced during secondary wastewater treatment (Metcalf and Eddy, 1991). A GTS introduces water into the center of the vessel inside a "turbulence-damping" cylinder. The injected water flows outward in the vessel's radial direction to the overflow collection launder that surrounds the perimeter of the settler. Radial flow from the center of the tank produces a progressively lower water velocity along the settling path as the water approaches the effluent weir surrounding the perimeter of the tank (Metcalf and Eddy, 1991). These flow dynamics help to minimize turbulence and maximize solids settling to the base of the GTS, which is either shaped into a steep 60° cone (as in the present study) or contains a scraper system to remove settleable solids. Reduction in sludge volume using gravity thickening mechanisms relies on the settling velocity of the solids contained in the wastewater influent flow and the eventual compaction of these solids as they collect at the base of the vessel. Compaction of suspended solids occurs in gravity thickeners as particulates are supported on top of each other (Qasim, 1999). Accordingly, continued compression of solids within the thickening basin is a function of the accumulation of additional weight above (Qasim, 1999). Concentrated sludge is then drawn off from a pipe located at the bottom-center of the sedimentation basin.

In aquaculture applications, a GTS is sometimes called an off-line settling basin because it is loaded intermittently. In these cases, GTS are used to collect, thicken, and store the biosolids contained in microscreen drum filter backwash and settling unit flushing flows (Chen et al., 1997; Bergheim et al., 1993, 1998; IDEQ, 1998; Brazil and Summerfelt, 2006; Summerfelt and Penne, 2007; Summerfelt and Vinci, 2008; Sindilariu et al., 2009). When used as off-line settlers, GTS are sized using a surface loading rate of approximately 0.28–0.46 L/s of flow per square meter of settler plan area (Bergheim et al., 1993, 1998; IDEQ, 1998). The cone bottom of a GTS will typically only provide short (days) to intermediate (weeks or months) term storage for collected solids. Concentrated biosolids are then removed at the base of the cone and are typically land applied, composted, or hauled to a landfill. Intermediate or long-term storage can result in the formation of compacted, sticky, and viscous solids that can make effective solids removal from the base of the cone more challenging (Summerfelt and Vinci, 2008).

In addition to the use of GTS in effluent treatment applications, they are also used in intensive aquaculture systems to remove settleable solids that are concentrated within the bottom drain flow exiting dual-drain circular culture tanks (Davidson and Summerfelt, 2004, 2005; Johnson and Chen, 2006; Wolters et al., 2009).

In an assessment of the sludge thickening capacity of a gravity settling cone, Bergheim et al. (1998) determined a solids removal efficiency of 75–90% despite the infrequent removal of settled solids from the base of the cone. In subsequent research, Sindilariu et al. (2009) and Brazil and Summerfelt (2006) assessed rotating drum filter backwash settling in off-line settling basins and determined 87% and 97% removal efficiency of total suspended solids, respectively.

1.3. Geotextile bag filters

GBF have been used to dewater high water content sewage sludge (Ashworth, 2003; Wett et al., 2005), mine water sludge and tailings fines (Newman et al., 2004), dairy and swine slurry lagoons (Baker et al., 2002; Johnson, 2004), and aquaculture wastewater (Sharrer et al., 2009). This durable, woven polyethylene fabric can be hydraulically loaded with solids laden water, and the approximately 425 μm pore size allows filtrate to pass through the fabric while retaining solids within the bag.

Applying a polymer is required to enhance floc formation, facilitate solids retention within the geotextile bags, while maintaining hydraulic permeability through the bags (Sharrer et al., 2009). Ebeling et al. (2005) provides details regarding polymer type and flocculation conditions, i.e., polymer dose, mixing speed and mixing duration, to effectively remove suspended solids and particulate phosphorus from water recirculating system microscreen drum filter backwash. Sharrer et al. (2009) describes GBF dewatering and chemical coagulant application (alum, lime, and ferric chloride) for dissolved phosphorus removal from water recirculating system microscreen drum filter backwash. Dissolved phosphorus precipitated by coagulants is subsequently removed as flocculated solids and precipitates are filtered across the geotextile material. However, leaching of biosolids after long-term storage can re-solubilize inorganic phosphorus, especially under anaerobic conditions (Ju et al., 2005; Yang et al., 2007). Solids can be loaded into the bag and stored for intermediate periods of time (3–12 months, depending on fill time). After being taken off-line and allowed to dewater and dry, sludge cake is sufficiently dewatered, i.e., to approximately 20% solids dry weight (Sharrer et al., 2009), for shoveling out of the GBF, either manually or using heavy equipment. The dewatered biosolids are suitable for land application, composting, incineration, or landfill.

Research assessing alum and polymer amended geotextile bags to dewater dairy lagoons indicates separation efficiencies calculated on a mass basis of 90.4% of total solids, 85% of total kjeldahl nitrogen, 100% of organic nitrogen, and 98.6% of phosphorus (Worley et al., 2008). In water recirculating system applications, dewatering microscreen drum filter backwash through geotextile bags amended with a polymer flocculant, but without a coagulant, has been shown to achieve separation efficiencies for total suspended solids, organic nitrogen, inorganic nitrogen, and total phosphorus of 96%, 73%, 42%, and 31%, respectively (Personal communication, Thomas Losordo, North Carolina State University, Raleigh, NC).

1.4. Inclined belt filter

Biosolids dewatering utilizing IBF technology combines the chemical conditioning of backwash to enhance floc formation with gravity filtering across a porous material. IBF differs from belt filter presses, which apply a chemically conditioned backwash flow to a gravity driven section of the filter where much of the water is removed, and the remaining sludge is mechanically compressed between opposing porous belts to remove additional water (MOP FD-3, 2008; Metcalf and Eddy, 1991). Gravity IBF, a more recent development in sludge thickening technology, dewaters chemically conditioned biosolids by gravity through a porous belt, but does not rely on mechanical compaction (Qasim, 1999). To chemically condition the biosolids, wastewater enters a reservoir equipped with mixers for chemical amendment in addition to floc formation and suspension. The solution then spills onto a gravity filtering zone where the solids are collected on the belt and scraped into a hopper. Collected sludge contains approximately 10% solids as dry weight (Ebeling et al., 2006) and can be pumped to a transport tank and land applied, composted, or hauled off-site for disposal. Filtrate concentrations of TSS and reactive phosphorus have been reported to be less than 30 and 0.07 mg/L, respectively (Ebeling et al., 2006). Use of an IBF to thicken aquaculture backwash (Fig. 1) is more mechanically complex than either GTS or GBF (Summerfelt and Vinci, 2008).

1.5. Objectives

A variety of solids thickening techniques are utilized in the aquaculture industry, but their treatment efficiency, complexity, labor requirements, and cost are vastly different. The primary objective of this research was to compare three solids dewatering mechanisms, i.e., GTS, IBF, and GBF, in the treatment of microscreen drum filter backwash and radial clarifier underflow from recirculating fish culture systems. These three technologies were chosen for comparative analysis because they each have distinct advantages: the GTS is the most commonly used technology for aquaculture dewatering applications, primarily because of its low operating and maintenance requirements (Summerfelt and Vinci, 2008); the IBF technology has recently been installed for dewatering biosolids contained in fish farm backwash flows at several European and North American, especially in situations where a low phosphorus concentration in treated effluent is required (Wolters et al. (2009) reports one of these applications); the GBF has also been used in several recent applications, particularly when a high solids content sludge is desired. In contrast, sludge treatment wetlands were not included in this study because we thought that a multi-year study would be required to properly characterize capture efficiency and dewatering capacity of wetlands that are operated to store the collected biosolids for up to 10 years. Centrifuges were not chosen because of their relatively high fixed and variable costs, plus concerns with relatively large maintenance requirements.

In this analysis, each technique's treatment efficiency was assessed in terms of solids capture efficiency (TSS, TVS), nutrient reduction (nitrogen and phosphorus) capacity, and chemical oxygen demand (COD) and $cBOD_5$ removal, as well as final solids and nutrient concentration of the thickened biosolds. A secondary objective was to perform a cost analysis of each technology so that a fish farmer can determine the most efficient and cost effective waste treatment technology based upon capital and operating costs as well as wastewater volume reduction, TSS and $cBOD_5$ removal, and nutrient retention.

Fig. 1. An inclined belt filter (IBF) and coagulation–flocculation tank operated for microscreen drum filter backwash dewatering at the Craig Brook National Fish Hatchery (East Orland, ME). Photo background shows alum and polymer dosing systems and chemical reservoirs (in background).

2. Methods

2.1. Wastewater sources

The comparison of GTS, IBF, and GBF was conducted at The Conservation Fund Freshwater Institute (Shepherdstown, West Virginia, USA) using waste generated from the facility's commercial scale fry rearing, partial-reuse (Summerfelt et al., 2004), and fully recirculating fish culture system (Davidson and Summerfelt, 2005), which were managed to produce approximately 35 mton/year (80,000 lbs/year) of rainbow trout (*Oncorhynchus mykiss*). A series of six pilot-scale fully recirculating fish culture systems that produced rainbow trout (Davidson et al., 2009) was also used to supply backwash for treatment. These backwash and flushing flows were collected (as produced) in a common sump for equalization and subsequent distribution to the experimental biosolids thickening systems.

2.2. Gravity thickening settler

A single 2.26 m diameter × 2.59 m tall (Fig. 2) GTS was loaded with biosolids and then emptied on three different occasions, with each loading event lasting 21 days. Water sampling events were conducted eight times during each 21 day biosolids loading period for a total of 24 sampling events. To assess GTS performance, wastewater was pumped from the common sump using a 1/3 hp Goulds (Seneca Falls, NY) submersible pump connected to a float switch that engaged the pump (as needed) at a prescribed sump depth. Wastewater was intermittently loaded at a surface loading rate of approximately 10,578 L/m^2/day resulting in a mean volume treated of approximately 38 m^3/day. No coagulant or flocculant amendments were administered. Influent samples were collected from the wastewater common sump and supernatant samples were taken from a collection port immediately subsequent to the supernatant overflow weir.

2.3. Geotextile bag filter

GBF performance was assessed using three replicated bags operated in parallel, simultaneously, during one 92 day period. The GBF were fabricated utilizing geotextile material (TenCate Geotube, Commerce, GA) with apparent pore openings of 425 μm. Each GBF measured approximately 1.4 m (4.6 ft) × 2.2 m (7.2 ft), resulting in a total surface area of 6.2 m^2 (66.2 ft^2) per bag. To capture filtrate from each GBF, bags were positioned at a 1% grade, atop a timber-framed gravel surface covered in pond liner material, and bags were placed upon PVC-framed plastic screen (Fig. 3). Wastewater was pumped to each GBF using three submersible pumps (Model 8-CIM, Little Giant Pump Co., Oklahoma City, OK) that were placed in the bottom of the common collection sump. A Paragon Model EL72 electronic time controller (Paragon Electrical Products, Downers Groves, IL) was programmed to engage hourly pumping events for 0.5 min per event. Immediately subsequent to each submersible pump outlet, a 2% alum solution (created by dissolving bulk dry aluminum sulfate, Univar USA Inc., Kirkland, WA) was applied as a coagulant at a concentration of 50 mg/L and a 2% polymer solution (CE 1950 polymer, Hychem Inc., Tampa, FL) was applied as a flocculant at a concentration of 25 mg/L. Coagulant and flocculant were pumped from individual reservoirs using Masterflex Economy Model digital drive peristaltic pumps (Cole Parmer Instrument Co., Vernon Hills, IL). Peristaltic pump initiation was controlled concurrently with the submersible pumps utilizing the same electronic time controller described above. Mixing of chemical and wastewater was facilitated using static inline mixers mounted immediately subsequent to chemical

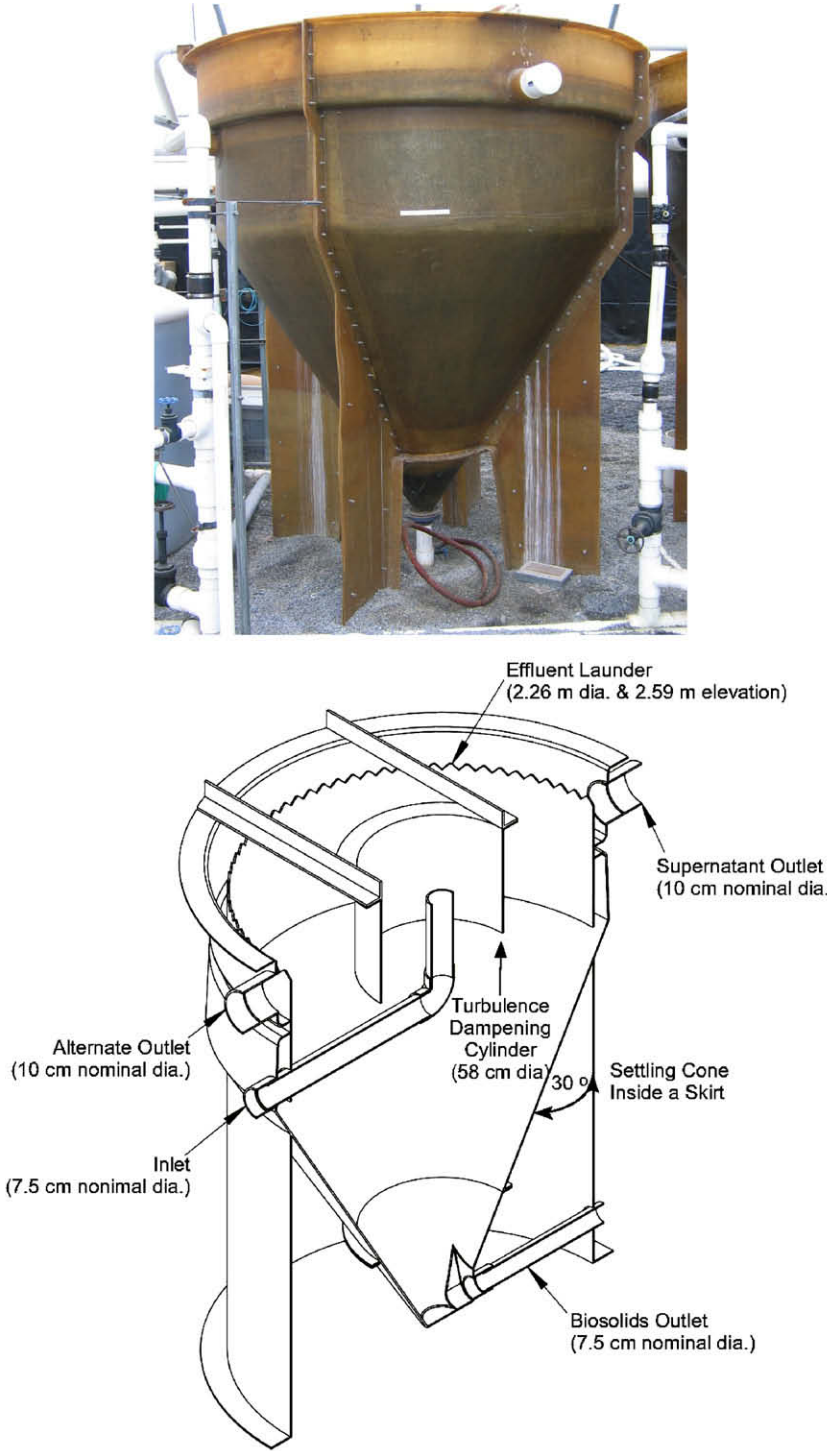

Fig. 2. Photo and cross-sectional illustration of the gravity thickening settler (GTS) that was studied.

addition, and contact time was enhanced with approximately 30 m (98 ft) of 5.1 cm (2 in.) diameter PVC pipe prior to each GBF influent.

Influent samples were taken at a sampling port subsequent to each submersible pump outlet but prior to chemical addition. Filtrate samples were taken from three individual filtrate collection tanks (Fig. 3) measuring approximately 0.74 m^3 (195 gal) in volume, which enabled discrete capture of the replicate filtrate flows. Total volume from the previous 24 h of filtrate production was captured in the collection tanks, manually homogenized, and sub-sampled.

2.4. Inclined belt filter

An IBF from Hydrotech (Vellinge, Sweden), with a coagulation-flocculation tank (Fig. 4), was evaluated over a 16 day period. A submersible pump located in the common wastewater sump

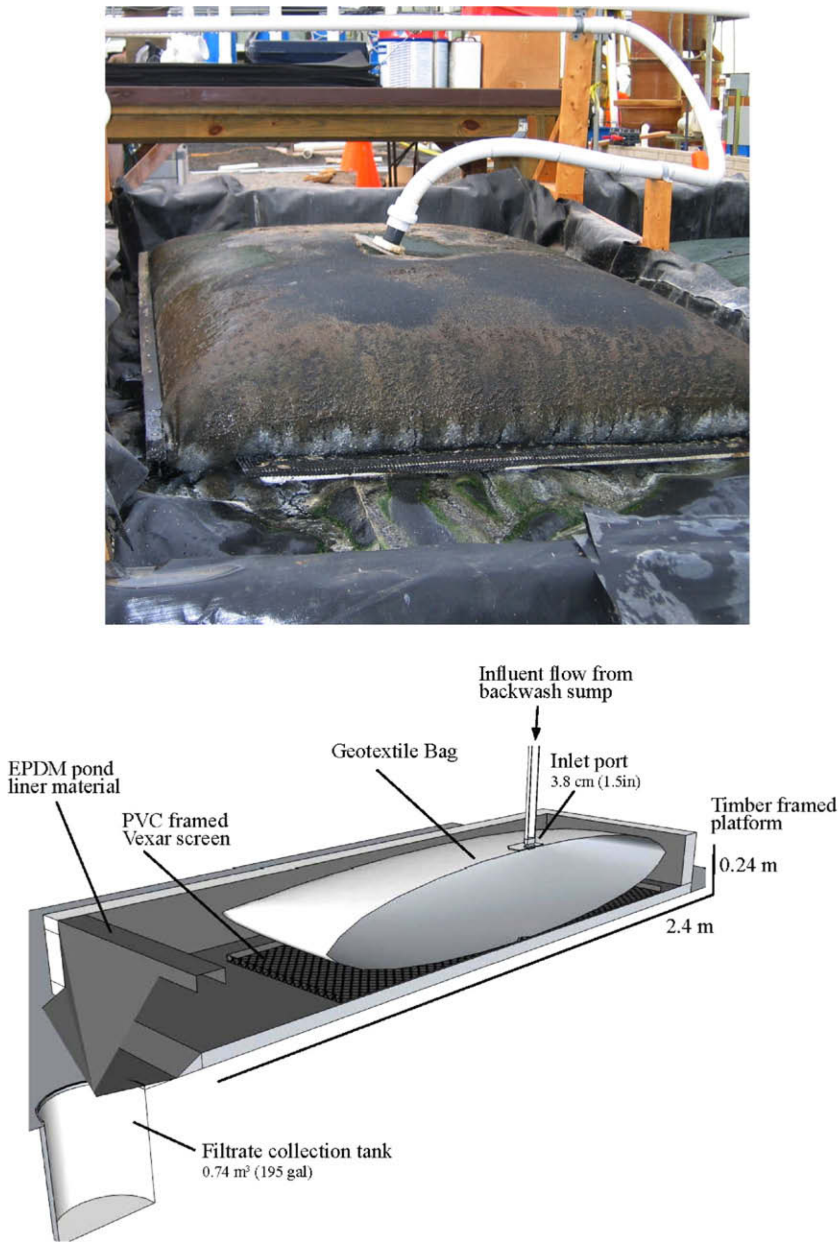

Fig. 3. Photo and cross-sectional illustration of the geotextile bag filter (GBF) used for dewatering aquaculture biosolids.

loaded the coagulation–flocculation tank once every 15 min for 2 min at a rate of 37.9 lpm (10 gpm). In the first chamber of the coagulation–flocculation tank, a 2% solution of alum (aluminum sulfate, Univar USA Inc., Kirkland, WA) was dosed at 50 mg/L and a slow-speed mixer (Fig. 4) promoted chemical mixing and maintained solids suspension. Wastewater then flowed into a relatively small chamber where a high-speed flash mixer (Fig. 4) mixed a 2% solution of Hychem CE 1950 polymer (Hychem Inc.) at a dose of 25 mg/L with the coagulated wastewater. Coagulated and polymer amended wastewater then entered a last reservoir where a slow-speed mixer (Fig. 4) was operated to facilitate biofloc formation and keep the biosolids in suspension. As the belt filter system was periodically loaded by additional pumping events, flocculated wastewater spilled into the IBF (Fig. 4). The IBF contained a permeable belt, inclined at a 10° angle, with a pore size of approximately 300 μm. Filtrate passed through the belt as flocculated solids collected on the belt surface, and head loss increased as the water level rose in the belt settling chamber. A level sensor engaged the continuous belt and spray wash system, and a rubber scraper removed solids into a collection hopper as the spray bar simultaneously cleaned the belt.

Belt filter influent samples were taken from a sampling port immediately prior to chemical amendment. Filtrate samples were taken from the system at a treated filtrate collection overflow site and spray wash samples were taken from sampling port located immediately after the spray wash apparatus.

2.5. Water quality analysis

Water samples collected to determine treatment efficiencies of the GTS (influent and effluent), GBF (influent and effluent), and IBF (influent, filtrate, and spray wash) were analyzed according to

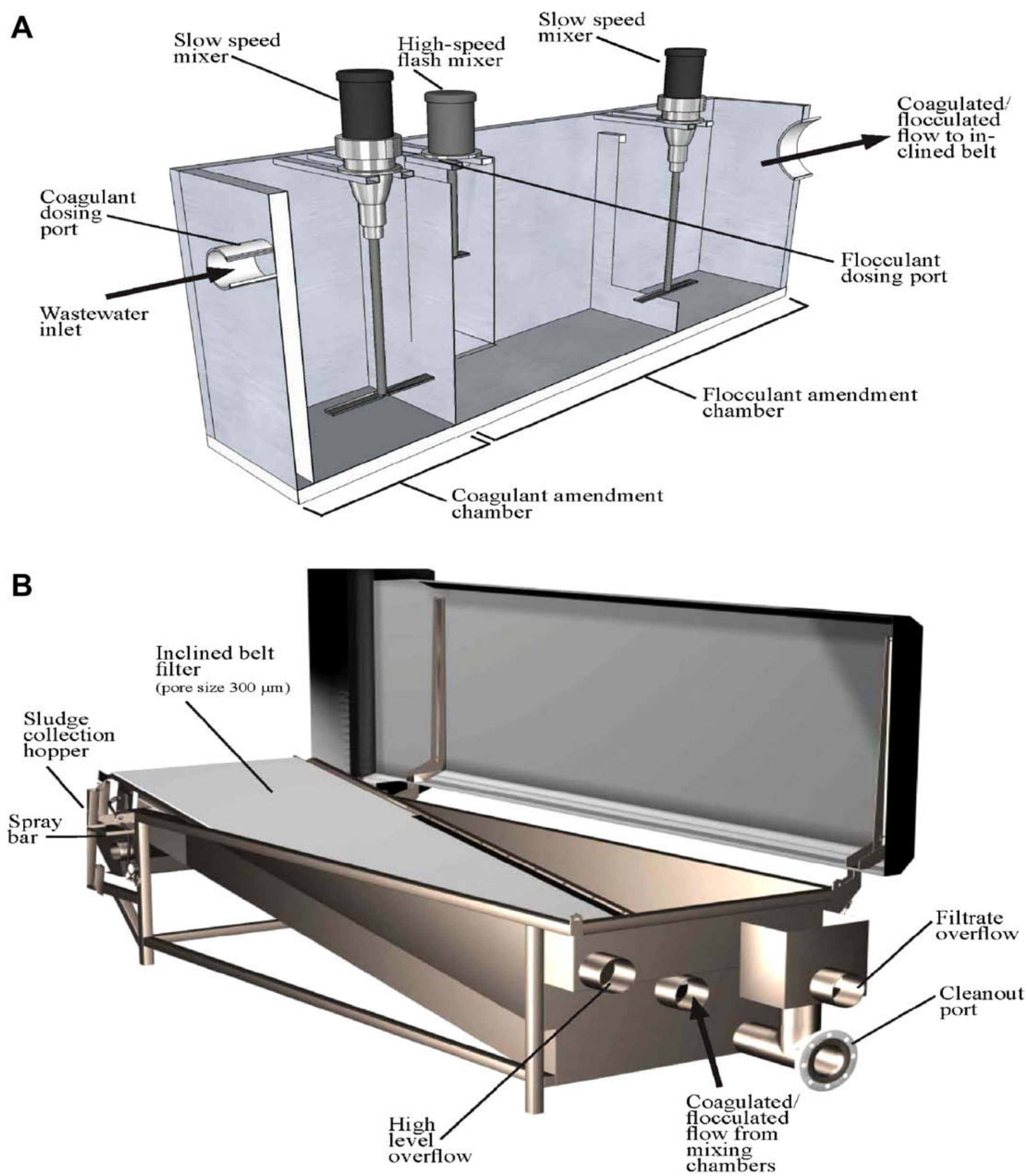

Fig. 4. Drawing shows the two main components of the inclined belt filter (IBF) system for dewatering microscreen drum filter backwash and radial clarifier underflow from a recirculating aquaculture system. (A) The coagulation/flocculation chambers facilitate chemical conditioning, flocculation, and mixing. (B) The IBF allows for solids dewatering and sludge collection (IBF Drawing Courtesy of Water Management Technologies, Baton Rouge, Louisiana, USA).

either APHA (1998) or Hach Chemical Company (Loveland, CO, USA). Analytical procedures used were: total suspended and total volatile solids (Standard Method – 2560), 5-Day carbonaceous biochemical oxygen demand (Standard Method – 5210), chemical oxygen demand (Standard Method –5220 D), total nitrogen (Hach Methods – 10071 and 10072), total ammonia nitrogen (Standard Method – 4500-NH_3 B & C), total phosphorus (Standard Methods – 4500 B-C and 4500 P-E), dissolved reactive phosphorus (Standard Method – 4500 P-E), alkalinity (Standard Method – 2302). Dissolved oxygen, temperature, and pH were determined using a Hach (Loveland, CO, USA) HQ40D handheld multi-parameter meter. Thickened biosolids were assessed at a contract laboratory (Reliance Laboratory, Martinsburg, WV) using Environmental Protection Agency (EPA) methods for total nitrogen (calculated), total kjeldahl nitrogen (EPA 351.3), total nitrate-nitrogen (SW 9210), total nitrite nitrogen (EPA 351.4), phosphorus (EPA 365.2), potassium (EPA 6010B), and percent solids (EPA 160.3).

2.6. Data analysis

Means and standard errors were calculated from data collected from all sampling sites. Removal efficiencies for the GTS and GBF were calculated based upon mean influent and effluent constituent concentration. Because the inclined belt filter utilizes water to clean the belt surface (spray wash) of residual waste, removal efficiencies were calculated to account for the solids not captured in the belt filter scrapings and re-saturated as a result of the cleaning process. Consequently, removal efficiencies for the inclined belt filter were calculated on a mass flow basis by determining the mass loaded to the inclined belt filter, captured with the belt scrapings, and un-captured due to spray wash cleaning in kilograms per day. Removal efficiencies were calculated based upon mean influent, effluent, and spray wash discharge mass, i.e., ((influent − (spray wash + effluent))/influent) ∗ 100.

3. Results and discussion

3.1. General water quality and captured solids characteristics

Study duration and sampling frequency are indicated in Table 1. Temperature, dissolved oxygen, pH, and alkalinity for influent, filtrate, and spray wash are summarized in Table 2. Final solids content of dewatered sludge was 9 ± 1%, 22 ± 1%, and 11 ± 0% for the GTS, GBF, and IBF, respectively. Nitrogen, phosphorus, and potassium (N, P, K) concentrations (on a dry weight basis) were 6.4 ± 2.0 (g/kg), 2.4 ± 1.1 (g/kg), and 0.1 ± 0.0 (g/kg) for the GTS, 35.6 ± 3.2 (g/kg), 1.5 ± 0.0 (g/kg), and 0.4 ± 0.0 (g/kg) for the geotextile bags, and 45.9 ± 1.7 (g/kg), 5.5 ± 1.0 (g/kg), and 0.9 ± 0.0 (g/kg) for the IBF. GBF appeared to be the most effective method for simple sludge volume reduction with the ability to dewater solids to an extent greater than 200-fold, which can significantly reduce sludge storage, handling and hauling, or composting costs. The IBF appeared to have the greater capacity at nutrient and $cBOD_5$ retention. It is likely that because the solids within the GBF were allowed to remain *in situ* until the bags were completely loaded (92 days) and allowed to dry for an additional 7 days, the long period of dewatering time more effectively thickened the solids. Conversely, the higher N, P, K concentrations observed in the IBF sludge cake likely reflected the rapid efficiency with which solids are separated from wastewater.

3.2. Solids and $cBOD_5$ removal

All three technologies performed similarly in terms of solids removal capacity measured as TSS and TVS (Table 3). Removal efficiencies for TSS were 92%, 95%, and 96% for the GTS, GBF, and IBF, respectively. Similarly, TVS removal efficiencies were 89%, 94%, and 97% for the GTS, GBF, and IBF, respectively. As a result, all technologies were quite efficient at capturing biosolids. Comparison of COD removal capacity indicates removal efficiencies of 80%, 70%, and 89% with the GTS, GBF, and IBF, respectively, indicating greatest COD removal when applying the IBF (Table 3). Similarly, $cBOD_5$ removal efficiencies were 47%, 57%, and 89% for the GTS, GBF, and IBF, respectively, further indicating greater performance applying the IBF (Table 3). Geotextile bags performed least effectively in terms of COD and $cBOD_5$ removal. It is likely that intermediate storage of biosolids within the GBF under anaerobic conditions resulted in the break down of organic matter and the release of organic compounds as measured by the COD and $cBOD_5$ tests. Conversely, the relatively rapid rate that the IBF separated biosolids from the backwash likely reduced the release of organic compounds.

3.3. Nitrogen and phosphorus removal

Comparison of nutrient reduction capacity indicates TN removal efficiencies of 58%, 39%, and 86% for the GTS, GBF, and IBF, respectively (Table 4), demonstrating some capture of organically bound nitrogen in all dewatering techniques. However, release of inorganic nitrogen (TAN) from captured biosolids was evident in all three dewatering technologies resulting in TAN removal efficiencies of −101%, −1461%, and −24% for the GTS, GBF, and IBF, respectively (Table 4). Clearly, the IBF performed the best in terms of reducing TAN leaching, because this unit rapidly separated biosolids from the wastewater. The geotextile bags performed poorly in this regard, as solids stored within the bags under anaerobic conditions promoted TAN leaching. Further, the GBF demonstrated an increase in nitrogen leaching rate over the course of the experiment and a high proportion of inorganic nitrogen (TAN) relative to the TN concentration in the bag filtrate (Fig. 5). However, in certain applications, such as a hydroponic operation (Adler et al., 2000) or nutrient deficient soil irrigation application, a low TSS and high dissolved nutrient filtrate could be considered a value-added resource.

All three technologies exhibited relatively efficient removal of total phosphorus, producing removal efficiencies of 74%, 68%, and 92% for the gravity GTS, GBF, and IBF, respectively (Table 4). More leaching of phosphorus occurred across the GTS and GBF, which resulted in effluent dissolved reactive phosphorus (DRP) removal efficiencies across these units of −145% and −1000%, respectively (Table 4). GBF filtrate total phosphorus concentration was primarily of the inorganic form (DRP) and the rate of leaching increased over time (Fig. 6). The IBF, which incorporated 50 mg/L of alum to precipitate DRP, was more effective in terms of DRP reduction – resulting in 51% removal efficiency. It is likely that the capacity for the IBF to coagulate dissolved phosphorus and rapidly separate

Table 1
Indicates study duration, sampling frequency, surface and hydraulic loading rates, final percent solids concentrations, and N, P, K concentrations for the gravity thickening settler (GTS), geotextile bag filter (GBF), and inclined belt filter (IBF).

	Geotextile bag filter	Inclined belt filter	Gravity thickening settler
Study duration (day)	92	16	21*
Sampling frequency (day)	44	8	8
Surface loading rate ($L/day/m^2$)	–	–	10578
Hydraulic loading rate ($L/day/m^2$)	66	4277	–
Final % solids	22 ± 1	11 ± 0	9 ± 1
Solids nitrogen concentration (g/kg)**	35.6 ± 3.2	45.9 ± 1.7	6.4 ± 2.0
Solids phosphorus concentration (g/kg)**	1.5 ± 0.0	5.5 ± 1.0	2.5 ± 1.1
Solids potassium concentration (g/kg)**	0.4 ± 0.0	0.9 ± 0.0	0.1 ± 0.0

* GTS study was performed three times, each for a 21-day period.
** Dry weight basis.

Table 2
Indicates influent, effluent (i.e., filtrate or supernatant), and spray wash temperature, pH, dissolved oxygen concentration, and alkalinity concentration (mean ± S.E.) across gravity thickening settler (GTS), geotextile bag filter (GBF), and inclined belt filter (IBF).

	Temperature (°C)	pH (SU)	Dissolved oxygen (mg/L)	Alkalinity (mg/L as $CaCO_3$)
Gravity thickening settler				
Influent	14.8 ± 0.2	7.51 ± 0.05	4.6 ± 0.4	279 ± 7
Effluent (Supernatant)	15.1 ± 0.3	7.23 ± 0.04	4.2 ± 0.2	312 ± 8
Geotextile bag filter				
Influent	17.3 ± 0.3	7.55 ± 0.02	7.6 ± 0.3	303 ± 10
Effluent (filtrate)	20.1 ± 0.4	7.20 ± 0.02	0.1 ± 0.0	363 ± 16
Inclined belt filter				
Influent	17.2 ± 0.8	7.58 ± 0.09	6.7 ± 0.5	268 ± 7
Effluent (filtrate)	18.8 ± 0.4	7.10 ± 0.07	1.7 ± 0.2	282 ± 7
Spray wash	19.6 ± 0.3	7.84 ± 0.05	8.3 ± 0.1	271 ± 12

Table 3
Summarizes TSS, TVS, turbidity, COD, and $cBOD_5$ influent and effluent concentrations (mean ± S.E.) and their respective removal efficiencies across the gravity thickening settler (GTS), geotextile bag filter (GBF), and inclined belt filter (IBF).

	TSS (mg/L)	TVS (mg/L)	Turbidity (ntu)	COD (mg/L)	$cBOD_5$ (mg/L)
Gravity thickening settler					
Influent	1002 ± 313	620 ± 148	301 ± 82	1268 ± 373	251 ± 55
Supernatant	84 ± 4	71 ± 4	61 ± 16	259 ± 27	133 ± 18
% Removal	92	89	80	80	47
Geotextile bag filter					
Influent	1874 ± 120	1317 ± 171	621 ± 31	1896 ± 125	541 ± 58
Filtrate	98 ± 4	79 ± 2	56 ± 3	577 ± 20	235 ± 25
% Removal	95	94	96	70	57
Inclined belt filter					
Influent	2084 ± 512	1946 ± 113	564 ± 125	2171 ± 652	956 ± 201
Filtrate	26 ± 5	30 ± 9	10 ± 3	174 ± 12	122 ± 17
Spray wash	215 ± 36	113 ± 18	93 ± 19	261 ± 47	109 ± 19
% Removal*	96	97	n/a	89	89

* Estimated percentage of the total mass removed in the IBF scrapings.

Table 4
Summarizes total nitrogen (TN), total ammonia nitrogen (TAN), total phosphorus (TP), and dissolved reactive phosphorus (DRP) influent and effluent concentrations (mean ± S.E.) and their respective removal efficiencies for the gravity thickening settler (GTS), geotextile bag filter (GBF), and inclined belt filter (IBF).

	TN (mg/L)	TAN (mg/L)	TP (mg/L)	DRP (mg/L)
Gravity thickening settler				
Influent	49 ± 7	1.9 ± 0.4	19 ± 4	1.4 ± 0.2
Supernatant	21 ± 3	3.8 ± 0.8	5 ± 1	3.4 ± 0.3
% Removal	58	−101	74	−145
Geotextile bag filter				
Influent	62 ± 4	1.8 ± 0.1	40 ± 2	1.0 ± 0.1
Filtrate	38 ± 2	28 ± 1	13 ± 1	11 ± 1
% Removal	39	−1461	68	−1000
Inclined belt filter				
Influent	100 ± 23	3 ± 1	32 ± 3	1.8 ± 0.3
Filtrate	11 ± 1	4 ± 1	1.2 ± 0.2	0.9 ± 0.2
Spray wash	13 ± 2	0.4 ± 0.1	6.1 ± 1.4	0.03 ± 0.02
% Removal*	86	−24	92	51

* Estimated percentage of the total mass removed in the belt filter scrapings.

solids from backwash flow prevented leaching of additional organically bound phosphorus. Conversely, continued loading of backwash into the GBF likely promoted phosphorus leaching from the solids stored inside the geotextile material.

Although differences existed in study duration and test conditions for each of the technologies evaluated, most differences were purposefully implemented to meet standard operating procedures for each technology. Study duration for each technology differed because the GBF (operated for one 92 day period) and GTS (operated for three 21 day periods) were only operated for sufficient time to fill their respective bags/vessels with dewatered biosolids; the IBF continuously scraped the collected biosolids from its belt, which allowed the unit to operate practically indefinitely; however, we operated the IBF only for sufficient duration (one 16 day period) to replicate the condition for data collection. In addition, some test conditions differed, e.g., no coagulant or flocculent amendments were used to pre-treat the wastewater entering the GTS because biosolids could be captured effectively during settling without the use of coagulation and flocculation aids. However, the wastewater entering the GBF and IBF had to be pre-treated with coagulation and flocculation aids to maintain permeability through the geotextile filter. We also could not evaluate all three technologies at full-scale simultaneously, because only sufficient backwash wastewater was available to load one full-scale technology at a

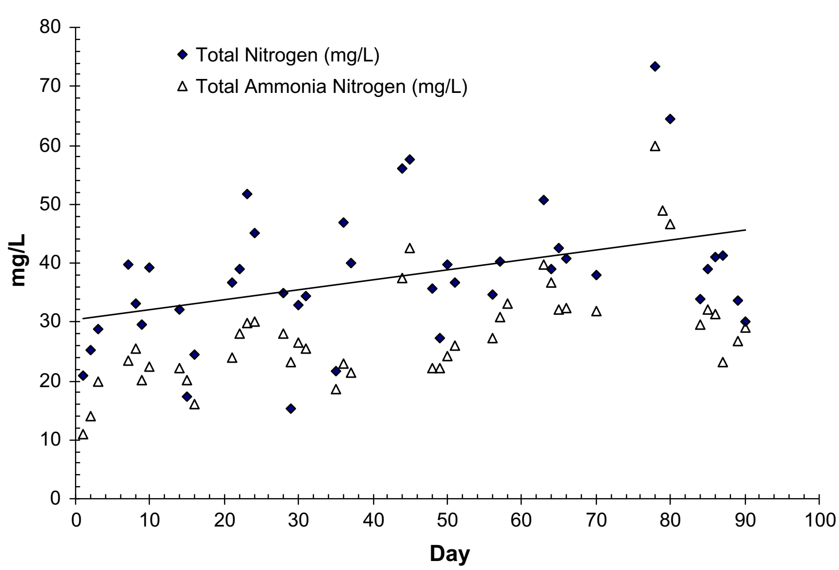

Fig. 5. Indicates increasing nitrogen leaching rate over time in geotextile bag filtrate and the proportion of inorganic nitrogen (total ammonia nitrogen) relative to the total nitrogen concentration.

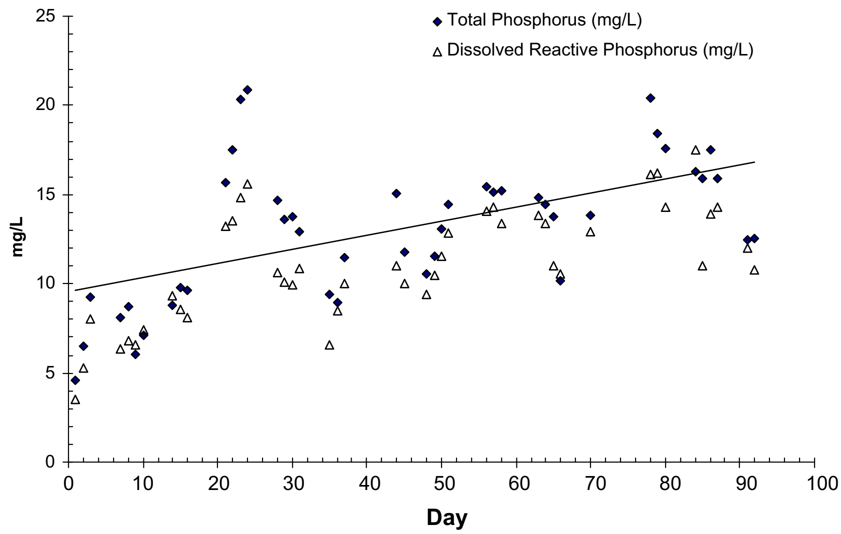

Fig. 6. Increasing phosphorus leaching rate over time in geotextile bag filtrate and the proportion of inorganic phosphorus (dissolved reactive) relative to the total phosphorus concentration.

time. Therefore, each technology was evaluated at different times, which allowed the concentration of wastes in the inlet to vary sufficiently to create slightly different test conditions for each technology. To compensate for the different inlet conditions, waste treatment efficiency were calculated for each dewatering technologies and waste treatment performance was compared on a treatment efficiency basis. We do not think that the differences in test conditions, study duration, or coagulant/flocculent aid requirements were sufficient to significantly change performance results or our final recommendations.

3.4. Cost analysis

A comparison of the costs associated with large-scale implementation of GTS, GBF, and IBF technologies at a hypothetical water recirculating system facility producing approximately 454 mt of fish annually (1000,000 lb/year) was determined. At a mean facility feed conversion ratio (FCR) of 1.4, approximately 0.2 kg TSS would be captured in the rotating microscreen drum filter backwash per kg of feed applied and would result in the total annual production of 127 mt of TSS. Assuming a total system recir-

Table 5
Indicates capital costs associated with installation of a gravity thickening settler (GTS), geotextile bag filter (GBF), and inclined belt filter (IBF) for dewatering biosolids from a hypothetical 454 mt/year water recirculating system.

Description	GTS Qty.	GBF Qty.	IBF Qty.	Unit	Unit cost[a]	GTS cost	GBF cost	IBF cost
Mobilization and demobilization of excavator/compactor	–	4	–	Ea.	249.18	–	997	–
Clearing and grubbing land for site preparation	–	3458	–	m^2	1.08	–	3735	–
Excavating bulk bank measure, excavator	–	530	–	m^3	1.95	–	1034	–
Compaction, riding, vibrating roller	–	1	–	Day	1357.12	–	1357	–
Solids equipment building	60	–	130	m^2	728.37	43,702	–	94,688
Equalization basin/lift station	1	1	1	Ea.	4543.94	4544	4544	4544
Duplex submersible sewage pump system	1	1	1	Ea.	3849.78	3850	3850	3850
Radial-flow gravity settling cone (30-m diameter, 60°)	2	–	–	Ea.	41,661.13	83,322	–	–
One year of geotextile bag material (3.05-m diameter)	–	876	–	m	147.93	–	129,587	–
Vinyl polyester liner and field installation	–	3485	–	m^2	32.73	–	114,064	–
Mixing tank and inclined belt filter system, installation	–	–	3	Ea.	116,696.25	–	–	350,089
Two general purpose laborers for equipment installation	5	5	–	Day	891	4455	4455	–
Alum and polymer dosing system	–	2	2	Ea.	19,618.50	–	39,237	39,237
Dosing system placement and installation	–	10	10	Day	1350.22	–	13,502	13,502
Permeate pumping system and installation	–	1	1	Day	7615.74	–	7616	7616
Solids pumping system (pump and control panel)	1	–	3	Ea.	12,338.23	12,338	–	37,015
Solids pumping system placement and installation	2	–	6	Day	891	1782	–	5346
Instrumentation (flow meters)	–	–	3	Ea.	5863.00	–	–	17,589
Drainage material, 3/4″ gravel fill	–	353	–	m^3	54.34	–	19,182	–
Piping, subdrainage, plastic, perforated PVC, 4″	–	1105	–	m	37.19	–	41,095	–
Slurry piping to storage tank (PVC, 30.5-m long)	1	–	3	Ea.	5997.17	5997	–	17,992
Above ground slurry tank (160-m^3) and installation	1	–	1	Ea.	81,168.73	81,169	–	81,169
Pipe fitter	5	10	10	Day	703.53	3518	7035	7035
System electrical wiring (electrician and helper)	10	–	15	Day	1101.99	11,020	–	16,530
Subtotal						255,697	391,289	696,201
Design (20%)						51,139	78,258	139,240
Construction admin (10%)						25,570	39,129	69,620
Contingency (25%)						63,924	97,822	174,050
Bond ($12/1000 + 10% O&P)						3132	6432	8002
Grand total						**399,462**	**612,929**	**1087,113**

[a] Assumes 10% overhead and profit for material and equipment, 78.2% overhead and profit for labor, and a 5% sales tax.

Table 6
Indicates energy consumption and chemical amendment operating costs for the gravity thickening settler, geotextile bag filter, and inclined belt filter for dewatering biosolids from a hypothetical 454 mt/year water recirculating system. Estimate based upon an electricity cost of $0.10 ($/kW h).

Wastewater treatment system	Operating unit	Energy consumption (kW/unit)	Run time/cycle (min/unit)	Number of cycles/day (per unit)	Daily energy consumption (kW h/unit)	Number of operating units	Unit monthly operational cost ($/month)
Gravity thickening settler	Solids pump	0.829	2.3	24	0.763	1	2.32
	Monthly operating cost					2.32	
	Annual operating cost					*27.83*	
Geotextile bag filter	Permeate pump	0.829	10	42	5.802	1	17.65
	Polymer storage mixer	0.41	5	1	0.0345	2	0.21
	Alum storage mixer (continuous)	0.41	60	24	9.9467	2	60.51
	Polymer dosing pump	0.13	0.42	1440	1.3000	2	7.91
	Alum dosing pump	0.21	0.42	1440	2.0722	2	12.61
	Alum addition				760	418.23	
	Polymer addition				38	109.44	
	Replacement geotextile bags					72.97	9573.33
	Monthly operating cost						10,199.88
	Annual operating cost						*122,186.83*
Inclined Belt Filter	Solids pump	0.829	1	156	2.155	3	19.72
	Clarified water pump	0.829	10	42	5.802	1	17.70
	Belt filter	0.21	0.5	180	0.3108	3	2.84
	Mixing tank mixer (continuous)	0.12	60	24	2.8800	6	52.70
	Mixing Tank Mixer (high speed)	0.12	1.50	720	2.1600	3	19.76
	Polymer storage mixer	0.41	1	1	0.0069	3	0.06
	Alum storage mixer (continuous)	0.41	60	24	9.9467	3	91.01
	Polymer dosing pump	0.13	0.42	720	0.6500	3	5.95
	Alum dosing pump	0.21	0.42	720	1.0361	3	9.48
	Alum addition					760	418.23
	Polymer addition					38	109.44
	Monthly operating cost						746.90
	Annual operating cost						*8726.17*

culating flow of 100,000 m^3/day and drum filter backwash totaling 0.50% of the total system flow, then a volume of approximately 500 m^3/day would require further solids dewatering by an on-site treatment system. Hydraulic loading rates used to size each solids dewatering technology were 28,500 L/min per unit for the GTS, 65 L/day per m^2 fabric area for the GBF, and 132 L/min per unit for the IBF.

Capital cost estimates for two GTS designed to dewater drum filter backwash are summarized in Table 5. Using two GTS would allow for one cone to be removed from service for short duration without serious interruption in solids dewatering capacity while biosolids are removed or when GTS maintenance is required. Major equipment costs include equalization basin/lift station installation, two 3.3 m (11-ft) diameter 60° cone-bottomed GTS, a 150 m^3 (40,000 gallon) cast-in-place tank for storing thickened biosolids, and solids pumping system to transfer settled solids to the storage basin. Costs of major GTS equipment, site mobilization, preparation, and installation, including sales tax and overhead and profit, total US $255,697 (Table 5).

Capital cost estimates for a GBF system designed to dewater the biosolids are reported in Table 5. Major equipment for GBF dewatering include equalization basin/lift station installation, first year of geotextile bags, alum and polymer dosing system, gravel pad and drain piping, and permeate pumping. Cost of major GBF equipment, site mobilization, preparation, and installation, including sales tax and overhead and profit, total US $391,289 (Table 5). However, additional capital cost associated with housing a geotextile bag, at the footprint required, to prevent freezing at higher latitude locations may reduce desirability of its application.

Capital cost estimates for an IBF system to dewater biosolids are indicated in Table 5. Major equipment, site mobilization, preparation, and installation costs for a treatment plant utilizing three IBF's would total US $696,201.

Cost multipliers associated with design fees, construction administration costs, contingency funds, and bond fees for any of the described dewatering options can be mitigated based upon the resources available to the fish farmer. However, assuming the cost multipliers listed (Table 5), total capital cost estimates for installing GTS, GBF, and IBF systems are US $399,462, US $612,929, and US $1087,113, respectively.

Estimated annual operating cost, including electrical expenses related to pumping biosolids and chemical amendments (for the GBF and IBF systems), as well as for purchasing alum and polymer, total US $27, US $ 121,186, and US $8726, respectively, for the GTS, GBF, and IBF systems (Table 6). Additional operating costs linked to the disposal of thickened waste are neglected, because they will likely vary based upon land application access and regulations, composting facilities, or local contract hauling fees.

According to this analysis, the GTS system provides biosolids dewatering capacity and waste capture at the lowest capital and annual operating cost, assuming that solids disposal fees are ignored for all options. In addition, the thickening cone's ease of use and lack of coagulant and flocculant requirements are beneficial in terms of maintenance and operating costs. Capital costs for both GTS and GBF were less than half of the capital cost of the IBF. The GBF system, however, had orders of magnitude higher annual operating costs, due to replacement of the geotextile bags, than the two other technologies.

4. Conclusions

All three biosolids thickening technologies demonstrated effective solids capture, but varying degrees of solids dewatering, which influences the cost of transporting these biosolids to nearby fields to reuse the nutrients. The GBF demonstrated the greatest ability to dewater solids, but with significant nutrient leaching into the filtrate. Nutrient leaching from the GTS was also evident, although less so than the GBF. The IBF produced the cleanest discharge, although more mechanically intricate, operationally complex, and capital outlay demanding than the GBF and GTS. In contrast, the GTS had the lowest capital and annual operating cost estimates, but provided intermediate treatment performance.

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