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Application of dissolved air flotation (DAF) in semi-aerobic leachate treatment

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ABSTRACT

Dissolved air flotation (DAF) was investigated in batch experiments as a treatment for semi-aerobic landfill leachate. This research was performed in three phases and focused on removing colour, COD, and turbidity. The first phase focused on saturator efficiency. The second phase evaluated leachate treatment using DAF alone, while the third phase consisted of coagulation with alum ($Al_2(SO_4)_3$) followed by DAF. Flow rate and pressure were the two main operating parameters in the first phase, and the highest saturator efficiency (73%) was at a flow rate of 6 L/min and a pressure of 400 kPa. With the same saturator operating parameters, the removal of COD (36%), colour (33%), and turbidity (32%) was fairly low in the second phase. In the third phase, a jar test indicated that pH and alum dosage were optimum at 7 g/L and 9.5 g/L, respectively. Operating parameters evaluated in the DAF system included coagulant dosage, injection time, and retention time. The best removal in the DAF system was obtained with a 4 min injection time, a 20 min retention time, and a 2.3 g/L alum dose, resulting in 70%, 79%, and 42% removal for colour, COD, and turbidity, respectively.

1. Introduction

Landfilling is a preferred management strategy for municipal solid waste disposal because of lower operation and maintenance cost compared to other alternatives [1–5]. A major problem that arises from landfills, however, is the production of leachate, which is typically hazardous and heavily polluted [6]. Leachate is mainly generated by the infiltration of rainwater through the landfill, chemical and biological processes within the landfill, and the water content of the waste itself [7]. Additionally, physical, hydrolytic and fermentation processes occur in landfills [8]. As a result of these processes, leachate is typically a very complex mixture. Sanitary landfill leachate contains very high concentrations of pollutants, including ammonia nitrogen, heavy metals, chlorinated organics, inorganic salts, and organic matter comprised of both biodegradable and recalcitrant carbon [9,10]. Factors that influence the composition and concentration of these contaminants are, for example, the type of waste, the age of the landfill and the quality of refuse [11]. For many years, landfill leachate treatment has been the subject of much research typically based on wastewater and drinking water technologies (e.g., aerobic and anaerobic biological treatment, coagulation–flocculation, membrane processes, and adsorption processes [12–15]).

The principle use of dissolved air flotation (DAF) is to separate suspended particles from liquids by bringing the particles to the surface of the liquid [16]. In addition, the DAF process is effective in reducing other parameters that are of primary concern in wastewater treatment (e.g., biological oxygen demand (BOD), chemical oxygen demand (COD), and turbidity [17]). DAF can also handle wide variations of influent with no degradation in the output of wastewater quality. DAF is an alternative process to sedimentation and offers several advantages, including better final water quality, rapid start-up, higher rates of operation, and thicker sludge. Furthermore, DAF systems need less space compared to normal clarifiers. Modular DAF components also allow easy installation and set up [18,19].

Most of the research performed using DAF has focused on oily wastewater [16,17,20–22] or wastewater contaminated with radionuclides [23]. Besides, DAF application was done in white waters in papermaking [24,25] and also in highly protein contaminated wastewater [26]. Application of DAF in various types of wastewater was successful by controlling some operational parameters. Rubio and coworkers [27], in their study on mercury removal from gold cyanide solution, indicate that the removal efficiency increase with increase in saturator pressure. The same finding was reported by Chung et al. [28] using higher pressure improves the turbidity removal. This is because when higher pressure was used in saturator, smaller bubbles were produced when the pressurised water and air released at atmosphere pressure. The smaller bubbles have higher rising velocity, which will lead to higher flotation of the particles [28]. In order to obtain smaller bubbles in the

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range of 10–100 μm, pressure at 400–600 kPa was recommended [29].

The present study gives an idea in order to apply this method as a large-scale application in the landfill area. To date, no study has been reported in the literature on the application of DAF for leachate treatment. The present work investigates the application of DAF in leachate treatment with and without alum coagulation. In addition, bubble volume concentration and efficiency of the unpacked saturator at different pressures and flow rates were also evaluated.

2. Materials and methods

2.1. Materials

A bench scale DAF unit was used for the experiments in this study (Fig. 1). The unit consisted of a compressor, a water tank, a high pressure pump, an unpacked saturator, and a flotation cell. The cell was equipped with a nozzle through which air saturated water was injected. The air injection nozzle that had been used (USM nozzle) was developed by Adlan et al. [30]. Four sampling points, at 7.5 cm, 15 cm, 30 cm, and 60 cm from the floor of flotation cell, and a scour valve were installed on the bottom of the flotation cell. The inorganic coagulant used in the investigation was alum (aluminium sulphate, $Al_2(SO_4)_3{\cdot}18H_2O$) powder form with M = 666.42 g/mol, 51–59% $Al_2(SO_4)_3$, pH 2.5–4 and supplied by Merck, Germany. A solution of alum (600 g/L) was prepared for the experiment. Sulphuric acid (H_2SO_4) was to adjust the pH during the coagulation process.

Leachate samples for the experiment were taken from the Pulau Burung municipal solid waste landfill site (PBLS) in Penang, Malaysia, 10 km west of Nibong Tebal, Penang. PBLS occupies an area of approximately 23.7 ha [31]. PBLS was developed into a semi-aerobic Level 2 sanitary landfill by establishing a controlled tipping technique in 1991. The landfill was further upgraded to Level 3 in 2001 by employing controlled tipping with leachate recirculation [32]. The piping system for leachate collection was built at the bottom of the landfill. The collected leachate is channelled into one of the two collection ponds. The volume of the first pond is approximately 200 m^3, while the volume of the second pond is approximately 11,400 m^3. Leachate samples were collected from the small collection pond, 10 times at 2 weeks interval within about 5 months from September 2007 to February 2008. The collections of the sample were done according to the standard methods for the examination of the water and wastewater [33]. The collected samples were stored in the cold room at 4 °C. However the characteristics such as pH, COD, colour, turbidity, ammonia nitrogen, alkalinity, suspended solids (SS) and dissolved oxygen (DO) were carried out immediately as the sample was taken to the laboratory according to standard methods for the examination of the water and wastewater [33].

2.2. Methods

The characteristics of leachate were analyzed before and after DAF process. The COD was determined based on the Method 5220 D (closed reflux, colourimetric method). Colours were reported as true colour (filtered using 0.45 μm filter paper) determined using DR 2010 HACH spectrophotometer, which was parallel with method 2120C. Turbidities were determined using the DR 2010 HACH spectrophotometer. Ammonia nitrogen was measured using Nessler method with DR 2010 HACH spectrophotometer. Alkalinities were reported as mg/L calcium carbonate and measured using 2320 B titration method. Suspended solids were determined using DR 2010 HACH spectrophotometer, which was comparable with method 2540 D. The pH and DO were measured using W-100 Witeg pH meter and WTW multi-parameter 340i, respectively.

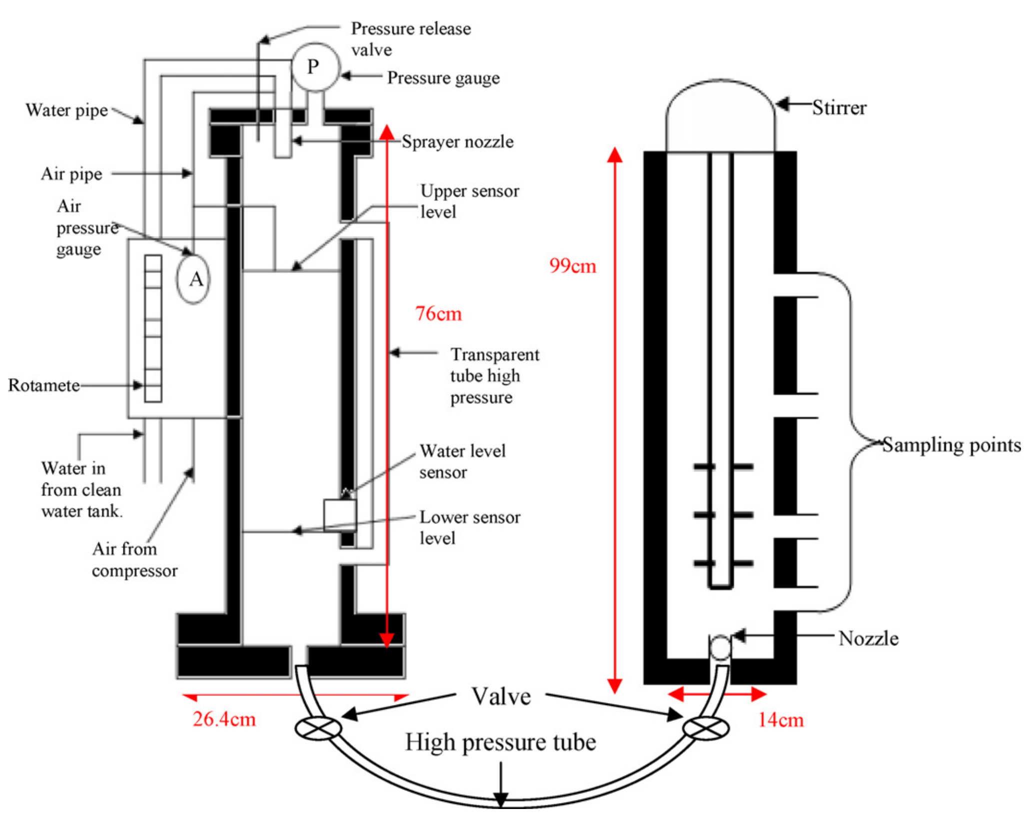

Fig. 1. Schematic diagram of the DAF batch study.

Table 1
Operational parameters for the leachate treatments.

Operational parameter	Range		
	First phase	Second phase	Third phase
Water flow rate	4–6 L/min	4 and 6 L/min	4 L/min
Saturator pressure	400–600 kPa	400 and 600 kPa	600 kPa
Injection time (IT)	–	2 min	2 and 4 min
Volume of leachate	–	8 L	4 L
Retention time (RT)	–	10 min	10 and 20 min
Dosage of coagulant			
(i) Jar test	–	–	7.2–11.0 g/L
(ii) DAF system	–	–	9.5 g/L, 4.5 g/L and 2.3 g/L
pH (Jar tester)	–	–	4–10

The experimental studies consisted of three phases and the operating parameters for each phase are shown in Table 1. During the first phase, the saturator efficiency and bubble volume concentration study was carried out. The saturator efficiency for the DAF process was determined following the procedures of Steinbach and Haarhoff [34], Haarhoff and Steinbach [35] and Rykaart and Haarhoff [36]. There were several assumptions made in the calculation for the determination of saturator efficiency. The nine important equations [34,35] (equation not discussed) were applied to solve it using MathCAD software with respect to the air precipitation efficiency. The method used for the determination of bubble volume concentration was based on Edzwald and Walsh [37].

During the second phase, leachate treatment using DAF alone was evaluated as follows: (i) leachate was introduced into the flotation cell, (ii) tap water was supersaturated with air from the compressor at the desired pressure in the saturator, and (iii) the supersaturated water/air from saturator was injected through a nozzle into the flotation cell. Retention time (RT) was recorded before each sample was collected from the sampling points.

For the third phase of the study, alum dosages at corresponding pH values were determined using a jar test (Jar Tester Model VELT Scientifica, JLT6). The third phase was performed as follows: (i) the pH of the raw leachate was adjusted to the value determined in the jar test, (ii) 4 L of pH-adjusted leachate was introduced into the flotation cell, (iii) coagulant was added to the cell, (iv) the leachate was rapidly mixed (470 rpm for 3 min) to ensure uniform mixing and to obtain a pint-point floc size, (v) air-rich water was injected from the saturator into the flotation cell for a specified injection time, and (vi) the leachate remained in the flotation cell for a specified retention time before samples were collected from each sampling point.

2.3. Calculation

2.3.1. Percentage removal

The removals of the studied parameters were calculated based on the following formula:

$$\left[\frac{C_i - C_f}{C_i}\right] \times 100 \quad (1)$$

where C_i and C_f are the initial and final concentration of the studied parameter. Here the concentration was using absolute contents (including the dilution effect of the tap water for the flotation).

2.3.2. Sediment percentage

The sludge volumes that were produced were measured using the following expression [38]:

$$\mathrm{SP}(\%) = \left\{1 - \left[\frac{V_0 - V_{60}}{V_0}\right]\right\} \times 100 \quad (2)$$

Table 2
Characterization of the semi-aerobic landfill leachate.

Parameter	Range[a]	Average[b]
pH	7.76–8.20	8.00
COD (mg/L)	2270–2945	2667
Colour (PtCo APHA)	3860–4248	4059
Turbidity (FAU)	203–308	248
Ammoniacal Nitrogen (NH_3-N)	983–2117	1760
Alkalinity (mg/L as $CaCO_3$)	9000–10400	9602
SS (mg/L)	177–254	211
DO (mg/L)	0.38–1.08	0.63

[a] The values are average of 3 times replication. The differences between the replication for each were less than 1%.
[b] Average of 10 samples taken at 2 weeks interval from September 2007 to February 2008.

where V_{60} is volume beneath the supernatant–suspension interface after 60 min of sedimentation and, V_0 is initial wastewater volume.

This formula was used in order to indicate the percentage of sludge that was produced at the studied coagulant concentration. The determination of this value was done during the preliminary study using jar test.

3. Results and discussions

3.1. Leachate characteristic

Several parameters were determined to characterize the raw leachate (Table 2). pH and COD were very high. Alkalinity and ammonia nitrogen (NH_3-N) were also high in the raw leachate. Biological oxygen demand (BOD_5) value for the raw leachate was around 75–188 mg/L which gives low BOD_5/COD ratio (0.03–0.06). Based on these characteristics, the leachate could be classified as “stabilized leachate” and resistant to biodegradation [39–41].

3.2. Saturator efficiency and bubble volume concentration

The saturator used in this study was an unpacked saturator, which requires less maintenance and has a longer lifespan than packed saturators [42]. Efficiency of the saturator is defined in terms of absolute air concentration and described as the ratio between the actual air mass transferred to the theoretical air mass transferable. Under the conditions tested herein, the maximum efficiency of the unpacked sprayer nozzle saturator was 73% (Fig. 2). This efficiency was achieved at the lowest tested saturator pressure (400 kPa) and highest tested flow rate of the water (6 L/min). This is due to increase in the air mass concentration of air in water after passing through the saturator. Based on two-way Analysis of Variance (ANOVA) with the significant level set to less than 0.05, the flow rate and operating pressure had a significant effect on the saturator efficiency (Table 3). Interaction between these

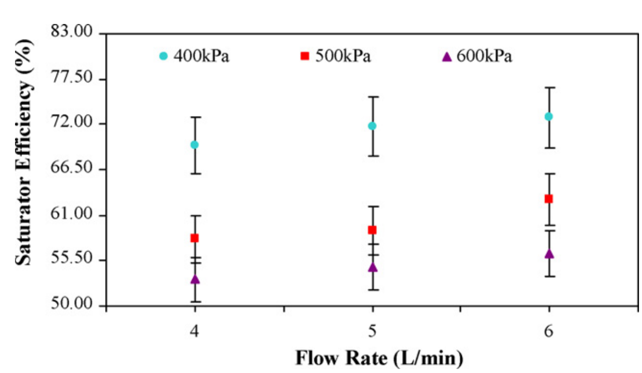

Fig. 2. Saturator efficiency at different flow rates and pressures.

Table 3
Two-way ANOVA for the saturator efficiency with a combination of pressures (400, 500, and 600 kPa) and flow rates (4, 5, and 6 L/min).

Source	DF	SS	MS	*F*	*P*
Pressure (kPa)	2	4268	2135	262	0.0
Flow rate (L/min)	27	223	112	14	0.0
Interaction	4	16	4	0.5	0.7
Error	81	659	8		
Total	89	5169			

R^2 = 87%.

two operating variables, however, did not have a significant effect on saturator efficiency. In contrast, the bubble volume concentration (BVC) increased as both the flow rate and pressure increased (Fig. 3). Under the conditions tested, the highest BVC (41522 ppm) was obtained at the highest tested pressure (600 kPa) and flow rate (6 L/min). According to Burns et al. [43], the bubble diameter decreases as the system saturation pressure and flow rate increase. Here, decrease in the bubble size will result in increase in bubble volume concentration [44].

Application of DAF process in wastewater treatment shows that the removal efficiency increases with increasing saturation pressure [27]. This observation was expected since higher dispersed airs that perform as a stripper to pollutants were produced at higher saturator pressure [45]. Thus higher BVC was needed in order to remove the contaminants from wastewater. However, higher saturator efficiency is important in DAF application in wastewater treatment in order to minimize the capital and operating cost [36].

3.3. DAF process in leachate treatment without coagulation

Four different combinations of saturator pressure (400 kPa and 600 kPa) and flow rate (4 L/min and 6 L/min) were evaluated in DAF treatment of leachate. The first treatment used high pressure (600 kPa) and low flow rate (4 L/min). The second treatment used 600 kPa with 6 L/min. The third treatment used 400 kPa with 4 L/min. The fourth treatment used 400 kPa with 6 L/min. ANOVA was used to examine the significant differences of the studied parameters.

In each of these four treatments, samples from three sampling points were analyzed. Based on this statistical analysis, for each treatment, the *p*-values were more than 0.05, which indicate no significant differences between the sampling points (Table 4). This is due to the floated solids were above the sampling points.

In contrast, significant differences (*p*-value < 0.05 with 95% confident level) were observed for each evaluated parameter (i.e., turbidity, colour, and COD) between the four treatments (Table 5). In Fig. 4, the second treatment (600 kPa, 6 L/min) had the highest removal efficiency (36%, 33%, and 32% for COD, colour, and

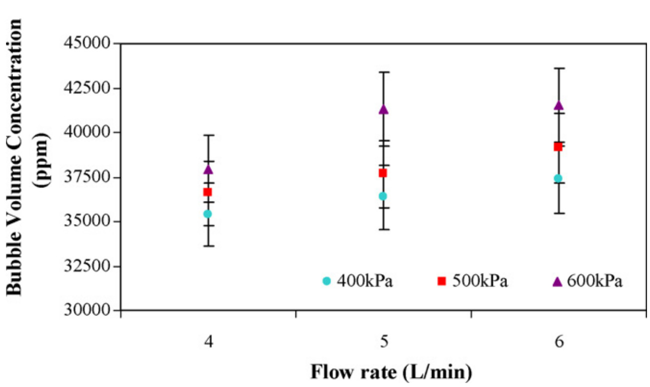

Fig. 3. Bubble volume concentration at different flow rates and pressures.

Table 4
Significant value of turbidity, colour, and COD removal at different sampling points using one-way ANOVA in Treatment 1 (6 kPa, 4 L/min), Treatment 2 (6 kPa, 6 L/min), Treatment 3 (4 kPa, 4 L/min), and Treatment 4 (4 kPa, 6 L/min).

Studied parameter	*p*-Value			
	Treatment 1	Treatment 2	Treatment 3	Treatment 4
Turbidity	0.4	1.0	0.8	0.8
Colour	0.5	0.8	1.0	0.6
COD	0.4	0.1	0.5	0.5

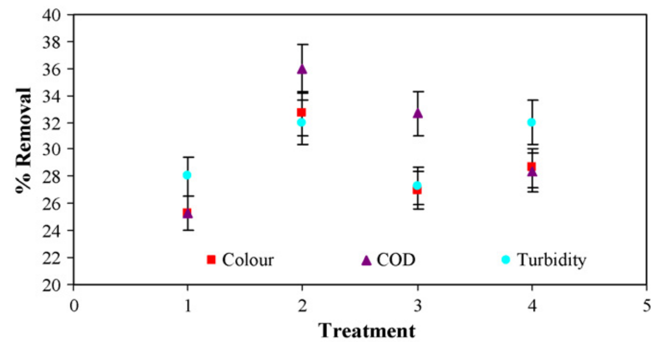

Fig. 4. Turbidity, colour, and COD removal with different treatments. Treatment 1 was at 6 kPa and 4 L/min. Treatment 2 was at 6 kPa and 6 L/min. Treatment 3 was at 4 kPa and 4 L/min. Treatment 4 was at 4 kPa and 6 L/min.

turbidity, respectively) compared to the other three treatments, likely because of the high BVC in the second treatment. Increasing both flow rate and pressure may have increased the amount of air available for flotation and resulted in an improvement in leachate treatment [46]. However, the variations in percent removal of turbidity colour, and COD with each treatment were considerably low. This result implies that the main pollutant in the leachate was in soluble organic and inorganic matter such as humic acid, fulvic acid, iron, sodium, potassium, sulphate, and chloride [4,47]. Due to that DAF process is unable to perform effectively. In order to improve the percentage removal, coagulation process was carried out. Basically coagulation process was chosen to induce floc development in the wastewater with high dissolved organic compounds. Thus the concentration of particulate matter and dissolved organic compounds was transformed into coagulated particle [38].

3.4. Leachate treatment using coagulation prior to DAF

3.4.1. Determination of the coagulant dosage range

Alum was chosen as the coagulant for the third and final stage of the study because it is widely used in water and wastewater

Table 5
One-way ANOVA of turbidity, colour, and COD removal between four different treatments.

Source	Degrees of freedom	Sum of squares	Mean square	*F*-value	*P*
Turbidity					
Treatments	3	543	181	18	0.0
Error	116	1151	10		
Total	119	1694			
Colour					
Treatments	3	890	297	34	0.0
Error	116	1001	9		
Total	119	1892			
COD					
Treatments	3	1574	525	21	0.0
Error	116	2915	25		
Total	119	4489			

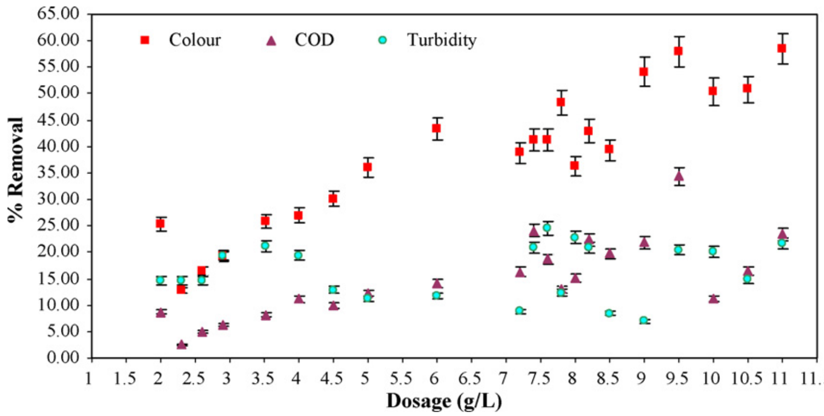

Fig. 5. The effect of dosage on percentage removal of colour, COD, and turbidity.

treatment. Optimization of this parameter was carried out using jar test. The alum concentration was varied from 2 g/L to 11 g/L. Overall, the percent removal of colour was higher than that of turbidity or COD, regardless of all alum doses (Fig. 5). In general, as the concentration of the coagulant increased, the percent removal of colour also increased. Similar results were reported by Aziz et al. [4]. This result may have occurred because, as the amount of coagulant increased beyond the optimum value, the produced colloids may have restabilized [4]. The COD and turbidity removal percentages, which ranged from 10% to 35%, followed similar trends. These indicate that, the COD and turbidity reduction were very close and independent of the coagulant dosage, with standard deviation value of 7.6 and 5.2 for COD and turbidity, respectively (Fig. 5). From this experimental work, 9.5 g/L alum dosage had been selected to carry out DAF process.

3.4.2. Determination of the optimum pH

9.5 g/L alum dosage was used to optimize the pH. The pH was adjusted from pH 4 to pH 10 using sulphuric acid. To determine the optimum pH, sulphuric acid (H_2SO_4) and sodium hydroxide (NaOH) were used to adjust the pH from 4 to 10. The percent removals of colour, COD, and turbidity were generally high at pH 7 (Fig. 6), which is consistent with the results of Ghafari [48]. Therefore, the optimum pH for alum treatment of leachate from PBLS was pH 7 [48].

3.4.3. DAF application in leachate treatment

Coagulation followed by treatment with the DAF system was evaluated after the coagulant dose and optimum pH were determined with the jar test. For alum pre-treatment followed by DAF, the leachate was first placed into the flotation cell and then coagulated with alum (9.5 g/L). After coagulation, coagulated leachate was subjected to DAF operating at the highest saturator efficiency (400 kPa, 6 L/min). Unfortunately, the amounts of sludge produced were lot, and the flotation process was unable to carry the sludge to the surface of the flotation cell, indicating that the alum dose was too high. Based on the formula (2) the sediment percentage using 9.5 g/L alum was 87.5%. Therefore, the alum dose was reduced to 4.5 g/L. At this concentration, the amount of sludge produced was still high, but flotation could still be performed. The sediment percentage of this dosage was 70%. At 10 min RT, turbidity removal was not as efficient as expected (Fig. 7). In contrast, COD and colour removal were greater than the removal of turbidity. This is due to the leachate characteristic which contains very high concentration of humic acid. The humic substances produce massive sludge and flocs [49]. This will make the bubbles difficult to carry the flocs to the surface, and resulted in high turbidity value. Greater removal efficiencies were obtained at this alum dosage at a 20 min retention time (RT) when using a 4 min injection time (IT) compared to a 2 min IT. This result is due to the increase in the amount of bubble concentration resulting from an increased injection time and additional time for flotation. The highest removals at 4.5 g/L alum for colour, COD, and turbidity were 89%, 70%, and 15%, respectively (Fig. 8).

In order to improve turbidity removal, the alum dose was further reduced to 2.3 g/L. At this concentration, the floc size was approximately 0.75–1.0 mm (Fig. 9) and the sludge volume was 50%. Here, fewer and lighter flocs were produced compared to the two previous alum concentrations. As a result of this change, the turbidity and COD removal increased to 41%, and 79%, respectively but colour removal decreased to 70% (4 min IT, 10 min RT; Fig. 7). However, increasing the RT up to 20 min did not significantly improve the percent removals for colour, COD, or turbidity, which were at 70%, 79%, and 42%, respectively (Fig. 8).

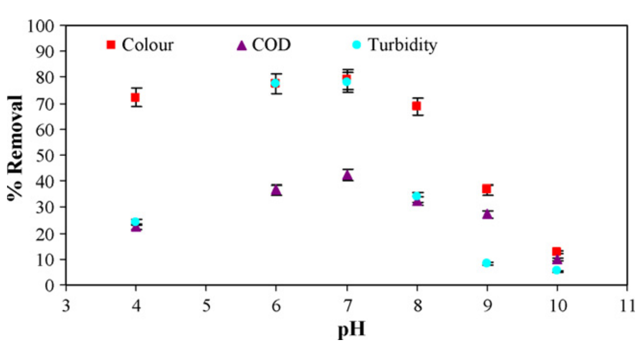

Fig. 6. Percentage removal of colour, COD, and turbidity at different pH values.

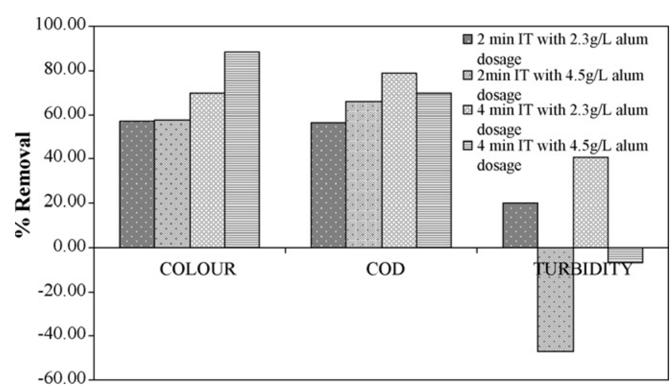

Fig. 7. Percentage removal of colour, COD, and turbidity at 10 min retention time (RT) with different dosage and injection time (IT).

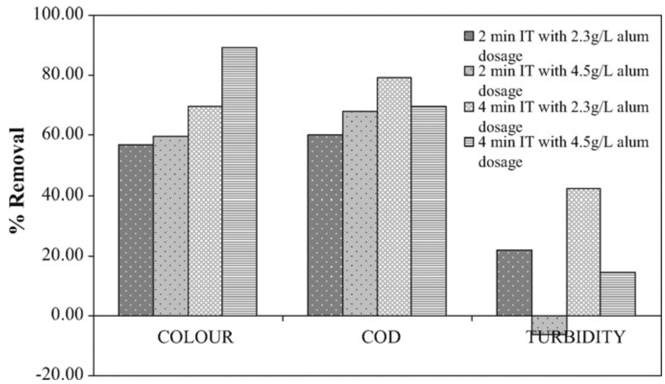

Fig. 8. Percentage removal of colour, COD, and turbidity at 20 min retention time (RT) with different dosage and injection time (IT).

Fig. 9. The sludge that produce at 2.3 g/L alum dosage.

Therefore the last phase of this study proves that the coagulation process enhanced the removal of the studied parameters, as observed by Zouboulis and Avranas [20]. The results also indicate that the production of sludge volume around 50% was able to make DAF works successfully. In addition the results from this study were also consistent with the findings of Zabel and Melbourne [50], who showed that small and light flocs are necessary for efficient DAF application for water or wastewater treatment.

4. Conclusion

This investigation focused on the feasibility of treating landfill leachate with DAF. The saturator efficiency (73%) was highest when the saturator was operated at 400 kPa and 6 L/min. In contrast, the highest bubble concentration (41,522 ppm) was observed at 600 kPa and 6 L/min. In the case DAF without coagulation, low percent removals of 36%, 33%, and 32% were observed for colour, COD, and turbidity, respectively. With coagulation followed by DAF, the highest removals were 70%, 79% and 42% for colour, COD, and turbidity, respectively. These removals were achieved using 2.3 g/L alum, a pressure of 400 kPa, a flow rate of 6 L/min, an IT of 4 min, and a RT of 20 min.

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