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Feasibility of landfill leachate reuse through adsorbent-enhanced constructed wetlands and ultrafiltration-reverse osmosis

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HIGHLIGHTS

- Constructed wetlands (CWs) with zeolite and biochar enhance the removal of contaminants.
- CWs provide great pre-treatment to ultrafiltration (UF) and Reverse Osmosis (RO).
- Adsorbent-enhanced CWs prior to an UF-RO system was the most economical alternative.
- CW-UF-RO is a promising on-site alternative to treat leachate to reuse standards.

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ABSTRACT

Landfill leachate poses challenges to physical, chemical, and biological processes at wastewater treatment plants. This study investigated the potential for highly treated landfill leachate to be reclaimed for irrigation or industrial applications. Four ultra-filtration reverse osmosis (UF-RO) pre-treatment alternatives were compared: 1) no pretreatment, 2) activated sludge, 3) constructed wetlands (CWs), and 4) adsorbent-enhanced CWs. Both CWs treatments were composed of a series of subsurface vertical-flow and horizontal-flow units. Pilot CW studies were carried out with and without zeolite addition to the vertical-flow CW and biochar addition to the horizontal-flow CW. Additional samples were collected of untreated and activated sludge treated leachate. The scenarios were systematically assessed through chemical characterization, UF-RO simulations, and a net present value analysis. The landfill leachate treatment train consisting of adsorbent-enhanced CW followed by UF-RO attained the highest water recovery rate and greatest cost savings compared with untreated landfill leachate disposal. The addition of low-cost adsorbents to CWs is a promising approach for enhanced pre-treatment prior to UF-RO for landfill leachate reclamation.

1. Introduction

In the United States, on-site treatment of landfill leachate is complex and expensive; therefore, it is predominantly discharged to nearby publicly owned treatment works (POTWs) [1,2]. Landfill leachate is characterized by low 5-day biochemical oxygen demand (BOD_5) to chemical oxygen demand (COD) ratios, which is indicative of low bioavailability of organic matter to microorganisms. It also contains high levels of ammonia nitrogen (NH_4^+-N), humic acids, and color, all of which interfere with physical, chemical, and biological treatment processes at POTWs and have the potential to foul membranes in advanced treatment processes [3].

Constructed wetlands (CWs) are low maintenance treatment systems that emulate natural physical, chemical, and biological processes to treat wastewaters [4]. Compared with free water surface CWs, subsurface flow (SSF) CWs provide greater assimilation potential per unit land area due to the larger surface area for microbial attachment provided by the media materials [5–7]. CWs can be designed in different flow configurations to synergize the advantages of each alternative and achieve higher pollutant removal [8–11]. Vertical SSF wetlands promote aerobic conditions for nitrification and can also achieve efficient removal of BOD_5, COD, and total suspended solids (TSS). Horizontal SSF wetlands promote anoxic conditions required for denitrification due to the continuous submergence of wastewater in the vegetation's rhizosphere

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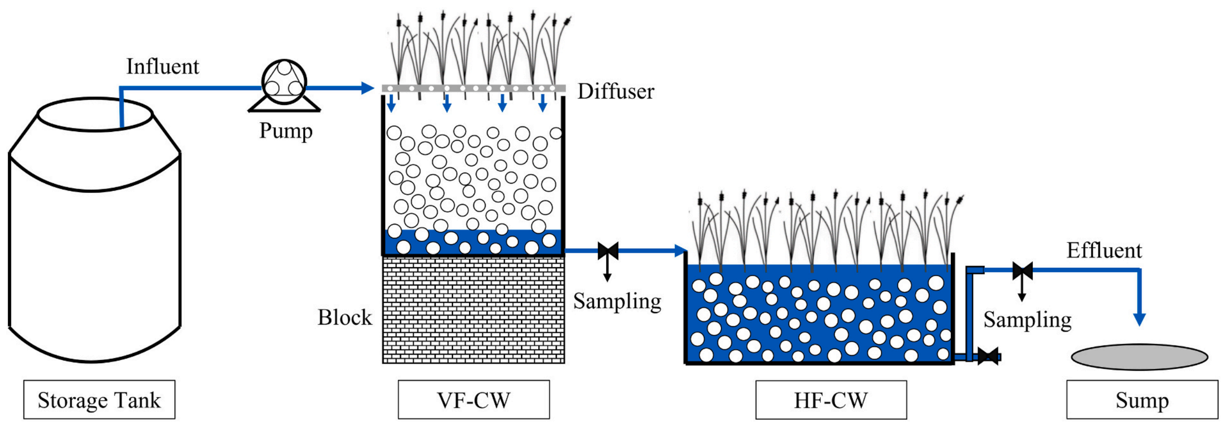

Fig. 1. Pilot CW schematic.

and can provide additional polishing of BOD, COD, and TSS [6–8,12]. Therefore, hybrid configurations consisting of a vertical SSF CW followed by a horizontal SSF CW can achieve high removal rates of total nitrogen (TN), organic matter, and solids [13,14].

Several prior studies have shown that adsorbent materials can be added to biofilm-based treatment processes to enhance leachate treatment [15,16]. Biochar is a low-cost adsorbent material obtained from the pyrolysis of biomass at high temperature in a limited oxygen environment. Biochar has many benefits for agriculture, such as increased soil nutrient availability, microbial activity, and water retention [17,18]. Due to its high surface area, biochar has a high COD adsorption capacity [19]. Significant color removal has also been reported in biochar-amended water and landfill leachate treatment systems [17,20].

Zeolite is a low-cost aluminosilicate mineral that contains alkali and alkaline-earth metal ions, which are easily exchangeable with surrounding cations, such as ammonium (NH_4^+) [21,22]. Zeolite has been used to reduce the concentration of free ammonia in high strength wastewaters to levels that are not inhibitory to sensitive microorganisms, such as nitrifiers [22–25]. Zeolite can also serve as a site for microbial biofilm growth [25]. As nitrifying bacteria within the biofilms use NH_4^+ adsorbed to the zeolite particles as an electron donor, the ion exchange capacity of the zeolite is bio-regenerated [16,23,24,26].

Aside from high levels of inorganic nitrogen, landfill leachate has high salinity and contains biologically recalcitrant organic compounds [27]. In order for landfill leachate to meet stringent water reuse standards, advanced treatment technologies, such as reverse osmosis (RO), are needed [28]. RO is a pressure-driven process that uses semi-permeable membranes to achieve high rejection rates of up to 99.9 % of contaminants, including organics and dissolved inorganic salts [27,29].

Due to the high salinity levels of landfill leachate, many ionic species become close to or above their solubility limit, which leads to a high Langelier scaling index (LSI) that correlates to a high scaling and fouling potential [30]. Scaling decreases membrane permeability and increases energy requirements for sufficient membrane flux to occur [29]. Silt density index (SDI) is also used as a fouling index for suspended and colloidal solids derived from metals and organic matter [31]. A high SDI is associated with decreased permeate flux and RO system rejection rates. High salinity, LSIs, and SDIs correspond to frequent membrane cleaning-in-place requirements and increased operation and maintenance (O&M) costs, such as antiscalant and chemical inhibitor applications. Pre-treatment technologies, such as ultrafiltration (UF) and CWs, have been shown to be effective in reducing the fouling potential of RO membranes [32]. UF effectively removes colloidal solids and organic macromolecules that tend to foul RO membranes through concentration of these contaminants and disposal with the UF waste and backwash streams. However, additional pre-treatment measures are often necessary due to fouling of the UF membranes. CWs are effective in reducing BOD, COD, NH_4^+-N and turbidity levels, which reduces the nutrient and solids loads on membrane filtration processes, including UF, and reduces biofouling of the membrane surfaces. [6–8,32–34].

Landfill leachate continues to be a threat not only to the environment, but also to POTWs that have not been purposely designed to treat this waste stream. In this study, we investigated the potential of enhancing wetland biogeochemical processes through addition of low-cost adsorbent materials, biochar and zeolite, followed by UF-RO treatment to achieve non-food agricultural and industrial water reuse of municipal landfill leachate. Four UF-RO pre-treatment alternatives were compared: 1) no pretreatment, 2) activated sludge (AS), 3) vertical flow-horizontal flow (VF-HF) CWs, and 4) zeolite and biochar enhanced VF-HF CWs. The different treatment alternatives were systematically assessed through bench- and pilot-scale studies, UF-RO simulations, and a net present value analysis. Conventional leachate disposal to an industrial wastewater treatment facility was also assessed (i.e., no reclamation alternative). Although the study uses specific conditions for a landfill in Florida, the findings from this study provide important insights for landfill leachate reclamation in a much broader context.

2. Materials and methods

2.1. Pilot-scale CWs

Two pilot-scale hybrid CWs were set up side-by-side at the Hillsborough County Southeast Landfill (Lithia, Florida, USA). Each hybrid SSF CW system consisted of a VF tank followed by a HF tank, as shown in Fig. 1. The control system utilized gravel as a conventional SSF-CW media material (control-CW) in both vertical and horizontal stages. Media in the amended system (adsorbent-CW) had gravel with zeolite (10 %, by volume) in the VF tank to improve nitrification, and biochar (13 %, by volume) in the HF tank to improve organic carbon and color removal [16]. Both CW systems were planted with cattails (*Typha latifolia*) and cordgrass (*Spartina alterniflora*) and fed with raw landfill leachate intermittently (15 min/2 h) with a daily inflow of 0.024 m^3 to achieve a hydraulic retention time of 11 days. Considering both prior studies [35] and personal consultation with the President (Gilbert Sharell) at Aquatic Plants of Florida (Sarasota, Florida, USA), two native plants, cordgrass (*Spartina alterniflora*) and cattails (*Typha latifolia*), were planted in CWs at a planting ratio of 1:1 with a total density of 10 plants/m^2. Both plants were tolerant to high salinity (electrical conductivity of 14–16 mS/cm) and exhibited good nutrient (nitrogen and phosphorus) uptake in CWs [35]. Details of the pilot-scale CWs design, construction, operation, and performance are available in Ergas and Arias [36].

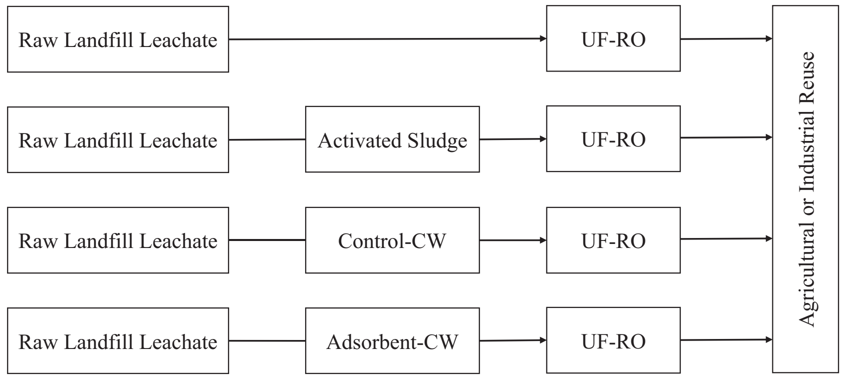

Fig. 2. Treatment strategies for landfill leachate.

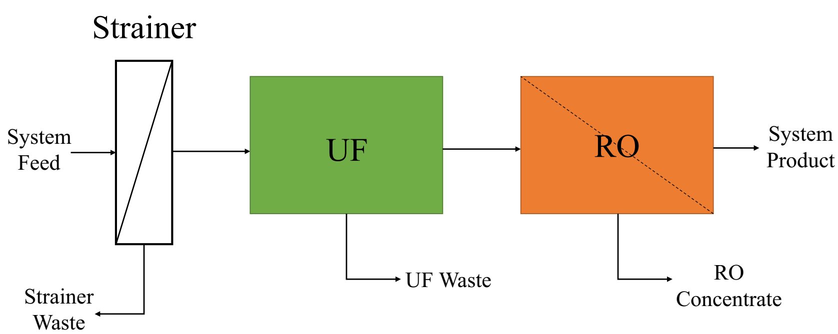

Fig. 3. Example of UF-RO system configuration included in the advanced treatment design model.

2.2. Feed stream samples and analysis

For a comparative analysis, four different samples were collected from the Hillsborough County Southeast Landfill: 1) Raw (untreated) landfill leachate, 2) landfill leachate treated using an onsite AS system, 3) control-CW effluent, and 4) adsorbent-CW effluent. Note that the onsite AS system included aerobic and anoxic zones with glycerol addition for partial TN removal. Wastewater characterization for each sample was guided by the feed stream requirements for the software used to model the UF-RO process. pH was measured using an Orion 5 Star Multifunction Meter (Thermo Scientific, USA). A portion of the samples were filtered through a 0.45 μm glass fiber membrane filters and used to measure pH, inorganic nitrogen species, anions, and cations. Inorganic nitrogen species (ammonia and nitrate + nitrite [NO_x]) were measured using an Ammonia Analyzer Model TL-2800 (Timberline, USA). Nitrite was measured using Standard Methods 4500. Cationic metals were measured by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES) at the University of South Florida Geochemistry Core facility. Sulfate was measured using a Hach Test 680, which was adapted from Standard Methods 4500E. Additional anions and cations were measured using a Metrohm 881 Compact IC Pro Systems (Metrohm, USA). Unfiltered samples were used to measure turbidity, TSS, and SDI_{15}. Turbidity was measured by Standard Methods 2130B using a Hach 2100Q Portable Turbidimeter. TSS was measured by Standard Methods 2540D. SDI_{15} was measured by ASTM Method D4189.

2.3. Model development

All four feed streams were modeled and evaluated with post-treatment consisting of UF and RO (Fig. 2). A water balance, based on 2020 rainfall precipitation and evapotranspiration data from the on-site weather station, was developed for a full-scaled CW system of approximately 47,300 m^2. The results showed that water gains/losses due to precipitation or evapotranspiration were expected to be negligible. Therefore, all four feed streams were modeled based on Hillsborough County's feed flow estimate of 757 m^3 per day (m^3/d) into the post-treatment systems.

Post-treatment systems (Fig. 3) were modeled using the DuPont™ WAVE design software. This software integrates both UF and RO into a single package, allows input of project-specific parameters with default values and design schematic recommendations, and allows design schematic modifications to be reflected throughout the combined system design. The software can create a comprehensive preliminary assessment of post-treatment design, including design warnings and O&M costs [37].

Initial modeling steps included defining the feed stream composition to accurately simulate the post-treatment design. All four feed streams were classified as wastewater. Water sub-types were suggested through solids content characterized through turbidity, TSS, and SDI_{15}. Detailed values of pH and ionic content were also required as inputs for an accurate RO design, with a subsequent charge balance adjustment where all ions were adjusted. Operating temperatures were set at default values at a minimum of 10 °C, a design value of 25 °C, and a maximum of 40 °C.

The initial UF design was set to default values except for module selection and configuration layout. The UF module that was chosen has 35 % higher permeability compared to older models, high effective membrane area (77 m^2), flow capacities >50 m^3/h, and is suitable for treating industrial wastewater. Recommended UF configurations consisted of the number of online trains, standby trains, maximum offline trains that would be backwashed/chemically enhanced backwashed through cleaning-in-place interventions, and number of modules per train. To standardized design, a common configuration across all four systems that contained the fewest online modules and the fewest overall number of modules was initially chosen. This common configuration consisted of 3 online trains, 0 standby trains, and 1 redundant train, with 6 modules per train.

Table 1
Feed stream and treated effluent characteristics for the three treatment alternatives.

Parameter	Raw landfill leachate	AS treated effluent	Control-CW effluent	Adsorbent-CW effluent
Turbidity (NTU)	86.3	42.3	2.87	1.58
TSS (mg/L)	118	94.5	30.3	24.2
SDI_{15} [a]	>6.67	>6.67	6.44	6.26
TDS [b] (mg/L)	14,000	12,600	12,700	11,900
LSI [c]	−4.03	−4.83	−4.02	−4.71
pH at 25 °C	7.61	6.95	7.83	7.30
BOD_5 (mg/L)	29.5	NM [d]	6.2	1.7
COD (mg/L)	482	NM [d]	373	273
Ca^{2+} (mg/L)	1930	1120	1050	669
Ba^{2+} (mg/L)	0.250	0.388	0.363	0.559
NH_4^+-N (mg/L)	367	4.55	144	46.5
K^+ (mg/L)	671	618	673	582
Na^+ (mg/L)	3290	3070	3410	3330
Mg^{2+} (mg/L)	640	276	466	281
CO_3^{2-} (mg/L) [e]	BDL [f]	BDL	BDL	BDL
HCO_3^- (mg/L)	BDL	BDL	BDL	BDL
NO_3^--N (mg/L)	BDL	251	79.5	176
Cl^- (mg/L)	6410	6000	6040	5810
F^- (mg/L)	BDL	BDL	BDL	BDL
SO_4^{2-} (mg/L)	137	121	104	128
PO_4^{3-} (mg/L)	3.84	BDL	BDL	BDL
Br^- (mg/L)	BDL	BDL	BDL	BDL

[a] $SDI_{15} > 6.67$ are a resultant that the total time required for 100 mL of sample to pass through the 0.45 μm filter exceeded 60 s, indicating >90 % pluggage and it is deemed that it is not necessary to continue the test [45].
[b] TDS concentrations were obtained from the WAVE software, based on the ionic balance of the feed stream composition.
[c] LSI was calculated based on pH at 25 °C, TDS concentration, Ca^{2+} concentration, HCO_3^- concentration (assumed to be 1 μg/L as its method detection limit), and temperature of 25 °C. LSI < 0 are indicative of water being undersaturated with respect to calcium carbonate and has a tendency to corrode.
[d] BOD_5 and COD for the AS treated effluent were not measured in this study.
[e] Sr^{2+}, SiO_2, B, and CO_2 are parameters that can be inputted into the WAVE software but were not measured in this study.
[f] BDL = below detection limit; NM = not measured.

The initial RO design consisted of 2 stages to increase water recovery. The RO element selected has high active area of 41 m^2, feed pressure of 70 bars, permeate flow rate of 34.2 m^3/d, minimum salt rejection rates of 99.25 %, and is suitable for handling industrial wastewaters with high electrical conductivity, such as raw landfill leachate. Typical number of elements per pressure vessel range from 6 to 8 for large-scale operations and can be reduced in subsequent stages [37]. The common RO configuration for this study consisted of 2 pressure vessels with 6 elements in the first stage and 2 pressure vessels with 4 elements in the second stage. An increase in the number of RO stages, number of pressure vessels per RO stage, and number of elements per pressure vessel were investigated but were deemed economically infeasible in terms of water recovery and costs compared to the determined common RO configuration. Pre-stage pressure drop and flow factors used were default values in the software, while stage back pressure in stage 1 and boost pressure in stage 2 were recommend values in the DuPont's Introduction to WAVE User Manual [37]. Cleaning-in-place interventions for the RO system were accounted for through literature review and manufacturer dose recommendations.

After initially modeling the four pre-treatment alternatives using a common UF-RO configuration, an optimized UF-RO treatment configuration was modeled for the two CW feed streams. Additional system water recovery was possible due to the higher water quality of the control-CW and adsorbent-CW feed streams. Optimization for both CW feed stream systems included decreasing the number of online UF modules due to the lower solids content compared to raw and AS treated landfill leachate (see Table 1). The RO design was optimized by: 1) Increasing the system recovery and 2) increasing the number of elements per pressure vessel in both stages to accommodate the software design warnings. These alterations of the common UF-RO treatment configuration allowed for an increase in feed flow rate and a slight increase in feed pressure to the RO component for an overall increase in UF-RO system recovery. Adding another pressure vessel to each RO stage and changing the number of elements per pressure vessel were analyzed but did not provide great additional economic and water recovery benefits. All other operating conditions remained the same as the common UF-RO treatment configuration.

2.4. Model simulations

Landfill leachate is characterized by a low biodegradability and high salinity (measured as electrical conductivity), COD, NH_4^+-N, and metals. The UF-RO treatment processes create very high quality permeate that are well below the Florida requirements for both non-food agricultural and industrial reuse, which include BOD_5, TSS, nitrate (NO_3^-), NH_4^+-N, TN, and electrical conductivity. Bypassing a portion of the feed water and blending it with the UF-RO treated effluent could meet all reuse requirements while lessening the hydraulic load on the UF-RO system and reducing costs. Therefore, a mass balance based on the most stringent reuse standard of electrical conductivity for industrial reuse of 1120 μS/cm was developed. Iterations were carried out in Microsoft Excel with the Excel Solver tool.

2.5. Alternative design modeling limitations

Although the WAVE software allows for input of project-specific parameters and system customization, it cannot represent every possible scenario. The software allows input of chemical additions to adjust the water stream chemical characterization. For UF, acid, oxidant and coagulants can be added. For RO, pH, CO_2 concentration, solubility of salts, and chlorine concentration can be adjusted. Barium sulfate ($BaSO_4$) scaling was a prominent RO solubility warning across all UF-RO modeling, which indicates a decrease in membrane permeability and an increase in energy requirements to allow for sufficient membrane flux to occur. Chemical adjustments were attempted, such as the addition of the antiscalant $Na_6P_6O_{18}$ and hydrochloric acid to avoid scaling; however, the chemical adjustments did not lower the saturation percentage of $BaSO_4$ to an acceptable value (<100 %). There was no flexibility to add another manufacturer's antiscalant into the software to accurately simulate a representative waste profile of the RO concentrate and system product profile of the RO permeate. Therefore, assumptions had to be made that the antiscalant addition from SUEZ did not chemically alter the RO products' profiles and that the RO system operating conditions, including membrane flux, did not change. It is noted that the DuPont software underpredicts solubility of salts, therefore a supersaturation error occurs; however, it can be taken as a conservative value for scaling potential [38].

2.6. Net present value analysis

A levelized cost approach was adopted using a net present value analysis, a landfill leachate flowrate of 757 m^3/day and a 20-year design life [39]. An assumed discount rate of 5 % was based on the requirements of the Hillsborough County Florida Water Enterprise Fund. Six scenarios were evaluated: four reuse alternatives (Fig. 2) and two non-reuse alternatives disposal of raw landfill leachate or adsorbent-CW treated effluent. Detailed unit cost estimates based on 2021 U.S. dollars (USD) for system components and materials and their respective references are summarized in Table S.1 in the Supplementary material.

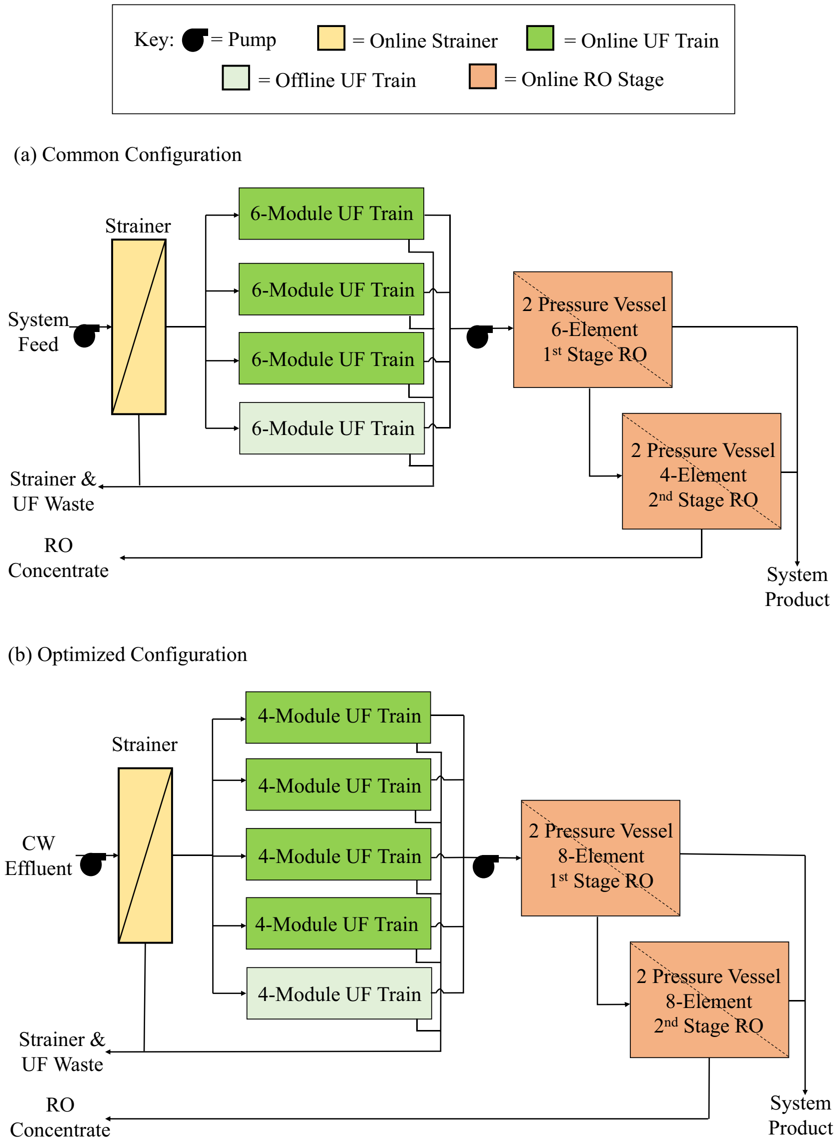

Fig. 4. UF-RO design configurations.

For this study, the disposal of waste streams for each alternative, raw landfill leachate or the treated effluent and RO concentrate, was separated into three categories: 1) Spray application on-site, which was approximated at 84.0 m^3/d [40], 2) disposal of 83.3 m^3/d via hauling to POTWs at a cost of USD $55.48 per m^3, and 3) remaining amount of treated effluent and RO concentrate disposal via hauling and solidification at a rate of USD $224.55 per m^3. Solidification would be performed by the contractor and includes transportation, solidification with absorbent stabilization, and disposal. For the UF-RO alternatives, a cash input was accounted for that includes industrial reuse water resale to a nearby power plant at a rate of USD $0.10 per m^3. Non-discounted payback periods for the CW alternatives were also calculated based on the initial capital deficit of the CWs and the UF-RO system with cost savings that were inclusive of the annual O&M differential between the raw landfill leachate to direct disposal alternative and the chosen alternative.

2.7. Net present value analysis assumptions

The net present value analysis for this study was done as a Class 4 estimate, which is based on limited information and can have wide variability in cost accuracy range. Therefore, the capital costs were accounted for with a 30 % contingency [41], as they were given as budgetary estimates (Table S1). The net present value analysis assumed that the construction period for the CWs and UF-RO system was within 1 year, capital costs contained a 30 % contingency, UF module replacement occurred every 2 years, RO element replacement occurred every 4 years, RO cleaning chemicals were to be used in a 30-minute cleaning cycle twice per year, and no decommissioning nor salvage costs were considered. Electrical requirements were provided by the WAVE software and RO antiscalant dosages were provided by the manufacturer.

The original research objective was to develop a post-treatment feasibility study of CW effluent; therefore, this analysis does not include the capital and O&M costs for the existing AS treatment system as well as the O&M costs for the CWs. Due to the exclusion of O&M costs for the existing AS treatment system, the alternative is considered to be an underestimate. O&M costs for CWs are also expected to be minimal as O&M is required periodically rather than requiring continuous on-site labor [5]. It was also assumed that the UF-RO design life is 20 years [39], but little research has been carried out on long-term RO treatment operation with landfill leachate beyond 10 years of operation [29,42].

Table 2
Feed water inflow and bypass quantities.

Alternative	Inflow quantity (m^3/d)	Bypass quantity (m^3/d)
Raw landfill leachate	741	16.2
AS treated landfill leachate	739	18.0
Control-CW	737	20.6
Control-CW optimized	740	16.9
Adsorbent-CW	733	24.6
Adsorbent-CW optimized	737	19.8

3. Results and discussion

3.1. Feed stream and treated effluent characteristics

Characteristics of the raw landfill leachate and treated effluents are summarized in Table 1. Additional details on CW performance can be found in Ergas and Arias [36]. Overall, both CW alternatives showcased the natural treatment processes that enhance the treatment of landfill leachate, such as microbial degradation, plant uptake, filtration, and sedimentation [7,43], which is reflected in the lower BOD_5, COD, SDI_{15}, TDS, TSS, and turbidity levels. Compared with the control-CW, the adsorbent-CW effluent had lower total inorganic nitrogen (NH_4^+-N + NO_x-N), SDI_{15}, TSS, and turbidity values due to the zeolite and biochar additions in the vertical-flow and horizontal-flow tanks, respectively. Zeolite enhances nitrification in intermittently operated vertical-flow CWs by adsorbing NH_4^+ during the wetting periods, which allows more time for nitrification in the unsaturated (i.e., aerobic) media during the dry periods between leachate applications [44]. Due to the higher nitrification rates and low bioavailability of organic carbon in the landfill leachate, effluent NO_3^- concentrations were higher in the adsorbent-CW. Biochar enhanced treatment by assisting in organic matter adsorption while improving wetland plant growth and rhizosphere microbial activity [15,17,19].

3.2. Modeling different UF-RO design alternatives

Details of the common and optimized UF-RO treatment configurations are presented in Fig. 4 and Table S2. Optimization allowed for the creation of two additional alternatives apart from the four standardized alternatives that were based on the common UF-RO treatment configuration. In addition, some feed water was able to bypass the UF-RO system due to the resulting high quality permeate with very low contaminant levels, especially electrical conductivity. The feed water inflow to the UF-RO system and bypass quantities of the six different alternatives are summarized in Table 2.

The control-CW and adsorbent-CW systems both had the potential to

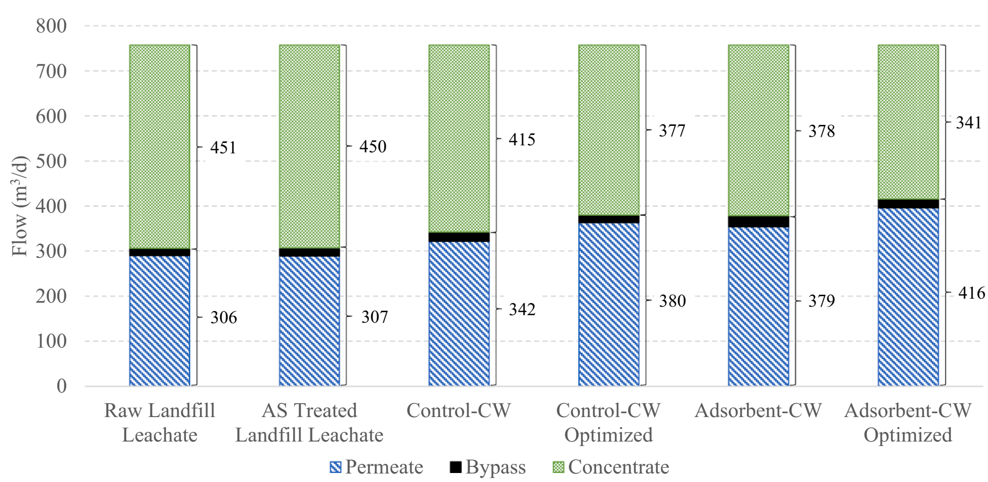

Fig. 5. UF-RO flow outputs for each alternative. Reclaimed water consists of the permeate and bypass flow streams. Concentrate consists of the strainer, UF, and RO wastes.

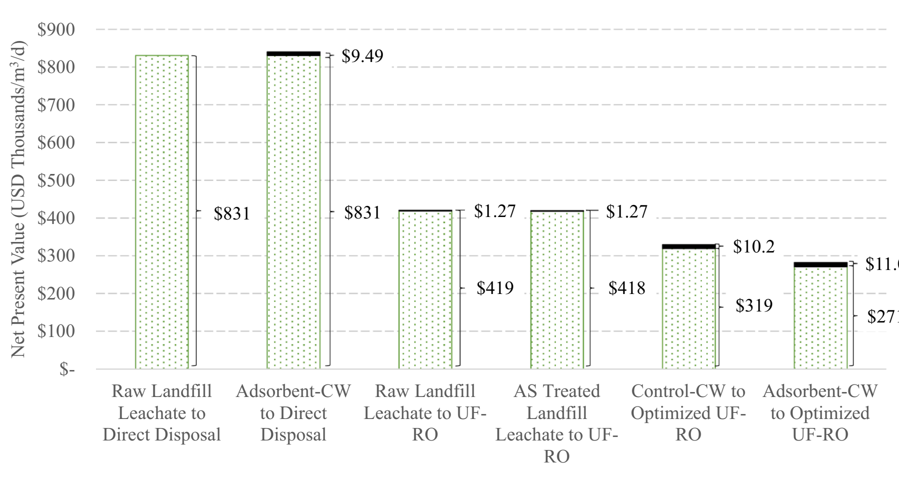

Fig. 6. Summary of net present values per m^3/d of leachate treated for various treatment alternatives.

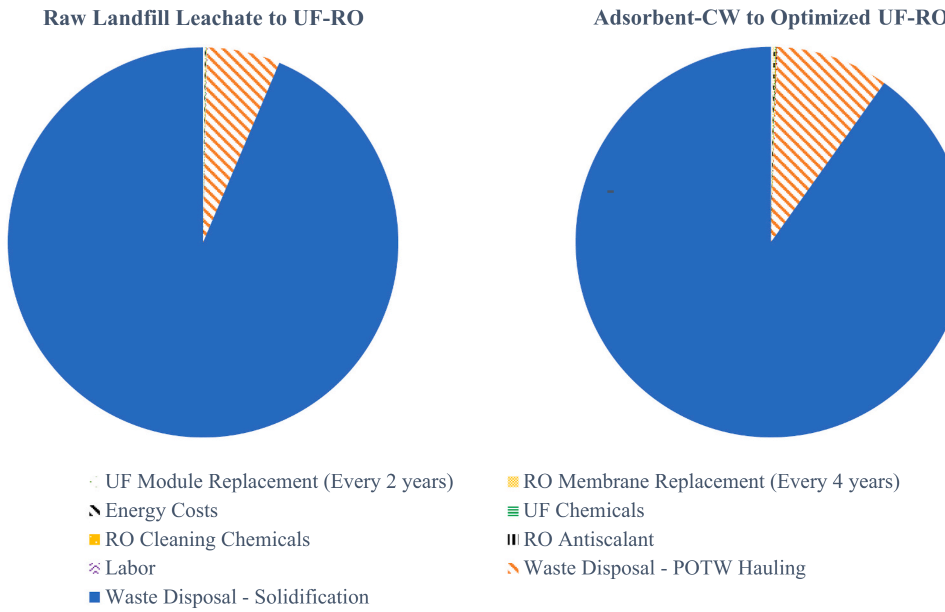

Fig. 7. Annual O&M cost breakdown for raw landfill leachate to UF-RO and adsorbent-CWs to optimized UF-RO alternatives.

generate more system product due to the higher water quality of the feed stream compared to the raw landfill leachate and AS treated landfill leachate feed streams (Fig. 5). Optimization for both CW feed stream systems included decreasing the number of online UF modules, increasing RO system recovery, and increasing the number of RO elements per pressure vessel in each stage. A reduction in the total number of UF modules also reduced capital and O&M costs. This optimization process overall generated a 12.9 % enhancement in system product for the control-CW system as it increased from 322 m^3/d to 363 m^3/d. For the adsorbent-CW system, the optimization process overall generated an 11.9 % enhancement in system product for the adsorbent-CW system as it increased from 354 m^3/d to 396 m^3/d.

3.3. Net present value analysis

The net present value analysis results per m^3/d of landfill leachate treated in 2021 USD for the study are presented in Fig. 6. The optimization of the control-CW to UF-RO system and of the adsorbent-enhanced system to UF-RO would lead to cost savings of USD $38.6 million and USD $37.9 million, respectively. The non-discounted payback period for the control-CW to optimized UF-RO system is 5.0 years, whereas the non-optimized alternative has a payback period of 5.4 years. The payback period for the adsorbent-CW to optimized UF-RO system is 4.9 years, whereas the non-optimized alternative has a payback period of 5.3 years. The optimization process reduced O&M costs, therefore reducing the payback periods and achieving an effluent that could meet reuse standards.

Across all alternatives, capital costs for constructing the on-site treatment systems are minimal compared to O&M costs (Fig. 6). The main cost drivers for all alternatives are disposal costs, which accounts for 99 % of the annual O&M costs (Fig. 7). Solidification is the largest contributor due to POTWs limiting the amount of landfill leachate that can be accepted into their facilities. In this case study, the amount of landfill leachate that was accepted by POTWs via the hauling contractor was 75.7 m^3/d, which is approximately 10 % of the landfill leachate treated. Therefore, on-site treatment of landfill leachate has the potential to provide great economic benefit while providing water recovery for reuse purposes. In addition to economic benefit, environmental benefits of on-site landfill leachate treatment include: reduction of human contact with untreated leachate, environmental risks caused by spills during transportation of leachate, and negative publicity. Other disposal alternatives were considered, such as deep well injection; however, due to the location of this case study, they were deemed not practical or economically feasible.

4. Conclusions

Due to the high salinity, color and high concentrations of NH_4^+-N, recalcitrant organic matter and metals in landfill leachate, it is in the best interest of POTWs and municipal solid waste managers for landfill leachate to be treated separately and preferably close to the source of generation. Membrane processes, such as UF and RO, have been used to treat high strength industrial wastewaters in the past; however, significant problems occur when wastewaters have high scaling and fouling potential. Hybrid vertical SSF to horizontal SSF CWs have been shown to be effective low-cost natural treatment systems for landfill leachate in the past. Our research shows that addition of low-cost adsorbent materials, zeolite and biochar, increases removal of total inorganic nitrogen, organic matter, and solids that are known to foul membranes, therefore providing an effective UF-RO pre-treatment alternative.

Due to more stringent regulations on POTW discharges, municipal solid waste managers are increasingly seeking alternatives for landfill leachate treatment and reuse. In this case study for Hillsborough County (Florida, USA), raw landfill leachate to direct disposal resulted in a net present value cost of USD $831,000 per m^3/d of landfill leachate treated. With treatment using adsorbent-enhanced CWs followed by an optimized UF-RO system, the net present value cost decreased to USD $282,000 per m^3/d of landfill leachate treated. The adsorbent-CW to UF-RO alternative is a promising option to reduce the amount of high strength landfill leachate that requires disposal via solidification. In addition, this option reduces the risk of potential leachate spills during transport and enhances the opportunity to beneficially reuse the water for industry and non-food irrigation. Implementation of these results with on-site leachate treatment facilities would be of economic and environmental benefit to Hillsborough County and other municipalities as it reduces the toxicity, flow, and risk of the industrial wastewater.

CRediT authorship contribution statement

Thanh Lam: Methodology, Formal analysis, Investigation, Writing –

original draft, Writing – review & editing, Visualization. **Xia Yang:** Investigation, Writing – review & editing, Visualization. **Sarina J. Ergas:** Conceptualization, Methodology, Resources, Writing – review & editing, Supervision, Funding acquisition. **Mauricio E. Arias:** Conceptualization, Methodology, Resources, Writing – review & editing, Project administration, Funding acquisition.

Declaration of competing interest

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Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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References

[1] S.C. Bolyard, B.F. Staley, State of practice of leachate management and treatment in the US, in: Sixteenth International Waste Management and Landfill Symposium, S. Margherita di Pula, Italy, 2017.
[2] S.C. Bolyard, B.F. Staley, State of practice of leachate management and treatment in the US, in: Global Waste Management Symposium, Indian Wells, California, 2018.
[3] S.C. Bolyard, A.M. Motlagh, D. Lozinski, D.R. Reinhart, Impact of organic matter from leachate discharged to wastewater treatment plants on effluent quality and UV disinfection, Waste Manag. 88 (2019) 257–267.
[4] USEPA, Constructed Treatment Wetlands, Office of Water, U.S. Environmental Protection Agency, Washington, DC, 2004.
[5] USEPA, Environmental Assessment for Final Effluent Limitations Guidelines and Standards for the Landfills Point Source Category, EPA-821-B-99-006, U.S. Environmental Protection Agency, Washington DC, 2000.
[6] USEPA, Wastewater Technology Fact Sheet Wetlands: Subsurface Flow, EPA/832/F/00/023, Office of Water, U.S. Environmental Protection Agency, Washington, DC, 2000.
[7] R.H. Kadlec, S.D. Wallace, Treatment Wetlands, CRC Press, Taylor & Francis Group, Boca Raton, Florida, 2009.
[8] J. Vymazal, Constructed wetlands for wastewater treatment: five decades of experience, Environ. Sci. Technol. 45 (2011) 61–69.
[9] N.E.C. Silvestrini, H.R. Hadad, M.A. Maine, G.C. Sánchez, M. del Carmen Pedro, S. E. Caffaratti, Vertical flow wetlands and hybrid systems for the treatment of landfill leachate, Environ. Sci. Pollut. Res. 26 (8) (2019) 8019–8027.
[10] H. Luo, Y. Zeng, Y. Cheng, D. He, X. Pan, Recent advances in municipal landfill leachate: a review focusing on its characteristics, treatment, and toxicity assessment, Sci. Total Environ. 703 (2020), 135468.
[11] A. Mojiri, Z. Ahmad, R.M. Tajuddin, M.F. Arshad, A. Gholami, Ammonia, phosphate, phenol, and copper(II) removal from aqueous solution by subsurface and surface flow constructed wetland, Environ. Monit. Assess. 189 (2017) 337.
[12] A. Yalcuk, A. Ugurlu, Comparison of horizontal and vertical constructed wetland systems for landfill leachate treatment, Bioresour.Technol. 100 (2009) 2521–2526.
[13] T.G. Bulc, Long term performance of a constructed wetland for landfill leachate treatment, Ecol. Eng. 26 (2006) 365–374.
[14] T. Saeed, M.J. Miah, N. Majed, M. Hasan, T. Khan, Pollutant removal from landfill leachate employing two-stage constructed wetland mesocosms: co-treatment with municipal sewage, Environ. Sci. Pollut. Res. 27 (2020) 28316–28332.
[15] P. De Rozari, M. Greenway, A. El Hanandeh, Nitrogen removal from sewage and septage in constructed wetland mesocosms using sand media amended with biochar, Ecol. Eng. 111 (2018) 1–10.
[16] B. Gao, X. Yang, E.A. Dasi, T. Lam, M.E. Arias, S.J. Ergas, Enhanced landfill leachate treatment in sequencing batch biofilm reactors (SBBRs) amended with zeolite and biochar, J. Chem. Technol. Biotechnol. 97 (3) (2021) 759–770.
[17] D. Mohan, A. Sarswat, Y.S. Ok, C.U. Pittman Jr., Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent – a critical review, Bioresour.Technol. 160 (2014) 191–202.
[18] K. Kasak, J. Truu, I. Ostonen, J. Sarjas, K. Oopkaup, P. Paiste, M. Koiv-Vainik, U. Mander, M. Truu, Biochar enhances plant growth and nutrient removal in horizontal subsurface flow constructed wetlands, Sci. Total Environ. 639 (2018) 67–74.
[19] C. Su, L. Zhao, L. Liao, J. Qin, Y. Lu, Q. Deng, M. Chen, Z. Huang, Application of biochar in a CIC reactor to relieve ammonia nitrogen stress and promote microbial community during food waste treatment, J. Clean. Prod. 209 (2019) 353–362.
[20] S.M.R. Joseph, P. Wijekoon, B. Dilsharan, N.D. Punchihewa, B.C.L. Athapattu, M. Vithanage, Anammox, biochar column and subsurface constructed wetland as an integrated system for treating municipal solid waste derived landfill leachate from an open dumpsite, Environ. Res. 189 (2020), 109880.
[21] H. Zheng, L. Han, M. Hongwen, Y. Zheng, H. Zhang, D. Liu, S. Liang, Adsorption characteristics of ammonium ion by zeolite 13X, J. Hazard. Mater. 158 (2008) 577–584.
[22] A. Amini, V. Aponte-Morales, M. Wang, M. Dilbeck, O. Lahav, Q. Zhang, J. A. Cunningham, S.J. Ergas, Cost-effective treatment of swine wastes through recovery of energy and nutrients, Waste Manag. 69 (2017) 508–517.
[23] V.E. Aponte-Morales, K.A. Payne, J.A. Cunningham, S.J. Ergas, Bioregeneration of chabazite during nitrification of centrate from anaerobically digested livestock waste: experimental and modeling studies, Environ. Sci. Technol. 52 (7) (2018) 4090–4098.
[24] V.E. Aponte-Morales, S. Tong, S.J. Ergas, Nitrogen removal from anaerobically digested swine waste centrate using a laboratory-scale chabazite-sequencing batch reactor, Environ. Eng. Serv. 33 (2016) 5.
[25] L. Guerrero, S. Montalvo, C. Huiliñir, A. Barahona, R. Borja, A. Cortés, Simultaneous nitrification-denitrification of wastewater: effect of zeolite as a support in sequential batch reactor with step-feed strategy, Int. J. Environ. Sci. Technol. 13 (2016) 2325–2338.
[26] T.H. Martins, T.S.O. Souza, E. Foresti, Ammonium removal from landfill leachate by Clinoptilolite adsorption followed by bioregeneration, J. Environ. Chem. Eng. 5 (2017) 63–68.
[27] M. Šír, M. Podhola, T. Patočka, Z. Honzajková, P. Kocurek, M. Kubal, M. Kuraš, The effect of humic acids on the reverse osmosis treatment of hazardous landfill leachate, J. Hazard. Mater. 207–208 (2012) 86–89.
[28] C.K. Chen, S.L. Lo, T.Y. Chen, Regeneration and reuse of leachate from a municipal solid waste landfill, J. Environ. Biol. 35 (2014) 1123–1129.
[29] T.A. Peters, Purification of landfill leachate with reverse osmosis and nanofiltration, Desalination 119 (1998) 289–293.
[30] D. Squire, J. Murrer, P. Holden, C. Fitzpatrick, Disposal of reverse osmosis membrane concentrate, Desalination 108 (1996) 143–147.
[31] J. Kucera, Reverse Osmosis: Industrial Application and Processes, John Wiley & Sons and Scrivener Publishing LLC, New Jersey and Salem, 2010.
[32] X.F. Huang, J. Ling, J.C. Xu, Y. Feng, G.M. Li, Advanced treatment of wastewater from an iron and steel enterprise by a constructed wetland/ultrafiltration/reverse osmosis process, Desalination 269 (1–3) (2011) 41–49.
[33] A.C. Syzdek, R.C. Ahlert, Separation of landfill leachate with polymeric ultrafiltration membranes, J. Hazard. Mater. 9 (1984) 209–220.
[34] A.A. Abbas, G. Jingsong, L.Z. Ping, P.Y. Ya, S.A. Wisaam, Review on landfill leachate treatments, J. Appl. Sci. Res. 5 (5) (2009) 534–545.
[35] P. Klomjek, S. Nitisoravut, Constructed treatment wetland: a study of eight plant species under saline conditions, Chemosphere 58 (5) (2005) 585–593.
[36] S.J. Ergas, M. Arias, Cost-Effective Hybrid Constructed Wetlands for Landfill Leachate Reclamation Final Report, Hinkley Center for Solid and Hazardous Waste Management, 2021. http://constructed-wetlands.eng.usf.edu/reports/Ergas-Arias-USF%20Leachate%20Wetlands%20Treatment%20final%20report%20revision%201.pdf.
[37] DuPont Water Solutions, Introduction to WAVE, DuPont de Nemours Inc., 2021. https://www.dupont.com/Wave/Default.htm. (Accessed 8 September 2021).
[38] S.F.E. Boerlage, M.D. Kennedy, I. Bremere, G.J. Witkamp, J.P. Van der Hoek, J. C. Schippers, The scaling potential of barium sulphates in reverse osmosis systems, J. Membr. Sci. 197 (2002) 251–268.
[39] R.V. Linares, Z. Li, V. Yangali-Quintanilla, N. Ghaffour, G. Amy, T. Leiknes, J. S. Vrouwenvelder, Life cycle cost of a hybrid forward osmosis – low pressure reverse osmosis system for seawater desalination and wastewater recovery, Water Res. 88 (2016) 225–234.
[40] Hillsborough County Solid Waste Management Division, Southeast County Landfill – Leachate Data Quarterly Report, 2021. http://prodenv.dep.state.fl.us/DepStaging/api/dms/8.320367.1.
[41] AACE, AACE International Recommended Practice No. 18R-97: Cost Estimate Classification System – As Applied in Engineering, Procurement, and Construction for the Process Industries, 2005. https://www.costengineering.eu/Downloads/articles/AACE_CLASSIFICATION_SYSTEM.pdf.
[42] W. Rukapan, B. Khananthai, C. Chiemchaisri, W. Chiemchaisri, T. Srisukphun, Short- and long-term fouling characteristics of reverse osmosis membrane at full scale leachate treatment plant, Water Sci. Technol. 65 (1) (2012) 127–134.

[43] C. Witthayaphirom, C. Chiemchaisri, W. Chiemchaisri, Optimization of reactive media for removing organic micro-pollutants in constructed wetland treating municipal landfill leachate, Environ. Sci. Pollut. Res. 27 (2020) 24627–24638.
[44] L. Rodriguez-Gonzalez, A. Miriyala, M. Rice, D. Delgado, J. Marshall, M. Henderson, S.J. Ergas, A pilot-scale hybrid adsorption–biological treatment system for nitrogen removal in onsite wastewater treatment, J. Sustain. Water Built Environ. 6 (1) (2020), 04019014.
[45] Nitto, Technical Service Bulletin: Procedure for Measuring Silt Density Index (SDI), 2013. https://membranes.com/docs/tsb/TSB113.pdf.