COST-EFFECTIVE HYBRID CONSTRUCTED WETLANDS FOR LANDFILL LEACHATE RECLAMATION

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ABSTRACT

The dominant landfill leachate management method in Florida is discharge to municipal wastewater treatment plants. However, high concentrations of recalcitrant organic compounds, ammonia and metals in leachate interfere with wastewater treatment processes. Prior studies have shown that sub-surface flow hybrid constructed wetlands (CWs) that combine vertical flow (VF) and horizontal flow (HF) are a cost-effective method for onsite landfill leachate treatment; however, information is limited on the ability of these system to meet reclaim standards for irrigation, industrial, aquifer recharge, surface water augmentation or direct and indirect potable reuse. Recent work by our lab and others suggests that hybrid CW performance can be enhanced by amending the media with low cost adsorbents such as zeolite and biochar. These materials adsorb contaminants such as ammonia and recalcitrant organic compounds, reducing their toxicity to microbes and enhancing biological activity of wetland plants and microbial communities. The goal of this project is to develop cost-effective hybrid CWs for onsite leachate treatment. The specific objectives are to: (1) Compare conventional and adsobent amended hybrid CW performance for landfill leachate treatment; (2) Develop a numerical process model that can be used to predict the performance of the of the hybrid CWs under varying operational and leachate characteristics; and (3) Carry out a preliminary evalutation of post-treatment requirements for reuse applications. Side-by-side pilot scale hybrid CW systems will be operated at Hillsborough County's Southeast landfill for ~ 6 months. Experiments will be set up to compare adsorbent amended hybrid CWs with conventional controls. Additional experiments will be carried out to evaluate an adsorbent amended CW as post-treatment for a conventional biological nutrient removal activated sludge process. A numerical process model will be developed and used to predict the performance of the hybrid CWs under varying operational and leachate characteristics. Post-treatment technologies required for reuse applications (e.g., irrigation, industrial and potable reuse) will be identified and assessed.

INTRODUCTION

In the US, there are > 1,900 active landfills, accepting > 250 million tons of municipal solid waste (USEPA, 2014). Leachate, the liquid that percolates through landfills, must be properly collected and treated to prevent ground and surface water contamination (USEPA, 2000). The most widely used leachate treatment method is discharge to publicly owned treatment works (POTWs). However, high concentrations of total ammonia nitrogen (TAN), chemical oxygen demand (COD), refractory organic matter and metals in leachate interfere with physical, chemical and biological processes at POTWs (Zhao et al. 2012). Onsite leachate treatment systems include landfill recirculation, evaporation, aerated lagoons, and conventional activated sludge processes. Physical and chemical processes, such as filtration, flocculation, ion exchange (IX) and granular activated carbon adsorption have also been used to enhance leachate treatment (USEPA, 2000). Sub-surface flow (SSF) hybrid constructed wetlands (CWs) that combine vertical flow (VF) and horizontal flow (HF) systems are a cost-effective method for onsite landfill leachate treatment (Kadlec, R.H., Wallace, S., 2008; Vymazal and Kröpfelová, 2009). Although effluents from CWs used for domestic wastewater have been reclaimed for irrigation and industrial reuse applications (*e.g.*, Lakeland, FL Se7en CW provides water for TECO's Polk Power Station), there is limited information on reuse of CW treated landfill leachate.

The overall goal of this project is to develop cost-effective hybrid CWs for treatment of landfill leachate for reuse applications. Our research group has recently carried out studies of hybrid adsorption biological treatment systems that use low cost materials with high adsorption capacity such as zeolite (Aponte-Morales et al., 2018) and biochar (Rahman et al., 2019). These materials enhance biological treatment by reducing the toxicity of wastewater and retaining pollutants. In the proposed study, pilot-scale hybrid CWs will be amended with zeolite and biochar to enhance biological treatment of landfill leachate. Post-treatment requirements will be evaluated for various reuse applications (*e.g.*, agricultural and residential irrigation, industrial reuse, aquifer recharge, surface water augmentation and direct and indirect potable reuse). The proposed project addresses the following Hinkley research agenda items:

(1) The treatment of landfill leachate is a big issue both economically and environmentally for most landfills and wastewater treatment plants. As a means of creating an onsite cost-effective long-term treatment process, what innovative technologies are available to engineer wetlands capable of treating landfill leachate?
(2) What cost-effective pretreatment processes should the leachate undergo to meet secondary drinking water standards? In the design of the wetlands or in the pretreatment process, what plants are best suited to treat the leachate?
(3) Landfill leachate causes problems at wastewater treatment plants due to high levels of humic acids. There is a need for landfill leachate pretreatment processes, which remove humic acids and is effective, affordable, and applicable. What processes, chemicals, or plants are best suited to mitigate the negative impact of humic acids as a pretreatment process at a landfill?

The guiding hypotheses of the proposed project are:

(1) Addition of zeolite, a natural mineral with a high NH_4^+ affinity, to VF-CW media reduces free ammonia toxicity to microorganisms and enhances biological nitrogen removal.
(2) Addition of biochar, a low-cost material produced from organic feedstocks such as wood chips, to HF-CW media enhances plant growth and retains recalcitrant organic matter, such as humic acids, to enhance its heterotrophic biodegradation.
(3) Adsorbent amended hybrid CWs can provide a cost-effective and low complexity landfill leachate treatment method compared with conventional onsite leachate treatment systems.

Specific objectives of the proposed project are to:
(1) Compare conventional and adsobent amended hybrid CW performance for landfill leachate treatment;
(2) Develop a numerical process model that can be used to predict the performance of the of the hybrid CWs under varying operational and leachate characteristics; and
(3) Carry out a preliminary assessment of post-treatment requirements for reuse applications.

LITERATURE REVIEW

Constructed Wetlands

CWs are used to treat wastewater through physical, chemical and biological processes, while also providing habitat for plants and animals and greenspace for recreation (Sun and Austin, 2007; Vymazal and Kröpfelová, 2009). CWs have been used in a variety of high strength polluted waters, including industrial wastewater, acid mine drainage, and swine production wastewater (Kadlec and Wallace, 2008). When compared to other leachate treatment technologies, CW offer a number of key advantages. First, they provide an alternative for onsite treatment, as full scale systems with documented performance are in the range 2-9 acres (Kadlec and Zmarthie, 2010; Sim et al., 2013). In addition to pollutant removal, CWs reduce leachate volume due to vegetation transpiration at a rate up to 9mm per day in tropical climates (Ogata et al., (2015). Moreover, CWs commonly have low operations and maintenance (O&M) requirements, as well as lower energy consumption compared with other treatment technologies (Arias and Brown, 2009).

CWs have been shown to remove a number of pollutants commonly found in leachate, including organic compounds, nitrogen compounds and trace metals (Table 1). There are several documented examples from tropical countries including Singapore, Thailand, and Malaysia (Akinbile et al., 2012; Ogata et al., 2018; Sim et al., 2013), where year-round warm temperatures favor vegetation growth and biogeochemical processes that promote good CW performance. The use of CWs for conventional wastewater treatment is a well-established practice in Florida, where lowland topography, warm climate, and abundant rainfall provide ideal conditions for wetlands. There is also some experience with CWs for leachate treatment in Florida, starting with the establishment of the CWs in the Perdido Landfill in Escambia County in the 1990s.

Table 1: Summary of leachate treatment performance with subsurface flow wetlands.

Pollutant type	**Inflow concentration (mg/L)**	**Percent removal**	**System type**	**Source**
TN	211	40-84%	Horizontal Flow (HF)	Sim et al. (2013); Vymazal and Kröpfelová (2009)
TAN	162	40%	HF	Vymazal and Kröpfelová (2009)
TAN	122	37-67%	Vertical Flow (VF)	Yalcuk and Ugurlu (2009)
TAN	122	30-49%	HF	Yalcuk and Ugurlu (2009)
Organic N	18.8	47%	HF	Vymazal and Kröpfelová (2009)
TKN	48.8	56	HF	Vymazal and Kröpfelová (2009)
NOx	15.8	19	HF	Vymazal and Kröpfelová (2009)
COD	212	13-36	VF	Yalcuk and Ugurlu (2009)
COD	212	11-61	HF	Yalcuk and Ugurlu (2009)
BOD		47	HF	Sim et al. (2013)
PO_4^{3-}-P		37-67	HF	Yalcuk and Ugurlu (2009)
TSS		57	HF	Sim et al. (2013)

Design Considerations for Constructed Wetlands Treating Landfill Leachate

There is no comprehensive design manual for CWs for leachate treatment (Kadlec and Zmarthie, 2010). Design must be site specific due to the highly variable flow rates and composition of landfill leachate, which depends on waste composition, landfill design and operation, moisture content, oxygen availability, climate and landfill age. However, a number of general considerations related to flow type, soil substrate and pre-treatment requirements are provided in the more general *Treatment Wetlands* design handbook (Kadlec and Wallace, 2008) as well as the scientific literature.

CWs can be classified into free water surface (FWS) or SSF systems. FWS are commonly used as polishing units, analogous to stabilization ponds, whereas SSF provide excellent Biochemical Oxygen Demand (BOD) and TSS removal. SSF CWs can be designed as horizontal flow (HF) and vertical flow (VF) systems. The VF-CW configuration promotes oxygenation of the soil substrate and nitrification while HF-CWs are particularly good at promoting treatment of phosphorus and total suspended solids (TSS). In practice, leachate treatment systems often use CW cells in series with different flow types to enhance pollutant removal (often referred to as "hybrid CWs"). In particular, VF-CWs are often used prior to HF-CWs to promote nitrification-denitrification for conversion of Total Nitrogen (TN) to nitrogen gas (N_2; Sun and Austin, 2007).

Soil substrate is another important consideration for CW performance. SSF-CWs require a substrate with very high hydraulic conductivity (e.g., gravel) to avoid short-circuiting and clogging. HF-CWs used for leachate treatment are highly vulnerable to clogging due to iron precipitation (Nivala et al., 2007). This issue has been addressed by pretreatment using sedimentation and aeration (Nivala et al., 2007). VF-CWs also require a medium with a high hydraulic conductivity (e.g., sand or gravel) but these systems are not as vulnerable to clogging.

The scientific literature highlights other issues that need to be considered in the design and maintenance of CWs for leachate treatment. Because leachate inflow is highly dependent on rainfall and regulated by evapotranspiration, storage during rainfall events and hydrologic monitoring are also important considerations (Kadlec and Zmarthie, 2010).

Use of Natural Zeolites to Enhance Biological Treatment Processes

The high TAN concentrations present in landfill leachate (300-2000 mg/L) are problematic for conventional biological nitrogen removal (BNR) processes. High free ammonia (NH_3) concentrations promote an imbalance in intracellular and extracellular pH of bacteria, affecting the proton motive force and inhibiting many energy-requiring functions of the cell (Martinelle et al., 1996). High TAN concentrations can also be detrimental to vegetation in CWs (Kadlec and Zmarthie, 2010). To control this issue, two-stage CWs with recirculation of treated effluent have been used to dilute the strength of the leachate being treated (Camaño Silvestrini et al., 2019).

Natural zeolites are porous aluminosilicate minerals with high IX capacities and selectivity for NH_4^+ (Hedström, 2001). They have been used to remove TAN from swine wastewater (Amini et al., 2017) and landfill leachate (Kargi & Pamukoglu, 2004). Clinoptilolite is the most commonly used zeolite due to its low cost; however, chabazite has a higher NH_4^+ capacity (Amini et al., 2017). In prior studies in our

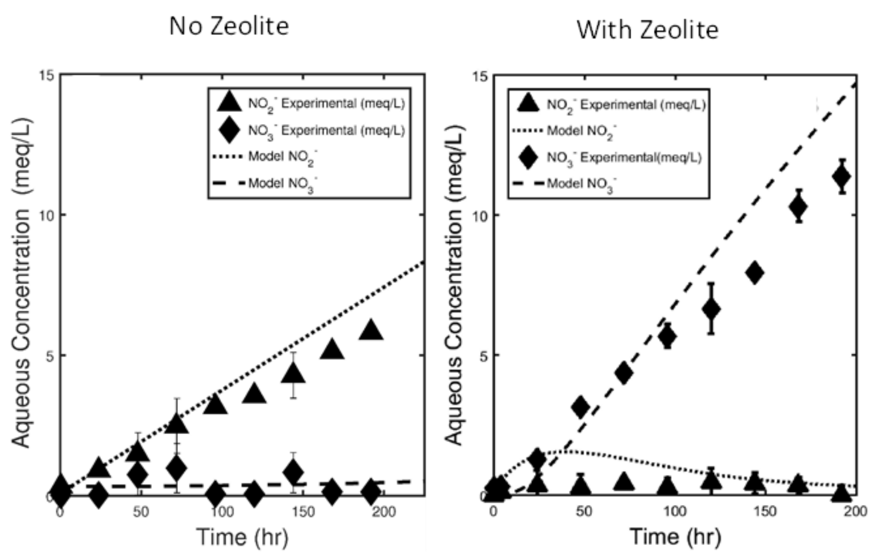

Figure 1: Aqueous NO_3^- concentration in batch reactors without and with chabazite amendment.

laboratory, natural zeolite materials have been used to enhance nitrogen removal by temporarily adsorbing NH_4^+, which reduces shock loads to sensitive microbial populations. Zeolite amended sequencing batch reactors (SBRs) were used for treatment of centrate produced from anaerobic digestion of swine manure (Aponte-Morales et al. 2016). Zeolite addition consistently reduced the free ammonia concentration to below the inhibitory levels, resulting in a doubling of the nitrification rate (Figure 1; Aponte-Morales et al., 2018). Importantly, the zeolite materials were bioregenerated, eliminating the need for chemical addition or production of waste brines.

Several studies have investigated zeolite treatment of landfill leachate (Kargi and Pamukoglu, 2004; Luna et al., 2007). ZELIC, which consists of zeolite, GAC, limestone, rice husk ash and Portland cement has been used for co-treatment of landfill leachate and domestic wastewater, with high removal efficiencies of color, TAN, and COD (Mojiri et al., 2014). Yalcuk and Ugurlu (2009) compared the performance of VF-CWs with and without zeolite addition for treatment of aged leachate from a landfill in Ankara Turkey. Better TAN removal was observed in the CW system with zeolite than without; however, the use of a hybrid CW system was not investigated in this study. PI Ergas is currently collaborating with researchers at Michigan State University who are investigating zeolite addition to hybrid CWs for onsite treatment of high-strength winery wastewaters under cold climate conditions.

Use of Biochar to Enhance Biological Treatment Processes

Biochar is a low-cost material produced by pyrolysis of organic feedstocks, such as wood chips, at high temperature under oxygen limiting conditions. In agriculture, biochar is used as an amendment to improve the quality of soils (Chan et al., 2007; Lehmann et al., 2011; Xu et al., 2012). Previous studies have shown that biochar addition to soil increases the surface area, surface charge, moisture holding capacity, and soil fertility and attracts beneficial fungi and microbes that enhance plant growth (Mohanty et al., 2014; Lehmann, 2007; Lehmann et al., 2006). Currently our research group is investigating the addition of biochar to bioretention cells for treatment of dairy farm runoff. In side-by-side bench-scale column studies, biochar amended columns (10% biochar by mass) achieved significantly higher TN and fecal indicator bacteria (FIB) removals than an unamended column (Rahman et al., 2019).

Due to its unique micro-physicochemical properties, such as high surface area, porous structure and various functional groups, biochar has a high adsorption capacity for nutrients and inorganic metals (Lau et al. 2017; Liang et al. 2006; Hale et al. 2012). Shehzad et al. (2016) showed that biochar could remove organic and inorganic pollutants from landfill leachate, with the highest adsorptive removal for color (95.1%), COD (84.94%), and TAN (95.77%). Paranavithana et al., (2016) showed that biochar addition could increase heavy metal adsorption, with an adsorption capacity of 30.1 mmol/g for Cd^{2+} and 44.8-46.7 mmol/g for Pb^{2+}. Similar results were also obtained when biochar was mixed into the substrate of CWs, showing effective toxic metal immobilization (Zhang et al., 2013; Cao et al., 2009).

The effect of biochar addition on organic pollutant removal in CWs treating domestic wastewater has been studied by several researchers. Zhou et al. (2017) showed that adding biochar to VF-CWs could be an effective strategy for low C/N wastewater treatment, resulting in high removal of COD (94.9%), TAN (99.1%), and TN (52.7%). Rozari et al. (2015) showed that sand amended with varying proportions of biochar in VF-CWs were effective in removing BOD_5, TSS, and volatile suspended solids (VSS). Kasak et al. (2018) also showed that biochar addition increased TN and TP removal (20% for TN and 22.5% for TP) in HF-CWs treating municipal wastewater and also enhanced plant biomass growth. Gupta et al. (2016) and Gao et al. (2019)

found that biochar was a valuable SSF CW amendment in HF-CWs, with more efficient removal of COD, TN, and TP. Because the recalcitrant organic matter and metals in leachate, the addition of biochar to HF-CWs treating landfill leachate is a promising strategy. However, no prior literature was found on the use of biochar in CWs treating landfill leachate.

RESEARCH APPROACH

Hybrid CWs are low cost, low complexity, treatment technologies that have been successfully used for treatment of landfill leachate. However, they have not been previously shown to produce water that can meet Florida's water reuse standards. The use of adsorbent materials, such as zeolite and biochar, has been shown to enhance biological treatment of nutrients and recalcitrant organic compounds. The proposed project will compare adsorbent amended hybrid CWs for treatment of landfill leachate with control hybrid CWs that utilize lightweight expanded clay aggregate (LECA) medium (Silvestrini et al., 2019), develop a numerical process model of the hybrid CWs that can be used for scale up, and perform a preliminary assessment of post-treatment requirements for various reuse applications.

Hillsborough County Southeast Landfill

The study will be conducted at the Southeast Landfill in Hillsborough County, approximately 40 miles southeast of the USF campus (see letter of support). The landfill was built in 1984 on portions of a phosphate mine. The landfill currently includes a Class 1 landfill, waste tire processing facility, yard waste and biosolids composting facility and a leachate treatment facility. A portion of the leachate is treated onsite using a conventional activated sludge system that includes an aerobic zone for nitrification followed by an anoxic zone with glycerol addition for denitrification. Additional leachate and effluent from the treatment system is hauled to a county POTW. Pilot CWs will be located in a containment area adjacent to the leachate treatment facility, which will allow access to both raw and treated leachate (Table 2). County MSW management staff have indicated that they are highly interested in the potential to implement the results from this study in wetlands adjacent to the landfill. Operations staff are enthusiastic about collaborating with us on this project, will monitor systems on days when USF students are not present at the facility and will allow access their laboratory for sample processing.

Table 2: Southeast Hillsborough County untreated and treated leachate characteristics (data from FDEP reports provided by Hillsborough County 2015-2018).

Parameter		Units	Untreated Leachate	Treated Leachate
pH		mg/L	6.0-7.5	7.2-8.2
Conductivity		umhos/cm	19,100-43,400	14,200-16,200
COD		mg/L	450-1000	600-2000
BOD$_5$		mg/L	10-35	2-44
Ammonia		mg/L	300-540	NP
Metals	Antimony	µg/L	40-430	3
	Arsenic	µg/L	8-80	7
	Barium	µg/L	50-1300	57
	Copper	µg/L	30-190	12
	Lead	µgL	15-160	0.52
	Zinc	µg/L	40-100	21

NP = data not provided. Ammonia concentrations were not required for FDEP reports since wastewater is discharged to a POTW with BNR. We will carry out a more detailed analysis of treated effluent quality before the start of this project.

Adsorption Isotherms

Isotherm studies for NH_4^+ removal by clinoptilolite and soluble COD and UV254 removal by biochar will be carried out using previously developed protocols (Aponte-Morales et al., 2016; Kasak et al., 2018). Data from these studies will be used to determine the required clinoptilolite and biochar fractions for the pilot CWs. Clinoptilolite will be obtained from St. Cloud Mining Company (Winston, NM). Currently our laboratory is working with two different biochar materials produced via slow pyrolysis kilns from commercial vendors (Table 3; Biochar #1: Biochar Now, Loveland, CO, Biochar #2: Biochar Supreme, Everson, WA). Feedstock for biochar #1 is virgin wood waste from sustainably-managed forests. Feedstock for biochar #2 is untreated wood debris. Data from these experiments will be fit to adsorption isotherm models. Results from a preliminary study of clinoptilolite adsorption of TAN using leachate collected from the Hillsborough County Southeast Landfill is shown in Figure 2.

Table 3: Characteristics of commercial biochars.

Parameter	**Biochar #1**	**Biochar #2**	**Method**
Organic carbon (%)	80.1	81.7	Manufacturer
Nitrogen (%)	0.4	0.32	Manufacturer
Ash (%)	5.8	1.2	Manufacturer
pH	10.1	8.5	*Standard Methods* 4500-H B
Conductivity (mmhos/cm)	414	310	*Standard Methods* 2510 B
Uniformity Coefficient	3.3	2.9	ASTM D6913/D6913M–17
Coefficient of Curvature	1.15	1.4	ASTM D6913/D6913M–17
Mesopores (cc/g)	0.152	0.062	Barrett, Joyner Halenda (BJH)
Micropores (cc/g)	0.189	0.0614	Horvath-Kawazoe (HK)
Surface Area m^2/g	537	136	Brunauer-Emmett-Teller (BET)
Cation Exchange Cap. (cmol/kg)	10.6	13.6	Ammonium Acetate Method

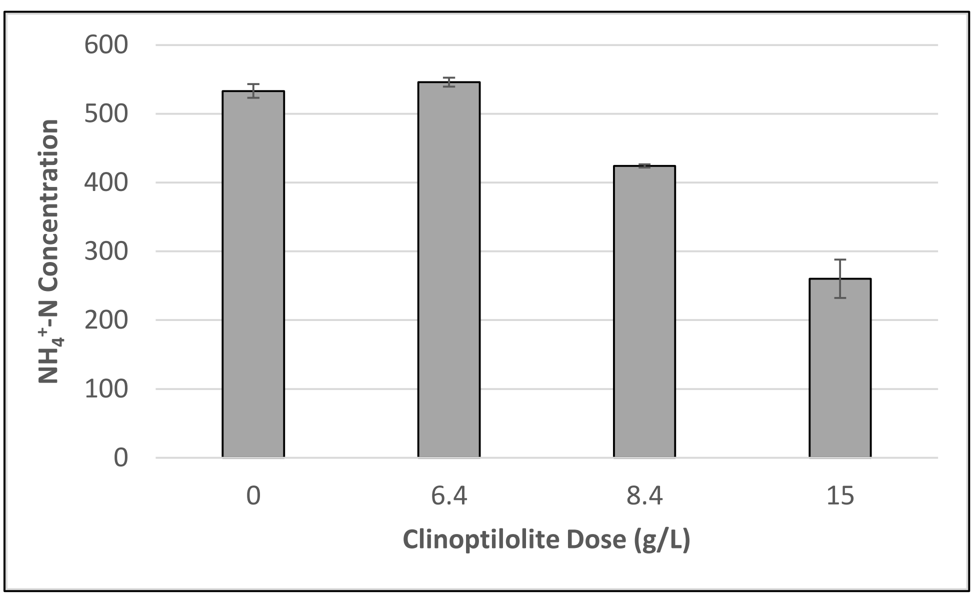

Figure 2: Preliminary adsorption studies of ammonia in landfill leachate by clinoptilolite.

Continuous Hybrid CW Studies

Three pilot-scale hybrid CWs systems will be set up at the Southeast Hillsborough County landfill (Table 4). A schematic of the study design is shown in Figure 3. Comparison of CW#1 and CW#2 investigates the role of adsorbent materials in leachate treatment. Comparison of CW2 and CW#3 evaluates the use of adsorbent amended hybrid CWs for full strength leachate treatment or as a post-treatment alternative for conventional BNR treatment. Pilot-scale hybrid CWs will consist of a VF CW (~150 L) followed by a HF CW (~250 L) (Figure 4). We will work with Hinkley Researcher, Ashley Danley-Thomson to identify and procure appropriate low cost, low maintenance, leachate tolerant plants for the pilot systems. Systems will be operated with raw or pre-treated landfill leachate with intermittent loading over a six month period. We will initially use previously published design operational parameters (e.g., aspect ratio, depth, hydraulic loading rate, cycle time; e.g., Bulc, 2006) but will adjust the parameters as systems acclimate and data is acquired and analyzed.

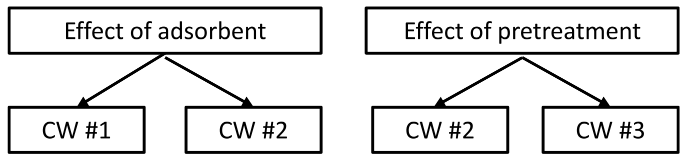

Figure 3: Study design.

Table 4: Media and influent for pilot-scale CWs.

Wetland	**V-CW medium**	**HF-CW medium**	**Feed**
CW#1	LECA	LECA	Raw leachate
CW#2	LECA + clinoptilolite	LECA + biochar	Raw leachate
CW#3	LECA + clinoptilolite	LECA + biochar	Pre-treated leachate

LECA= lightweight expanded clay aggregate

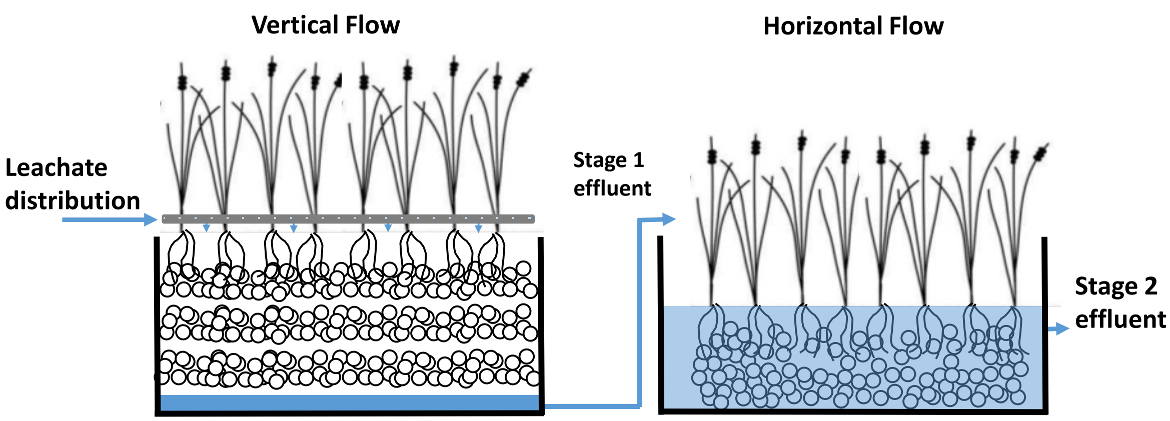

Figure 4: Pilot system schematic (not to scale).

Analytical Methods

Samples will be collected from the influent, stage 1 effluent, and stage 2 effluent weekly until the systems stabilize and then biweekly thereafter. *Standard Methods* (APHA, 2012) will be used to measure total and volatile suspended solids (TSS/VSS 2540), pH (4500-H), alkalinity (2320), conductivity (2510), TN (4500-C) and TP (4500-E). Anion (NO_2^-, NO_3^-, SO_4^{2-}, PO_4^{3-}) and cation (NH_4^+, Na^+, K^+, Mg^{2+}, Ca^{2+}) concentrations will be measured ion chromatography. Metals analysis will performed periodically by ICP-OES at USF's geosciences core laboratory facility. Organic matter characterization will include measurements of BOD5 (5210B), sCOD (5220), UV254 (5910B). Full wavelength scans (200 nm-800 nm) using a UV/Vis Spectrophotometer (Easton, MD) will be carried out periodically.

Monitoring and Modeling

The Pilot CWs will be instrumented with logging sensors to measure and record water levels, temperature and conductivity at hourly time steps for the entire length of the study. These sensors will be used to monitor changes in the quality of inflow leachate, to accurately estimate the performance of the CWs and hydraulic conditions (loading, retention time, and head), and to detect clogging in the event this becomes an issue in the cells. Moreover, temperature and conductivity data will be used in conjunction with the leachate characterization data to understand biological activity and fate of minerals through the CWs. Each cell will be instrumented with one water level logger and 2 sets of temperature and conductivity loggers at the inlet and outlet. Instruments will be serviced and data downloaded monthly.

The high frequency level, temperature, conductivity monitoring data will be combined with leachate characterization analysis to develop a numerical process model of the CW performance, in particular for nitrogen and organic carbon. The objective of this model is to predict the daily and long term performance of the systems under varying operational, media and leachate characteristics. As a secondary objective, this model could also be used to characterize the design parameters of a full-scale CW assuming similar leachate and environmental conditions as observed during the pilot study. Process-based modeling and design tools have been well documented for CWs (Kadlec and Wallace, 2008), and recent investigations have characterized models for specific treatment of leachate in humid environments (Cancelli et al., 2019).

The proposed model will be based on a mass balance of water, carbon, and nitrogen and first-order removal kinetics on each of the CW cells. The water balance equation will drive the storage of water through the system:

$$\frac{\Delta V}{\Delta t} = Q_i - Q_o + (PxA) - (ETxA)$$

Where ΔV is the change in volume, Δt is time (days), Q_i in the cell inflow rate, Q_o is the outflow rate, P is rainfall precipitation, ET is evapotranspiration, and A is the CW cell surface area. Each of these terms will be estimated using well-established hydrological methods that relate water level data to flow rate and ET. Internal hydraulics will be estimated differently for VF and HF, the former requiring consideration of the specific soil media under unsaturated flow conditions. Pollutant mass balances need to consider water flows and will generally take the following form for a single CW cell:

$$\frac{\Delta M_y}{\Delta t} = Q_i C_i - (Q_o C_y) - (\alpha ETxA_y C_y) - (kA_y(C_y - C^*))$$

Where $M$is the mass of pollutant, C is concentration, α is the transpiration fraction of ET, k is the first-order areal removal rate, and $C^*$is the CW background concentration. In the case of nitrogen compounds, the mass balance will be applied to organic N, TAN and NO_3^-, and the resulting three equations will be solved sequentially. Mass balance equations will be solved numerically using well-established explicit Runge-Kutta methods. The model will be developed both in script (Python) and spreadsheet (Excel) forms to facilitate distribution and use.

Post Treatment Requirements for Reuse

A preliminary assessment will be carried out of post-treatment requirements for reuse. Model simulations will be used for full-scale system simulation. Effluent quality data will be compared with regulatory standards for agricultural and residential irrigation, industrial reuse (*e.g.*, cooling water), aquifer recharge, surface water augmentation and direct and indirect potable reuse. Post-treatment requirements will be identified to achieve these standards, including coagulation-flocculation-sedimentation-filtration, dissolved air floatation, advanced oxidation processes (*e.g.*, ozone, photolysis, photocatalysis), biofiltration, IX, granular activated carbon and membrane processes (*e.g.*, UF, NF, RO). We will work closely with our TAG and other partners to rank the technologies based on: capital costs (*e.g.*, equipment, permitting, engineering and mobilization), O&M costs (*e.g.*, energy, chemicals and labor), benefits (*e.g.*, avoided leachate disposal costs, reclaim water value), and acceptability to end users (*e.g.*, reliability, constructability, required level of operator training). The preliminary assessment will inform the direction for a potential follow-up project.

PRACTICAL SPECIFIC BENEFITS FOR END USERS

As stated in the Hinkley Center research agenda, "The treatment of landfill leachate is a big issue both economically and environmentally for most landfills and wastewater treatment plants." Use of the proposed hybrid CWs for onsite landfill leachate treatment benefits Florida MSW managers because of their low complexity, low capital and O&M costs and proven long-term performance for removal of organic matter, nutrients and metals from landfill leachate. Addition of low cost adsorbent materials, clinoptilolite and biochar, is expected to reduce reactor volume requirements and improve effluent quality. Effluents from the proposed CWs can be safely discharged to POTWs or treated further to meet reclaim water standards.

PROJECT TIMELINE AND MILESTONES

The timeline for the project by quarter and deliverables are shown in Table 5. Dr. Ergas will lead the bench-scale laboratory studies and analytical chemistry. Dr. Arias will lead pilot scale CW design, construction and modeling. Both faculty will work together on pilot system operation, reuse assessment and research dissemination.

Table 5. Timeline for Project Completion.

Task	Q1	Q2	Q3	Q4	Deliverable
Isotherm studies	(shaded)				Data for CW studies
CW construction/ start up	(shaded)	(shaded)			Three pilot CWs
Pilot operation & modeling		(shaded)	(shaded)	(shaded)	Process model, Journal publication
Preliminary reuse assessment			(shaded)	(shaded)	Journal publication
Education & outreach	(shaded)	(shaded)	(shaded)	(shaded)	Publications & presentations to K-12 and USF students, professionals & community members
Quarterly & final reports	■	■	■	■	Reports for Hinkley and USF websites

BUDGET AND JUSTIFICATION
A budget for this project is shown in Table 6. One full time and one half time graduate student will be hired to carry out the day-to-day work on the project. Benefits include fringe benefits, health insurance, and tuition. Research supplies are requested for bench and pilot studies. Travel funds are needed for field work and results dissemination.

Table 6: Project budget.

Budget item	**Hinkley Center**	**USF Cost Share**	**Total Project**
Principle Investigators Salary		6,471	6,471
Graduate Research Assistants	39,000		39,000
Benefits	3,635	1,901	5,536
Domestic Travel	2,000		2,000
Materials & Supplies	5,607		5,607
Tuition	7,758	3,425	11,183
Total	**$58,000**	**$11,797**	**$69.797**

TECHNICAL AWARENESS GROUP
A technical awareness group (TAG) has been developed composed of individuals who are knowledgeable in the field of landfill leachate management, CW systems and other related issues and are willing to serve as advisors and peer reviewers to ensure project success (Table 7; see letters of support). The PIs and students associated with this project will hold at least two TAG meetings over the course of the project. Remote participation in the TAG Meeting will be made available via Gotomeeting or Zoom. Video recording, notes and slides from TAG meetings will be posted on the project website.

Table 7: TAG members.

Name	**Position/Affiliation**	**Email**
James S. Bays	Technology Fellow, Jacobs Engineering	Jim.Bays@jacobs.com
Kimberly A. Byer	Solid Waste Management Division Director, Hillsborough County	ByerK@hillsboroughcounty.org
Stephanie Bolyard	Research and Scholarship Program Manager, EREF	sbolyard@erefdn.org
William J. Cooper	Prof. Emeritus, UC Irvine (Courtesy Prof. Environmental Engineering UF)	wcooper@uci.edu
Ashley Danley-Thomson	Assistant Professor, Florida Gulf Coast University	athomson@fgcu.edu
Ashley Evans	Market Area Engineer, Waste Management, Inc., Florida	aevans19@wm.com
Melissa Madden-Mawhir	Senior Program Analyst, FDEP	Melissa.Madden@FloridaDEP.gov
Larry E. Ruiz	Landfill Operations Manager Hillsborough County	RuizLE@hillsboroughcounty.org

PROJECT DELIVERABLES

Results from this project will be disseminated widely to a variety of stakeholders including FDEP and county regulators, county MSW directors and their staff, private waste management companies and other associated industries, university and K-12 students, engineers, operators, scientists and community members. Project deliverables will include an abstract, quarterly progress reports, a draft and final technical report, a project website, TAG meeting slides and videos, photos and tracking information for faculty, staff, and students working on the project and other periodic updates as requested (which may include in state travel). The project website will include the project abstract, full proposal, TAG members and TAG meeting information, photos of investigators and students associated with the project, and acknowledgment of sponsorship and funding from the Hinkley Center. The website will be updated regularly by posting quarterly reports, TAG meeting notes, slides and videos. The website will remain active at least 18 months after the project completion (see http://bioenergy-from-waste.eng.usf.edu/ for website from prior Hinkley funded project). The PIs will incorporate information from this project in classes they teach (Biological Principles in Environmental Engineering, Ecological Engineering). In addition, PI Ergas is faculty advisor to the USF student chapter of the Florida Water Environment Association (FWEA). Students in FWEA regularly participate in outreach activities, such as USF's Engineering Expo (http://expo.eng.usf.edu/), which brings K-12 students, teachers and families to USF each spring. Displays and activities at these events will provide an opportunity K-12 students, teachers and families to learn about MSW technologies.

Our past performance attests to our commitment to supporting students and disseminating the results of our Hinkley Center funded research. Prior Hinkley funds to PI Ergas supported two postdocs, 3 master's students, 6 undergraduates and one visiting PhD student. Research was disseminated through 8 reports, 2 MS theses (Hinds, 2015; Dixon, 2018), 3 newsletter articles, 10 poster presentations and 3 conference presentations, 2 peer reviewed journal articles (Hinds et al., 2015; Lee et al., 2019) and 1 book chapter (Hinds et al., 2017). One manuscript is currently in review in *Environmental Engineering Science* and one is in preparation. The research has been integrated into courses taught by the PIs, outreach activities at local schools, and the USF Engineering Expo. Video interviews with the PIs and their students are posted on the Hinkley Center website.

PLAN FOR SEEKING FUNDING FROM OTHER SOURCES

Future research directions include: 1) investigation of nitrogen and organic matter removal mechanisms by zeolite and biochar in adsorbent amended hybrid CWs, 2) microbial community and functional genes responsible for the degradation of organic N and UV-quenching substances, 3) additional pilot- and full-scale studies of onsite landfill leachate treatment, 4) development of life cycle and economic assessment tools to assist in onsite landfill leachate treatment and reuse decision making. Funding sources include EREF, DoE, NSF, USEPA and USDA.

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