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Original Research

Efficient Industrial Wastewater and Leachate Evaporation Utilizing Heat Localization in Porous Media

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Abstract

In this paper, an efficient industrial wastewater and leachate evaporation method is proposed and tested experimentally. The goal of this study is to investigate whether the addition of a carbon foam (CF) porous layer can lead to energy savings by evaporating more water mass per unit of energy input. The standard boiling evaporator layout was redesigned by placing the heating element in the upper region of the tank and CF underneath the heat source. The CF purposed to localize the energy in an area by the water's surface and minimize conduction heat losses to the rest of the water. A 90.2% reduction in energy lost to regions outside of the CF isolated control volume, specifically during the evaporator preheating process was observed with the addition of 100 Pores Per Inch (PPI) CF. In addition, a reduction in evaporative energy intensity was observed yielding results of 3.344 $\frac{kJ}{g}$, 3.441 $\frac{kJ}{g}$, and 3.644 $\frac{kJ}{g}$ for the 100 PPI, 45 PPI, and 10 PPI tests, respectively. This new evaporation design provides a more energy- and cost-efficient method for reducing the volume of various industrial wastewater and leachate concentrations onsite.

Keywords
Evaporation; leachate treatment; industrial wastewater; wastewater treatment; porous medium; heat localization

1. Introduction

In the United States, 52.6% of Municipal Solid Waste (MSW) generated is sent to landfills [1]. Water that passes over landfill contents and accumulates pollutants in the process is a type of wastewater called leachate. The specific leachate pollutants depend on multiple variables, including the composition of the landfill and the climate [2]. Leachate poses harm to humans and the environment [3]. Additionally, leachate generated from closed landfills can lead to even greater contamination than active ones, making it crucial to continue monitoring and treating leachate after a plant's closure [4]. Another common wastewater comes from industrial sources, which may have a smaller volume, but contains more pollutants such as oil and grease [5]. Some industrial wastewater sources are metal, and food processing, as well as petroleum refineries [6].

Biological, physic-chemical, and thermal treatments are options for treating leachate and industrial wastewater. Biological treatment is commonly used to remove organic and nitrogenous matter [7]; however, it is often less effective with leachate with a high concentration of toxic pollutants [2]. Physic-chemical treatments, which can be used as either a pretreatment or as a primary treatment approach, offer a range of methodologies. One of these is the coagulation-flocculation process, involving the addition of chemicals that encourage the agglomeration of fine particles into more substantial, easily separable clumps or 'flocs' [8]. Another is chemical precipitation, which operates on the principle of inducing the formation of insoluble precipitates by introducing particular chemicals, effectively rendering dissolved ions separable from the water body [9]. For instances with high ammonium content, ammonium stripping can be utilized [10]. This method capitalizes on the pH-driven conversion of ammonium to gaseous ammonia, which then gets stripped from the solution. Filtration methods also play a pivotal role, with nanofiltration (NF) using specialized membranes to sift out nanosized particles and certain dissolved molecules [11]. Reverse osmosis (RO) operates on a similar principle, employing a semipermeable membrane to exclude dissolved solids, certain organics, and bacteria from passing through. Ultrafiltration, another membrane-centric process, is tailored to separate suspended solids, colloids, and larger molecular structures from wastewater [12]. Lastly, there's the adsorption technique, where pollutants adhere to the surface of adsorbent materials resulting in their effective removal from the wastewater. These methods are best for leachate containing high molecular organic compounds [2].

To enhance treatment outcomes and address a broader spectrum of contaminants, combined methods have emerged in the realm of leachate treatment [13]. A synergistic approach, such as the integration of nanofiltration (NF) with adsorption, as explored by [14], capitalizes on the strengths of both methods. While NF selectively sieves out solutes based on size and electrostatic interactions, adsorption further polishes the effluent. This dual method achieved a 97% removal efficiency for COD, as shown in Table 1. Another intriguing combination is that of NF and coagulation. As demonstrated by Trebouet et al., the coagulation process initiates by forming flocs from the contaminants, which NF then effectively separates, achieving an 80% COD removal efficiency and a

21% NH_3N removal rate [15]. Similarly, the pairing of ultrafiltration (UF) with adsorption, studied by Pirbazari et al. (1996), targets both suspended and dissolved pollutants [16]. UF works to remove larger contaminants, and the subsequent adsorption stage deals with finer, dissolved entities, achieving a 97% COD removal efficiency. Such integrative approaches not only enhance treatment performance but also cater to varying leachate characteristics. One drawback of physic-chemical treatment is that it usually takes place off-site, which requires a large volume of leachate to be transported, increasing the risk of spills [17]. Thermal treatment such as evaporation can be used to decrease the volume of wastewater [2]. While the volatile components contained within the exhaust gas of thermal treatment requires additional effort to handle [17], its ability to handle a variety of wastewater makes it a suitable option [18]. Thermal treatment also requires less area compared to biological treatment [19].

Table 1 Comparative analysis of various leachate treatment methods indicating initial concentrations and removal efficiencies for Chemical Oxygen Demand (COD) and NH_3N.

Treatment Method	**Initial Concentration in Leachate (*mg/L*)**		**Removal Efficiency (%)**	**Reference**	
	COD	$\boldsymbol{NH_3N}$	**COD**	$\boldsymbol{NH_3N}$	
Coagulation-flocculation	5350	940	NA	80	Tatsi et al. [8]
Chemical precipitation	7511	5618	53	98	Li et al. [9]
Ammonium stripping	5690	2215	NA	95	Diamadopoulos [10]
Nanofiltration	3000	950	89	72	Ozturk et al. [11]
Reverse Osmosis	3840	NA	98	NA	Chianese et al. [12]
Evaporation	NA	818	NA	97	Sprovieri et al. [13]
NF + adsorption	1450	NA	97	NA	Meier et al. [14]
NF + coagulation	2150	215	80	21	Trebouet et al. [15]
UF + adsorption	3050	1678	97	NA	Pirbazari et al. [16]
RO + evaporation	19900	4000	88	97	Palma et al. [18]

Numerous studies have been conducted on leachate evaporation. Marks et al. [20] investigated a two-stage flash evaporation process with various leachate concentrations. Birchler et al. [21] used air stripping to remove volatile compounds, followed by a four-stage flash evaporation process. Di Palma et al. [18] combined evaporation and reverse osmosis. Landfill gas (LFG) can be used to power thermal evaporators [21, 22]. LFG is a byproduct generated during the landfill decomposition process and contains a significant amount of methane [22, 23]. LFG is often burned to minimize greenhouse gas emissions [24].

Many methods have been proposed to treat industrial wastewater. Tagliabue et al. [25] used reverse osmosis to treat fertilizer factory wastewater with high solute content. Kang [26] used a biological method to treat wastewater from heavy crude oil recovery. Nasr et al. [27] investigated chemical treatment of wastewater from both a chemical and plastic shoe manufacturing factory. anaerobic co-digestion is another method used for treating wastewater with high oil and grease content [28].

To offer a more granular understanding of the efficiencies of various treatment methods, Table 1 provides a quantitative comparison of several techniques, illustrating the effectiveness of each method in mitigating key pollutants, namely Chemical Oxygen Demand (COD) and NH_3N. RO stands out with a removal efficiency for COD at 98%, as demonstrated by Chianese et al. Evaporation achieves a 97% NH_3N removal rate [12] which is similar to chemical precipitation's 98% [9]. Additionally, the synthesis of methods, such as RO combined with evaporation, seems to provide a balanced efficiency for both contaminants, suggesting that hybrid approaches may be beneficial for holistic water treatment.

Table 2 provides an overview of the energy consumption (in kWh/t) and operational costs (in $/t) of various leachate treatment techniques, including physic-chemical, biological, and submerged combustion evaporation based on [29]. As shown, physic-chemical and biological have lower energy consumption and operational cost. However, an often overlooked advantage of evaporation techniques is the feasibility of on-site implementation, which eliminates the substantial expenses and potential risks associated with transporting leachate off-site for treatment. Thus, the seemingly higher costs of evaporation methods may be offset by savings in transportation. Despite the array of treatment options, evaporation has emerged as a technique deserving of deeper exploration, especially given its potential synergies with renewable energy sources such as LFG and novel materials such as Carbon Foam (CF).

Table 2 Comparison of Energy Consumption and Operation Costs for Different Treatment Methods.

Method	**Energy Consumption (kWh/t)**	**Operation Cost ($/t)**
Physic-Chemical	14	2.2
Biological	NA	2.06-3.16
Submerged Combustion Evaporation	15	12.38

Since wastewater varies depending on the source, a treatment that is insensitive to the variations and that is economical is essential [30]. The concentration of leachate contaminants can range from parts per million to parts per thousand [20]. Wastewater sources without on-site leachate treatment can ship it to a water treatment plant, increasing the operational costs [20, 31]. Thus, if the volume of the wastewater can be reduced, less water must be shipped. One thermal treatment option to do this is evaporation by boiling, which is a simple option that can take wastewater of various concentrations. Another benefit is the option to use LFG to fuel evaporators [21]. Zhao et al.

[32] investigated the economic performance of using LFG to fuel evaporators at a treatment plant using a system dynamics model. It was found that by treating up to 41% of the plant's leachate on-site using LFG-fueled evaporators, a revenue 35% higher than the benchmark could be achieved. Finally, while a significant amount of experimental research on leachate evaporation was conducted over ten years ago, recently, leachate evaporation may be gaining more attention as LFG's ability to function as a renewable energy source is explored further [22, 33].

Porous medium has been used extensively with solar evaporators to increase the evaporation rate and can have a similar effect on gas or LFG powered thermal evaporators. Without the addition of porous medium to solar evaporators, a significant amount of solar energy absorbed at the water's surface is dissipated to the underlying water [34, 35]. This generates a heat loss due to conduction and convection. Thus, with the addition of the porous medium, the energy transfer and solar vapor generation processes are localized at the surface, minimizing the heat lost to the bulk water [36]. In other words, since the solar energy is isolated in the upper region of the volume, energy is not wasted on heating a large amount of underlying water. The addition of porous medium can increase solar efficiencies from 30% up to 90% or higher [36].

Ghasemi et al. [37] achieved an 85% solar efficiency with a double layer porous medium with CF serving as the bottom layer to minimize conduction to the bulk water. Canbazoglu et al. [38] used CF to localize the solar energy and increase the evaporation rate of an ethanol-water mixture. Ni et al. [39] demonstrated steam generation with a low-cost multilayer medium, including a thermally insulating floating foam.

Water evaporation by boiling is sometimes regarded as a high energy consumption method [40]. But its ability to handle a variety of leachate and potential to be powered by LFG at a low cost makes it a feasible option. In order to minimize the energy consumption of evaporators, effective heat exchange is essential [30]. The use of porous medium with solar evaporators has led to significant innovation and progress in the study of solar evaporators. The fundamental problem of heat dissipation that porous medium addressed in the case of solar evaporators has yet to be solved for powered boiling evaporators. Powered boiling evaporators have the heat source at the bottom of the tank and likely experience similar heat dissipation losses to solar evaporators. This observation indicates a clear gap in the literature concerning efficient evaporation methods that can be both energy-conserving and universally applied across varying leachate and industrial wastewater types.

To address this identified gap this study investigates the effects of the addition of CF and heat localization on powered evaporators. A novel powered evaporator layout was proposed to minimize the heat losses due to conduction and convection, with two main differences from the standard: first, the heating source was placed by the water's surface to localize the energy and steam generation process. Second, CF was added underneath the heat source to minimize conduction to the underlying water. The power savings demonstrated holds promise for a simple and more economical method of leachate volume reduction and treatment.

2. Methods

The experimental setup used in this study composed of a cylindrical polycarbonate container to house a wastewater mixture. The container was wrapped in insulation on the vertical sides. By the insulation and container characteristics, the boundary conditions of the container are assumed to be adiabatic. A 350 *W* spiral heating element was used. As illustrated in Figure 1, a 20 Amp,120 *Volt*

AC voltage transformer was used. The heating element was mounted in the upper region of the volume using an acrylic circular mount. Duocel CF purchased from ERG Aerospace, USA was used. The disk-shaped CF has a diameter of 10.16 *cm* and was secured 2 *cm* below the heating element. The purpose of this 2 *cm* gap was to prevent the CF from absorbing thermal energy directly (by conduction) from the heating element.

Figure 1 Data Acquisition Device (top left), Power Analyzer (bottom left) and 120 V Power Supply.

Tests with wastewater at 350 *W* were done using 10, 45, and 100 PPI CFs, shown in Figure 2. The CF thermal properties are depicted in Table 3. This power setting was selected based on a previous study that found that the benefits of CF's insulating capability become more apparent at higher energy levels [40]. The CF pore sizes selected were based on a prior study on solar evaporators that found that pore size reduction led to greater evaporation rates [41, 42].

(a) (b) (c)

Figure 2 Carbon Foams at (a) 100 Pores Per Inch (PPI) CF, (b) 45 PPI, and (c) 10 PPI.

Table 3 Carbon Foam Thermal Properties [41].

Properties	Value	Unit
Specific Heat Capacity	1.26	*j/g·K*
Thermal Conductivity	0.033-0.05	*W/m·K*
Layer Thickness	0.012	*m*

Wastewater used for the experiments was made with 1250 g of tap water, 20 g of sawdust, 50 mL (39.07 g) of SAE 0W-20 full synthetic engine oil (made by Super Tech), and 100 g of dirt, as shown in Table 4.

Table 4 Details of Waste Water Components.

Waste Water Components	Mass (gram)	Concentration by Mass (%)	Specific Heat Capacity, c_p
Water	1,250	88.71	4.186
Sawdust	20	1.4	0.9
Oil	39.07	2.8	1.97
Dirt	100	7.1	1.48
Total	1,409.07		

Sawdust is an organic waste material that can be found in many industrial wastewaters, especially those from wood processing or manufacturing industries. Its presence in the simulated wastewater helps mimic the organic load and suspended solid content typical in some industrial effluents. The organic nature of sawdust can also represent the biodegradable portion of the waste, which plays a significant role in biological treatment processes. Engine oil represents hydrocarbon contaminants, which are common pollutants in industrial wastewaters, particularly from automotive industries, machinery workshops, or petroleum refineries. Dirt can simulate the inorganic and particulate matter found in real-world wastewater. It can originate from soil erosion, stormwater runoff, or various industrial processes. The presence of dirt in the simulated wastewater provides a realistic representation of the sedimentation and suspended solids challenges in wastewater treatment. Given that the paper addresses the evaporation method for treating industrial wastewater and leachate, it's crucial to simulate a wastewater composition that embodies a broad spectrum of contaminants found in real-world scenarios. With the methods and materials discussed in this paper, there are not significant environmental concerns to address as the only gaseous emissions are water vapor since all materials studied have a boiling point above that of water.

Thermocouples were placed directly in the fluid at regions specified by Figure 3(a). The thermocouples are connected to a data acquisition device (Keysight, Model 34970A), recording temperature measurements at thirty-second intervals. The first thermocouple, TC1, is located at the mouth of the container to verify the vapor temperature. TC2 is situated above the CF, the region where the heat is localized. TC3 and TC4 are located below the CF to measure the heat dissipation. During the tests without CF, the dimensions of all TCs were kept consistent. The container was placed on an analytical scale (Sartorius Entris 2202-1S) so the water mass evaporated is recorded during the experiment, Figure 3(b). The apparatus was placed on a vibration-free table. At the time of this experiment, the average ambient lab temperature was 22.3°C with an average lab relative humidity of 60%.

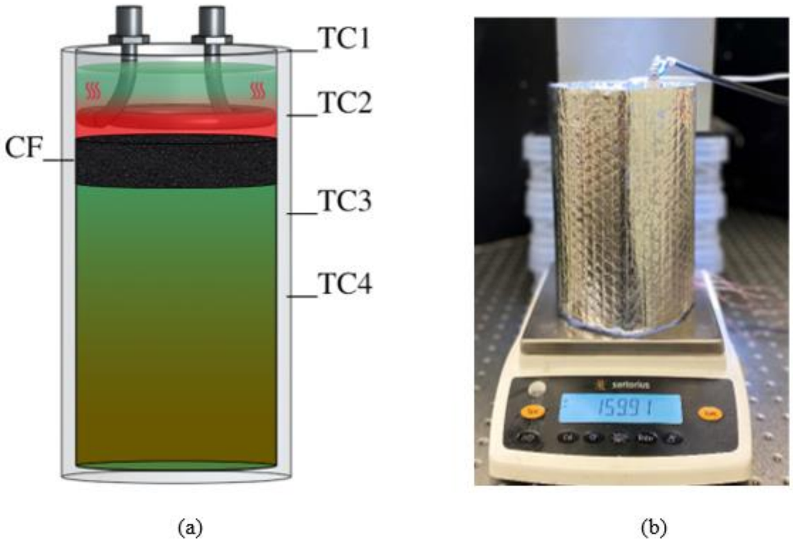

Figure 3 (a) Thermocouple Locations and (b) Evaporator and Analytical Scale.

2.1 Analytical Methods

To form a process of quantifying the effectiveness of the CF for each test, it is necessary to take another look at the objective. The goal of this study is to test the effectiveness of CF to effectuate energy savings by evaporating more water mass per unit of energy input. By the design of the experimental setup, the evaporated mass of water alone cannot be used because the CF retains energy in the entire volume above it. Only including the energy of the evaporated mass would neglect a significant portion of the energy retained in the localized heat region. Hence the control volume (CV) for analysis is defined as the summation of regions 1 and 2 above the CF as shown in Figure 4. Each region corresponds to the thermocouple names within the region specified in Figure 3(a) and shown again in Figure 4.

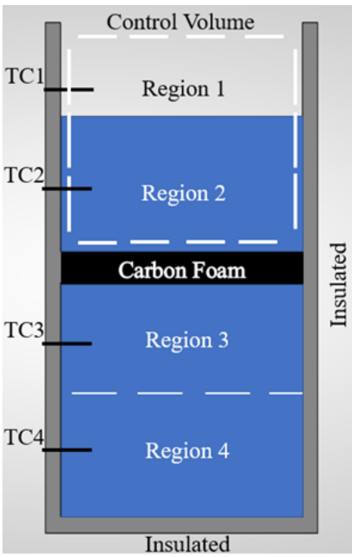

Figure 4 Definitions of Regions and the Control Volume.

As discussed in the experimental methods, the test volume is a simulation wastewater containing water, sawdust, dirt, and oil. The analysis of energy content in each region must take these materials into account. The energy balance equation for CV is shown by Eq. 1 where the general heat transfer equation expanded to include the constituents of each volume:

$$\dot{Q}_2 = m_o c_{p_o} \frac{dT}{dt} + m_s c_{p_s} \frac{dT}{dt} + m_w c_{p_w} \frac{dT}{dt} \tag{1}$$

where subscripts *o*, *s,* and *w* represent oil, saw dust and water, respectively.

The sawdust is dispersed evenly throughout the water volume, but the total volume of oil is localized at the top of the water volume. This results in Eq. (1) only applying for CV where the oil is present. The CV also differs from the remaining regions by the evaporated mass of water. To account for this, the mass of water in the CV must be updated for each minute to subtract the mass that was evaporated during that time.

The heat transfer equation for the Regions 3 and 4, without any oil in these regions, is simply:

$$\dot{Q}_{3,4} = m_s c_{p_s} \frac{dT}{dt} + m_d c_{p_d} \frac{dT}{dt} + m_w c_{p_w} \frac{dT}{dt} \tag{2}$$

Where the subscript *d* represents dirt.

The control volume (CV) shown in Figure 4 is defined as the sum of Region 2 energy content and the evaporated mass energy content of Region 1. The energy used for evaporation can be calculated by Eq. (3) where $\dot{m}_E$ and L_w are mass of evaporation rate and latent heat of fusion from liquid to vapor for water, respectively.

$$\dot{Q}_1 = \dot{m}_E L_w \tag{3}$$

The total energy of the CV is shown as Eq. 4.

$$\dot{Q}_{CV} = \dot{Q}_1 + \dot{Q}_2 \tag{4}$$

The sum of the energy content of Regions 3 and 4 can be seen as wasted thermal energy as shown in Eq. 5. In an ideal scenario, all the heat from the heating source could be delivered for evaporation only, and the amount of heat to go below the CF (as shown by Q_{Waste}) could be zero.

$$\dot{Q}_{Waste} = \dot{Q}_3 + \dot{Q}_4 \tag{5}$$

2.2 Uncertainty Analysis

The Holman equation [43] can be used to quantify the uncertainty resulting from the measured parameters. Where E is the uncertainty in the function, y is the calculated parameter, and x_i is the measurement uncertainty.

$$E(y) = \sqrt{\sum_{i=1}^{n} \left(\frac{\partial y}{\partial x_i} * E(x_i) \right)^2} \tag{6}$$

In this study, the measurement uncertainty for mass is 0.01 g and for temperature is 0.01°C. From this, the mass flow rate, temperature difference, and thermal power uncertainties are calculated as follows.

$$E(\dot{m}) = \sqrt{E(m)^2 + E(m)^2} \tag{7}$$

$$E(\Delta T) = \sqrt{E(T)^2 + E(T)^2} \tag{8}$$

$$E(Q) = \sqrt{\left(c_p \Delta T * E(\dot{m})\right)^2 + \left(\dot{m} c_p * E(\Delta T)\right)^2} \tag{9}$$

The results of this uncertainty analysis are depicted in Table 5.

Table 5 Uncertainty Analysis Results.

Parameter	Uncertainty	Uncertainty (%)
Mass	0.01414	0.923
Temperature	0.01414	0.943
Thermal Energy	126.82	0.578

3. Results and Discussion

Figure 5 compares the evaporated mass curves for three grades of porosity of CFs and a control sample without CF present. If the percentage water mass reduction is known, then the comparison between the time required by each sample to reach that percent water mass reduction can easily be seen.

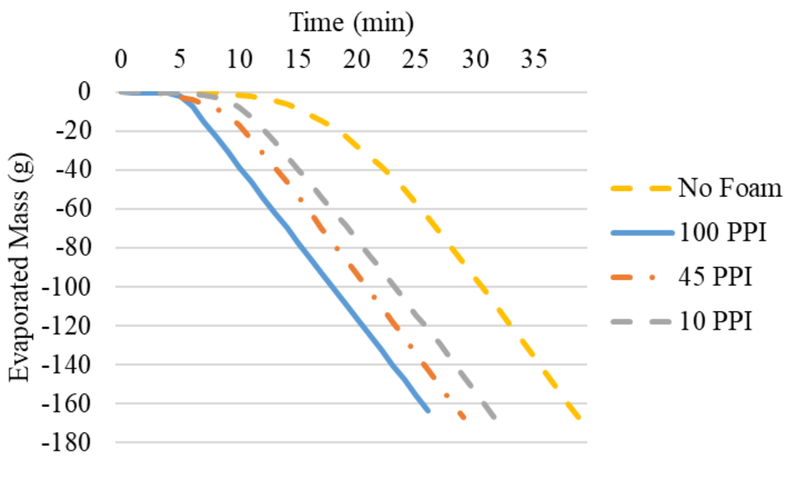

Figure 5 Evaporated Mass Comparison.

The region of each curve represented by a constant slope, shows the maximum rate of evaporation at a steady-state condition. As the rate of evaporation is a function of the power input by the heating element, the energy savings can be seen as the water mass evaporated initially departs zero. The time required by the test to reach the maximum evaporation rate decreases as the porosity of the CF increases. To further analyze the energy savings between tests, a thermodynamic analysis will be discussed.

The temperature profiles of the waste water below the CF (Regions 3 and 4), also known as the non-control volume, is the first indication that thermal energy is being retained above the CF. By insulating the bulk volume from open convection through adding CF, more thermal energy is retained in the control volume, above the CF. This increased thermal energy in the control volume directly corresponds to increased water mass evaporation. It should be noted that the average temperature of the non-control volume region will eventually reach the boiling point of water. The energy savings therefore reach a maximum as the temperature data for the test without CF reaches 100°C. As can be observed from Figure 6, 100 PPI CF gives the highest energy saving as the temperature rise in the area below the CF is the slowest. This means that the majority of energy goes into evaporation as 100 PPI CF insulate the heat localized zone effectively.

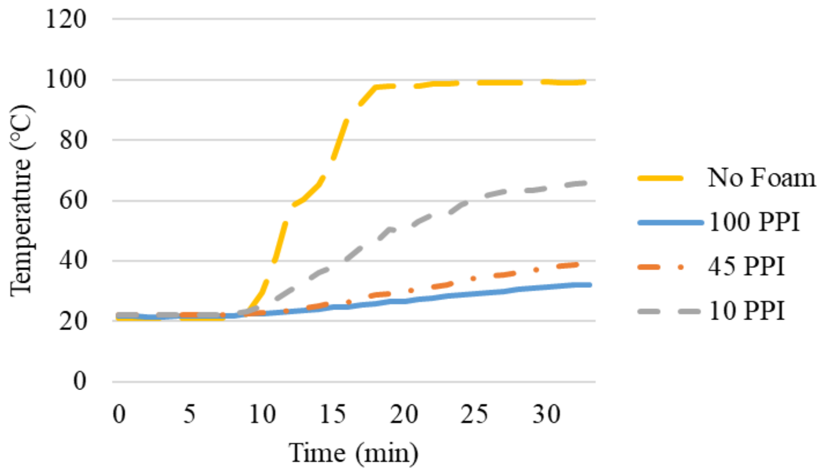

Figure 6 Average Non-Control Volume Temperature Comparison.

Figure 7 represents the energy savings between samples as the area between the power curves. As seen in Figure 6, the test without CF reaches the maximum rate of evaporation at 19 min. Beyond this, the thermal power in the non-control volume regions will approach the same values.

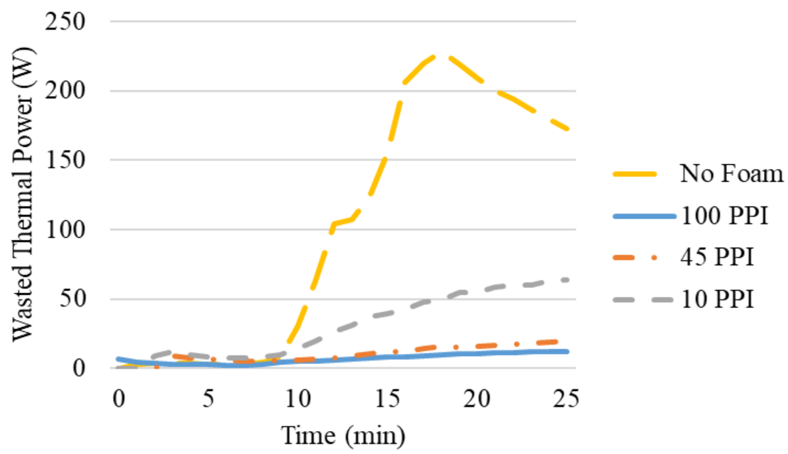

Figure 7 Energy Content Wasted.

Figure 7 shows energy wasted (the area below each curve) for tests with various CFs and the baseline test where there is no CF. This figure shows that with a constant location of CF, a significant energy saving can be achieved during the transient, or heating up, portion of an evaporator's operation. Nonetheless, for evaporators with regular "batch" operation, the energy savings for introduction of CF (or higher porosity CF) can be substantial. During a batch operation, an evaporator will be loaded with the wastewater and then allowed to heat until the percent water mass evaporated is achieved before loading more wastewater.

By adding CF layer, the energy reduction can be calculated as a percent difference of the energy of the test without CF (baseline test) compared to the CF tests.

Table 6 shows that 100 PPI CF can save 90.2% of energy from being wasted (by going to heat the water below in CF), hence evaporation begins earlier as the density of the CF increases. These energy savings occur because of the average temperature within the region above the CF reaches evaporation temperature.

Table 6 Energy Use Reduction.

CF	**Energy Intensity (*kJ/g*)**	**Energy Intensity Reduction (%)**	**Wasted Energy Reduction (%)**
100 PPI	3.344	21.9%	90.2
45 PPI	3.441	19.7%	82.7
10 PPI	3.644	14.9%	49.3
No Foam	4.284	N/A	N/A

Once this volume reaches an average boiling temperature, this only results in greater mass evaporation. For a constant heater energy input, that water mass evaporation rate will be constant. It is important to note that this has the largest impact on the batch-type operations being simulated in this study. For an evaporator with a continuous flow into the evaporation region, this transient or heating up portion will occur as more leachate is brought into the evaporation region. This would result in continuous energy savings as the heater energy input would continually be bringing fresh leachate up to its evaporation temperature.

The energy intensity for each CF test is defined as the evaporated mass per amount of input energy as evaluated at the end of the tests. These intensities also represent a design effectiveness that can be compared to the latent heat of water. As a design's energy intensity approaches the latent heat for these transient regions of the evaporator operation, the closer it is to channeling all input energy into the evaporation process. An evaporator with a lower energy intensity means that the evaporator loses more energy to the regions of the evaporator that are not reaching the boiling point.

For use in large-scale batch or continuous use systems, some special considerations must be made. First, depending on the density of CF pores and particulate composition of treated wastewater, the CF will need to be cleared regularly to clear water pathways. CF is capable of being used many times before disposal, but it is brittle. Reducing the amount of cleaning actions is vital to extending the life of the CF. Also, the density of CF used should be considered. While there is certainly greater energy savings available with higher densities, a site-specific economic analysis would need to be considered to determine the best application. Further study would be required to determine whether the energy savings seen can be scaled up proportionally with system size. As a system's size increases, the volume of water heated would also increase, potentially, a proportional increase in heater input would continue to yield consistent energy savings.

4. Conclusions

In this paper, the effect of insulating porous layer of CF on the energy requirement for evaporation of industrial wastewater and leachate is experimentally investigated. By reducing the thermal energy transfer to the bulk volume (non-control volume) with the introduction of CF at various porosities, the energy requirement to heat the control volume to its maximum rate of evaporation is vastly reduced. As compared to the baseline test (without CF), the energy reduction during the evaporator preheating process using 100 PPI, 45 PPI, and 10 PPI were 90.2%, 82.7%, and 49.3%, respectively. Interestingly, with such a large increase in density between 45 and 100 PPI foams, the energy reduction is not correlated directly to the foam density. The effect that the CF density has on energy reduction appears to approach a threshold. As the percentage energy reduction approaches 100%, the added CF density required to achieve more energy reduction may give the lower density CF more value for lower cost with a comparable performance. Nonetheless, the energy savings shown with all three densities of CF have been shown to be significant for leachate evaporation.

The results indicate that the addition of advanced materials like CF can significantly enhance traditional treatment methods, offering a more economical and efficient approach to leachate volume reduction and treatment. When placed in the broader context of the wastewater treatment landscape, these findings reveal a domain abundant with opportunities and challenges. The potential for evaporators to be powered by LFG provides an economical benefit. Future works can investigate the performance of the redesign evaporator presented in this paper with various wastewaters. Another direction could investigate the long-term durability and cost-benefit analysis of CF-integrated evaporation systems. Additionally, studying the performance of this design on a larger scale would be insightful. Lastly, it would be interesting to explore how the evaporator design detailed in this paper could synergize with other processes, such as reverse osmosis, to further optimize wastewater treatment. Many challenges, however, still persist, such as finding a durable CF that can withstand long-term use. Also, integrating this novel evaporator layout with other stages of wastewater treatment or within existing treatment plants could present challenges related to compatibility, space requirements, and operational synchronization.

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Author Contributions

Abdel Zaro identified a vital gap in the research field and, in collaboration with Dr. Languri, led to the study's conception and design. Abdel Zaro constructed the experimental setup. His contributions extended to the data collection and analysis. Moreover, Abdel was responsible for writing the introduction of the paper and also played a significant role in the overall writing process. Spencer Jones contributed to the data collection, data analysis, and results discussions and took the lead in writing the results and analysis section. Spencer's experience helped the team better present the results finding. Dr. Ethan Languri, who serves as the Corresponding Author and PI of the project, identified the industry-driven challenge of wastewater management and utilized his preliminary experimental and numerical studies in porous media flows and heat localization to develop this paper's idea. Dr. Languri guided the design, setup development, testing, data analysis and discussion, ensuring relevance in the findings, revising the paper, overseeing the finalization of the manuscript, and managing communications related to the publication process.

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Competing Interests

The authors have declared that no competing interests exist.

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