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Analysis of the Extraction Capacity of Lipid Material from Landfill Leachate for Biofuel Production

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Abstract

Landfill leachate, a pollutant with potential risks to groundwater, contains lipidic materials that can be recovered for biodiesel production. This study evaluated the efficiency of three pretreatment methods—thermal (200˚C and 250˚C), acidification (pH 2), and ultrasound (40 Hz for 120 min)—on lipid extraction from leachate samples collected in a landfill in southern Minas Gerais, Brazil. Lipid extraction was performed using a Soxhlet apparatus, and parameters relevant to biodiesel production were analyzed, including acidity, free fatty acid (FFA) content, and saponification index. Leachate characterization included pH, acidity, alkalinity, and oil and grease content (OGC). Thermal treatment at 250˚C resulted in the highest lipid yield (104.67 ± 5.04 $mg \cdot g^{-1}$), followed closely by ultrasound (101.17 ± 0.59 $mg \cdot g^{-1}$), indicating that both methods were effective, with thermal treatment slightly outperforming ultrasound in terms of yield. Despite a lower yield (55.7 ± 3.01 $mg \cdot g^{-1}$), acidification was the most economically viable method due to lower energy demands. The extracted lipids contained approximately 98% FFA, indicating the necessity of acid-catalyzed pre-esterification prior to biodiesel synthesis. The study highlights the potential of transforming landfill leachate into a renewable energy resource through scalable and cost-effective processes.

Keywords

Thermal Treatment, Acidification, Ultrasound Treatment, Biodiesel

1. Introduction

The leachate generated in landfills poses a serious threat to the quality of groundwater, resulting in significant losses of drinking water and causing irreparable damage to the environment and human health. The current national scenario highlights serious issues, as only 59.5% of the waste generated in Brazilian municipalities was treated in landfills in 2018, resulting in the generation of 32 million tons of untreated waste [1].

To address this situation, the Brazilian Committee on the Environment and Sustainable Development (CMADS) approved Bill 1516/19, establishing the mandatory treatment of landfill leachate within a maximum period of two years [2].

Landfill leachate is a dark-colored liquid with a strong odor, produced by the physical, chemical, and biological degradation of waste. It contains a complex mixture of organic and inorganic compounds, including nitrogenous substances, heavy metals, and in some cases, lipid-rich materials derived from the disposal of food waste, animal fats, and other organic matter [3].

Although several studies have investigated lipid recovery from sewage sludge for biodiesel production [4], there is still a significant gap in the literature regarding the use of mature landfill leachate for this purpose. This gap is largely due to the high variability of leachate composition, which depends on landfill age, climatic conditions, and the nature of the disposed waste [5]. As landfills mature, their leachates undergo complex chemical transformations that reduce biodegradability and increase the presence of recalcitrant compounds, while also concentrating contaminants such as heavy metals and non-lipid organic materials. Heavy metals (e.g., Pb, Cd, Hg, Cr) can adsorb or complex with functional groups of lipids, particularly phospholipids, altering their structure and reducing extraction efficiency. In parallel, non-lipid organics such as proteins and carbohydrates are prone to co-extraction, which decreases purity, favors emulsification, reduces recovery yield [6]. Nevertheless, the high organic load and presence of lipids in certain landfill leachates open promising opportunities for biodiesel production. Lipids are a key feedstock for biodiesel due to their high energy content and suitability for transesterification processes. In particular, lipids containing long-chain saturated and monounsaturated fatty acids yield biodiesel with desirable properties such as high cetane number and oxidative stability [7]. Waste-derived lipids, although often rich in free fatty acids (FFAs), can be pretreated through acid esterification to become viable for biodiesel synthesis [8]. Therefore, utilizing lipids extracted from leachate not only contributes to cleaner waste management but also provides an alternative and low-cost feedstock for renewable energy production.

What makes landfill leachate particularly valuable, compared to other organic waste streams such as food waste or wastewater sludge, whose higher compositional variability and moisture content often require more complex and costly pretreatment processes for efficient lipid extraction [9] [10], is its high degree of biological degradation and concentration of soluble organic matter, resulting from prolonged percolation through heterogeneous waste layers under anaerobic conditions. This unique composition often leads to a higher proportion of microbial lipids and breakdown products, including FFAs and other lipidic compounds [5] [11].

These characteristics not only enhance the leachate's bioenergy potential, particularly for lipid-based energy recovery routes, but also imply lower pre-treatment costs and higher conversion efficiencies per unit volume when compared to less stabilized substrates like fresh food waste or primary sludge [12] [13]. As a result, the cost of energy generation from leachate could potentially fall below USD 100 per MWh [14] [15], reinforcing its attractiveness as a competitive and underexplored alternative in the circular bioeconomy.

In this context, this study proposes to analyze the lipid extraction capacity from mature leachate collected from a landfill in southern Minas Gerais, Brazil, evaluating three pretreatment methods (thermal, acidification, and ultrasound) and assessing the physicochemical characteristics of the leachate. The goal is to determine the feasibility of using these lipids for biodiesel production, contributing to both environmental protection and energy generation through waste valorization.

2. Methodology

2.1. Obtaining the Leachate Sample

The leachate sample was collected at the final drainage point of an active municipal landfill located in the southern region of Minas Gerais, Brazil. The landfill has been in continuous operation for 13 years and serves a population of approximately 137,000 inhabitants. The sample was obtained at the base of the landfill's drainage system, ensuring that the material had percolated through all waste layers—approximately 50 meters in vertical height—thus representing a mature leachate with advanced degradation stages. Collection was performed manually using a clean, high-density polyethylene (HDPE) container with a total capacity of 20 liters. The sample was transported under cooled conditions to the laboratory within two hours of collection. Upon arrival at the Water Quality Laboratory of the Center for Environmental Quality Studies (CEQUAM) at Universidade Federal de Itajubá (UNIFEI), the material was immediately refrigerated at −4˚C until further analysis, in accordance with standard procedures outlined in ABNT NBR 9898:1987.

For the pretreatment experiments, the leachate was homogenized and then aliquoted into 100 mL borosilicate glassware for each experimental condition.

Leachate characteristics are highly variable, influenced primarily by factors such as the landfill's age, the composition of the disposed waste, seasonal rainfall, and local climatic conditions. To ensure that the collected sample was representative of typical landfill leachate for this specific site, sampling was conducted immediately after the rainy season in June, a period when leachate generation is generally at its peak due to increased infiltration and percolation of rainwater through the waste mass. Sampling in this period captures the leachate composition under realistic operational conditions, including the mixture of organic compounds, nutrients, and potential contaminants [6] [5].

2.2. Characterization of Landfill Leachate and Extracted Lipid Material

In order to determine the physicochemical parameters of the landfill (LF) leachate, pH value analyses were performed (ASTM E70-20), acidity index (ISO 660-2020), alkalinity (ISO 99631-:1994) and TOG (AOCS 920.39-2012.). The analyses and calculations of these acidity and alkalinity parameters were also based on the literature on *physical-chemical methods for food analysis* from the Adolfo Lutz Institute [16].

To characterize the lipid material from the leachate, determinations on the acidity index were made [16] as well as additional tests measuring free fatty acids were also performed (ASTM D 5555-95, 2001) and also saponification index tests (AOC D 3-25, 1995). The analyses of the lipid material had to undergo a dilution process in distilled water because the product after extraction of raw material had high viscosity, which would be an impediment to measuring the parameters mentioned.

2.3. Pretreatment of Landfill Leachate to Improve Lipid Extraction

The pretreatments applied were intended to improve the extraction capacity of lipid material from the sample, using three techniques: thermal treatment [17], by acidification [18] and by ultrasound [19]. The lipid extraction efficiency for each process was evaluated, using the Soxhlet process, by TOG measurements (AOAC 920.39-2012). All pretreatment and extraction experiments were performed in triplicates.

2.3.1. Pre-Heat Treatment

In order to investigate the effect of the heat treatment as a pretreatment for lipid extraction, the furnace (SSA 30 L Model) was heated until the temperature stabilized at 200˚C. After reaching this temperature, the 25 mL leachate sample was inserted into the oven and heated to 200˚C for 5 minutes. The sample was then cooled in a thermal oven (Solid Steel 40 L Model) at a temperature of 20˚C, for 5 minutes. The same procedure was performed for other leachate samples, applying a temperature of 250˚C, with both samples being stored in beakers in a thermal oven at 21˚C for later analyses. These temperatures were chosen based on the work of CHOI [17].

2.3.2. Pretreatment by Acidification

To evaluate the effects of pretreatment by acidification for the extraction of lipid material from LF leachate, 40 mL of leachate sample was used, and the pH value of the sample was measured (pH meter PHS3BW). Then, a 0.1 N HCl solution was gradually added to the sample using a pipettor until the pH value reached 2. The sample was stored in a thermal oven at 21˚C for later analysis.

2.3.3. Pretreatment by Ultrasound

The procedure began with the separation of 100 mL of leachate into 500 mL beakers. The samples were placed in an ultrasonic bath, and three 120-minute intervals were conducted, at a frequency of 40 Hz [19].

2.4. Soxhlet Extraction Process

The lipid extraction process was carried out using the Soxhlet technique (AOAC 920.39-2012). The procedure adopted was characterized by the analysis in triplicate of the pretreatment samples stored in a thermal oven at 21˚C. In the analysis of the preheat and ultrasound pretreatment samples, the posttreatment liquid raw material was transferred to 100 mL evaporation porcelain for drying in a thermal oven at a temperature of 100˚C for a drying period of 12 hours. In the analysis of the pretreatment by acidification, due to the lipid material having accumulated in the liquid phase of the solvent, direct drying of the solvent was carried out instead of the liquid raw material, with the following steps being the same as those previously mentioned, and all samples (thermal, ultrasound and acidification) having been collected in solid state. After carrying out this preprocedure, the Soxhlet technique applied was based on the gravimetric difference of beakers without material and after the passage and drying in an oven of the liquid hexane solvent over the solid raw material, in which the raw material was retained in Styrofoam tubes with the continuous passage of refluxing solvent.

2.5. Efficiency Per Cost Comparation

The total pretreatment cost per kilogram of lipids extracted was calculated by combining the energy cost, chemical input cost, and any additional operational expenses:

$$C\_total = ((E \times C\_energy) + C\_chem + C\_oper)/M\_lipid \quad (1)$$

where:

- C_total = total pretreatment cost per kg of lipid (USD/kg);
- E = energy consumed (kWh);
- C_energy = cost of electricity ($USD \cdot kWh^{-1}$);
- C_chem = cost of chemicals used (USD);
- C_oper = other operational costs (USD);
- M_lipid = mass of lipid extracted (kg).

3. Results and Discussion

3.1. Preliminary Analysis of the Raw Leachate Sample

The data obtained for the characterization of the raw leachate were summarized in Table 1.

The analyses of the raw leachate sample served as an indication of its quality for its capacity to be used in the removal of lipid material, considering the possible variations that the material may present depending on the origin and physical-chemical composition of the leachate coming from it.

That is considering that a landfill, over the course of its operation, can go

Table 1. Raw leachate sample data.

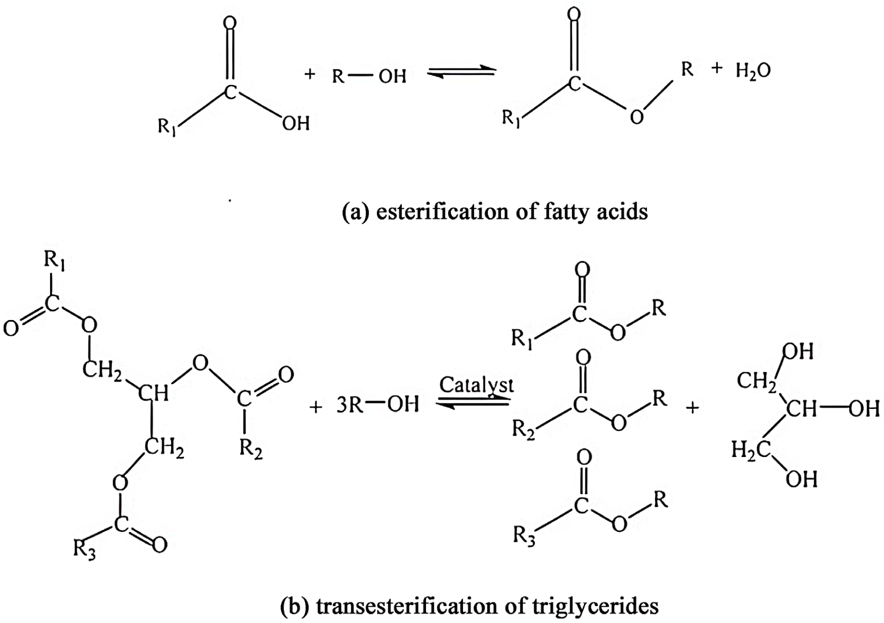
Parameter	Value
pH	8.9
Acidity index	28.62 mg $NaOH \cdot g^{-1}$
Alkalinity	250.00 $mg \cdot L^{-1}$ of $CaCO_3$
Total Oil and Grease (TOG)	8 ppm

Source: Own authorship.

through different phases, such as hydrolysis, acidogenesis, acetogenesis and methanogenesis, in which the complex material is progressively transformed into simpler compounds [3]. The first characteristic we can evaluate in the material is its pH and alkalinity, which helps us determine what stage of degradation it is in [20].

In the context of energy production, it is desirable that the leachate is mainly in the initial stages of degradation [21]. This is due to the fact that for the viability of biodiesel production from this material, the presence of high quantities of fatty acids, which can be used in the esterification process, and triglycerides, in the transesterification process, is of utmost importance, as demonstrated in **Figure 1**.

On the other hand, when the landfill is older, the leachate contains free fatty acids in high concentration, acting as undesirable components because they favor saponification when basic catalysts are used [22], and damaging subsequent biodiesel extraction processes.



Source: Adapted from FUKUDA [23].

Figure 1. Stephs in esterification and transesterification of fatty acids.

Therefore, the alkalinity test can be useful in assessing the maturity of the material, calculating the concentration of bicarbonate ions (HCO_3^-) and carbonate (CO_3^{2-}) in the middle. As evidenced in research by Tchobanoglous, Theisen and Vigil [24], the results indicate that recent landfills, with less than 2 years of operation, have an average alkalinity in the range of 1000 to 10,000, with a pH between 4.5 and 7.5. In contrast, older landfills, with more than 10 years of operation, have an alkalinity range of 200 to 1000 and a pH between 6.6 and 7.5.

Therefore, obtaining a referentially low alkalinity value of 250.00 mg·L^{-1} of $CaCO_3$ may indicate that the leachate analyzed comes from leachate that is already in the methanogenic phase, corroborated by the obtaining of a pH that is alkaline, a pH of 8.9, characteristic of the environment with a majority of methanogenic bacteria.

When analyzing the acidity index, relevant information is obtained about the presence of acids in the medium, which come from the acidogenic phase. A high value may indicate that, even when the material is in the methanogenic phase, there is still the presence of non-hydrolyzed acids, preferably free fatty acids, although with the presence of others in smaller quantities, such as carboxylic and fatty acids [3].

In the analyses of oil and grease content (OGC), obtaining 8 ppm per sample is an indication that the leachate contains lipid materials of animal, vegetable and other sources. This high value differs from the results obtained by Moura [25] for landfills of the same time period; however they can be attributed to the fact that the sanitary landfill from which the material studied comes, receives waste from urban and rural areas and with the deposition of type II A waste, therefore also having the disposal of general organic materials from food industries (NBR 10004) unlike the industrial waste previously studied by Moura [25]. Therefore, in addition to conventional urban organic waste, such as food scraps and waste, there are also contributions of organic waste of animal origin from farms and rural land.

3.2. Analysis of Leachate Pretreatment Processes

Leachate, being a percolate with variations in the amount of volumetric formation according to the region's rainfall and the capacity to penetrate the landfill layers, has the capacity to drag and retain organic materials with variations in relation to the location of the landfill and its climatic conditions [26].

If we consider the purpose of biodiesel production, it is possible to extend this concept of leachate entrainment to the retention of biodegradation microorganisms from the landfill in the material under study. Thus, it is possible to use not only the free lipid fraction present in the material, but also the lipids coming from microorganisms and complexes from the environment [19].

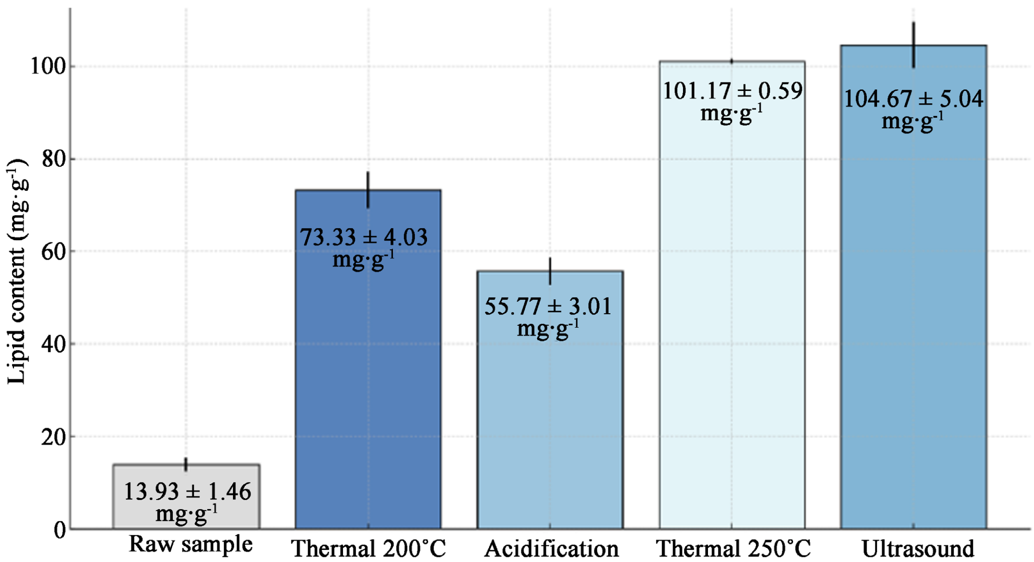
Cellular lipids may include diglycerides, triglycerides, phospholipids, monoglycerides, sterols, and free fatty acids (FFAs) [27]. Besides, fatty acids, sterols and some aliphatic components can be found in up to 36.8% cellular lipids [28]. These quantities can be used in the biodiesel production process, especially with the use of pretreatments that mainly aim at cell disruption and the breakdown of complexes.

The choice of the organic solvent to be used for the removal of these specific components from the leachate also affects the efficiency of the process. For the removal of materials released by cell rupture, such as phospholipids, the use of polar organic solvents, such as methanol, is more suitable [29]. Other possibilities, such as the use of mixtures of polar and nonpolar organic solvents, may also prove effective for the comprehensive extraction of lipid materials in the leachate [30]. However, when the main objective is the recovery of the fraction of triglycerides released by cell rupture, the use of a nonpolar organic solvent, such as hexane, becomes more advantageous considering the specific application for the polarity of the target lipid [31].

Furthermore, the high affinity for neutral lipids, low polarity, and excellent lipid solubility, particularly for triacylglycerols and free fatty acids. Hexane is widely recognized in standard methods for lipid extraction due to its efficient recovery of nonpolar lipid fractions and ease of evaporation at relatively low temperatures (boiling point ~69˚C), which minimizes thermal degradation of the extracted compounds [32] [33].

In this study, the lipid extraction process was preceded by three different cell disruption pretreatment techniques: thermal, ultrasound, and acidification. These methods were selected based on their ability to enhance cell lysis and improve the release of intracellular lipid content into the extraction medium.

The efficiency of each pretreatment was subsequently evaluated using the Soxhlet extraction method with hexane as the solvent, as previously justified. The lipid extraction yields were quantified and expressed as the amount of lipid material (in milligrams) extracted per gram of raw leachate sample. The comparative results for each pretreatment method are presented in **Figure 2**.



Source: Own authorship.

Figure 2. Extracted amount of lipids from landfill leachate using different pretreatments.

3.2.1. Acidification

The use of acidification as a pretreatment technique for lipid extraction obtained the results of lower extraction capacity when compared to thermal and ultrasound pretreatment. However, a satisfactory result was obtained, 73.33 ± 4.03 $mg\cdot g^{-1}$, because it was higher than the lipid extraction capacity of the raw material only by applying the Soxhlet technique, 13.93 ± 1.46 $mg\cdot g^{-1}$.

The acidification technique was chosen based on its ability to, in addition to acting on the cellular disruption of microorganisms present in the leachate, also potentially be capable of breaking the bonds between lipids in emulsions, linked to carbohydrates and proteins in the medium, increasing the efficiency of the extraction of lipid material [19]. The low efficiency compared to other techniques can possibly be attributed to the high severity of cell disruption associated with this technique, indicating greater lipid degradation and resulting in lower extraction yields.

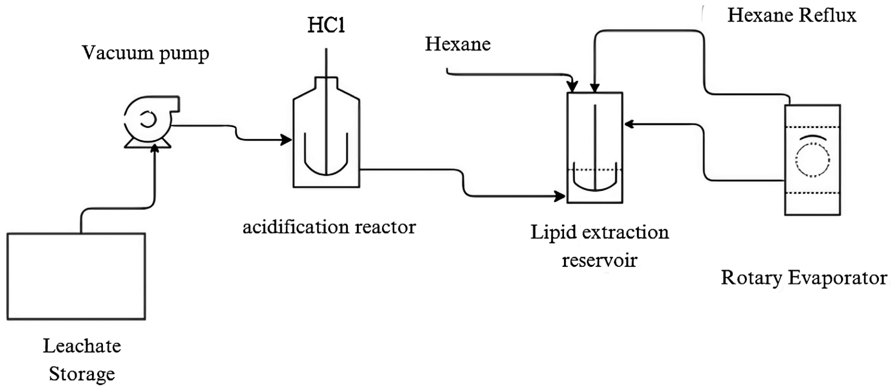
As highlighted in research by Olkiewicz *et al.* [18] and Kech *et al.* [34], the acidification as a pretreatment may increase the presence of free fatty acids at the expense of esters for transesterification. However, this technique may be advantageous in allowing liquid-liquid extraction as demonstrated in **Figure 3**, with consequent reduction in costs related to subsequent steps, such as drying of the raw material by Soxhlet extraction, which normally represents a significant part of the process costs.

Source: Own authorship.

Figure 3. Lipid material from landfill leachate retention in hexane top layer in liquid-liquid extraction.

Furthermore, a quantitative cost analysis reinforces the economic viability of the acidification pretreatment method. Based on experimental data, the lipid yield obtained through acidification was 55.7 ± 3.01 $mg\cdot g^{-1}$ of dry leachate, corresponding to approximately 2.23 g of lipids extracted from a 40 mL sample. The total cost of processing this volume—factoring in electricity consumption, chemical reagents (HCl and NaOH), and operational costs—was calculated at US$ 0.0595, leading to an estimated cost of US$ 26.71 per kilogram of lipid extracted using formula 1.

This cost is significantly lower than the estimated US$ 35 - 50/kg for Soxhlet extraction, which demands higher energy input due to prolonged heating cycles and solvent reflux. Acidification, on the other hand, relies primarily on pH adjustment and liquid-liquid separation at ambient temperature, resulting in minimal electricity consumption (~0.2 kWh per batch) and reduced solvent loss, especially when hexane is recovered through low-temperature distillation with >90% efficiency [33] [31]. A simple model is presented in **Figure 4**.



Source: Own authorship.

Figure 4. Proposed model for pretreatment of the landfill leachate by acidification.

In consideration of the environmental benefits and drawbacks of using acid pretreatment on a large scale, studies by Agarwal *et al.* indicate that the main challenge is the disposal of the acidic material, which can alter the pH of water and soil and pose potential environmental risks that must be carefully managed [35]. Conversely, the ability to perform lipid extraction at ambient temperature reduces the formation of volatile compounds, minimizing air emissions. Furthermore, recent research on green solvents for large-scale liquid–liquid extraction suggests that process optimization can further mitigate environmental impacts by improving biodegradability and reducing toxicity [36].

3.2.2. Ultrasound

In the case of the ultrasound technique, which is based on cell rupture through cavitation of microbubbles in the cell membrane, this process has a gentler approach due to the possibility of controlling frequency and retention time, with potentially less loss of lipid material when compared to acidification [37]. However, the ultrasound pretreatment presents significant economic limitations under the tested conditions. The procedure involved subjecting 100 mL of leachate to three 120-minute cycles at 40 Hz in an ultrasonic bath (300 W), totaling 6 hours of operation. This resulted in an energy consumption of approximately 1.8 kWh, corresponding to an energy cost of US$ 0.27 (based on US$ 0.15/kWh). No chemical reagents were employed; however, operational expenses, including labor and equipment wear, were estimated at US$ 0.50 per batch. The lipid yield from this treatment was approximately 111.4 *mg*, resulting in a calculated cost of US$ 24.33 per kilogram of lipid extracted using formula 1.

These values highlight that, although ultrasound can be effective in disrupting particulate organic matter then acidification, the method currently demands high energy inputs and extended processing time, as well as long retention periods to avoid damage to the component of interest considering the non-application of frequencies higher than 80 Hertz [37], which sharply reduce its economic feasibility. Pilot-scale implementation would require substantial investment in high-capacity ultrasonic equipment and further optimization of frequency and exposure time. Therefore, while ultrasound remains a promising tool for enhancing lipid extraction efficiency but not for up scaling, its viability in leachate valorization depends on future process intensification strategies that reduce energy consumption and improve yield per cycle.

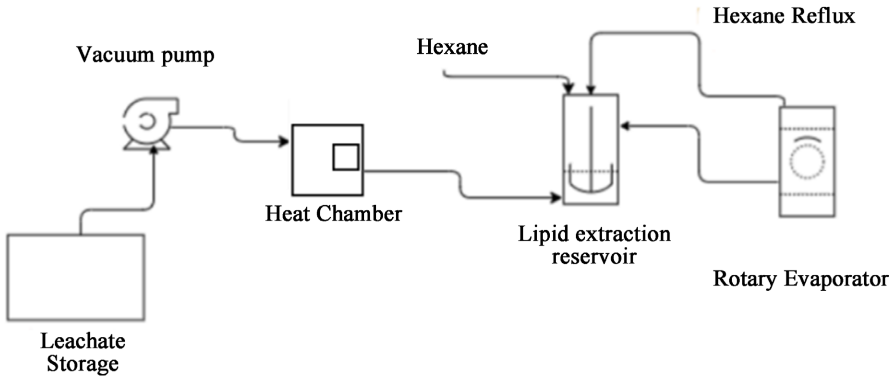
3.2.3. Thermal treatment

Thermal pretreatment showed a lipid extraction efficiency similar to that from ultrasound pretreatment, with a value of 104.67 ± 5.04 mg·g^{-1} at 250˚C. However, at 200˚C, the efficiency was lower, with 73.33 ± 4.03 mg·g^{-1}, but still higher than that obtained with acidification pretreatment. The gradual increase in temperature in two ranges, 200˚C and 250˚C, resulted in greater efficiency in the cell rupture process, considering that the gradual variation in the amplitude of the thermal shock established greater cellular stress for rupture. This statement is corroborated by studies of Lee *et al.* 17], which indicate that the gradual increase in temperature has such an effect, although there are limitations above 300˚C, resulting in consequences similar to those of acidification in lipid degradation.

Thermal pretreatment at 250˚C was the most effective method, yielding 104.67 ± 5.04 mg·g^{-1} of lipids, followed closely by ultrasound-assisted extraction (101.17 ± 0.59 mg·g^{-1}). Both methods significantly outperformed acidification (55.7 ± 3.01 mg·g^{-1}). At 200˚C, the yield was lower (73.33 ± 4.03 mg·g^{-1}), but still superior to the acidification method. The gradual increase in temperature between 200˚C and 250˚C enhanced the cellular rupture process due to progressive thermal stress, as supported by Lee *et al.* [17]. However, the literature also cautions against temperatures above 300˚C, which may induce lipid degradation effects similar to acid hydrolysis.

From an operational standpoint, thermal treatment offers favorable economics. Each 250 mL sample required approximately 5 minutes of heating in a laboratory oven operating at 1.5 kW, totaling 0.125 kWh per sample. This corresponds to an energy cost of US$ 0.019 (at US$ 0.15/kWh). No chemical reagents were required (Laboratory scale), and additional operational costs (e.g., handling, maintenance) were estimated at US$ 0.10 per batch. Given the lipid yield per 100 mL sample of 10.47 g, the total cost per kilogram of lipid extracted was calculated using formula 1, with result of US$ 11.71 per kg of lipid.

This result indicates that thermal pretreatment is significantly more cost-effective than ultrasound, with a similar extraction efficiency and a markedly reduced processing time (5 min vs. 6 hours). Furthermore, the scalability of heat-based systems—through the integration of autoclaves, heat exchangers, or continuous thermal flow reactors—makes it a technically feasible and economically sustainable strategy for lipid recovery from leachate on a pilot or industrial scale. These findings support the thermal method as a robust and efficient alternative in waste-to-biodiesel valorization schemes, as illustrated in Figure 5.



Source: Own authorship.

Figure 5. Proposed model for thermal pretreatment of landfill leachate.

3.3. Comparation of Cost per Pretreatment

Table 2 presents a comparative summary of four pretreatment methods applied

Table 2. Cost per pretreatment for lipid extraction form landfill leachate.

Parameter	Acidification	Ultrasound	Thermal (200˚C)	Thermal (250˚C)
Lipid Yield ($mg \cdot g^{-1}$)	55.7 ± 3.01	105.34 ± 4.21	73.33 ± 4.03	104.67 ± 5.04
Energy Consumption (kWh/sample)	0.20	1.80	0.085	0.125
Energy Cost (US$/sample)	0.03	0.27	0.013	0.019
Chemical Cost (US$/sample)	0.04	—	—	—
Other Operational Costs (US$)	0.05	0.20	0.08	0.10
Total Cost (US$/kg lipid)	5.04	24.33	11.34	11.71
Processing Time	~30 min	6 h (3 × 120 min)	5 min	5 min
Equipment Scalability	High (low-tech)	Limited (high-cost equipment)	High (autoclave-compatible)	High (autoclave-compatible)
Key Advantages	Low-cost, low energy	High yield at lab scale	Fast, moderate cost, scalable	Fast, scalable, energy efficient
Key Limitations	Lower yield	High energy/time requirement	-	Risk of degradation > 300˚C

to leachate samples—acidification, ultrasound, and thermal treatments at 200˚C and 250˚C—with respect to lipid extraction efficiency, energy and operational costs, scalability, and key technical considerations. The economic analysis was based on direct measures of energy consumption and estimated market prices for chemicals and operational inputs. This integrative assessment highlights the trade-offs between extraction yield and total cost, offering insights into the most suitable methods for large-scale applications.

As shown in Table 2, the lipid yield obtained from landfill leachate (55 - 105 mg·g^{-1} dry solids) is within the same order of magnitude as sewage sludge (80 - 200 mg·g^{-1}), demonstrating that this challenging waste stream can serve as a viable lipid source. Although conventional feedstocks such as vegetable oils (200 - 400 mg·g^{-1}) and animal fats (>700 mg·g^{-1}) exhibit higher yields and lower market costs [38]-[40], they are also associated with sustainability concerns, including competition with food production and land-use impacts. In contrast, valorizing landfill leachate contributes to both waste management and pollution mitigation, transforming an underutilized residue into a renewable energy feedstock. While the current processing costs (US$ 5.0 - 24.3 per kg lipid) remain higher than those of established feedstocks (soybean oil: ~US$ 0.70 - 1.00 per kg; animal fats/waste cooking oil: ~US$ 0.30 - 0.60 per kg) [38]-[40], advances in pretreatment, purification, and process integration are expected to reduce these gaps, reinforcing the potential of landfill leachate as a complementary and environmentally strategic biodiesel feedstock.

3.4. Analysis of Extracted Lipid Material

The data obtained for the characterization of the raw leachate were summarized in Table 3.

Table 3. Lipid material sample data.

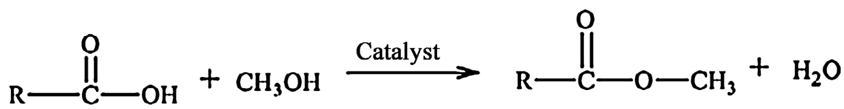
Parameter	Value
Acidity index	4.09 mg NaOH·g^{-1}
Free fatty acid index	4.00 NaOH·g^{-1}
Saponification index	112.24 mg NaOH·g^{-1}

Source: Own authorship.

The first point to be observed in the analysis of Table 3 data is the fact that the acidity index value drops and the similarity with the free fatty acid index value.

Obtaining approximate values between the number of free fatty acids and the acidity index, derived from the analysis of the lipid material, suggests that the leachate sample primarily presents a degradation of the lipid material into simpler forms, such as free fatty acids. This result is in line with the pH and verification of the maturity of the percolate, which indicates that the material has already passed through the initial phases of hydrolysis, acidogenesis and acetogenesis. However, for the production of biofuels, these values are not effective due to the tendency to favor the saponification reaction, when alkaline catalysts are applied, to the detriment of transesterification in the environment in question. In addition, they are also not in accordance with the values defined by Brazilian standards [41].

A possible advantage of the system is that the lipid extraction process using hexane in a Soxhlet apparatus resulted in the purification of the acidic components in the medium, yielding a lipid material composed of approximately 98% Free Fatty Acids (FFAs). This high FFA content, although initially a challenge for biodiesel production due to risks of soap formation and corrosion in alkaline transesterification, can be addressed through acid-catalyzed pretreatment. Specifically, the application of sulfuric acid (H_2SO_4) in the presence of methanol enables the conversion of FFAs into fatty acid methyl esters (FAMEs) via esterification. This strategy not only prepares the feedstock for subsequent base-catalyzed transesterification but also aligns with established methodologies in the literature. For instance, Sharma *et al.* [42] achieved 97.3% ester content after applying acid pre-esterification to animal fats with high FFA levels, while Supeno *et al.* [43] demonstrated 96.1% ± 0.4% conversion at room temperature in a pilot-scale setup. Moreover, Nakpong *et al.* [44] reported 98.4% biodiesel yield from coconut oil (12 wt% FFA) using similar two-step strategies. These findings support the feasibility of converting leachate-derived lipids—despite their high acidity—into biodiesel-compatible materials through scalable and cost-effective esterification techniques, aiming at the occurrence of esterification, as shown in **Figure 6**



Source: RAEISSI [22].

Figure 6. Esterification of free fatty acids.

Studies have already been carried out using two main techniques regarding the application of transesterification with acid catalyst and pre-esterification and transesterification with basic catalyst [45]. The results suggest that, with the application of acid-catalyzed pre-esterification, it is possible to obtain a material with over 97% ester content, thereby meeting European standards for biodiesel production. Therefore, it is possible to consider future analyses to obtain a material suitable for biodiesel production, even with high concentrations of FFAs compared to studies by Moura [25].

In saponification index analysis, which consists of the complete hydrolysis of triacylglycerols in alkaline solutions, results in the formation of fatty acid salts and can be used for a rapid assessment of the ester formation potential by determining the percentage of esters using Equation (1) [28].

$$\% \text{ of esters} = 100 * \frac{\text{IS} - \text{IA}}{\text{IS}} \quad (1)$$

Considering the criteria established by the National Oil and Gas Agency for biodiesel [41], the material shows potential for biodiesel production, as the theoretical ester content (96.65%) is close to the minimum requirement of 96.5%. However, given the high free fatty acid (FFA) content (~98%), the raw material does not meet this specification without further processing. Therefore, the implementation of acid-catalyzed pre-esterification is essential to convert FFAs into esters and ensure compliance with ANP standards

Comparing these results to the study by Canesin [28], which reported a saponification index of 196 mg $NaOHg^{-1}$ of sample for soybean oil and 182.5 for residual poultry slaughterhouse oil, it was concluded that the material under analysis has, respectively, 42.7% and 38.5% less capacity for conversion into biofuel compared to conventional sources. Even with a lower value, the source of the material has its advantage, since it is a residue with no other practical uses.

Furthermore, when compared to other non-conventional lipid sources, landfill leachate shows competitive or even superior performance. For instance, Zhu et al. [31] reported lipid yields ranging from 2.5% to 10.3% (dry basis) from municipal sewage sludge, while hydrothermal pretreatment at 200˚C increased yields up to 14.01% as studied by Chen et al. [46]. Similarly, grease trap waste has been studied as a feedstock with high free fatty acid (FFA) content, requiring pre-esterification to reduce FFA to acceptable levels before transesterification. Tran *et al*. [47] demonstrated a reduction of FFA to 0.84% after treatment with 3 wt% sulfuric acid at 75˚C for 3 hours. These findings reinforce the potential of landfill leachate as a promising alternative for biodiesel production, especially when optimized pretreatment methods are employed

4. Conclusions

The results obtained in relation to the raw leachate indicate that the leachate studied is not ideal to produce biodiesel, due to the age of the leachate and the biodegradability phase of the organic matter, which resulted in a high acidity index. However, with regard to the oil and grease content, the values obtained are satisfactory for lipid extraction analyses.

In the studies of the applied pre-treatments, the results demonstrated that ultrasound stood out as the most effective method, providing the greatest amount of extracted lipids considering the low standard deviation between samples. Furthermore, thermal treatment has also proven to be efficient and cost-effective, making it a viable option for larger scales. Although acidification has shown lower efficiency in lipid extraction, its use may be cost-effective, especially in subsequent stages of the biodiesel production process. In terms of cost, acidification was the most economical method (US$5.04/kg lipid) due to low energy and chemical expenses. Ultrasound, despite the highest lipid yield, had the greatest total cost (US$24.33/kg) driven by high energy and operational demands. Thermal treatments at 200˚C and 250˚C balanced yield and cost effectively (~US$11.3 - 11.7/kg), with low energy consumption and short processing times, making them promise for scale-up.

The analysis revealed that the lipid material extracted from the leachate contains fewer saponifiable components compared to conventional sources, along with a notably high concentration of free fatty acids (FFAs). This composition presents a significant barrier to direct transesterification, as high FFA levels can hinder biodiesel yield and catalyst performance. Therefore, the feasibility of biodiesel production from this feedstock depends on the implementation of additional steps—particularly acid-catalyzed pre-esterification—to reduce FFA levels and enhance the efficiency of subsequent conversion processes. Further research is essential to optimize these steps under scalable and cost-effective conditions.

The environmental benefits of this study are evident, as it demonstrates the potential to reduce the pollutant load of landfill leachate by extracting organic compounds that would otherwise contribute to elevated chemical and biochemical oxygen demand, promote aerobic decomposition, and generate odors. Moreover, the process helps mitigate soil and water contamination by removing organic pollutants from the leachate while simultaneously valorizing this material as a renewable energy source [48]. When considering the scale-up of pre-treatment methods, acidification requires the careful use of chemicals, whereas ultrasound and thermal pre-treatment primarily raise questions related to cost and operational efficiency rather than environmental downsides. Studies like this are crucial for advancing environmental management, enabling the transformation of waste into valuable resources through the production of clean energy.

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Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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