


Research Article

# Experimental Study on the Treatment and Reduction of Trace Metals, VSS, and TSS in Leachate Using Integrated Anaerobic -Aerobic system

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## Abstract

This study evaluates the performance of a combined Upflow Anaerobic Sludge Blanket (UASB) reactor and aerated lagoon system for treating leachate from the Aghajari landfill. A 500 L UASB reactor served as the primary treatment unit, followed by a 1000 L aerated lagoon for further purification. The system's efficiency was assessed by measuring the removal of chemical oxygen demand (COD), Trace metals (Mn, Zn, Cu, Fe, Ni), and pH stability. The UASB reactor showed robust performance with an average COD removal efficiency of 79%, peaking at 97% at an organic loading rate (OLR) of 12 kg/m<sup>3</sup>·d. However, at an OLR of 20 kg/m<sup>3</sup>·d, the aerated lagoon's COD removal efficiency decreased to 60%, indicating sensitivity to higher organic loads. The UASB reactor effectively removed Trace metals (Mn, Zn, Cu, Fe, Ni) with efficiencies between 70% and 90%, while the aerated lagoon's performance was comparatively lower.

The analysis of volatile suspended solids (VSS) showed a significant reduction due to biological solids' settling and compaction, with the highest VSS concentrations in the reactor's lower sections. The mixed sludge acted as an effective adsorbent for Trace metals, reducing their toxicity and solubility.

In conclusion, the combined UASB-aerated lagoon system is an effective solution for Aghajari landfill leachate treatment.

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**Keywords:** UASB; Aerated lagoon; COD; Trace metal; Organic loading rate (OLR); Leachate treatment

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## 1. Introduction

The persistent challenge of municipal solid waste (MSW) management in the 21st century is inextricably linked to the proliferation of landfill sites, which remain the predominant global disposal method despite their significant environmental legacy. A central and enduring environmental burden of this practice is the generation of landfill leachate, a complex and highly contaminated aqueous effluent. This hazardous liquid is formed through the percolation of meteoric water (rainfall, snowmelt) through layers of decomposing waste, facilitating the dissolution, suspension, and transport of a vast array of organic and inorganic pollutants derived from the waste matrix (Kurniawan et al., 2022). Recognized as a critical vector for subsurface pollution, leachate migration from disposal sites constitutes a severe, long-term threat to groundwater resources—a primary source of potable water for billions—and poses significant risks to adjacent soil ecosystems and surface water bodies (Igwegbe et al., 2021; U.S. EPA, 2022). Its hazardous profile is defined by extreme concentrations of organic matter, evidenced by chemical oxygen demand (COD) values routinely in the tens of thousands of mg/L, high ammonium-nitrogen ( $\text{NH}_4^+\text{-N}$ ) content, elevated salinity (chlorides, sulfates), a cocktail of toxic trace metals (e.g., Pb, Cd, Cr, Zn, Ni, Cu), and an evolving spectrum of synthetic organic compounds and pathogens (Anjum et al., 2023). The exponential increase in global waste generation, driven by urbanization and industrial consumption, has only intensified the scale of this problem, making the development of effective and sustainable leachate treatment technologies not just an engineering priority but a fundamental requirement for environmental stewardship and public health protection (Khan et al., 2022; Okpan et al., 2017).

### 1.1. Determinants of Leachate Characteristics: A Multivariate Analysis

The chemical and physical composition of landfill leachate is not static; it is a dynamic fingerprint that evolves in response to a complex interplay of intrinsic and extrinsic factors. This variability is fundamental to understanding its treatability and environmental impact. Primary determinants include:

**Waste Composition and Landfill Age:** The type of deposited waste (organic, plastic, construction, hazardous) directly dictates the pollutant inventory. Furthermore, landfills undergo distinct stabilization phases: an initial acetogenic phase (young landfill) producing acidic, highly biodegradable leachate rich in volatile fatty acids (VFAs), followed by a methanogenic phase (mature landfill) with more neutral pH, lower biodegradability (BOD/COD <

0.1), and elevated concentrations of refractory humic substances and ammonia.

**Hydro-Climatic and Operational Factors:** The volume and quality of leachate are profoundly influenced by local precipitation patterns, temperature, evaporation, and evapotranspiration. Landfill engineering (liner systems, cover design, leachate collection) and operational practices (waste compaction, leachate recirculation) further modulate moisture content, hydraulic pathways, and biochemical reactions within the waste mass (Mishra et al., 2023; Tałaj et al., 2024).

Consequently, leachate is a heterogeneous mixture containing substantial quantities of organic carbon (as VFAs, phenols, and humics), nitrogen (primarily as  $\text{NH}_4^+\text{-N}$ ), phosphorus, trace metals, inorganic ions, and dissolved gases. The organic fraction, particularly VFAs like acetic and propionic acid, drives microbial processes but also contributes to acidity, while phenolic compounds add persistence and toxicity (Pieus Thanikkal & Pooppana Antony, 2021; Wijekoon et al., 2022). This complex pollutant matrix, if unmanaged, leads to the pervasive contamination of groundwater, surface water, and soil, with cascading effects on ecosystem viability and human health (Landrigan et al., 2018).

### 1.2. Treatment Paradigms: From Unit Processes to Integrated Solutions

Addressing the recalcitrant and variable nature of landfill leachate necessitates advanced treatment strategies that transcend conventional municipal wastewater approaches. These methodologies can be broadly categorized:

**Physicochemical Processes:** Techniques such as coagulation-flocculation, chemical precipitation, adsorption (e.g., on activated carbon or biochar), and advanced oxidation processes (AOPs like Fenton, ozonation) are highly effective for removing colloidal solids, color, specific refractory organics, and heavy metals. However, they often entail high operational costs, chemical consumption, and secondary waste (sludge) generation, making them less suitable as stand-alone solutions for bulk organic removal (Gheidene, 2024).

**Biological Processes:** Leveraging microbial catalysis, biological treatment offers a more sustainable route for degrading biodegradable pollutants. Aerobic systems (e.g., activated sludge, membrane bioreactors) excel at nitrification and polishing but are energy-intensive for high-strength waste. Anaerobic treatment, particularly using high-rate reactors like the Upflow Anaerobic Sludge Blanket (UASB), is exceptionally suited as a primary treatment. UASB reactors efficiently degrade high organic loads at short hydraulic retention times, produce valuable methane-rich biogas, generate minimal sludge, and create

reducing conditions conducive to the precipitation of metal sulfides (Collivignarelli et al., 2021; Smith et al., 2021).

Given the multifaceted contaminant profile, integrated hybrid systems that combine the strengths of different processes represent the state-of-the-art. For instance, coupling an anaerobic pre-treatment stage (UASB) with an aerobic polishing stage (e.g., aerated lagoon) leverages the high organic removal capacity and energy recovery of the former with the superior nutrient removal and effluent polishing capabilities of the latter, achieving synergistic performance and operational robustness (Kurniawan et al., 2022).

### 1.3. Research Context, Novelty, and Investigative Framework

The efficacy of UASB technology for various high-strength wastewaters, including leachate, is well-documented. Studies have demonstrated COD removal efficiencies exceeding 90% under optimal conditions, explored performance across varying organic loading rates (OLRs), and investigated specific aspects like nitrogen transformations (Santos et al., 2023; Tsui et al., 2020; Khardmand et al., 2008). Furthermore, research on combined anaerobic-aerobic systems highlights their potential for enhanced treatment (Loganath et al., 2020; Zhang et al., 2024). However, a comprehensive evaluation of a UASB-aerated lagoon system specifically tailored to treat landfill leachate—with concurrent analysis of organic, nutrient, solids, and multi-metal dynamics under variable loading—remains an area for deeper exploration, especially for region-specific leachate characteristics.

This study introduces a novel investigation focused on the landfill leachate from Aghajari City, Iran, a region characterized by a hot, arid climate and a waste stream influenced by local urban and industrial activities. Despite evident environmental challenges, no prior dedicated research has developed or evaluated leachate treatment solutions for this specific context. Therefore, the primary novelty of this work lies in the holistic application and assessment of an integrated UASB-Aerated Lagoon pilot-scale system for Aghajari leachate. The research moves beyond reporting aggregate removal efficiencies to provide a mechanistic investigation into:

System performance and stability across a defined range of Organic Loading Rates (OLRs).

The synergistic relationship between the anaerobic (UASB) and aerobic (lagoon) stages. The fate and removal mechanisms of a targeted suite of trace metals (Mn, Zn, Cu, Fe, Ni) within the anaerobic environment. The dynamics of biomass development, granulation, and solids separation.

### 1.4. Objectives and Investigative Scope

Building upon this context, the present study is designed with the following specific objectives:

To evaluate the treatment efficacy and operational stability of a combined UASB reactor (500 L) and aerated lagoon (1000 L) system for raw leachate from the Aghajari landfill.

To determine the optimal organic loading rate for the UASB reactor and quantify its cascading impact on the performance of the subsequent aerated lagoon. To characterize the removal efficiencies and elucidate the dominant sequestration mechanisms for key trace metals within the UASB sludge bed. To analyze process parameters including pH stability, VFA/alkalinity balance, nitrogen transformation pathways, and solids (VSS/TSS) behavior to inform system optimization and scaling.

By addressing these objectives, this research aims to bridge a critical knowledge gap, providing both fundamental insights into integrated biological treatment processes and practical, data-driven guidance for sustainable leachate management in the Aghajari region and analogous environments worldwide.

### 1.5. The study area

The study area is Aghajari City in the southeast of Khuzestan province, Iran. Its population is about 18,000 people. The weather of this city is hot and dry and its temperature reaches 50 °C in summer.

Aghajari Waste Management Comprehensive Plan, the information on waste production in the region, According to Jundi-Shapur University of Ahvaz.(2020). "Feasibility study and presentation of suitable options for integrated solid waste management: Related to the Aghajari Integrated Waste Management Plan Database," Research project, Ahvaz, Iran, as shown in Table 1.

Aghajari City has a population growth rate of 0.7% per year. Currently, about 4 tons of waste is produced in Aghajari City and it is predicted that it will reach 6 tons per day in the coming years. The quality of this city's waste includes 51.5% perishable waste, 17% paper, and cardboard. 75.19% plastic, 2.5% glass, 3% textiles, and 2% metals. The density of waste is 215 kg/m<sup>3</sup>. The produced leachate has a COD of about 28,000 to 35,000. The BOD is in the range of 18,000 to 2,400.

## 2. Materials and methods

The leachate used in this study was collected from the dumpsite of Aghajari City. The key characteristics of the leachate are provided in Table 2.

**Table 1.** According to the Share of urban waste components in Aghajari region from 2008 to 2033

Components	Years	Recent by weight of component in defferent years				
	2008	2013	2018	2023	2028	2033
Perrishable waste	64	61.5	59	56.5	54	51.5
Paper & Card board	9.5	11	12.5	14	15.5	17
plastic	11	12.75	14.5	16.25	18	19.75
Glass	4	3.5	3	2.5	2.5	2.5
Textales	3	3	3	3	3	3
Matals	2	2	2	2	2	2
Other component	6.6	6.25	6	5.75	5	4.25

**Table 2.** Characteristics of the Aghajari city dumpsite leachate

Pollutants	Amount (mg/L)	Average (mg/L)
COD	28000-35000	32000
BOD	18000-24000	21000
TSS	1000-7600	5400
Nitrate according to (N)	150-260	220
Ammonia nitrogen in Terms of (N)	180-210	190
PH	3.5-5-5	5.1
Zn	21,2-25,8	23.5
Mn	54,11-72,24	63.175
Cu	0,27-0,29	0.28
Fe	65,18-70,21	67.69
Ni	13,3-19.8	16.55

A UASB reactor was employed, consisting of a cylindrical PVC vessel with a diameter of 15 cm and a height of 170 cm. The reactor was equipped with sampling valves positioned at 20 cm intervals, and a gas outlet was located at the top. To inoculate the reactor, approximately 4 liters of activated sludge, which had been stored in a sealed container for one month, were used. This sludge contained 7 liters of leachate diluted to a Chemical Oxygen Demand (COD) concentration of 1000 mg/L, serving as the necessary nutrients for the system. In the initial stage, leachate with a COD concentration of 2000 mg/L was introduced into the reactor, flowing from the bottom to the top with a volumetric loading rate of 1 g/L/d. The hydraulic retention time (HRT) was maintained at 1 day. The organic loading rate of the system varied between 1 and 20 kg/m<sup>3</sup>/d of COD. During the experiment, the pH of the reactor remained within the optimal range of 7–8, which is ideal for the activity of anaerobic microorganisms. Parameters such as pH, COD, temperature, and total suspended solids (TSS) were regularly monitored. Since COD measurements provide faster results compared to BOD, COD was used as the primary parameter for daily monitoring of the pollution load in the biological treatment system. COD measurements were taken at both the reactor inlet and the clarifier outlet to assess the daily efficiency of the UASB anaerobic treatment process. An aerated lagoon

was incorporated as a supplementary anaerobic treatment system. The pilot-scale aerated lagoon consisted of a tank with dimensions of 0.5×0.5×0.5 meters. To prevent flow short-circuiting, a barrier was installed at the entrance. Aeration was achieved through a diffuser installed at the bottom of the tank, maintaining a dissolved oxygen concentration between 2 and 3 mg/L. The effluent from the aerated lagoon was directed to a sedimentation unit to further enhance the treatment efficiency. The sedimentation tank had dimensions of 0.5×0.5×0.2 meters and a retention time of 6 hours. A schematic representation of the UASB reactor, aerated lagoon, and sedimentation tank is shown in [Figure 1](#). To establish the aerated lagoon, 10 liters of fresh brown sludge were obtained from a sewage treatment plant using an activated sludge system and added to the lagoon. To prevent organic shock, the leachate was initially diluted with chlorine-free water to a COD concentration of 1000 mg/L, and this diluted leachate was added gradually to acclimate the aerobic microorganisms. Every 5 days, the COD concentration of the leachate was doubled until it reached 3000 mg/L. The Mixed Liquor Suspended Solids (MLSS) in the aerated lagoon were measured at 3500 mg/L, which is suitable for efficient aerobic treatment ([Ivanov., 2020](#)). Retention times of 2, 4, 6, 8, 10, and 12 hours were tested by adjusting the flow rate to determine the optimal removal efficiency of

organic compounds. Throughout the study, the dissolved oxygen concentration in the lagoon was maintained at a minimum of 3 mg/L.

Heavy metals (Cd, Cr, Pb, Ni, Zn and Cu) were determined by Atomic Absorption Spectrophotometry (240 Duo (Zeeman & FS), Agilent, Santa Clara, CA, USA) and determination of Cl<sup>-</sup> by Ion Chromatography (CIC-300, SHINEHA, Qingdao, China).

### 2.1. Recommendations for Pre-Treatment Strategy Implementation

To enhance the robustness, efficiency, and operational stability of the proposed integrated UASB-aerated lagoon system for full-scale application, the implementation of a targeted pre-treatment step is strongly advised. The design and operational logic for this pre-treatment should be adaptive, based on influent characteristics and primary treatment objectives.

#### Pre-Treatment as a Primary Conditioning Step (For Solids and Hydraulic Management)

When raw leachate is characterized by high and variable Total Suspended Solids (TSS > 2000 mg/L) — a condition evident in the Aghajari leachate — a continuous physicochemical pre-treatment process is essential at the inlet.

##### A coagulation-flocculation unit

followed by lamellar sedimentation should be employed. This step will significantly reduce the inert particulate load before the biological reactors. The primary benefit is hydraulic: by lowering the influent TSS, the UASB reactor can be operated at the recommended higher upflow velocity (~0.3 m/h) to promote granulation (Gagliano et al., 2020) without the risk of washout from excessive inert solids. This directly addresses the core granulation limitation identified in this study (Section 3.6) and transforms the UASB from a system challenged by solids separation into one optimized for high-rate organic and metal removal.

#### Pre-Treatment as a Protective Buffer (For Toxicity and Shock Loads)

Landfill leachate composition is notoriously dynamic. Periods of high ammonia, fluctuating pH, or surges in specific toxic metals (e.g., Nickel) necessitate a pre-treatment buffer to protect the sensitive anaerobic consortium in the UASB.

**An equalization tank with integrated pH control** (using lime or caustic soda)

provides critical stabilization. Furthermore, for targeted removal of metals that show inconsistent biological sequestration — such as Nickel in this study — chemical precipitation (e.g., using sulfide or hydroxide) can be applied at this stage. This proactive removal of inhibitory compounds before biological treatment prevents process upset, ensures consistent UASB performance, and guarantees final effluent compliance for all target metals.

#### Inter-Stage Treatment for Enhanced Polishing (For Advanced Nutrient Removal)

If the treatment objective prioritizes advanced nutrient removal, particularly nitrification in the aerated lagoon, the data suggests that residual soluble organics from the UASB effluent can inhibit nitrifier activity (Section 3.3). In this scenario, instead of pre-treating raw leachate, an inter-stage treatment between the UASB and the lagoon is more efficient and economical. Technologies such as chemical coagulation or adsorption (e.g., using powdered activated carbon, PAC) can be applied to the UASB effluent to remove recalcitrant organic compounds. This effectively lowers the biodegradable carbon-to-nitrogen ratio entering the aerated lagoon, reducing oxygen competition and creating an ideal environment for robust and reliable nitrification.

#### Proposed Integrated Process Flow with Adaptive Pre-Treatment:

A flexible, full-scale design should incorporate:

1. **Screening & Equalization:** For flow and load homogenization.
2. **Adaptive Pre-Treatment Module:** A physicochemical unit (coagulation/sedimentation with pH control) that can be selectively engaged based on real-time monitoring of raw leachate TSS, pH, and specific conductivity.
3. **Core Biological System:** The UASB reactor, now operating under optimal hydraulic conditions (controlled upflow velocity ~0.3 m/h).
4. **Optional Inter-Stage Polishing:** A tertiary coagulation or adsorption step, activated when stringent nutrient removal is required.
5. **Aerated Lagoon & Final Clarification:** For reliable nitrification and final solids separation.

This adaptive, multi-barrier approach ensures that the biological treatment train consistently receives a conditioned, non-inhibitory feed. It directly mitigates the key limitations identified in this research — suboptimal granulation and variable nickel removal — while leveraging the demonstrated strengths of the integrated UASB-aerated lagoon system for high-efficiency organic decomposition and metal sequestration. This results in a resilient, scalable, and compliance-ready treatment solution for landfill leachate.

### System Operation Under High Ambient Temperature

The entire pilot-scale system (UASB reactor and aerated lagoon) was operated in an uncontrolled environment exposed to the natural diurnal and seasonal temperature variations of Aghajari. The temperature of the influent leachate and within the reactors was monitored daily. The UASB reactor operated in the high mesophilic to thermophilic transition range (35-42°C) due to ambient heat and exothermic biological activity, which is favorable for

high-rate anaerobic digestion. No external heating or cooling was applied, simulating realistic full-scale conditions. In the aerated lagoon, high ambient temperatures contributed to increased evaporation rates; therefore, periodic make-up water was added to maintain constant volume and prevent salinity build-up. This operational approach allowed for the assessment of system resilience and performance under the region's characteristic thermal stress.

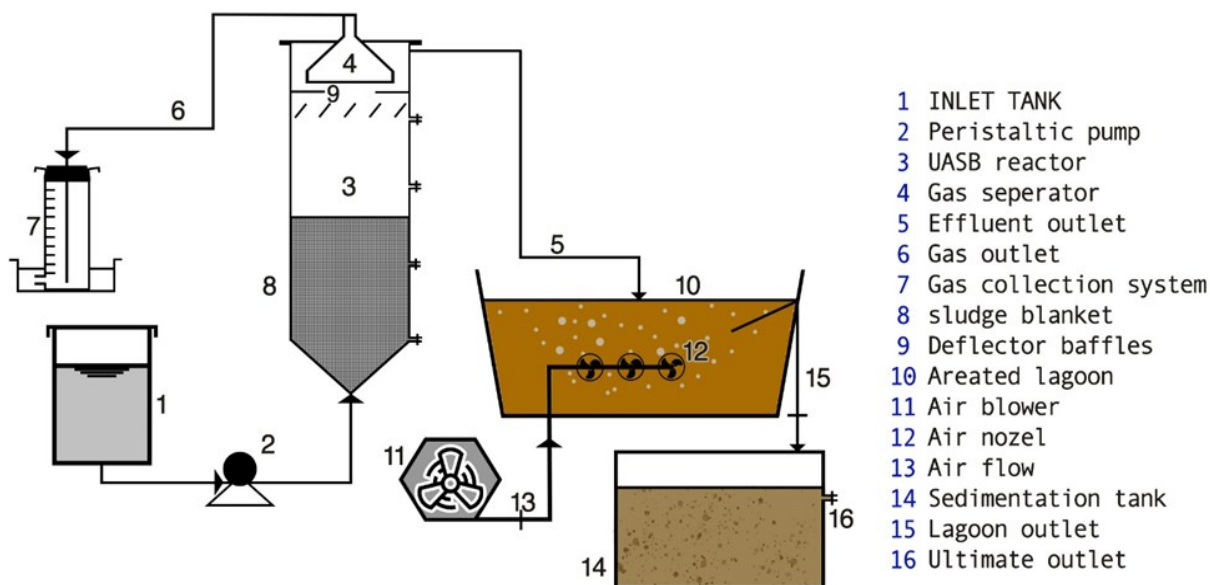


Figure 1. schematic view of the UASB reactor, aerated lagoon, and sedimentation tank



Figure 2. UASB- AERATED LAGOON system

## Experiments Conducted and Methodology

Atomic absorption spectrometry (AAS) is an analytical technique used to determine the concentration of specific elements in a sample. The method operates by measuring the absorption of light by free, ground-state atoms in a gaseous medium. A light source, typically a hollow cathode lamp specific to the element being analyzed, emits a characteristic wavelength. This light passes through a cloud of atoms produced by an atomizer—such as a flame, plasma, or electrothermal device—which vaporizes and atomizes the sample. The atoms absorb a fraction of this light, exciting them from their ground state, and the amount of absorbed energy is measured by a detection system comprising a monochromator, a detector (like a photomultiplier tube), and an electronic readout. This absorbance is directly proportional to the concentration of the analyte atoms in the sample. For certain elements like mercury, specialized modifications such as flow injection mercury systems are employed. Overall, AAS provides a

reliable means for the quantitative spectroscopic detection of numerous metal ions. The experiments deemed essential for this research include: COD, BOD, TSS, VSS, alkalinity, heavy metals, ammonia, temperature, and pH. All of these parameters, with the exception of ammonia, were analyzed in accordance with Standard Methods guidelines.

### Temperature

Since temperature plays a critical role in biological treatment processes, careful regulation is essential to ensure it remains within optimal operational limits. During summer, when ambient temperatures exceeded 35°C, the system relied on natural environmental conditions. In winter, however, an external temperature regulation device was employed to raise and maintain the temperature at approximately 35°C. This was achieved by enclosing the anaerobic reactor within a jacket of plastic tubing, through which heated water from the regulation device was circulated. As a result, the effluent temperature of the reactor was increased to around 37°C.

**Table 4.** Experiments and Methods for Treating Aghajari Landfill Leachate (Standard Methods, 2014)

Parameters	Instructions
COD (Chemical Oxygen Demand)	Dioxide cromate method (508 A. Dichromate Reflux Method)
BOD (Biological Oxygen Demand)	BOD meter
TSS (Total Suspended Solid)	Filtration & drying 103C-105oC 209 D. Total Nonfilterable Dried at 103-105
VSS (Volatile Suspended Solid)	Filtration & Drying at 550oC 550C 209 E. Total Volatile and Fixed Residue at 550o C
Alkalinity	Titration by normal H <sub>2</sub> SO <sub>4</sub> pH=4.5 (403 ALKALINITY)
PHOSPHORUS	424 F. Ascorbic Acid Method
NH <sub>4</sub> -N	Titration by normal H <sub>2</sub> SO <sub>4</sub> to pH=8.3 (2008 ·Kazemi)
Temperature ©	212 TEMPERATURE by mercury-filled Celsius thermometer
pH	pH Meter
Cu	Atomic Adsorption 313 A. Atomic Adsorption Spectrophotometric Method
Zn	Atomic Adsorption 328 A. Atomic Adsorption Spectrophotometric Method
Mn	Atomic Adsorption 319 A. Atomic Adsorption Spectrophotometric Method
Fe	Atomic Adsorption 315 A. Atomic Adsorption Spectrophotometric Method
Ni	Atomic Adsorption 321 A. Atomic Adsorption Spectrophotometric Method

### 3. Results and discussion

#### 3.1. Overall System Performance and COD Removal Dynamics

The integrated UASB-aerated lagoon system demonstrated substantial efficacy in treating the high-strength leachate from the Aghajari landfill. The primary metric, Chemical Oxygen Demand (COD) removal, showcased the complementary roles of the anaerobic and aerobic stages. As illustrated in [Figure 3](#), the UASB reactor achieved a progressive increase in COD removal efficiency from 51% to a maximum of 79% as the Organic Loading Rate (OLR) increased from 1 to 12 g/L·d. This positive correlation within this range aligns with the principle that higher substrate availability can enhance the metabolic activity of anaerobic consortia, provided the system remains stable ([Zhang et al., 2020](#)). However, beyond the optimal OLR of 12 g/L·d, efficiency declined to 61% at 20 g/L·d. This downturn is attributed to the accumulation of Volatile Fatty Acids (VFAs) during the acidogenesis phase, which can lower the pH and inhibit methanogenic activity, a common bottleneck in high-rate anaerobic systems under overload conditions ([Li et al., 2023](#)). The subsequent aerated lagoon served as a crucial polishing step, further degrading residual biodegradable organics. Its efficiency, however, was inversely related to the OLR applied to the preceding UASB, decreasing from 81% at an inlet OLR of 10 g/L·d to 56% at higher loads ([Figure 3](#)). This indicates that the aerobic stage received a more recalcitrant or shock-load effluent when the UASB was overloaded, challenging the capacity of the aerobic biomass. Despite this, the synergistic combination of both units yielded a consistently high overall COD removal efficiency of 94-97%, underscoring the robustness of the hybrid configuration. This finding corroborates the advantage of integrated systems noted by [Kurniawan et al. \(2022\)](#), where anaerobic pretreatment mitigates the organic load on downstream aerobic processes, enhancing overall treatment resilience.

#### 3.2. Process Stability: pH Buffering and VFA Dynamics in the UASB

A key factor for successful anaerobic digestion is maintaining pH stability. Remarkably, as shown in

[Figure 4](#), the pH in the UASB reactor remained steady between 7.0 and 7.3 despite a significant rise in VFA concentration from 1400 to 2300 mg/L across the tested OLR range (2-20 g/L·d). This stability can be directly attributed to the reactor's inherent high alkalinity, measured between 2500 and 4000 mg/L as CaCO<sub>3</sub>. This strong buffering capacity effectively neutralized the acidifying potential of the produced VFAs. The calculated VFA-to-Alkalinity ratio, a critical stability indicator ([Li et al., 2023](#)), ranged from 0.37 to 0.85. Ratios below 0.4 signify stable operation, which was maintained for a significant portion of the experiment.

The approach towards the 0.8 threshold at the highest OLRs signals the onset of potential instability, explaining the concurrent decline in COD removal efficiency. This interplay highlights that for the Aghajari leachate, alkalinity is not a limiting factor under moderate loads, but monitoring the VFA/Alkalinity ratio is essential for preventing process failure at peak loads.

#### 3.3. Nitrogen Transformation Across Anaerobic and Aerobic Stages

The fate of nitrogen species, primarily ammonia (NH<sub>3</sub>-N), differed markedly between the two treatment stages, consistent with their underlying microbiology. The UASB reactor exhibited limited ammonia removal (13-27%), as anaerobic processes are not designed for nitrification ([Figure 5](#)). The modest reduction likely resulted from microbial assimilation and possible stripping due to biogas production.

In stark contrast, the aerated lagoon achieved substantial ammonia removal, averaging 94%. This high efficiency confirms the establishment of active nitrifying bacteria (*Nitrosomonas* and *Nitrobacter*), which convert ammonia to nitrate in the presence of dissolved oxygen. The observed decline in removal efficiency at the highest organic loads suggests that heterotrophic bacteria, thriving on the abundant carbon, may have outcompeted the slower-growing nitrifiers for oxygen and space, a phenomenon well-documented in combined carbon and nitrogen removal systems ([Cao et al., 2021](#)). This presents a clear optimization target: balancing the organic load to the aerobic stage to ensure effective nitrification alongside carbon removal.

### 3.4. Removal and Mechanism of Trace Metals

The UASB reactor proved highly effective in removing trace metals, a significant advantage for landfill leachate treatment. As depicted in Figures 6 and 11, removal efficiencies for Zn, Mn, Cu, and Fe were consistently high (70-99%), while Ni removal was more variable and lower (46-97%).

The primary removal mechanism is not biological degradation but physicochemical sequestration under anaerobic conditions. Sulfide ions ( $S^{2-}$ ), generated by Sulfate-Reducing Bacteria (SRB), react with dissolved metal cations to form highly insoluble metal sulfide precipitates (e.g., ZnS, CuS). Simultaneously, the rise in pH within the reactor favors the precipitation of metal hydroxides.

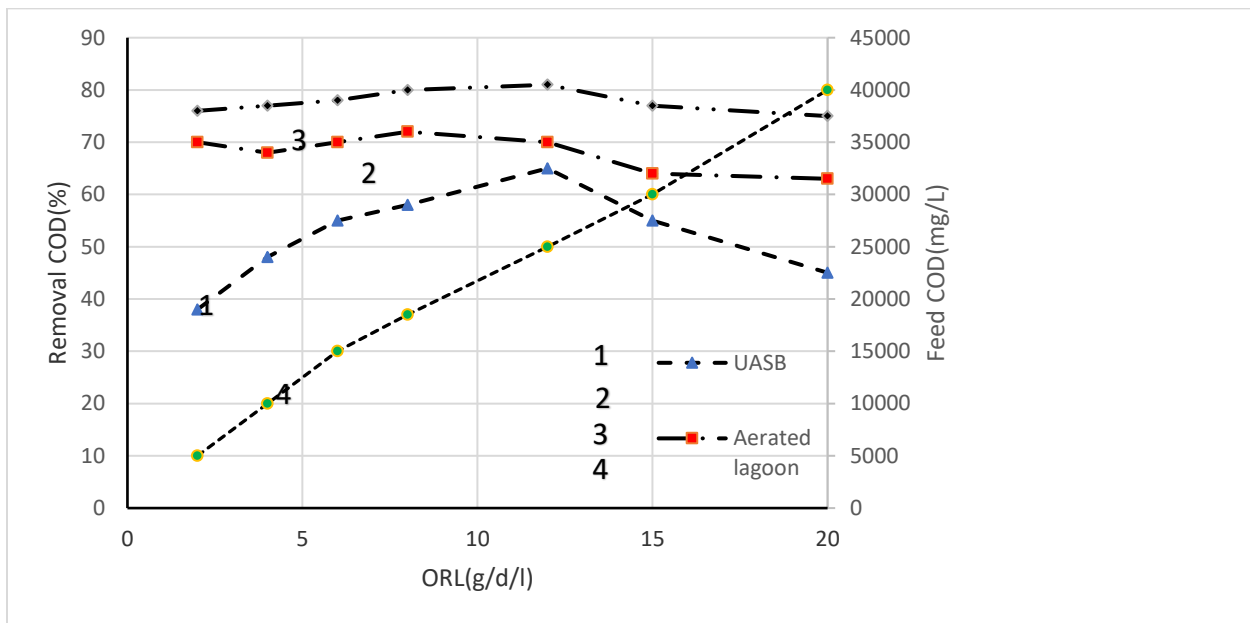


Figure 3. COD removal rate with increasing organic load rate (OLR)

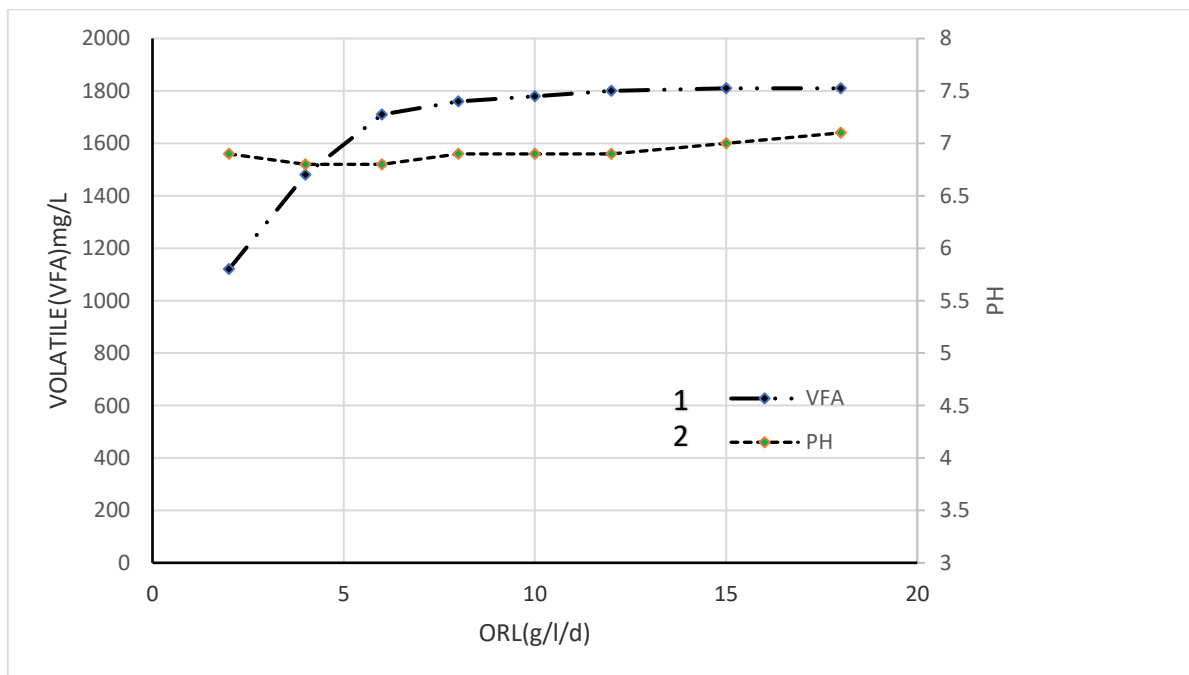
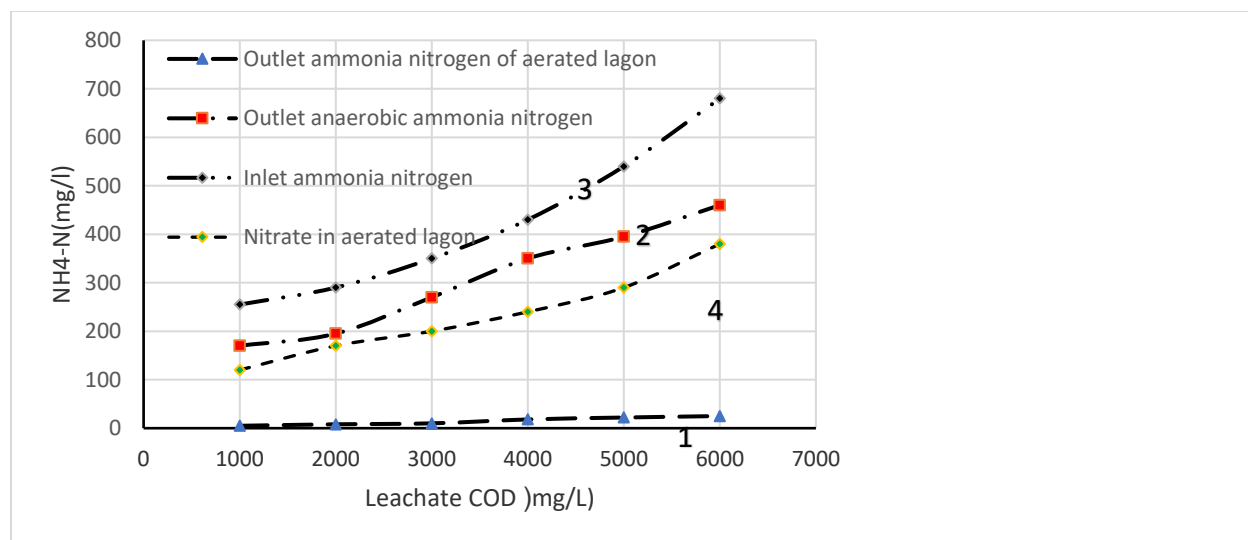


Figure 4. pH changes and volatile acids in the UASB reactor



**Figure 5.** Nitrogen changes in anaerobic and aerobic reaction

These precipitates become entrapped within the dense sludge blanket. The high efficiency for metals like Cu and Zn aligns with the low solubility products of their sulfides, as reported by Liu et al. (2024). The sub-optimal and inconsistent removal of Ni may stem from its comparatively higher solubility or the formation of weaker complexes under the prevailing reactor conditions, indicating a need for targeted investigation or supplementary treatment for this specific metal.

### 3.5. Biomass Dynamics and Sludge Bed Stratification in the UASB Reactor

The performance of a UASB reactor is intrinsically linked to the development and spatial organization of its microbial biomass, primarily tracked through Volatile Suspended Solids (VSS). In this study, long-term monitoring of the reactor bottom revealed a robust and continuous accumulation of biological solids. VSS concentrations increased progressively from 45,000 mg/L to 80,000 mg/L over the 180-day experimental period (Table 5, Figure 7). This positive trajectory indicates successful microbial acclimatization to the high-strength leachate and effective retention of anaerobic biomass, a fundamental prerequisite for stable operation under varying organic loads. The sustained growth suggests that inhibitory compounds in the Aghajari leachate did not critically impair the anaerobic consortium, allowing for the establishment of a resilient microbial

community.

Beyond total accumulation, the vertical stratification of biomass within the reactor provides deeper insight into the sludge bed's physical and functional maturity. A systematic sampling campaign after six months of operation revealed a definitive concentration gradient (Table 6, Figure 8). VSS levels were highest at the lowest sampling point (~85,000 mg/L) and declined steadily with height, reaching approximately 65,000 mg/L at the mid-level ports before dropping to near-zero in the upper reactor section. This pronounced gradient is a classic hallmark of a well-formed granular sludge bed. It results from the gravitational settling of dense, mature microbial granules, which form the core of the treatment process at the reactor base.

The consistent low VSS concentration in the upper sections confirms that the upward flow velocity was sufficiently low to prevent significant washout of settled biomass, allowing clear phase separation between the sludge blanket and the treated effluent. The point at which the VSS concentration plateaus at a minimal level (around valve 6 in this setup) effectively defines the operational height of the active sludge bed, a critical parameter for reactor design and performance assessment. This stratification underscores the successful formation of settleable biomass aggregates, which are essential for maintaining high solids retention time (SRT) independent of hydraulic retention time (HRT).

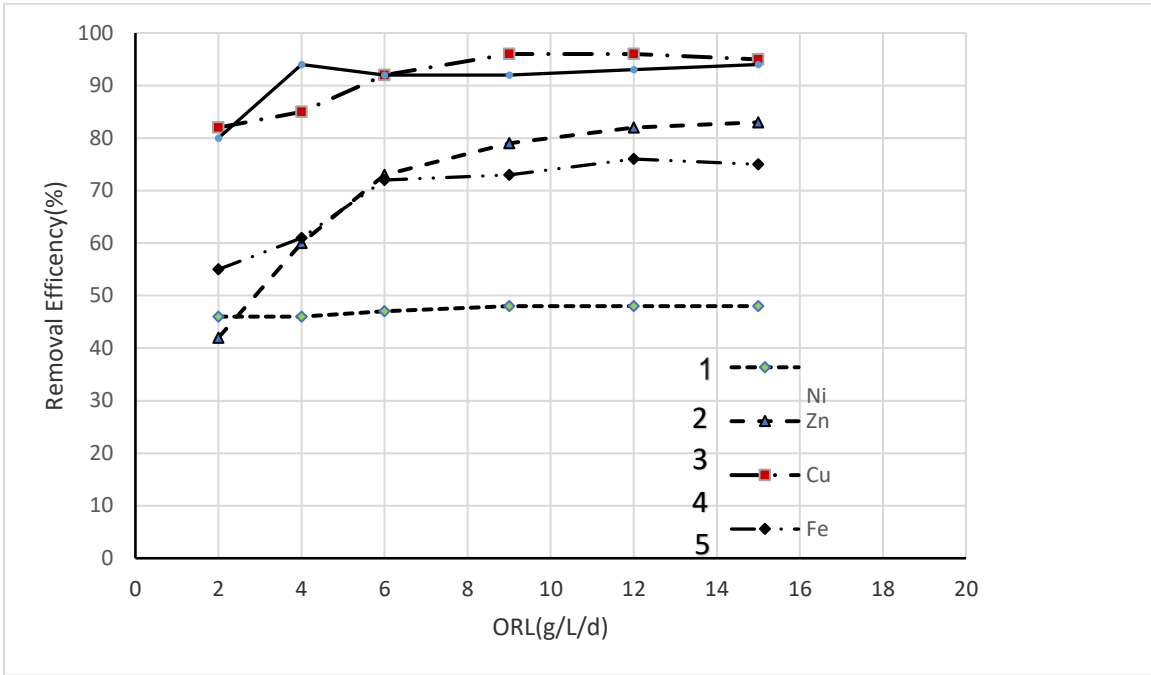


Figure 6. Removal of Trace metals in the UASB reactor

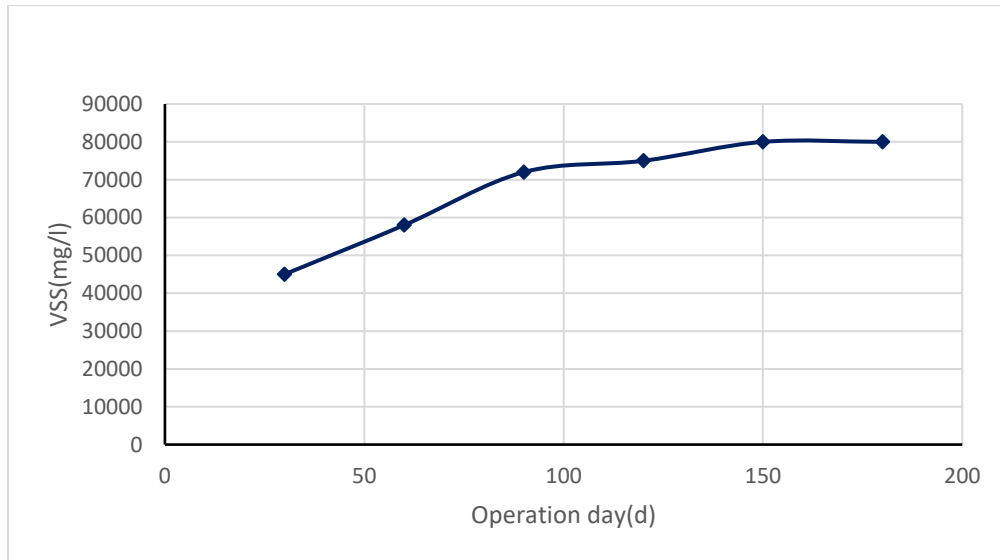


Figure 7. VSS concentrations from the second sampling valve at the bottom of the reactor

Table 5. (VSS) concentrations from the second sampling valve at the bottom of the reactor

day	30	60	90	120	150	180
VSS (mg/L)	45000	58000	72000	75000	80000	80000

### 3.6. Granulation Process and its Impact on Effluent Solids Quality

While biomass growth was evident, the system's ability to form a fully optimized granular sludge bed and achieve consistent solids-liquid separation was challenged by the selected hydraulic regime. The influent Total Suspended Solids (TSS) concentration averaged 1700 mg/L. However, the effluent TSS profile was highly dynamic, with concentrations initially rising and peaking at approximately 3500 mg/L around the 90-day mark before gradually declining (Figure 9). This pattern points to a suboptimal granulation process, primarily governed by the low applied upflow velocity of 0.05 m/h.

In UASB technology, a sufficient upflow velocity is not merely for distribution; it acts as a vital selection pressure. As emphasized by Gagliano et al. (2020), velocities in the range of 0.3-1.0 m/h are typically required to continuously wash out light, dispersed, and flocculent biomass that has poor settling characteristics. The low velocity of 0.05 m/h in this study was insufficient to provide this selective force. Consequently, less-dense, non-granular flocs accumulated within the sludge bed. These flocs have lower sedimentation rates and are prone to periodic, erratic washout during flow variations or gas production, directly explaining the spikes and high variability observed in the effluent TSS data. This phenomenon is visually corroborated by the comparison of inlet and outlet TSS across different OLRs (Figure 10), which shows the system often failed to reduce, and sometimes even increased, the solids load in the effluent.

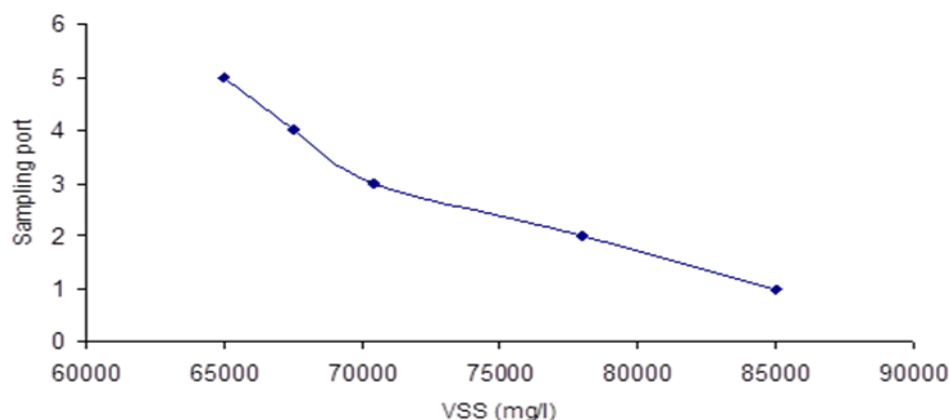
It is noteworthy that granules sampled from the lower bed region were 1-2 mm in diameter, confirming that granulation was initiated. However, the persistent high effluent TSS indicates that the process was incomplete. The reactor environment fostered the growth of anaerobic biomass but lacked the hydraulic shear necessary to selectively retain only the densest, fastest-settling granules—a process crucial for developing a sludge bed with superior settling properties and producing a clear effluent. Therefore, optimizing the upflow velocity is identified as the key engineering parameter to transition from a system with active biomass to one with a truly granular, high-performance sludge bed.

### 3.7. Mechanisms and Performance Variability in Trace Metal Sequestration

The UASB reactor proved to be a highly effective bioreactor for the immobilization of trace metals, a significant advantage for landfill leachate treatment where metals pose a long-term environmental risk. Removal efficiencies for Zinc (Zn), Manganese (Mn), Copper (Cu), and Iron (Fe) were consistently robust, frequently exceeding 85-95% across the tested Organic Loading Rates (OLRs) (Figures 6 & 11). The dominant removal mechanism is abiological precipitation within the anaerobic milieu. Sulfate-reducing bacteria (SRB), integral members of the anaerobic consortium, generate sulfide ( $S^{2-}$ ) as a metabolic end-product. Dissolved metal ions readily react with sulfide to form highly insoluble metal sulfide precipitates (e.g., ZnS, CuS, FeS).

**Table 6.** VSS concentrations at various heights

Sampling part	1	2	3	4	5
VSS(mg/L)	85000	78000	70400	67550	65000



**Figure 8.** The VSS concentrations at various heights

Concurrently, the stable, neutral-to-alkaline pH maintained in the reactor (Section 3.2) favors the precipitation of metal hydroxides. These insoluble compounds are effectively trapped and concentrated within the dense, stationary sludge blanket. This mechanism aligns with findings from other high-sulfate wastewaters, such as those reported by Liu et al. (2024), and underscores the dual benefit of UASB systems: organic matter degradation coupled with passive metal removal.

In contrast, the behavior of Nickel (Ni) was markedly different and less effective. Its removal efficiency was not only lower on average but also exhibited high variability (46-97%) with no discernible correlation to OLR (Figure 11). This inconsistent performance suggests that nickel removal is governed by a more complex set of physicochemical and possibly biological interactions.

Potential explanations include: 1) the higher solubility product of nickel sulfide (NiS) compared to sulfides of Zn, Cu, or Cd, leading to less spontaneous precipitation; 2) competition with other abundant cations (e.g., Fe<sup>2+</sup>) for the limited sulfide pool; or 3) the formation of soluble nickel-organic complexes with compounds present in the leachate, which shield the nickel ion from precipitation reactions. This variability and lower removal efficiency highlight a critical treatment gap. For leachates with significant nickel content, the standard UASB process may require supplementation, such as post-treatment adsorption or the careful dosing of specific precipitants, to meet stringent regulatory limits. The data strongly indicate that metal removal in a UASB is not uniform and must be evaluated on a metal-by-metal basis, considering the specific geochemical matrix of the wastewater.

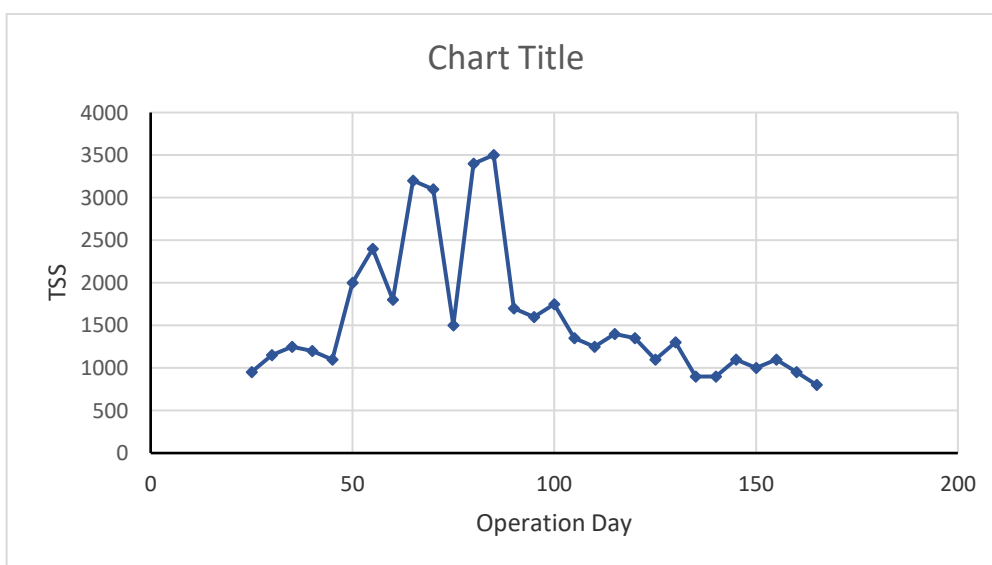


Figure 9. The amount of TSS in the outlet of the UASB reactor during the operation

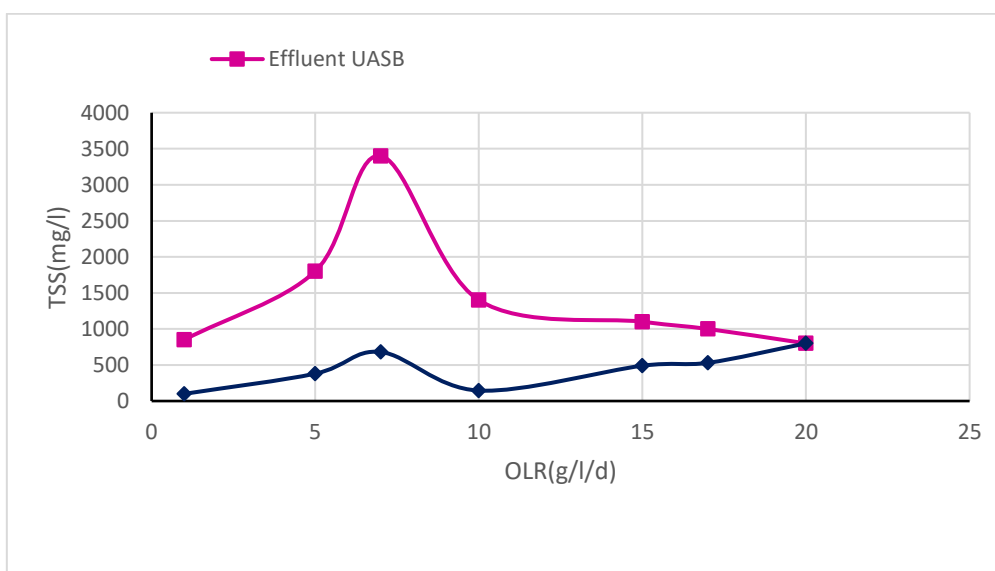


Figure 10. The amount of TSS in the inlet and outlet of the UASB reactor due to OLR increase

### 3.8. Integrated Performance Analysis: Synergies and Operational Constraints

The collective data from this study paint a comprehensive picture of the integrated UASB-aerated lagoon system's capabilities and its operational boundaries. The UASB reactor served as a potent primary treatment unit, adept at dismantling high organic loads (COD removal up to 79%) and immobilizing a broad spectrum of trace metals through synergistic biological and chemical pathways. Its performance window was clearly defined, with an optimal OLR around 12 g/L·d, beyond which acidogenic imbalance threatened stability.

The subsequent aerated lagoon fulfilled its role as an effective polishing stage, achieving remarkable nitrification (~94% NH<sub>3</sub>-N removal) and further COD reduction. However, its efficiency was contingent on the quality of the UASB effluent, diminishing when faced with shock loads of residual organics, thereby demonstrating the interdependence of the two stages.

The most salient operational constraint identified was hydrodynamic. The deliberately low upflow velocity (0.05 m/h), while conserving biomass, inadvertently hindered the evolution of a mature granular sludge. This led to the core challenge of poor solids separation, as evidenced by the erratic and often high effluent TSS. This finding has direct practical implications: scaling this promising hybrid technology requires a paradigm shift from focusing solely on metabolic performance to equally prioritizing the hydraulic engineering that shapes the sludge microbiome's physical structure. Future implementations must carefully balance the hydraulic selection pressure to foster granulation without causing biomass washout, thereby unlocking the full potential of the UASB stage for both organic and solid pollutant removal.

### 3.9. Temperature and pH

Temperature and pH are critical operational parameters in Upflow Anaerobic Sludge Blanket (UASB) reactors. For effective mesophilic operation, temperature must be maintained above 25°C, while the internal pH should remain within a narrow range of 6–8 to sustain methanogenic bacterial activity. In this study, challenges with both parameters were observed during reactor operation. Figure 12 illustrates the temporal variations in temperature and pH throughout the experimental period, with the x-axis representing operational time (days) and the y-axis denoting the corresponding parameter values. Throughout the first three months, both temperature and pH remained within optimal UASB operating ranges without significant fluctuation. However, after 90 days of operation, the reactor temperature decreased to 16°C, and

by day 95, the effluent pH had increased to 8.9. This pH elevation can be attributed to the transition into methanogenic phase, where alkalinity production exceeds acid generation—an indication of the system's inherent stability against volatile fatty acid (VFA) accumulation during acidogenesis. To restore optimal conditions, corrective measures were implemented. Concentrated hydrochloric acid was introduced into the influent stream, adjusting the inlet pH to 5.4. This intervention successfully stabilized the UASB effluent pH within the target range of 7–8. Concurrently, to address the temperature decrease, a warm-water circulation system connected to an external heater was installed around the reactor, raising the operational temperature to approximately 27°C. These adjustments demonstrate the system's responsiveness to controlled interventions and underscore the importance of continuous monitoring and adaptive management in maintaining stable anaerobic treatment performance.

### 3.10. Fate and Management of Metal-Enriched Sludge: A Critical Evaluation

A principal outcome of metal sequestration in the UASB reactor is the transfer of contaminants from the leachate into the sludge biomass, generating a concentrated solid residue. While this purifies the effluent, it creates a consequential waste stream requiring managed disposal to prevent secondary pollution. The stability of the sequestered metals—predominantly as sulfides and hydroxides—is inherently linked to the sludge's reducing, neutral-to-alkaline environment. Exposure to oxidizing conditions during subsequent handling, dewatering, or disposal risks the resolubilization of metals like Fe and Mn, and could mobilize the more variably removed Ni. Consequently, this sludge transitions from a biological by-product to a potential repository of hazardous materials. Sustainable process integration, therefore, mandates a strategy for this metal-laden sludge. Viable management pathways include:

**Stabilization/Solidification:** Using binders (e.g., cement, lime) to immobilize metals within a monolithic matrix, thereby reducing leachability to meet regulatory standards (e.g., TCLP).

**Secure Monofilling:** The final disposal of stabilized, dewatered sludge in engineered hazardous waste landfills.

**Resource Recovery:** For sludges with high concentrations of valuable metals (e.g., Cu), techniques like bioleaching could be explored for metal extraction, aligning with circular economy goals, though economic feasibility must be confirmed. A critical next step for this technology's application is a detailed characterization of the UASB sludge, employing sequential extraction and leaching tests (e.g., TCLP) to define its stability and classify its hazard potential. This completes the treatment lifecycle assessment and is essential for designing a compliant and environmentally sound sludge management protocol.

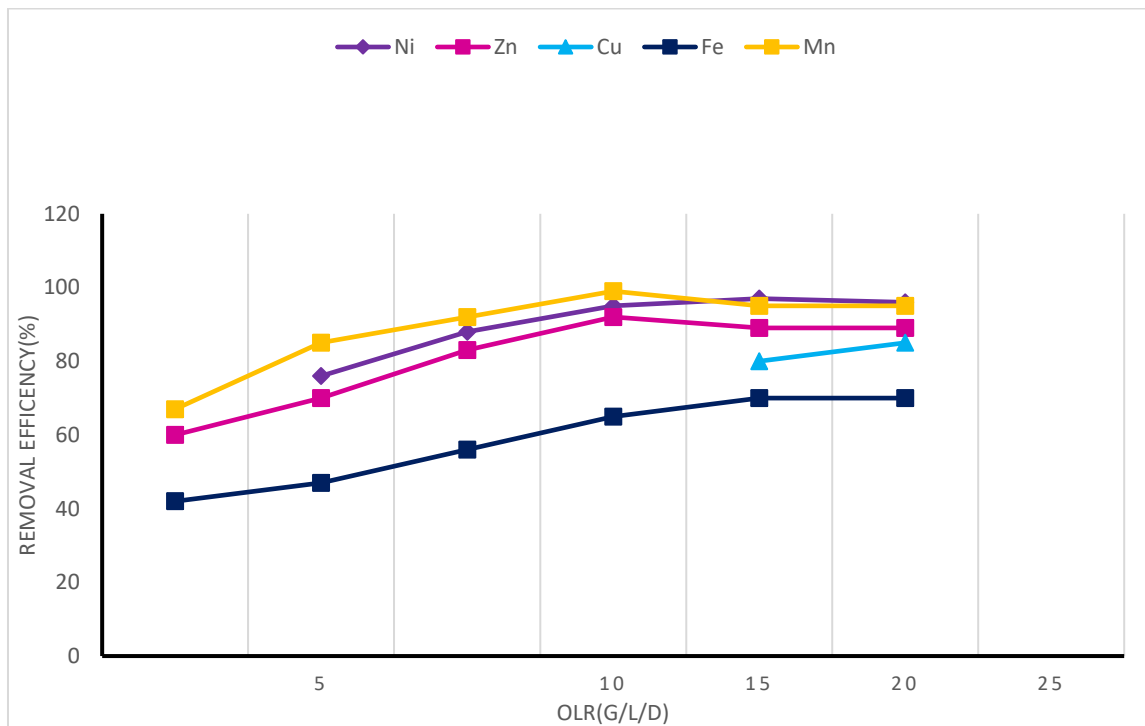


Figure 11. Trace Metals Removal Efficiency with Increasing Organic Load

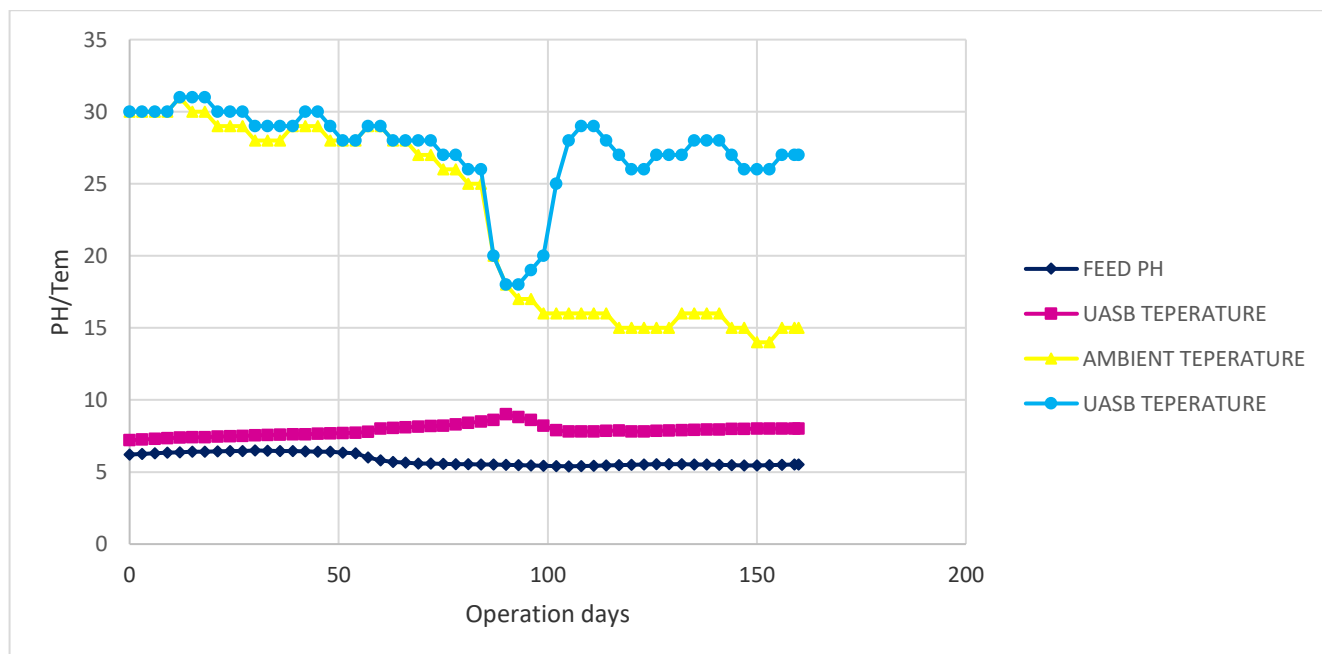


Figure 12. Variations in temperature and pH during UASB system operation

### 3.11. Study Limitations and Future Research Directions

#### 3.11.1. Limitations of the Study

While this study provides valuable insights into the performance of the integrated UASB-aerated lagoon system, several limitations should be acknowledged:

The research was conducted at a laboratory/pilot scale. The system's performance under full-scale, real-world conditions—including flow fluctuations, seasonal temperature variations, and changing leachate composition—remains to be validated.

The study focused on leachate from the specific Aghajari landfill. The findings may not be directly generalizable to leachates with significantly different characteristics, such as age, composition, or pollutant concentrations.

The operational period, though sufficient for acclimatization and performance assessment, was limited. Long-term effects, including sludge aging, potential accumulation of inhibitors, microbial community shifts, and the stability of metal precipitates within the sludge bed, were not evaluated.

The suboptimal granulation and TSS removal, linked to the low upward velocity (0.05 m/h), represent a constraint identified but not optimized within the experimental design, limiting maximum system efficiency for solids separation.

The removal efficiency for Nickel (Ni) was comparatively lower and inconsistent. The specific mechanisms limiting Ni removal and strategies for its enhancement were not deeply investigated.

### 3.12. Future Research Directions

Based on the findings and limitations, the following avenues for future research are proposed:

**Scale-up and Optimization:** Conduct pilot or full-scale studies to validate performance under field conditions. Focus on optimizing critical parameters, particularly the upflow velocity (towards the recommended 0.3 m/h) and Hydraulic Retention Time (HRT), to improve granulation, TSS removal, and overall process stability.

**Mechanistic and Microbial Insights:** Employ advanced molecular techniques (e.g., metagenomics) to characterize the evolution and functional dynamics of microbial communities under varying organic loads. Investigate specific pathways and consortia responsible for trace metal immobilization, particularly for challenging metals like Nickel.

**Long-term Performance and Sludge Management:** Perform long-duration studies to assess system resilience, sludge production rates, and the long-term fate and stability of sequestered metals within the sludge. Develop and evaluate strategies for the safe handling, disposal, or resource recovery from metal-laden sludge.

**Process Integration and Enhancement:** Explore integrating this hybrid system with a complementary polishing step (e.g., adsorption, advanced oxidation) to further reduce residual nutrients (ammonia, nitrate) and refractory organic compounds. Investigate targeted pre- or post-treatment methods to specifically enhance Nickel removal efficiency.

**Broad Applicability Assessment:** Test the efficacy of the integrated UASB-aerated lagoon system on leachates from landfills of different ages and waste compositions to determine its broader applicability and define optimal operational ranges for varied influent characteristics.

**Sludge Characterization and Management:** Investigate the leaching potential (e.g., via TCLP), chemical speciation, and long-term stability of metals in the accumulated UASB sludge under different storage conditions. Develop and evaluate integrated downstream processes for sludge

stabilization (e.g., solidification) or explore the feasibility of selective metal recovery to close the material loop and ensure a truly sustainable treatment solution.

## 4. Conclusion

Landfill leachate presents a persistent environmental challenge due to its complex and variable matrix of high-strength organics, ammonia, and trace metals. This study demonstrates that an integrated Upflow Anaerobic Sludge Blanket (UASB) reactor and aerated lagoon system constitutes a viable, energy-efficient treatment train for such recalcitrant wastewater, particularly in hot, arid regions like Aghajari. Beyond validating its core efficacy, our investigation delivers critical insights that refine the application guidelines and highlight targeted research priorities for advancing sustainable leachate management. The system's performance underscores a synergistic division of labor. The UASB reactor served as the workhorse for primary degradation, achieving a peak COD removal efficiency of 79% at an optimal organic loading rate (OLR) of 12 kg COD/m<sup>3</sup>·d under naturally thermophilic conditions (25–27°C). This stage also proved remarkably effective as a biogeochemical trap for trace metals, with removal efficiencies exceeding 90% for Zn, Cu, and Mn, primarily through in-situ precipitation as insoluble sulfides and hydroxides. This dual function—high-rate organic removal coupled with passive metal immobilization—represents a significant advantage, reducing the pollutant load before the energy-intensive aerobic stage. The subsequent aerated lagoon then excelled as a polishing unit, achieving ~94% ammonia removal via robust nitrification, a task for which anaerobic systems are inherently unsuited.

However, this research transcends performance reporting by identifying and explaining two pivotal constraints that define the system's operational envelope and scalability. First, we reveal a fundamental engineering-design imperative: the applied upflow velocity of 0.05 m/h was insufficient to promote the formation of a dense, granular sludge bed. The resulting predominance of flocculent biomass led to poor settling characteristics and variable effluent TSS, highlighting that optimal UASB performance is co-dependent on appropriate hydraulic selection pressure, not just microbial activity. For full-scale implementation, operating at a higher velocity (~0.3–1.0 m/h) is non-negotiable to ensure effective granulation, clear effluent, and enhanced volumetric capacity. Second, we provide a nuanced, metal-specific account of contaminant fate that exposes a critical treatment gap. While the sequestration of most target metals was highly efficient, the removal of Nickel (Ni) was inconsistent and comparatively lower. This finding is crucial; it

demonstrates that biological sulfide precipitation is not a panacea and that the geochemical behavior of individual metals within the complex leachate matrix dictates removal efficiency. The recalcitrance of Ni signals the need for integrated, targeted tertiary treatment—such as adsorption or specific chemical precipitation—to meet stringent discharge standards, guiding future hybrid system design. In conclusion, this work validates the UASB-aerated lagoon system as a robust framework for decentralized leachate treatment in challenging environments. Its principal contributions are threefold: (1) providing a climate-adapted, synergistic treatment model, (2) establishing hydraulic velocity as a key driver of sludge ecology and effluent quality in UASBs treating solid-rich streams, and (3) delineating the specific limitations of biological metal removal, with Ni identified as a priority pollutant for supplementary treatment. To realize this system's full potential, subsequent research must focus on optimizing the hydraulic regime for granulation, developing cost-effective polishing steps for nickel and residual recalcitrant organics, and formulating sustainable management strategies for the resultant metal-enriched sludge. This pathway bridges mechanistic understanding with practical engineering, offering a tangible route toward more resilient and circular leachate management solutions.

#### Authors Contribution

All authors have contributed equally to prepare the paper.

#### Availability of data and materials

The data that support the findings of this study are available from the corresponding author, upon reasonable request.

#### Conflict of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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