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LANDFILL EVOLUTION AND TREATABILITY ASSESSMENT OF HIGH-STRENGTH LEACHATE FROM MSW WITH HIGH ORGANIC AND MOISTURE CONTENT

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The generation of contaminated leachate remains an inevitable consequence of the practice of solid waste disposal in landfills. The collection and treatment of leachate have become common practice in order to prevent environmental pollution. Leachate treatment is highly dependent on the quality of leachate, which in turn is influenced by various factors including waste composition and operational procedures. This paper investigates the treatability of high-strength leachate from pre-sorted and baled municipal solid waste characterized by high organic and moisture content. For this purpose, waste disposal and leachate generation rates were monitored. Leachate samples were collected and analysed for selected indicators including BOD, COD, pH, and NH_4-N and a pilot scale treatment plant with coagulation, precipitation and sequential batch biological reactors was constructed to evaluate the feasibility of leachate treatment. Concentration levels were related to biological activity within the landfill and the results indicated that (1) pre-sorting and baling of the waste did not hinder waste stabilization; and (2) the high organic and moisture contents resulted in an extremely strong leachate, particularly at the onset of biodegradation processes, which can affect the leachate treatment facility. The effectiveness of the pilot plant in treating the leachate exceeded 90% using COD and NH_4-N as indicators.

Keywords: Solid waste; High organic content; Pre-sorting; baling; Leachate quality; Landfill stabilization; Leachate treatment; Sequential batch reactor

I. INTRODUCTION

Economic considerations continue to keep landfills as the most attractive disposal route for municipal solid waste (MSW). Alternatives to landfilling (e.g. incineration, composting) are considered as volume reduction processes because they produce waste fractions (e.g. ashes, slag) that ultimately must be disposed of. As waste is deposited into a landfill, leachate is formed when the refuse moisture content exceeds its field capacity. This process is influenced

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by many factors, which can be divided into those that contribute directly to landfill moisture (rainfall, initial moisture content, etc) and those that affect leachate or moisture distribution within the landfill (refuse age, compaction, etc). While increased moisture content is the major contributor to leachate formation, it is also commonly associated with enhancing biodegradation processes in landfills [1–3]. Indeed, it is not unusual to design a landfill cover to capture water (i.e. increase infiltration) to enhance biodegradation, thus promoting rapid stabilization and reducing the time required for the return of the landfill to beneficial land use [4].

Leachate formation is of great environmental concern because soluble organic and inorganic compounds are encountered in the refuse at emplacement or are formed as a result of chemical and biological processes within the landfill. The composition of landfill leachate can exhibit considerable spatial and temporal variations depending upon site operations and management practices (pre-treatment, irrigation, recirculation, liquid waste co-disposal), refuse characteristics (composition, age, moisture content) and internal landfill processes (hydrolysis, adsorption, biodegradation, contact time, partitioning, precipitation, gas generation, etc) [5]. While it is difficult to generalize as to the concentration of a particular chemical in leachate at a specific time, in most cases, concentrations increase during a relatively short initial phase. Afterwards, concentrations decrease with time [6–10].

Various physical, chemical, and biological treatment processes have been investigated in the last two decades to evaluate the treatability of leachate from landfills [11–13]. Applicable types of treatment depend on the leachate quality and quantity as well as the desired treatment level. The present study evaluates monitoring data from an 18-month field scale investigation at a landfill site with the objectives (1) to define the potential effects of waste composition (high organic and moisture content) and operational procedures (pre-sorting and baling) on biodegradation processes and leachate quality, and (2) to assess the treatability of the leachate at a pilot scale treatment plant with coagulation, precipitation, and sequential biological batch reactors. For this purpose, leachate generation rates were recorded alongside the amount of waste deposited. Chemical analysis was performed on leachate samples collected periodically from the landfill and several parameters were monitored including Biological Oxygen Demand (BOD), Chemical Oxygen Demand (COD), pH, and ammoniacal-nitrogen (NH_4-N). Concentrations were then related to biological activity within the landfill and a pilot plant was constructed and operated for a period of 12 months to evaluate the effectiveness of the system in treating the leachate using COD and NH_4-N as indicators.

II. LANDFILL CHARACTERIZATION AND OPERATIONAL PROCEDURES

The landfill, which is the site of an abandoned quarry that was converted to a MSW disposal facility, is located 16 km south of Beirut (Lebanon) and 4 km inland (from the Mediterranean sea) at an average altitude of 250 m above mean sea level. The landfill is planned for development over an area of 20 ha approximately, and receives about 1700 to 2100 tonnes/day of waste generated from the Beirut area and its surroundings. The landfill will have an expected active life of 10 years with a final waste height exceeding 45 m.

Following its collection, the waste is transported into a sorting and processing facility where large items (i.e. cardboard, PVC plastic containers), the recyclable waste fraction (i.e. glass, metals), and a fraction of compostable organic food waste are removed. After the sorting process, the waste is compacted under a 190 to 250 bar pressure into bales ($\sim 1.1 \times 1.1 \times 1.75\,m^3$) prior to disposal into the landfill, which consists of three cells with different areas and capacities (Table I). The baling process increases the waste density from

TABLE I Areas and capacities of landfill cells

Cell	*Area (m^2)*	*Expected waste capacities (tonnes)*
1	77 800	1 362 167
2	52 609	928 108
3	63 800	1 009 725
Total	194 209	3 300 000

0.40–0.55 tonnes per cubic metre (T/m^3) to 0.6–0.8 T/m^3. The corresponding average field and saturation capacities are about 45 and 55%, respectively.

In the raw waste stream originating from Beirut, food waste constitutes about 65% of the waste stream resulting in a relatively high moisture (60 to 70%) [14, 15]. Sorting and processing alters the initial composition. Nevertheless, the food fraction remains high since a minor fraction of the initial food content is removed. Moreover, many other components (glass, metals, paper and cardboard, etc) are sorted out in relatively larger fractions, reducing the total amount of waste and hence increasing the food fraction. This translates directly into a lower absorptive capacity and a significant increase in leachate generation potential [16]. Composition of waste before and after the sorting and processing phases are summarized in Table II.

III. LEACHATE GENERATION

While waste disposal at the site started in October 1997, measuring leachate generation rates was not initiated until April 1998. Figure 1 depicts the quantities of leachate collected and waste deposited from 1998 to 2000.

The equivalent average leachate generation during this period was about 150 litres of leachate per ton of refuse, which is relatively high for pre-sorted waste. This large amount can be attributed to the large fraction of organic matter and moisture remaining in the waste stream and the contribution of rainfall infiltration (~ 800 mm per year) to leachate formation, particularly during the operation phase when the final cover is not in place.

TABLE II Waste composition before and after sorting and processing

Waste category	*(% wet weight)*	
	Before sorting and processing	*After sorting and processing*
Putrescibles	60.8	45.2
Paper/cardboard	19.8	15.9
Plastics	9.6	8.071
Rubber (tires)	0.1	0.04
Glass	5.7	4.87
Metal	1.6	0.2
Yard waste	0.1	0.1
Wood	0.2	0.1
Other (textile, leather)	1.6	1.6
Unclassified (mixed refuse)	0.5	0.5

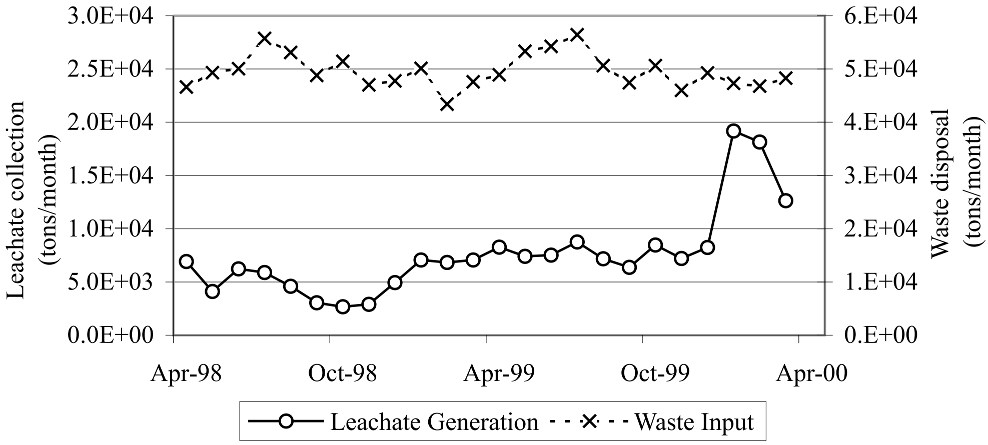

FIGURE 1 Leachate collected and waste deposited from 1998 to 2000.

IV. LEACHATE CHEMICAL ANALYSIS

In addition to a high initial moisture content, depolymerization and hydrolysis reactions of solid substrates during the aerobic degradation will increase the moisture content of the baled waste [17]. After placement and self-compaction in the landfill, the density of the baled waste may reach 0.9 T/m^3 while the field capacity can decrease to 40%. Naturally, this will result in a significant release of leachate. The effects of waste pre-sorting and baling at the site are noticeable in the leachate chemical quality data, as will be discussed.

Based on previous studies [8], since the refuse is delivered as unshreded bales, slower biodegradation and leachate flow with a relatively low contaminant concentration are expected. This was not the case because the waste in the previous studies was below field capacity and hence moisture infiltrated the bales. In this study, the waste is deposited with initial moisture content above field capacity and hence moisture will be squeezed out of the bales. Lower biodegradation rates due to baling do not seem to prevail at the landfill site. In fact, shifting to methanogenic conditions has occurred over an exceptionally short period of about one year. This can be attributed to two factors: (1) the high organic fraction and an initial moisture content that equals or exceeds field capacity leading to a significant biological activity and depletion of available oxygen, and (2) low porosity of the refuse (owing to the high compaction ratio) which prevents air from entering the refuse layers.

IV.1. Chemical Analysis Methods

The methods of analysis, detection limits and reference methods used to characterize raw and treated leachate are presented in Table III.

IV.2. Leachate Quality

The BOD/COD ratio can be considered as a measure of the biodegradability of the organic matter, and hence of the maturity of the leachate and the landfill, which typically decreases with time [13]. A BOD/COD ratio greater than 0.5 indicates a young landfill, whereas when the ratio is less than 0.1, the landfill can be considered old and stable [18]. Other useful leachate parameters include pH, an indicator of the aggressiveness of the leachate and aerobic

TABLE III Method of analysis, detection limits and reference methods

Parameter	*Method of analysis*	*Detection limit*	*Reference method*
PH	pH / Titra meter	NA	SM 4500-H^-
Chemical Oxygen Demand (COD)	Spectrophotometer	10 mg/l	SM 5220 D
Biochemical Oxygen Demand (BOD)	Oxygen meter	2 mg/l	SM 5210 B
Ammonia Nitrogen (NH4-N)	Spectrophotometer	NA	SM 4500-NH_3

SM = *Standard Methods for the Examination of Water and Wastewater,* 20th edn
NA = Not applicable

versus anaerobic conditions in the refuse. NH_4-N seems to be the constituent that lasts longer in landfill leachate and may be used to determine the remaining pollution potential in the landfill and the required after-care period [19]. In this study, a leachate quality monitoring programme was initiated at the subject site in July 1998. Leachate parameters including BOD, COD, pH and NH_4-N concentrations were monitored (Figure 2, a–d).

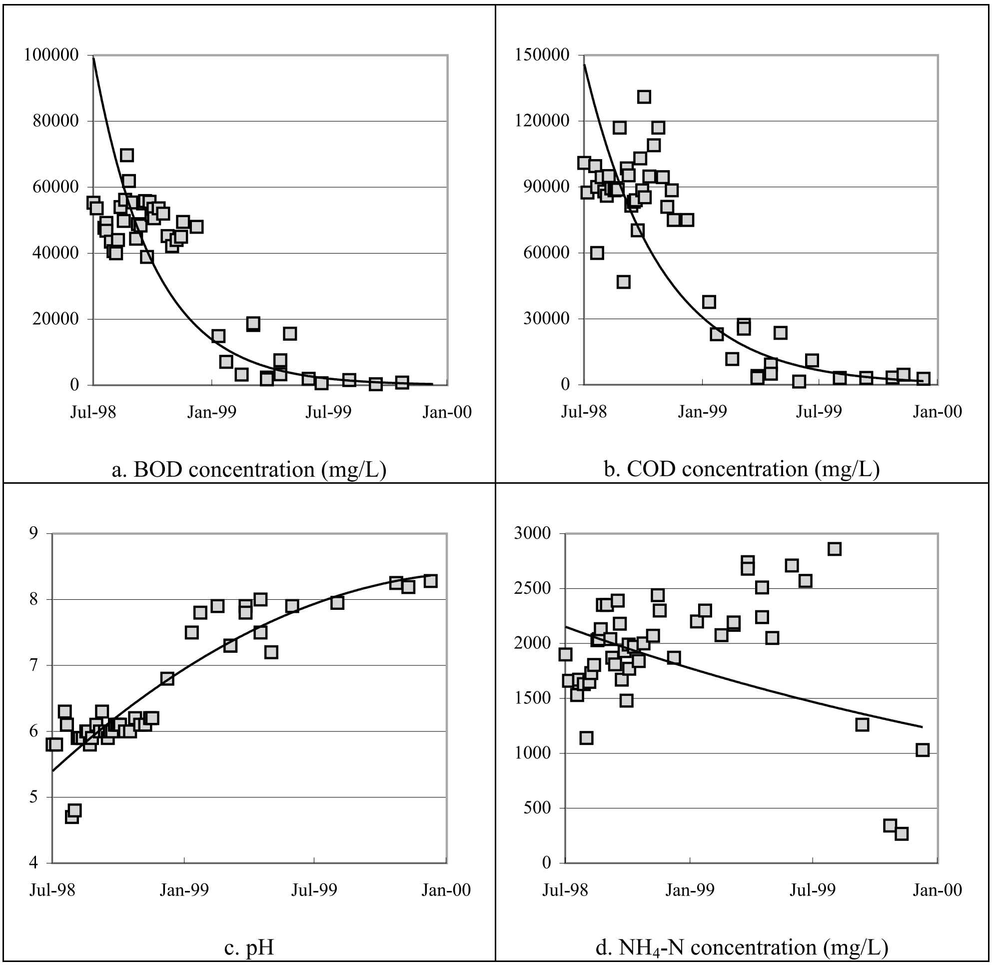

FIGURE 2 Leachate quality for selected parameters.

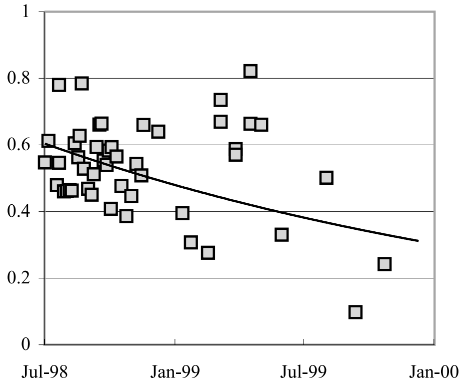

FIGURE 3 BOD/COD ratio in the leachate.

The onset of the methanogenic phase appears to have been very rapid. Parameters correlated to the “age” of the landfill exhibited a shift towards anaerobic phase characteristics within a relatively short period after waste deposition. Around 14 months after the start of the operations, the pH had risen above 7, indicating optimal conditions for methanogenesis and the BOD/COD ratio had fallen below 0.3 (Fig. 3). Even though the newly deposited layers at the top of the landfill may exhibit acetogenic characteristics, the leachate collected emanates from the bottom layers or has been residing in these layers long enough to shift its bacterial activity to anaerobic.

The data collected were fitted with trendlines to represent the average temporal variations. However, the fitted trendline should be considered with care in view of the short time span. The concentration of most contaminants is currently in a fast declining stage. Ultimately, the concentration will stabilize or decrease very slowly. Hence, the rate of concentration decrease, depicted by the trendlines, is not expected to hold in the future. Despite the above-mentioned shortcomings, several inferences can be made from the available data to yield an understanding of the leachate quality expected at the site.

- Initial BOD and COD levels are high compared with the data reported in the literature [18, 20]. Initial BOD levels of 50 000 mg/l are above the 5000 to 30 000 mg/l range usually observed in landfills. However, BOD values of 1000 mg/l at the end of the monitoring time span, 2 years after disposal at the site started, are typical of 10-year old landfills [18]. Similarly, initial COD levels of 100 000 mg/L are above the typically encountered range of 10 000 to 60 00 g/L [18]. The COD drops sharply after 2 years to around 3000 mg/L, a level usually found in leachates of 15 year old landfills [18, 20]. The behaviour of the BOD and COD trendlines can be attributed to the high initial organic and moisture contents leading to significant biological activity and oxygen demand during this stage. The quick depletion of readily biodegradable matter and the drainage of excess moisture contribute to the sharp reduction in biological activity and hence the observed decrease in COD and BOD levels.
- pH variation confirms the conclusions that were based on COD and BOD variations. pH starts at 5.5 and increases to around 8 within 2 years after the start of operations at the site. Alkaline pH (>7) is normally encountered at landfills 10 years after waste disposal [18, 20].
- NH_4-N concentrations fluctuate very little during the monitoring period. NH_4-N represents constituents that are slightly affected by biodegradation or physico-chemical attenuation

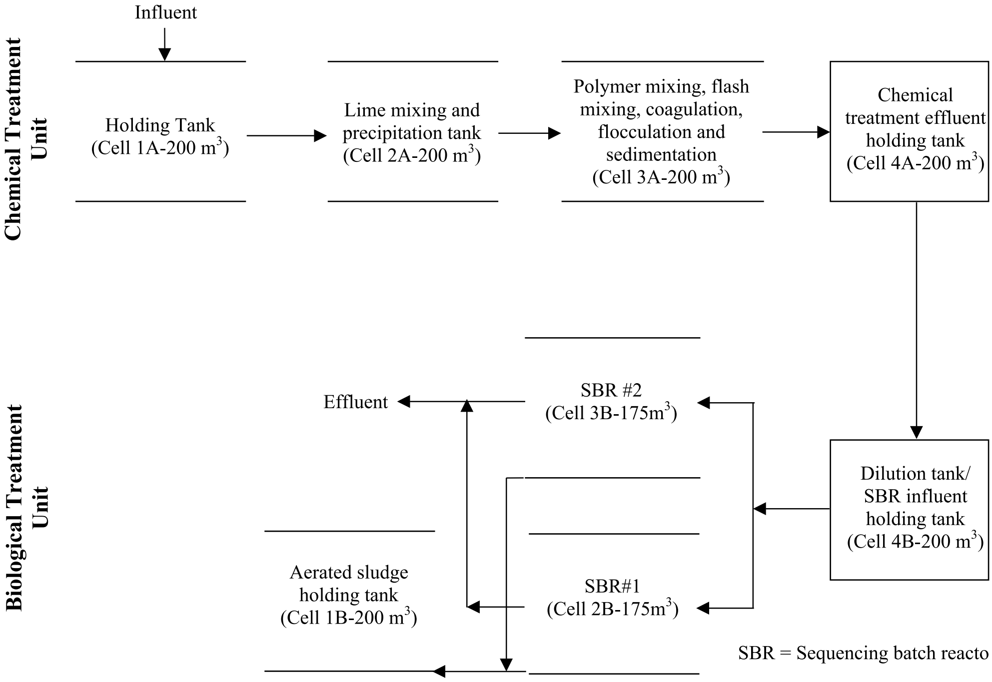

FIGURE 4 Pilot plant treatment processes.

processes. NH_4-N has been found in significant levels in leachate collected from 50 year old landfills. The concentrations of this constituent are 50 to 100% higher than typical values for young landfills [18, 20]. This can be attributed to high moisture flux that creates suitable conditions for pollutant release.

V. LEACHATE TREATMENT

The pilot scale leachate treatment plant consisted of a chemical treatment unit and a biological treatment unit as depicted in Fig. 4. The chemical treatment unit relies on precipitation and coagulation processes. The biological treatment unit consists of two sequencing batch reactors (SBR) operating in 24-hour cycles. After introduction into the SBR, the leachate is first exposed to anaerobic conditions, oxygen level in the SBRs is then increased and aerobic treatment occurs with settling as the last stage.

V.1. Chemical Treatment Unit

The unit consists of a precipitation process and a coagulation process. These two processes are designed to remove part of the suspended and colloidal particles that do not settle alone due to their small size ($< 100\ \mu m$). The precipitation was successful in reducing BOD and COD. pH was raised to 8.5 during this process. Figure 5 depicts a summary flow chart of the precipitation process.

Coagulation further reduced suspended solids and neutralized pH. Figure 6 depicts the diagram of the coagulation process. Sludge from both processes is recycled to the landfill. Removal efficiencies for parameters such as BOD, COD and NH_4-N were 50 to 60% at the

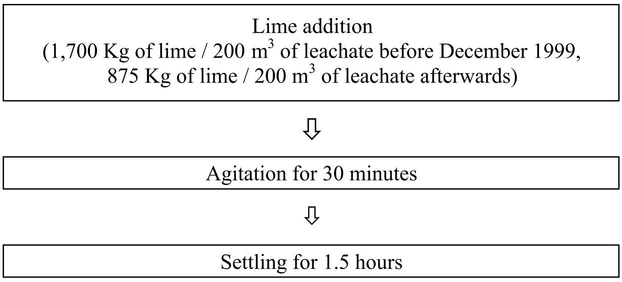

FIGURE 5 Precipitation process.

initial stages. Starting in November 1999, removal efficiencies dropped to 23, 20 and 8% for COD, BOD and NH_4-N, respectively.

V.2. Biological Treatment Unit

The biological unit used in the pilot plant consists of two SBRs operating in parallel in a 24-hour cycle with a population of microorganisms operating under aerobic or anaerobic conditions. The SBRs used at the site are $10\times5\times3.75\,m^3$ tanks yielding a volume of $175\,m^3$. Parameters monitored continuously in the reactors include: dissolved oxygen, temperature, pH, and water level. The 24-hour SBR cycle covers several phases including:

- The anaerobic phase follows the filling of the tank. This phase allows anaerobic reactions to occur and enhances the nitrification/denitrification process in order to decrease the NH4-N concentration in the liquor.
- The aerobic reactions during which dissolved oxygen (DO) level is increased to the set aerobic conditions. The DO concentration in the tanks is kept in the range of 2–4 mg/l and controlled by sensors, programmable logic controls, automated valves, and air blower units.
- Settling, during which air injection and mixers are stopped to allow the activated sludge to settle and clarified effluent to be treated.

V.3. Biological Treatment Operations

Several management parameters were varied to improve the performance of the biological treatment unit and maximize removal efficiency. These parameters include: dilution with effluent leachate or groundwater, addition of bacterial populations (such as nitrifying

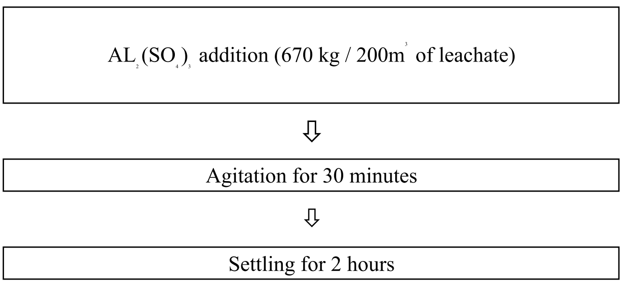

FIGURE 6 Coagulation process.

TABLE IV Description of the phases of operation of the biological treatment unit

Phase	*Duration, days*	*Description*	*Observations*
1	43	☐ Dilution with groundwater and recycled leachate ☐ Addition of coolers at the air blowers outlets ☐ Addition of nitrifying bacteria	☐ A dilution ration of 1:0.375 recycled/ chemically treated maximized the treatment efficiency of COD (92–99%) ☐ NH_4-N removal efficiency was around 65% ☐ Warm ambient temperatures caused SBR temperatures to increase to around 42°C ☐ High temperatures reduced removal efficiency of the system significantly due to reduced oxygen transfer efficiency. ☐ Coolers failed to significantly reduce temperatures in the SBRs and increase removal efficiency ☐ Addition of nitrifying bacteria did not improve NH_4-N removal efficiencies due to high SBR temperatures
2	33	☐ SBRs were operated in a recirculation mode ☐ Afterwards, influent was composed of 50% chemically treated leachate + 50% recirculated leachate	☐ Recirculation mode operation improved the treatment ability of the bacterial population after a period of harsh conditions at the end of phase 1 ☐ Temperature remained high suggesting that temperature control with recirculated leachate as dilution water is difficult during periods with relatively warm ambient temperatures.
3	29	☐ Influent: 25% chemically treated leachate + 75% recirculated leachate ☐ Addition of Phosphoric acid depending on COD concentration ☐ COD loading rate 93 kg/day/tank ☐ NH_4-N loading rate 5.2 kg/day/tank	☐ Lower ambient temperature reduced SBRs temperature from around 42 to 38°C ☐ Removal efficiencies in this phase were improved to around 90% for COD and 99.9% for NH_4-N mainly due to reduced temperatures.
4	29	☐ Influent: 25% chemically treated leachate + 75% recirculated leachate ☐ Cooling system turned off ☐ Operational cycle reduced to 21 hours (13.5 aerobic and 7.5 anaerobic)	☐ COD removal rates were in the range of 80 to 96% ☐ NH_4-N removal rates dropped to the range of 68 to 90% ☐ This drop in efficiency is attributed to a decrease in MLSS concentration during this phase to a range of 500 to 2200 mg/l
5	60	☐ Same as in 4 ☐ Sludge removal stopped five days after the start of this phase to allow increase in MLSS concentrations	☐ COD removal rates ranged from 77 to 95% ☐ NH4-N removal rates ranged from 68 to 99% ☐ MLSS concentration increased to 4000 mg/l
6	33	☐ Same as in 5 ☐ Assumed to start when MLSS concentration exceeded 4000 mg/l ☐ Minimum removal rates were correlated with high concentration in the influent leachate	☐ COD removal rates ranged from 90 to 98% ☐ NH_4-N removal rates ranged from 87 to 99% ☐ MLSS concentration increased to 5500mg/l

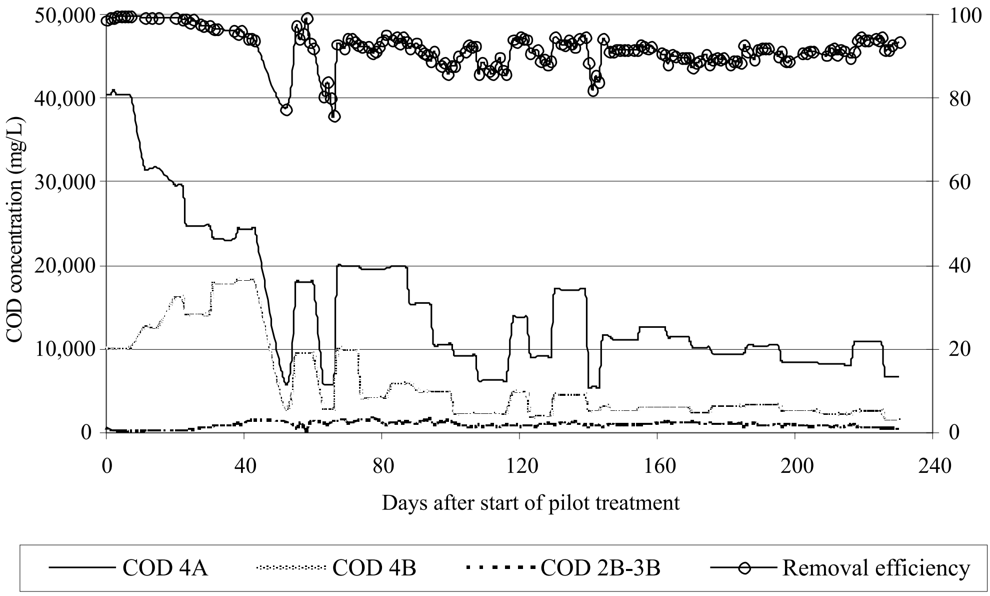

FIGURE 7 Treatment performance of the biological unit for Chemical Oxygen Demand.

bacteria), cooling system at the air blower outlets in the SBRs, addition of phosphoric acid solution, and changes in SBR operation sequence (variation in aeration period, anoxic period, etc). The corresponding operational phases to identify the optimal operational procedures for the unit are summarized in Table IV.

VI. TREATMENT EFFICIENCY

As previously noted, the treatment plant is divided into two units: a chemical unit and a biological unit. The chemical unit is a preparatory treatment for the biological unit that reduces suspended solids and metal concentrations (potentially inhibitory to the microorganisms in the biological phase) and increases the pH. Tests carried out before and after the chemical treatment phase for COD, TSS, NH_4-N, nitrate, nitrite, sulfate, and orthophosphate indicate removal efficiencies ranging from 10 to 25% depending on raw leachate influent quality.

Figures 7 and 8 depict influent and effluent concentrations and removal efficiencies for the biological unit using COD and NH_4-N, respectively. While COD removal efficiency was relatively stable and high, NH_4-N removal efficiency was initially low but picked up at the end of the pilot tests due to the high effluent recycling rate and lower temperatures in the SBRs.

Table V presents minimum and maximum values for the influent and effluent concentration and removal efficiencies. Note the wide variation in influent concentrations of the two indicator parameters. This variation indicates the need for a flexible system that can handle severely varying influent qualities, particularly if the leachate is generated from freshly deposited refuse. Similarly, Table VI lists minimum and maximum values for parameters that are deemed relevant for the SBR performance analysis. Stabilization of these parameters is crucial for the optimal performance of the treatment system. The removal efficiency is especially sensitive to MLSS concentration as depicted by observations from phase 4.

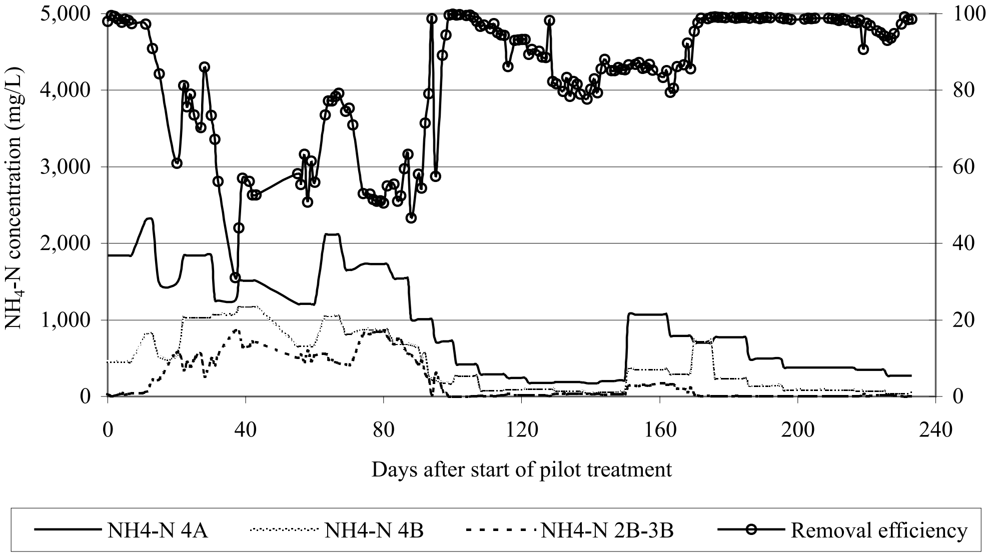

FIGURE 8 Treatment performance of the biological unit for NH_4-N.

VII. CONCLUSIONS

The present study investigated the potential effects of waste composition (high moisture and organic content) and operational procedures (sorting and baling) on biodegradation processes and leachate quality using field-scale monitoring data of leachate quality for 18 months. A description and a performance assessment of a leachate treatment pilot plant were provided. The pilot plant consisted of a chemical treatment unit (precipitation and coagulation) and a biological treatment unit (two aerobic sequential batch reactors).

TABLE V Ranges for COD and NH4-N in and out of the biological treatment unit

Parameter	C_{in} *(mg/l)*		C_{out} *(mg/l)*		*Removal efficiency*	
	Min	*Max*	*Min*	*Max*	*Min*	*Max*
COD	5440	41 000	95	1802	75.9	99.8
NH_4-N	174	2,300	1	863	31	99.86

TABLE VI Ranges for parameters influencing biological unit performance

Parameter	*Min*	*Max*
Treated raw leachate (m^3/day)	0	17.4
Mixed liquor suspended solids concentration in the SBRs (mg/l)	100	14 633
Effluent suspended solids concentration (mg/l)	5	855
Nitrate concentration in the SBRs (mg/)	0.68	2220
Nitrite concentration in the SBRs (mg/l)	0.017	790

Selected leachate characteristics were related to biological activity within the landfill and the results indicated that (1) pre-sorting and baling of the waste did not hinder waste stabilization; and (2) the high organic and moisture contents resulted in an extremely strong leachate, particularly at the onset of biodegradation processes, which can affect the leachate treatment facility. Shifting to methanogenic conditions occurred over an exceptionally short period of about one year. This can be attributed to the high organic fraction and an initial moisture content that exceeds field capacity. Around 14 months after the start of the operations, the pH had risen above 7, indicating optimal conditions for methanogenesis, and the BOD/COD ratio has fallen below 0.3, confirming that the waste is well into the "moderately stable" stage.

The pilot tests demonstrated that the process is capable of achieving high removal efficiency using COD and NH_4-N as indicators when effected under optimal conditions. However, various problems were encountered, especially during the summer when SBR temperatures exceeded 40°C, adversely affecting the performance of the system. Effluent from the chemical treatment plant continued to exhibit a wide variation of biological indicators and contaminant concentrations, suggesting potential difficulties in stabilizing the biological system performance. The pilot plant results can be used as a benchmark towards the design of a full-scale treatment plant taking into consideration the possibility of wide fluctuations in influent leachate characteristics.

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