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Characterizing Seasonal Variation in Landfill Leachate Using Leachate Pollution Index (LPI) at Nam Son Solid Waste Landfill in Hanoi, Vietnam

Son Tran Hoai [1,*], Huong Nguyen Lan [1], Nga Tran Thi Viet [1], Giang Nguyen Hoang [2] and Ken Kawamoto [2,3]

[1] Faculty of Environmental Engineering, National University of Civil Engineering, No.55 Giai Phong Street, Hai Ba Trung District, Hanoi 11616, Vietnam; huongnl2@nuce.edu.vn (H.N.L.); ngattv@nuce.edu.vn (N.T.T.V.)
[2] Faculty of Building and Industrial Construction, National University of Civil Engineering, No.55 Giai Phong Street, Hai Ba Trung District, Hanoi 11616, Vietnam; giangnh@nuce.edu.vn (G.N.H.); kawamoto@mail.saitama-u.ac.jp (K.K.)
[3] Graduate School of Science and Engineering, Saitama University, 255 Shimo-okubo, Sakura-ku, Saitama 338-8570, Japan
* Correspondence: sonth@nuce.edu.vn; Tel.: +84-983-317-087

Abstract: The improper treatment of landfill leachates is one of the major problems associated with waste landfilling and causes serious environmental pollution at waste landfill sites and their surroundings. To develop a suitable landfill leachate treatment system and to minimize the risk of environmental pollution, it is important to characterize seasonal and temporal variations of landfill leachates. This study investigated the leachate quality of the Nam Son waste landfill in Hanoi, Vietnam in 2017–2019 and characterized the potential risks of landfill leachate using a leachate pollution index (LPI). The results of this study showed that the seasonal and temporal variation of the overall LPI during the monitoring period was small and in the range of 20–25 (values 2.5 times higher than the maximum permissible limits of Vietnam National Technical Regulation on Industrial Wastewater). The LPI sub-indices attributed to organic and inorganic pollutants were major components of the LPI. Especially, the annually averaged values of LPI of inorganic pollutants were 7.7 times higher than the maximum permissible limits, suggesting that the treatment of inorganic pollutants, such as ammonium-nitrogen (NH_4^+–N) and total nitrogen (TN), is highly required at Nam Son landfill to prevent environmental pollution surrounding the landfill site.

Keywords: solid waste landfill; landfill leachate; leachate pollution index; monitoring; Nam Son waste treatment complex; Hanoi city

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1. Introduction

An engineered municipal solid waste (MSW) landfill is designed to carefully isolate the dumped waste from the surrounding environment to prevent water, soil, and air pollution. The isolation is accomplished commonly with a combination facility including a bottom liner, gas ventilation, drainage system, and daily soil cover as well as a facility for treatment of landfill leachate [1]. In most countries, it has been reported that landfill leachate contains various types of organic compounds, such as easily and non-biodegradable carbons, humic, and fulvic acids; inorganic compounds such as colloids; heavy metals; non-organic salts such as sodium, calcium, sulfate, and ammonia; other toxic and hazardous substances due to the lack of separation of dumped MSW [2–5]. The composition and potential pollutants of landfill leachate and the volume of leachate generated depend on many factors including waste composition, degree of compaction, age of dumped waste, seasonal variations in precipitation, landfill temperature, chemical and biological activities in a waste body, hydrogeological conditions in the vicinity of the landfill site, and management practices of MSW landfills [6–8].

In order to characterize the contamination potential of landfill leachate, an easy-comparison index could be a useful tool. Kumar and Alappat [9,10] proposed a technique to quantify the leachate contamination potential of different landfills on a comparative scale in terms of a leachate pollution index (LPI). An LPI is a quantitative tool that measures the leachate pollution potential and can be used not only for characterizing MSW landfills but also for planning and designing remedial measures to prevent environmental pollution. Moreover, LPI sub-indices have been developed to describe the dominating pollutants and their impact [11].

To date, only few data have been available for characterizing landfill leachates in Vietnam, and the quality and severity of contamination potentials have not been fully understood. Especially, a quantitative indicator has not been applied to evaluate the severity of the contamination potential of landfill leachates in Vietnam. This study, therefore, analyzed the quality of landfill leachates at the Nam Son landfill in Hanoi, a typical MSW landfill in Vietnam, based on leachate quality monitoring from 2017 to 2019 and characterized the seasonal and temporal variations of leachate quality and severity of contamination potential based on the calculated LPI values. The report on this study could contribute to the improvement of treatment facilitates of landfill leachates and the diminution of the adverse impact on the surrounding environment of MSW landfills in Vietnam.

2. Current Status of Solid Waste and Landfill Management in Hanoi, Vietnam

One of the most common techniques for handling MSW in developing countries has been landfilling because of the higher capacity and lower capital and operation costs than modern waste management methods [12,13]. In Vietnam, the volume of MSW reaches more than 64,000 tons/day, and waste generation is increasing at ~5.1%/year [14]. Regarding four currently common methods for treating MSW in Vietnam—landfilling (63%), composting (4%), recycling (10%), and incineration (14%) [14]—landfilling is the major disposal method. According to a report by the Ministry of Construction [15], there are a total of 657 landfill sites under operation in Vietnam (total area = 4900 ha), and 31% of these are certified as engineered landfills with sanitary conditions. In Hanoi, the daily MSW generation is estimated at approximately 6,500 tons [15]. There are four landfills which are engineered landfills with a large capacity, namely, Nam Son, Kieu Ky, Xuan Son, and Nui Thong landfill sites. Hanoi city set a plan to operate 17 solid waste disposal complexes including eight existing zones and upgrading and expanding nine newly established zones [16].

The concentrations of some indicators of landfill leachates taken from typical MSW landfills in big cities of Vietnam reported in the literature are summarized in Table 1 [17–22]. It can be seen that 5-day biochemical oxygen demand (BOD_5) and chemical oxygen demand (COD) varied irrespective of the operation periods and locations, and total suspended solids (TSS) varied greatly. The leachate quality of a landfill, however, varies widely due to the presence of many factors: lack of MSW classification from sources of households and institutes, seasonal climate variations (dry and rainy seasons), landfill management practices, and operation periods. Thus, it is difficult to characterize the leachate quality using samples taken during a certain sampling period. In order to have an accurate characterization of landfill leachate, it is important to carry out a long-term leachate quality monitoring using a set of samples fully considering seasonal and temporal variations.

Table 1. Leachate quality indicators at several municipal solid waste (MSW) landfills in Vietnam.

	Landfill Site					QCVN 40 (Column B) [7]/QCVN 25 [8]
	Nam Son	Xuan Son	Go Cat	Thuy Phuong	Trang Cat	
City, Year	Hanoi, 2013	Hanoi, 2012	Ho Chi Minh, 2007	Hue, 2009	Haiphong, 2013	
Parameters						
pH	6.8–8.0	7.7	7.4–7.6	7.7–8.5	6.5–8.2	5.5–9
TDS (mg/L) [1]	6.9×10^3–2.0×10^4	-	-	-	4.5–9.2	-
TSS (mg/L) [2]	1.2×10^2–2.2×10^3	9.9×10^2	7.0×10^2–2.0×10^3	42–84	21–78	100
COD (mg/L) [3]	1.0×10^3–2.3×10^4	3.5×10^3	1.4×10^4–1.7×10^4	6.2×10^2–2.4×10^3	3.3×10^2–1.0×10^3	150/ 400
BOD_5 (mg/L) [4]	5.0×10^2–1.2×10^4	2.2×10^3	6.3×10^3–9.2×10^3	1.5×10^2–4.0×10^2	1.2×10^2–4.7×10^2	50/ 100
BOD_5/COD	0.49–0.54	0.61	0.46–0.58	0.16–0.23	0.37–0.47	-
TN (mg/L) [5]	4.2×10^2–2.3×10^3	62	1.8×10^3–2.9×10^3	-	1.8×10^2–5.1×10^2	40/ 60
NH^{4+}–N (mg/L)	-	17	1.7×10^3–2.4×10^3	1.8×10^2–6.4×10^2	-	10/ 25
NO^{2-}–N (mg/L)	-	13	0–6.2	-	-	-
TP (mg/L) [6]	6.5–25	4.3	10–20	-	3.9–8.6	6
Total Hardness (mg $CaCO_3$/L)	-	-	-	1.4×10^3–4.9×10^3	-	-
Cl (mg/L)	-	-	-	5.2×10^2–1.2×10^3	-	1000
As (mg/L)	0.001–0.003	0.2	-	-	0.047–0.086	0.1
Pb (mg/L)	0.050–0.086	0.34	-	-	<0.05	0.5
Cd (mg/L)	0.010–0.025	0.14	-	-	<0.01	0.1
Hg (mg/L)	0.0001–0.0009	-	-	-	0.0001	0.01
Reference	[17]	[18]	[19]	[20]	[17]	[21,22]

[1] TDS: Total dissolved solids; [2] TSS: Total suspended solids; [3] COD: Chemical oxygen demand; [4] BOD_5: 5-day biochemical oxygen demand; [5] TN: Total nitrogen; [6] TP: Total phosphorus; [7] QCVN 40:2011/BTNMT: National Technical Regulation on Industrial Wastewater; [8] QCVN 25:2009/BTNMT: National technical regulation on wastewater of the solid waste landfill sites.

3. Materials and Methods

3.1. Study Site

Landfill leachate was collected from the Nam Son waste treatment complex in Hanoi, Vietnam (hereafter, Nam Son landfill) in this study (Figure 1). The Nam Son landfill site is the biggest MSW landfill site in Hanoi and is located 45 km north from the center of Hanoi city. The site is located in Soc Son District, which is generally hilly and a region of moist tropical monsoon heat. The average annual rainfall is 1670 mm, and the average air humidity is 84% here [23]. The geological and hydrogeological structures are complex, according to the report of three bore holes drilled 28–30 m deep around the north of the Nam Son landfill; the stratigraphic column consisted of five layers: from surface to 1.5–2.0 m: soil, soft-red clay; from 1.5–2.0 to 6.0–7.5 m: mixed sand, interbred with clay; from 6.0–7.5 to 11.2–14.2 m: medium saturated sand; from 11.2–14.2 to 13.0–17.6 m: weathered siltstone; and from 13.0–17.6 to 28–30 m: shale weathering [23]. In 1999, the landfill was designed to occupy a total area of 83.5 ha with ten cells of buried waste and to accept 2000 tons/day of waste (Phase 1). Each cell bottom was constructed with a liner sheet of high-density polyethylene (HDPE) on top of a clay layer with a tube network to collect leachate. The volume of received waste steadily increased and currently has exceeded 5000 tons/day. The first cells were filled completely in 2014 and presently new cells with a total area of 75 ha are under operation (Phase 2) [23]. Nam Son landfill accepts MSW consisting of mostly organic waste (51.9%) and a large amount of inorganic waste such as plastic and vinyl (3%), paper (2.7%) glass (0.5%), leather and rubber (1.3%) metals (0.9%), inert matter (38%), and other materials [14,24].

At the site, landfill leachate is collected by wells with a tube network and discharged into a bio-lake/leachate reservoir (leachate collection pond in Figure 1). According to the report by the Hanoi Urban Environment Company (URENCO), each ton of waste will generate 0.43 m^3 leachate, which means that with 5000 tons of waste per day, Nam Son landfill will generate approximately 2150 m^3 of leachate per day. It was also reported that the amount of leachate generated from the natural rainfall was 363 m^3 per day, so that the total amount of leachate generated was about 2500 m^3 per day. All the leachate is directed to a biological pond that has a volume of approximately 200,000 m^3. The collected leachate is pumped up and brought to three wastewater treatment plants with the maximum treatment capacity of 3200 m^3/day, but they only worked at the capacity of 2150 m^3/day [25]. The wastewater treatment plants used conventional leachate treatment methods, such as air stripping, coagulation, flocculation, aerobic and anoxic tanks/sequencing batch reactor (SBR), settling, filtration and disinfection; the systems required a large amount of chemicals, and the efficiency is not constant but depends on climate conditions and the volume of inlet leachate [26]. The bottom of the cells was covered with a geotextile layer that laid directly on the original ground to prevent leakage of landfill leachate into surrounding areas.

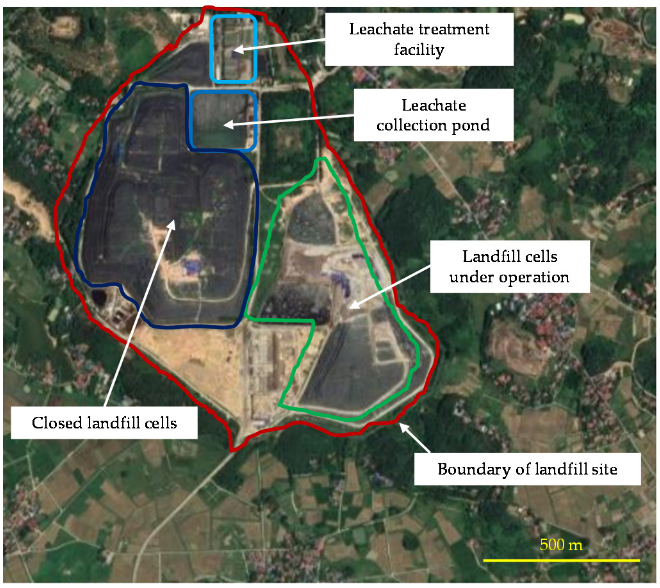

Figure 1. Nam Son landfill site (Source: 2015 Google Inc. 12 December 2020).

The distance from Nam Son landfill to surrounding villages is only 200–500 m so that the impact of environment pollution looks potentially serious. According to inhabitants of the nearby Lai Son village, the odors from the landfill are unbearable. In both the dry and rainy seasons, the air the villagers inhale and water they use are highly contaminated due to the high concentrations of poisonous sediments on the surface, in the groundwater, and vapors in the proximity of the landfill [23].

3.2. Sampling and Analysis of Landfill Leachate

Landfill leachate samples were collected from the leachate collection pond (Figure 1) at the Nam Son landfill from 2017 to 2019 at 3 month intervals (March, June, September, and December). The samples were collected with polypropylene bottles and were stored at 4 °C in the laboratory for the wastewater quality analysis. Wastewater quality parameters and testing methods are summarized in Table 2. Mainly, four groups of pollutants: (i) general wastewater quality parameters, (ii) anions and cations, (iii) organic pollutants, and (iv) heavy metals were measured following Vietnamese standards (TCVN) [21], Standard Methods for the Examination of Water and Wastewater (SMEWW) [27], and Selected Analytical Methods for Environmental Remediation and Recovery [28].

3.3. Leachate Pollution Index (LPI)

The landfill leachate pollution index (LPI) is a quantitative tool to evaluate the leachate contamination potential of landfill leachate [9–11]. In this study, the overall LPI and three sub-indices of LPI—LPI organic (LPI_{or}), LPI inorganic (LPI_{in}), and LPI heavy metals (LPI_{hm})—were used. Each sub-index can be calculated:

$$LPI = \frac{\sum_{i=1}^{n} W_i p_i}{\sum_{i=1}^{n} W_i} \times 100 \quad (1)$$

Then, the overall LPI can be calculated:

$$\text{Overall LPI} = 0.232\ \text{LPI}_{or} + 0.257\ \text{LPI}_{in} + 0.511\ \text{LPI}_{hm} \quad (2)$$

where LPI is the leachate pollution index, W_i is the weight for the *i*th pollutant variable, P_i is the sub-index score of the *i*th pollutant variable, and n is the number of leachate pollutant variables used in calculating the LPI. The W_i and P_i are selected according to the instructions of Kumar and Alappat [9–11], the P_i is changed or reselected when the concentration of *i*th pollutant changes. Table 3 exemplifies the LPI calculation. The leachate quality parameters of BOD_5, COD, phenolic, and coliform for calculating LPI_{or}, pH, NH_4^+–N, Cl^-, and total nitrogen (TN) for calculating LPI_{in}, and Fe, Cu, Ni, Zn, Pb, Cr, As, CN, and Hg for calculating LPI_{hm} were used in this study.

Table 2. Leachate quality parameters and testing methods.

Parameter	Testing Methods [1]	Parameter	Testing Methods
Odor	SMEWW 2150 (2012)	Ni	SMEWW 3125 (2012)
pH	TCVN 6492 (2011)	Pb	SMEWW 3125 (2012)
Dissolved oxygen (DO)	TCVN 7325 (2004)	Zn	SMEWW 3125 (2012)
BOD_5	TCVN 6001-1 (2008)	Cr (VI)	SMEWW 3500Cr.B (2012)
COD	SMEWW 5220C (2012)	CN^-	SMEWW 4500 (2012)
Suspended solids (SS)	SMEWW 2540D (2012)	Phenol	TCVN 6216 (1996)
As	SMEWW 3125 (2012)	S^{2-}	SMEWW 4500 S^{2-}D (2012)
Cd	SMEWW 3125 (2012)	F^-	SMEWW4500 F^-B&D (2012)
Cr (III)	SMEWW 350Cr.B (2012)	NH_4^+–N	TCVN 6179-1 (1996)
Cu	SMEWW 3125 (2012)	TN	TCVN 6638 (2000)
Fe	SMEWW 3125 (2012)	TP	TCVN 6202 (2008)
Hg	SMEWW 3125 (2012)	Cl^-	SMEWW4500 (2012)
Mn	SMEWW 3125 (2012)	Coliform	TCVN 6187-1 (2009)

[1] TCVN: National standards of Vietnam issued by the Vietnam Standard and Quality Institute; SMEWW: Standard methods for the examination of water and wastewater, American Public Health Association, American Water Works Association, and Water Environment Federation.

Table 3. Sub-indices and leachate pollution index (LPI) calculated for leachate samples in March 2017 and December 2019.

		LPI in March 2017					LPI in December 2019				
Index	**Parameter**	**Value**	**P_i**	**W_i**	**W_iP_i**	**LPI**	**Value**	**P_i**	**W_i**	**W_iP_i**	**LPI**
LPI_{or}	BOD_5	2.0×10^3	40	0.267	10.7		1.48×10^3	32	0.267	8.54	
	COD	4.14×10^3	62	0.263	16.3		2.96×10^3	58	0.263	15.3	
	Phenolic	0.60	5	0.246	1.23		0.40	5	0.246	1.23	
	Coliform	5.0×10^7	100	0.224	22.4	50.6	1.06×10^8	100	0.224	22.4	47.4
LPI_{in}	pH	8.65	5	0.214	1.07		8.23	5	0.214	1.07	
	NH_4^+–N	9.08×10^2	95	0.198	18.8		1.47×10^3	100	0.198	19.8	
	Cl^-	1.62×10^3	11	0.187	2.06		9.61×10^2	7	0.187	1.31	
	TN	1.45×10^3	50	0.206	10.3	40.1	1.72×10^3	60	0.206	12.4	42.9
LPI_{hm}	Fe	6.35	5	0.088	0.44		1.25×10^1	6	0.088	0.53	
	Cu	0.019	5	0.098	0.49		0.026	5	0.098	0.49	
	Ni	0.183	5	0.102	0.51		0.085	5	0.102	0.51	
	Zn	0.443	5	0.110	0.55		0.344	5	0.110	0.55	
	Pb	0.025	5	0.123	0.62		0.135	6	0.123	0.74	
	Cr	0.090	5	0.125	0.63		0.038	5	0.125	0.63	
	As	0.137	5	0.119	0.60		0.031	5	0.119	0.60	
	CN	0.027	5	0.114	0.57		0.006	5	0.114	0.57	
	Hg	0.002	5	0.121	0.61	5.0	0.001	5	0.121	0.61	5.2
Overall LPI						24.6					24.7

4. Results and Discussion

4.1. Seasonal and Temporal Variations of Landfill Leachate Quality

Measured leachate quality parameters from 2017 to 2019 are summarized in Table 4. Generally, December to March is the dry season, and June to September is the rainy season in Vietnam. Organic pollutants, such as BOD_5 and COD, decreased slightly during the monitoring periods of 2017–2019 (6.9×10^2–3.8×10^3 mg/L in 2017 and 4.3×10^2–2.7×10^3 mg/L in 2019 for BOD_5; 1.5×10^3–7.8×10^3 mg/L in 2017 and 1.0×10^3–6.1×10^3 mg/L in 2019 for COD). To clarify the seasonal and temporal variations of organic pollutants, the measured BOD_5, COD, and BOD_5/COD ratio are shown with monthly rainfall and averaged temperature in Figure 2. It can be seen clearly that BOD_5 and COD in the dry season (December to March) became 5–8 times higher than those in rainy season (June to September), suggesting that the concentrations of organic pollutants depend highly on the dilution by rainfall. Besides, the volume of the leachate collection lake is around 200,000 m^3, equal to more than 70 days of a hydraulic retention time. It created an anaerobic condition that reduced the concentration of organic matter, mixing of fresh and old leachate and rainwater in the lake.

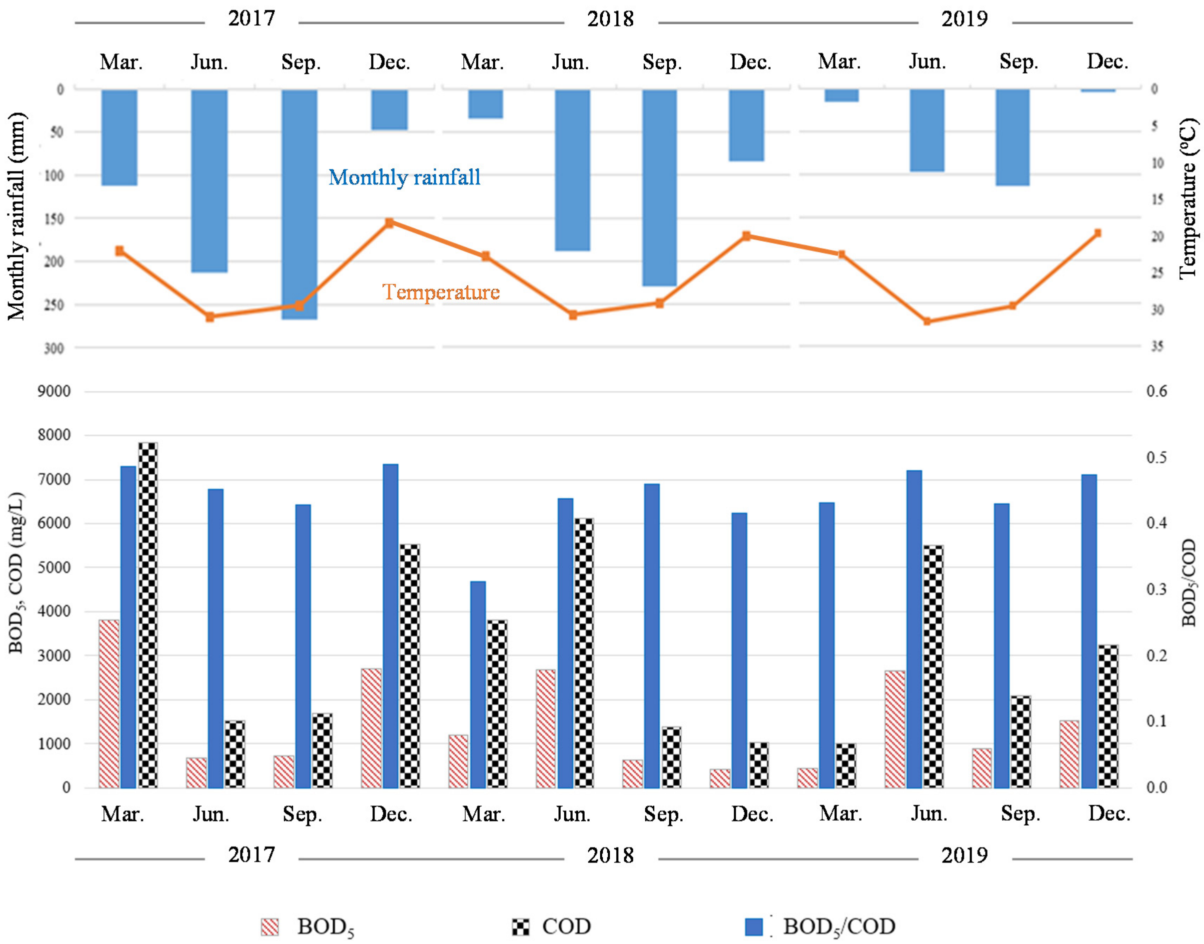

Figure 2. Seasonal variation of BOD_5, COD, and BOD_5/COD of Nam Son landfill leachate from 2017 to 2019. Note that the permissible levels of BOD_5 and COD are 50 and 150 mg/L (QCVN 40:2011/BTNMT. National technical regulation on industrial wastewater).

Table 4. Summary of leachate quality parameters of Nam Son landfill from 2017 to 2019 [1].

	2017				2018				2019			
Parameters	**Mar.**	**Jun.**	**Sep.**	**Dec.**	**Mar.**	**Jun.**	**Sep.**	**Dec.**	**Mar.**	**Jun.**	**Sep.**	**Dec.**
Temperature (°C)	22	28	33	20	27	32	29	25	24	30	29	22
pH	7.8	8.4	9.8	8.6	7.6	7.8	6.5	8.1	8.0	8.6	8.0	8.3
DO (mg/L)	0	0.32	0	0	0	0.1	0	0	0	0	0.35	0.28
BOD_5 (mg/L)	**3.8×10^3**	**6.9×10^2**	**7.2×10^2**	**2.7×10^3**	**1.2×10^3**	**2.7×10^3**	**6.3×10^2**	**4.3×10^2**	**4.3×10^2**	**2.6×10^3**	**8.9×10^2**	**1.5×10^3**
COD (mg/L)	**7.8×10^3**	**1.5×10^3**	**1.7×10^3**	**5.5×10^3**	**3.8×10^3**	**6.1×10^3**	**1.4×10^3**	**1.0×10^3**	**1.0×10^3**	**5.5×10^3**	**2.1×10^3**	**3.2×10^3**
SS (mg/L)	**2.7×10^2**	**1.7×10^2**	**1.6×10^2**	**9.6×10^2**	**2.5×10^2**	**6.7×10^2**	**4.9×10^2**	**1.6×10^2**	0.8×10^2	**3.0×10^2**	0.8×10^2	0.4×10^2
As (mg/L)	**0.24**	**0.14**	**0.13**	0.038	0.001	0.010	0.007	0.025	0.004	0.014	0.075	0.03
Cd (mg/L)	0.0012	0.001	0.0009	0.0005	0.001	0.039	0.0006	0.025	<0.0002	0.01	0.0008	0.0005
Cr (III) (mg/L)	0.097	**0.14**	0.085	0.040	0.095	**0.13**	0.008	**0.28**	0.005	0.039	0.069	0.035
Cr (VI) (mg/L)	<0.01	<0.01	<0.01	<0.01	<0.01	<0.017	<0.01	<0.04	<0.04	<0.01	0.069	0.035
Cu (mg/L)	0.019	0.035	0.016	0.007	0.015	0.034	0.005	0.75	0.015	0.018	0.039	0.032
Fe (mg/L)	**8.5**	**6.4**	**6.4**	4.1	**8.5**	**10**	0.98	**41**	0.7	**19**	**23**	**8.1**
Hg (mg/L)	**0.0061**	**0.0005**	**0.001**	**0.0006**	**0.006**	**0.008**	**0.0002**	**0.003**	**0.0009**	**0.001**	**0.0005**	**0.002**
Mn (mg/L)	0.41	0.22	0.23	0.56	0.40	0.47	0.03	**10.4**	0.01	**7.5**	**5.4**	0.6
Ni (mg/L)	0.32	0.21	0.13	0.069	0.32	0.39	0.008	0.45	0.017	0.084	0.039	0.2
Pb (mg/L)	0.023	0.04	0.013	0.024	0.002	0.014	0.009	**1.65**	0.008	0.008	0.024	**0.5**
Zn (mg/L)	0.28	1.1	0.33	0.11	0.29	0.25	0.069	**8.4**	0.083	0.28	0.25	0.77
CN^- (mg/L)	<0.004	0.019	0.028	0.034	<0.004	<0.02	0.011	0.009	0.007	0.008	0.005	0.005
Phenol (mg/L)	**1.4**	0.22	0.25	**0.50**	**1.5**	0.41	0.26	0.20	0.17	**0.92**	0.37	0.14
S^{2-} (mg/L)	**16**	**21**	**5.4**	**17**	**16**	**13**	0.48	0.01	0.35	**11**	**5.3**	**0.85**
F^- (mg/L)	**11**	**11**	6.4	4.3	**10**	**11**	**9.1×10^2**	**31**	**50**	**49**	**11**	**13**
$NH_4{}^+$–N (mg/L)	**1.2×10^3**	**6.3×10^2**	**7.6×10^2**	**1.0×10^3**	**5.3×10^2**	**8.6×10^2**	**9.7×10^2**	**1.1×10^3**	**1.2×10^3**	**1.2×10^3**	**1.3×10^3**	**2.1×10^3**
TN (mg/L)	**1.3×10^3**	**1.6×10^3**	**1.6×10^3**	**1.4×10^3**	**1.3×10^3**	**1.3×10^3**	**1.1×10^3**	**1.4×10^3**	**1.5×10^3**	**1.5×10^3**	**1.4×10^3**	**2.5×10^3**
TP (mg/L)	**9.7**	0.74	**13**	3.1	**9.7**	**23**	**13**	**21**	**12**	3.6	**15**	**22**
Cl^- (mg/L)	**1.8×10^3**	**1.5×10^3**	**1.5×10^3**	**1.6×10^3**	**1.8×10^3**	**1.9×10^3**	**1.3×10^3**	**1.3×10^3**	**1.2×10^3**	**2.4×10^2**	**1.4×10^3**	**9.8×10^2**
Coliform (MPN/100 mL)	**4.7×10^7**	**3.6×10^7**	**7.5×10^7**	**4.3×10^7**	**4.5×10^7**	**4.6×10^7**	**4.3×10^9**	**7.5×10^8**	**3.9×10^8**	**3.1×10^7**	**3.1×10^6**	**2.7×10^6**

[1] Note that the values of indicators exceeding the permissible levels (QCVN 40:2011/BTNMT on National technical regulation on industrial wastewater) are given in bold.

Moreover, the BOD_5/COD ratio became almost constant, ranging between 0.4 to 0.5 throughout the whole monitoring period (Figure 2). It is well known that the BOD_5/COD ratio of landfill leachate depends on the age of the dumped waste and decreases with age due to the decomposition of easily biodegradable waste [29]. For example, Mohamed et al. [30] reported that BOD_5/COD became >0.5 for young landfills (<2 years) and showed a decrease with age; the BOD_5/COD ratio for mature landfills became <0.1 with typically >10 years use. Based on this viewpoint, Nam Son landfill (Phase 2 operation began from in 2014) in this study can be categorized as a young landfill. However, it is noted that the leachate collection pond at the Nam Son landfill site collects leachate not only from new cells but also old cells (Phase 1). This may lower BOD_5 and COD values compared to other young landfills dumped with fresh waste [2,3,30].

During the monitoring period, the pH ranged between 6.5 and 9.8, and mostly around 8.0. The weak alkalinity indicates that landfill leachate of the Nam Son landfill site has completed the acidification phase and is in the methanogenic phase [31]. Ammonia-nitrogen (NH_4^+–N) and total nitrogen (TN) increased slightly, and this was probably caused by the biological decomposition of organic N into ammonium N due to the increase in landfill age [6]. In addition, several trace metals, such as Fe, Mn, As, Ni, Zn, and Pb, were detected to some extent with seasonal and temporal variations, while other metals, CN, Cr, Cd, and Hg, were not detected significantly. Their concentrations during the monitoring period became lower than 0.01 mg/L.

4.2. Seasonal and Temporal Variations of LPI

Seasonal and temporal variations of calculated LPI values are shown with monthly rainfall and average temperature in Figure 3. The overall LPI became less sensitive to monthly rainfall and the temperature and ranged between 20 and 25 during the monitoring period. Among the sub-indices of LPI, LPI_{or} and LPI_{in} were higher than LPI_{hm}, indicating that the LPI of the Nam Son landfill was mainly dominated by the organic and inorganic pollutants. Taking a closer look at the figures, LPI_{or} varied depending on the monthly rainfall and a higher LPI_{or} in the dry season (March and December) and lower LPI_{or} in the rainy season (June and September). This is in accordance with the trend of BOD_5 and COD in Figure 2, meaning that these parameters controlled the severity of LPI_{or} in the calculation. Moreover, correlations between LPI_{in} and monthly rainfall decreased because a high concentration of NH_4^+–N was maintained during the monitoring period (Table 4).

Sewwandi et al. [3] investigated the LPI values of MSW dumping sites in different climate zones of Sri Lanka and showed that landfills in wet zones had the higher overall LPI of 16–43 compared to those at intermediate and dry zones. Esakku et al. [32] investigated seasonal variations of LPI values at MSW dumping sites in India and Sri Lanka and reported that the LPI decreased by 50% during the monsoon period (from October to December 2002). Compared to those reported results, it can be seen that the seasonal and temporal variations in LPI at Nam Son landfill in this study were small (around 10–20%).

Lastly, annual averaged LPI values of Nam Son landfill from 2017 to 2019 were calculated and are shown in Table 5. For reference, LPI values calculated from the maximum permissible limits in QCVN 40:2011/BTNMT National Technical Regulation on Industrial Wastewater [21] are also given in Table 5. The annual averaged values of overall LPI at Nam Son landfill was approximately 2.5 times higher than that of the maximum permissible limits in QCVN 40. Especially, the annual averaged values of LPI_{in} were 7.7 times higher than the maximum permissible limits in QCVN 40. This strongly suggests that not only treating the organic pollutants, such as BOD_5 and COD, in landfill leachate but also treatment of inorganic pollutants, such as NH_4^+–N and TKN, is highly required at Nam Son landfill to prevent environmental pollution surrounding the waste landfill site.

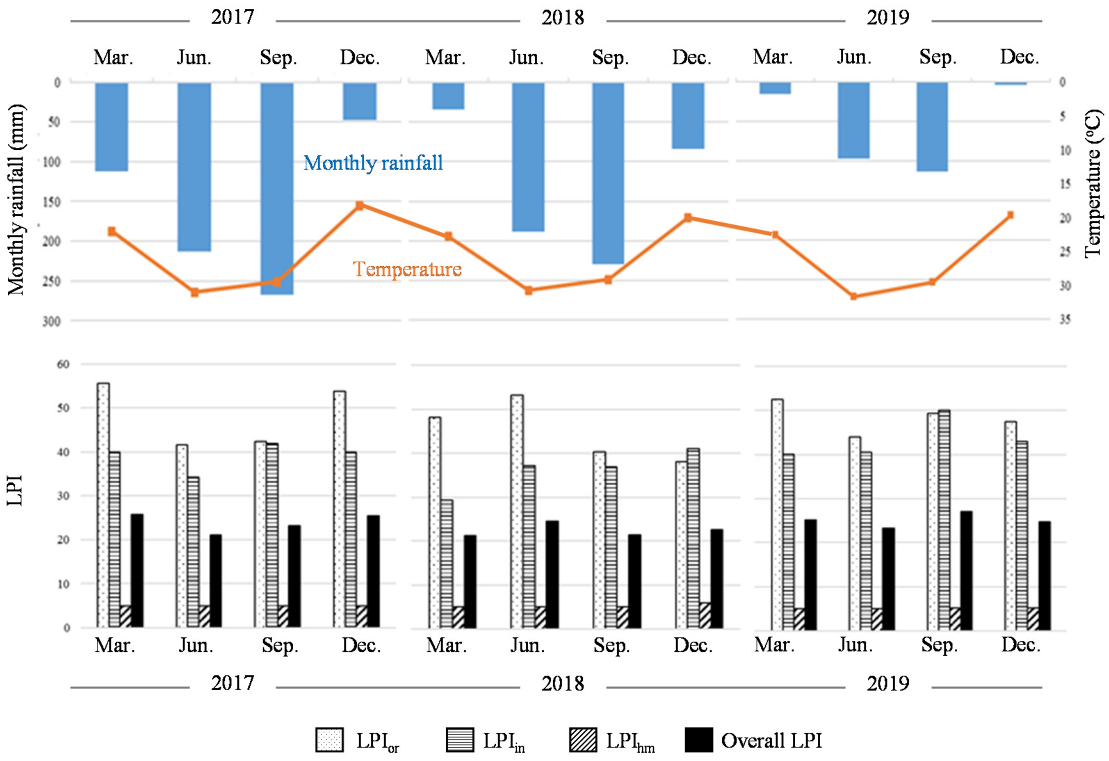

Figure 3. Seasonal variation in the LPI values of Nam Son landfill leachate from 2017 to 2019.

Table 5. Annual averaged LPI values of Nam Son landfill leachate from 2017 to 2019. The LPI values calculated from QCVN 40:2011/BTNMT National technical regulation on industrial wastewater in Vietnam are also given.

	2017	**2018**	**2019**	**QCVN 40 [21]**
LPI_{or}	50.6	48.2	46.9	24.4
LPI_{in}	40.1	35.8	42.4	5.5
LPI_{hm}	5.0	5.8	5.2	5.0
Overall LPI	24.6	23.3	24.4	9.6

5. Conclusions

This study revealed the complexity of the leachate of Nam Son landfill, especially the existence of high concentrations of organic compounds, nutrients, and bacteria. The BOD_5 and COD of landfill leachates in the dry season were 5–8 times higher than those in the rainy season, while BOD_5/COD was almost constant, ranging between 0.4 and 0.5 throughout the whole monitoring period. The results also suggest the insufficient capacity of the current leachate treatment plant and the need to upgrade the treatment capacity and continuous monitoring to avoid environmental pollution of and environmental incidents in the surrounding areas.

This study also emphasizes that LPI indicators (i.e., LPI_{or}, LPI_{in}, LPI_{hm}) are suitable to evaluate the overall degree of leachate pollution. It also specifies the most critical indicators that contribute to overall LPI. This method would be helpful for management authorities to monitor and carry out suitable measures to prevent environmental pollution at landfill sites and leachate ponds. This study suggests that management authorities should develop the official technical guideline for calculating the LPI indicator to monitor the leachate quality of landfill sites in Vietnam.

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