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Municipal Solid Waste and Leachate Characterization in the Cairo Metropolitan Area

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Abstract: The composition of municipal solid waste (MSW) in the Cairo metropolitan area is investigated. The outputs of MSW sorting analysis at various locations in Cairo with different waste management schemes are presented. Organics (58–75%) and plastic waste (19–28%) are the main components of MSW in Cairo with a higher percentage of organics in landfills compared to dumpsites. The leachate quality is analyzed, and the analysis results indicate that the concentration of macro inorganic pollutants (NH^{4+}, Na^{+}, Ca^{2+}, and Cl^{-}) and heavy metals (e.g., Cd^{2+} and Zn^{2+}) are exceeding the majority of values reported in the literature in various cities all over the world. There was no evidence of an effect of the recycling process on chloride concentration in leachate, while the concentration of iron was reduced. The variation of leachate quality with time for two samples collected from the same municipal solid waste landfill is presented. The first leachate sample is a two-year-old, and the second sample is a sixteen-year-old. There was a significant increase in the concentration of chloride, sodium, chromium, calcium, and magnesium. The implications of the leachate quality in Cairo on the longevity of barrier systems in an MSW landfill are discussed.

Keywords: municipal solid waste; waste stream; landfills; municipal solid waste leachate; leachate age; barrier systems; geomembranes

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1. Introduction

Municipal solid waste (MSW) composition varies from one country to another, and even inside the same country, due to differences in cultural background, income level, waste management scenarios, and social circumstances [1–3]. The municipal solid waste leachate is formed due to the leaching of soluble salts and biodegraded organic components inside the waste mass by rainfall or moisture percolating through the waste. Subsequently, the composition of leachate varies between different regions due to the variability of waste decomposition besides other factors such as rate of rainfall, ambient temperature, rate of waste disposal, and daily cover that contributes to the suspended solids in the waste [3,4]. Municipal solid waste leachate is a complex fluid with characteristics that varies over the different phases of the leachate starting from the acetogenic phase for young leachate to the methanogenic phase for older leachate [5]. The MSW leachate is composed primarily of dissolved organic, inorganic, and xenobiotic compounds, inorganic ions, and heavy metals [6–8]. The concentration of various elements and compounds in the MSW varies with time [9] due to several factors such as variations in a waste stream, rate of waste disposal, and changes in organic loading attributed to the biodegradation of waste [10].

Proper waste management is crucial since poor waste management could have an adverse effect on the environment and the health of living organisms. Indeed, the long-term cost associated with poor waste management could be higher than primary proper waste management [11]. Waste disposal has developed from dump sites at which the waste is in direct contact with the ground to engineered landfills that comprise base barriers that separate the waste from groundwater [12]. Landfilling is the most common waste disposal method in many countries [13–15], and landfills are the destination for waste either directly from the source (if landfilling is adopted solely as a waste management system), or the residual waste by-product from other waste management techniques [13]. This could be attributed to the relatively low construction and operation cost relative to other waste disposal methods [16].

Reduction of waste volume disposed into a landfill could be needed if the land area assigned for landfilling is limited, or to increase the landfill's cells capacity to extend the service time of an existing landfill without the need to construct a new one. Waste volume reduction methods include (a) waste compaction, (b) landfill bioreactors, (c) recycling, (d) composting, and (e) waste incineration. Waste compaction aims to reduce the air voids entrapped inside the waste mass, subsequently reducing the total waste volume and increasing the air space in a landfill [17]. Landfill bioreactors involve air and/or liquid circulation within the waste mass to motivate the aerobic bacterial processes (in presence of oxygen) or anaerobic waste biodegradation (in absence of oxygen) [18,19]. Both processes result in accelerated waste biodegradation in less time and hence increased landfill air space is obtained. Recycling is a waste diversion process that aims to reduce the waste mass and volume disposed into a landfill through the separation of waste either at the source or at a recycling plant, followed by the collection of similar waste components, then the manufacturing of marketable products [20–22]. Another waste diversion process is composting (mechanical biological treatment) which involves the bio decomposition of organic waste under controlled aerobic conditions into a humus-like product, known as compost, which can be used in land remediation, restoration, and agriculture [23–26]. Finally, incineration of waste involves burning the waste inside an incinerator turning the waste into bottom ash, fly ash, air pollution control residues, and gaseous products principally carbon dioxide and water vapor [27,28]. This process reduces the waste volume by approximately 90% [29], with the remaining volume of waste either diverted or landfilled.

Each of the foregoing waste reduction approaches has advantages and disadvantages. Recycling provides a sustainable solution that promotes the waste value and turns it into products, but the revenue of waste reduction, increasing air space in a landfill, and selling recycled materials shall overweight the cost of separation, recycling awareness campaigns, and recycling plants. Similarly, waste composting results in a 20–40% reduction in waste volume [30]. However, high heavy metal concentrations in compost applied to food crops, especially partially oxidized ones, might have an adverse effect on crop yields. Moreover, higher metal concentrations were reported for composted soil and plants [25,31–33]. The Waste Framework Directive (2008) considered waste disposal through landfilling as the least preferable scenario and favored waste reduction, reuse, recycling, and recovery, respectively. Nevertheless, this recommendation [34] was describing waste management alternatives for more developed countries. In contrast to developed countries, engineered landfills are considered a reasonable waste management development from uncontrolled dumping practices in less developed countries [35]. Therefore, Egyptian environmental authorities decided to construct several engineered modern landfills in various governorates in the country along with intermediate waste transfer stations to increase the waste collection efficiency and protect the environment. A notable number of these landfills are located in the Cairo metropolitan area, since it is the most populous region in Egypt (≈20 million residents), with the greatest share of the amount of waste generated in Egypt with more than six million tons of waste generated annually [36] out of the twenty-one million tons/year produced all over Egypt [37]. However, these landfills could provide a relatively cheap waste disposal solution and protect the environment if designed properly. The first step towards a sustainable design of an MSW landfill is proper identification of the waste stream, the chemical composition of effluent leachate, and the variation of the leachate quality over time. Thus, the objectives of this study are (i) to analyze the composition of the waste stream for various scenarios of waste management in the Cairo metropolitan area, (ii) to identify the leachate quality in a dumpsite, a landfill after the recycling process, as well as a landfill that receives waste directly from the source, and (iii) to present and analyze the variation in the concentration of leachate with time in one of Cairo's major MSW landfills.

2. Field and Experimental Investigation

2.1. Study Scope

The geographic scope of the study is the Cairo metropolitan area (Figure 1). This study involved three districts: (1) Southern and Western districts of Cairo (15th May landfill), (2) Northern and Eastern Cairo (El-obour landfill, and El-wafaa & El-amal landfill), and (3) Giza (Shabramant dumpsite). The waste in the Northern and Eastern regions is initially placed at a transfer station, then separated in an MSW recycling plant, and finally disposed of at El-Obour landfill (at the time of this study) and previously disposed of at El-Wafaa & El-Amal landfill. In the Southern and Western regions, the waste is collected from the source, then transferred to a waste treatment and disposal facility, where organic waste is composted, recyclables separated, and the non-recyclable portion is disposed of at the May 15 landfill. In contrast, the waste was disposed of directly into the Shabramant dumpsite without intermediate processing. The composition of MSW in each region was examined at various disposal locations: the transfer station, recycling plant, and landfill. Therefore, this study investigates the effect of various combinations of waste management methods on the composition of MSW dumped in a landfill, and subsequently, the leachate composition.

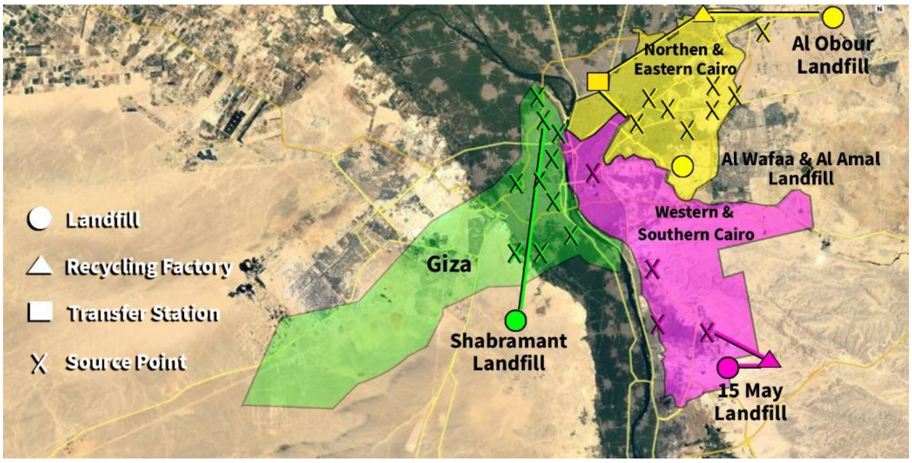

Figure 1. Municipal solid waste and leachate sampling locations in the Cairo metropolitan area.

2.2. Waste Composition Analysis

Waste composition analysis was performed at nine sites. These sites were selected to track the waste composition through the different regions of the Cairo metropolitan area from the source to the final destination in the three aforementioned districts in Cairo. The nine sites were selected to represent the waste composition at collection, transfer, and disposal sites as follows: three sites where the waste was directly collected from the source without any losses, a transfer station, two recycling plants, a dumpsite (Shabramant, Giza, Egypt), and two landfills. The dumpsite (Shabramant in Giza) had neither a barrier system, nor a leachate collection system, while the two landfills were the 15th May landfill in Southern & Western Cairo, and the El-Obour landfill in Northern & Eastern Cairo. The 15th May landfill was an engineered landfill with a leachate collection system and was receiving waste for three years. The El-obour landfill was a landfill with a barrier system, but without a leachate collection system, and had started receiving waste a few months before the study. Therefore, the waste analysis in the Northern & Eastern region of Cairo was performed in the El-Obour landfill, while the leachate analysis (Section 2.3) was performed for samples collected from the El-wafaa & El-amal landfill that was closed in 2018. Both landfills were receiving the waste from exactly the same districts and hence the leachate samples collected from El-wafaa & El-amal landfill were considered representative of the waste composition analyzed at the El-obour landfill.

The waste composition analysis was performed at the source, transfer stations, recycling plants, dumpsites, and landfills before the intervention of scavengers at the inlet of these sites at various times during the study's duration (March 2020 to March 2021). The waste sorting was conducted in accordance with the American standard test method for the determination of the composition of unprocessed municipal solid waste (ASTM D34) [38]. An approximately clean levelled surface covered with tarpaulin was selected for discharging the load of a random truck. The discharged truck load was moved longitudinally using a front-end loader along one side to obtain a representative waste sample. Three sorting samples were analyzed at each site, each of 91–136 kg to represent the characteristics of a collection truckload. Each sample was sorted manually, and each component of the waste was placed inside a container, then the weight of each waste component and the container was measured using a calibrated scale. The weight of each component was calculated by subtracting the empty container weight, then the fraction weight of each component was estimated as a ratio of the total weight of all waste components.

The desired level of precision (e) of the waste composition analysis was estimated based on the number of samples (truck loads; n) of three, viz:

$$e = \frac{t^{*} \cdot s}{\sqrt{n} \cdot x} \quad (1)$$

where, t^{*} (unitless): t-student statistic corresponding to the desired level of confidence; s (unitless): estimated standard deviation; and x (unitless): estimated mean.

The major component of the analyzed MSW in Cairo was food waste, hence s and x were assumed as 0.03 and 0.1 based on values provided by [38]. These values were estimated based on MSW analysis data at various locations in the United States of America (ASTM D34). Consequently, the confidence level was estimated using the following equation:

$$\text{Confidence Level} = 1 - \text{e} \quad (2)$$

The confidence level for the analysis results at each site was 71.5%, and could be increased to 80% (6 samples) and 84% (9 samples) on grouping results from various sites.

2.3. Leachate Chemical Analysis

MSW leachate samples were collected from two landfills and a dumpsite in Cairo metropolitan area, namely, El-wafaa & El-amal (landfill serving Northern and Eastern Cairo; 16 years old), 15th of May City (landfill serving Southern and Western Cairo; 3 years old), and Shabramant dumpsite (Giza; 15 years old). Samples were collected from the leachate collection sump (El-wafaa & El-amal landfill), or pump station (15th May landfill), and a fresh leachate pond formed at the Shabramant dumpsite. Three samples were collected from each site and stored in polyethylene bottles in a fridge at 4 °C. Then the leachate samples were analyzed in accordance with APHA (2005) [39]. The analyzed components were (abbreviation and/or analysis method is mentioned in parenthesis): chemical oxygen demand (COD), biological oxygen demand (BOD), total solids (TS; convection oven drying procedure), organic nitrogen (N; Total Kjeldahl Nitrogen-TKN), ammonium nitrogen (NH_4^+; chromatography mass spectrometry), potential of hydrogen (pH; pH meter), total alkalinity (TA; titration; expressed by % calcium carbonate), volatile fatty acids (TFA; ion-exclusion chromatography), and elements concentration (inductively coupled plasma mass spectrometer and ion chromatography).

3. Results & Discussion

3.1. Waste Composition

This section presents the results of waste analysis at the source at the three regions investigated in Cairo, followed by an illustration of the variation of waste composition from the source to the dumpsite/landfill passing by an intermediate transfer station or a recycling plant.

Three MSW samples were collected from the source before scavenging activities and their composition was analyzed. The main components of the waste (Table 1) were organics (range: 61% to 71%; confidence level = 71%) and plastics (range: 15–25%; confidence level = 71%). The one-way analysis of variance (ANOVA) between observations of organic, plastics, and textiles waste components fraction at the three zones studied in the Cairo metropolitan area (Northern and Eastern, Southern and Western, and Giza) showed that there was a statistically significant difference (at 95% confidence level) that was greater than would be expected by a chance. Yet the statistical comparison using the student t-test (at 95% confidence level) between every two groups separately had shown that the difference was statistically insignificant between the observations of organics and plastics in Southern and Western Cairo, and Giza. Thus, the source of difference was the waste composition in Eastern and Northern Cairo, and this could be attributed to the difference in socioeconomic conditions among the three studied zones. The Northern and Eastern zone is predominantly urban residential, administrative, and commercial area, whereas Giza involves urban and rural districts. Finally, the Southern and Western zone involves industrial activities. Notwithstanding this statistically significant difference between mean values of observations between the Northern and Eastern zone of Cairo, besides the obvious difference in socioeconomic activities among the three zones under study, the mean waste components fraction at the three zones was estimated to obtain the percentage of each component at 84% confidence level (Table 1) and to compare the obtained waste composition in Cairo (current study) with that reported by the Egyptian environmental affairs agency (EEAA) for the waste composition in Egypt (Figure 2). The organics were 56% [37] and 64% (current study), while the plastics were 13% (EEAA) and 21% (current study). Moreover, the fraction of paper and cardboard reported by [37] for all Egypt was 10% and in Cairo (current study) was 4%. Hence, the percentage of organics and plastics in Cairo is higher and this could indicate a significant difference in waste composition in Cairo compared to other governorates in Egypt, or a change in the socioeconomic conditions since the EEAA report publication time. Similarly, the percentage of organics in Assiut (a governorate located 400 km to the south of Cairo) was 41% [40] which is less than the values in Cairo (60–71%; current study) and [37]. In conclusion, the statistically significant difference in waste composition across various zones of Cairo, and Assiut compared to the averaged values over Egypt [37] suggests that waste composition analysis shall be presented for each region independently and cannot be generalized all over Egypt. Additionally, the waste composition shall be analyzed periodically to monitor the variation in waste composition; this would highlight the socioeconomic changes and could aid in better waste management, the design of recycling systems, and engineering design for landfills. These socioeconomic changes might involve an increase in the usage of lightweight plastic packaging instead of heavier-weight glass and steel cans packaging [41]. This phenomenon is known as an evolving ton, where the recyclable waste has declining tonnage compared to volume [42], and hence material recovery facilities shall do more recyclables processing for a proximate revenue [41].

Table 1. Municipal solid waste composition (mean ± standard deviation) at the source.

Waste Composition [a] (%)	Northern & Eastern Cairo [a]	Southern & Western Cairo [b]	Giza [c]	Average Values
Organics	71 ± 3.4	60± 2.9	61 ± 2.8	64 ± 3.0
Plastics	15 ± 1.7	25 ±2.8	25 ± 2.3	21 ± 2.3
Textiles	2.5 ± 0.4	2.4 ± 0.4	7.4 ± 2.4	4.1 ± 1.1
Paper & Cardboard	4.0 ± 1.4	4.9 ± 1.7	3.1 ± 0.6	4.0 ± 1.2
Diapers	6.1 ± 2.6	7.5 ± 3.2	2.6 ± 0.8	5.4 ± 2.2
Wood	0.6 ± 1.1	0.0 ± 0.0	1.0 ± 1.4	0.6 ± 0.8
Metals	0.3 ± 0.4	0.4 ± 0.4	0.3 ± 0.3	0.3 ± 0.3
Glass	1.0 ± 1.0	0.0 ± 0.0	0.5 ± 0.5	0.5 ± 0.5

[a] Sampling dates: 10 March 2020, 20 February 2021, and 27 February 2021; [b] Dates of sampling: 7 February 2021, 15 February 2021, and 23 February 2021; [c] Dates of sampling: 8 February 2021, 16 February 2021, and 24 February 2021.

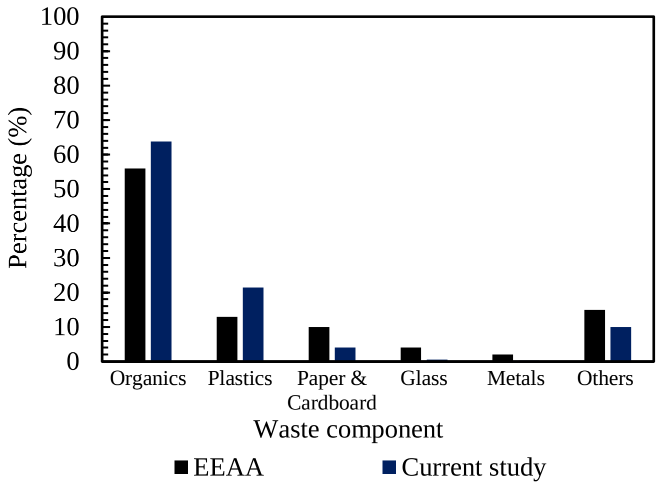

Figure 2. Comparison between the waste composition in Cairo (current study) and the generalized composition in Egypt issued by the Egyptian environmental affairs agency "Reprinted/adapted with permission from Ref. [17]. 2010, the Authors".

MSW was tracked through the successive waste management stages in Northern & Eastern Cairo, from source to El-obour landfill passing through a transfer station and a recycling plant. Three samples were analyzed at each stage and the waste components fraction was obtained (Table 2). The analysis showed that the organic fraction was reduced, and the plastic fraction increased at the transfer station compared to the source. Furthermore, the coefficient of variation increased from 5.3% and 11.6% to 8.6% and 28.4% for organics and plastic waste, respectively, indicating greater dispersion around the mean value. Since the waste at source samples was collected from areas covered with collection services, the results imply direct disposal of waste at the transfer station. Hence, the results imply a deficiency of waste collection coverage in Northern and Eastern Cairo. Comparing the transfer station samples to that at the recycling plant manifests the scavenging activities occurring at the transfer station. For instance, the plastics fraction decreased from 23% ± 7% to 17% ± 5%, and the percentage of papers and carboards decreased from 3.3% ± 1.2% to 1.4% ± 1.4%. Finally, the MSW landfilled at El-obour landfill was composed of organic waste (75% ± 4.4%) and plastics unsuitable for reprocessing (20% ± 3.6%), and textiles (5.2% ± 5.2%). The textile fraction of the landfilled waste was minor. However, the coefficient of variation for the textiles waste reaching the landfills was 100% (mean = standard deviation) because the data points were highly distant from the mean implying a significant variability in the landfilled textiles waste fraction.

Table 2. Municipal solid waste composition (mean ± standard deviation) in the various waste management stages in Northern & Eastern Cairo; rounded to two significant digits.

Waste Composition [a] (%)	Source	Transfer Station	Recycling Plant	Landfill (El-Obour Landfill)
Organics	71 ± 3.4	63 ± 5.4	65 ± 3.4	75 ± 4.4
Plastics	15 ± 1.7	23 ± 6.5	17 ± 5.0	20 ± 3.6
Textiles	2.5 ± 0.4	3.9 ± 2.0	6.0 ± 7.0	5.2 ± 5.2
Paper & Cardboard	4.0 ± 1.4	3.3 ± 1.2	1.4 ± 1.4	0.0 ± 0.0
Diapers	6.1 ± 2.6	5.3 ± 1.4	8.1 ± 4.0	0.2 ± 0.3
Wood	0.6 ± 1.1	0.0 ± 0.0	1.3 ± 2.3	0.0 ± 0.0
Metals	0.3 ± 0.4	0.0 ± 0.0	0.8 ± 0.8	0.0 ± 0.0
Glass	1.0 ± 1.0	1.6 ± 1.4	0.9 ± 1.1	0.0 ± 0.0

[a] Sampling dates: 10 March 2020, 20 February 2021, and 27 February 2021.

In Southern & Western Cairo, waste collected from the source was processed at a recycling plant before disposal at the landfill. Waste composition analyses were performed to obtain the waste component fraction at the source, recycling plant, and landfill (Table 3). Plastics, textiles, paper, and cardboard fractions decreased at the recycling plant compared to the source, and consequently, the organic waste fraction increased. The statistical comparison between the organic and plastics fraction at the recycling plant and the landfill using the student *t*-test (confidence level = 95%) showed that the difference in the mean values between the two groups was not great enough and it could be relevant to random variability in sampling. For instance, the *p*-value (probability that difference between observations occurred by chance) was 0.518 (>0.05) for organics and 1.00 (>0.05) for plastics. The higher coefficient of variation for organics in the landfill (COV = 10%) compared to the recycling plant (COV = 1%) could be attributed to the presence of a composting plant at 15th May city in the vicinity of the landfill analyzed herein.

Table 3. Municipal solid waste composition (mean ± standard deviation) in the various waste management stages in Southern & Western Cairo; rounded to two significant digits.

Waste Composition [a] (%)	Source	Recycling Plant	Landfill [b] (15th May Landfill)
Organics	61 ± 2.9	74 ± 0.8	71 ± 7.3
Plastics	25 ± 2.8	19 ± 1.5	19 ± 5.9
Textiles	2.4 ± 0.4	0.7 ± 1.1	6.2 ± 5.7
Paper & Cardboard	4.9 ± 1.7	1.3 ± 0.4	0.0 ± 0.0
Diapers	7.5 ± 3.2	3.4 ± 1.4	4.1 ± 3.9
Wood	0.0 ± 0.0	0.5 ± 0.7	0.0 ± 0.0
Metals	0.4 ± 0.4	0.0 ± 0.0	0.0 ± 0.0
Glass	0.0 ± 0.0	1.1 ± 0.1	0.0 ± 0.0

[a] Sampling dates: 7 February 2021, 15 February 2021, and 23 February 2021; [b] Composting plant exists in the vicinity of the 15th May landfill.

In Giza, the waste was transferred directly from the source to the dumpsite without intermediate waste reduction processes. Thus, the waste components were analyzed at the source and Shabramant dumpsite (Table 4). The difference in mean values of all waste components with the exception of glass was not great enough ($p > 0.05$) suggesting that the source of this difference was random variability in sampling. Furthermore, this statistically insignificant difference could be attributed to the absence of any waste reduction processes in Giza such as recycling and composting. Additionally, most of the scavenging activities probably occur at the dumpsite in this zone.

Table 4. Municipal solid waste composition (mean ± standard deviation) in the various waste management stages in Giza; rounded to two significant digits.

Waste Composition [a] (%)	Source	Dumpsite [b]
Organics	61 ± 2.8	58 ± 7.1
Plastics	25 ± 2.3	28 ± 6.6
Textiles	7.4 ± 2.4	4.2 ± 1.4
Paper & Cardboard	3.1 ± 0.6	3.2 ± 1.2
Diapers	2.6 ± 0.8	1.9 ± 1.9
Wood	1.0 ± 1.4	1.1 ± 1.9
Metals	0.3 ± 0.3	0.6 ± 0.5
Glass	0.5 ± 0.5	2.7 ± 1.2

[a] Sampling dates: 8 February 2021, 16 February 2021, and 24 February 2021; [b] Composting plant exists in the vicinity of 15th May landfill.

In short, the waste management processes had an obvious effect on the waste components fraction disposed of at the landfill or the dumpsite. The recycling process resulted in a reduction in plastics (25% to 19%) and an increase in organics (61% to 74%) as evident from the waste analysis in Southern and Western Cairo, and Giza (Tables 3 and 4). The waste management in the earlier zone involved the recycling process, while the latter did not involve the recycling process. Both zones had statistically insignificant differences between the mean values of organics and plastics fraction in the source. The increase in organic fraction associated with the recycling process can be reduced by composting considering environmental protection measurements. The foregoing results present the waste composition along the waste track from source to disposal at a dumpsite or a landfill. These results could not be used to assess the efficiency of waste recovery by recycling due to the scavenging activities which are common in Cairo at source, transfer stations, and recycling plants.

3.2. Leachate Composition

Leachate samples were collected from two landfills and a dumpsite in Cairo metropolitan area and were analyzed according to the parameters indicated by [43] for leachate characterization (Table 5). ANOVA one-way analyses were performed to compare the mean values of the concentration of various elements composing the leachate. The difference between the mean values of all concentrations was statistically significant (at confidence level = 95%) and greater than would be expected by chance, except for the BOD and NH_4^+. This finding was in good agreement with the statistical comparison between the waste components fraction at these zones of Cairo metropolitan area. Similarly, the difference in the mean values of the leachate concentrations was statistically significant (confidence level = 95%) with the exception of BOD, TFA, N_{org}, and NH^{+4}, while the difference in the mean values of the waste component fraction between Giza and Southern and Western Cairo was statistically insignificant (at confidence level = 95%). This statistically significant difference in leachate quality between the two waste streams of statistically insignificant difference could be relevant to various factors. The most important is that the leachate samples were collected from the waste stream in the dumpsite (Giza), since there was no leachate collection system at that site, while in the landfill (Southern and Western Cairo) the leachate samples were collected from a leachate collection system. Although samples collected from a well within the waste mass should have higher strength than those collected from a leachate collection system [44,45], the strength of the leachate collected from the dumpsite was mostly less than the one collected from the leachate collection system in the landfill based on the concentration of various leachate parameters (Table 5). This could be attributed to the difference in leachate age at both sites (fifteen years for the Shabramant dumpsite, and three years for the 15th May landfill). Similarly, the leachate samples collected from El-waffa & El-amal landfill (Northern & Eastern Cairo; 16-year-old; TDS = 45,800 ppm) could have lower TDS compared to the leachate collected from the 15th May landfill (Southern & Western Cairo; 3-year-old; TDS = 88,700 ppm) due to various factors such as the difference in waste composition and age, the efficiency of the leachate collection system (clogging, leachate flow rate), and the variation concentration of key contaminants in leachate with time. The range of leachate quality concentrations was estimated (Table 5) for comparison purposes with leachate quality presented in the literature in different regions/countries over the world (Tables 6 and 7).

Table 5. Leachate composition (mean ± standard deviation) in Cairo metropolitan area; digits are rounded to three significant digits.

Parameter	Unit	Giza (Shabramant Dumpsite) [a]	Southern & Western Cairo Landfill (15th May Landfill) [b]	Northern & Eastern Cairo (El-Wafaa & El-amal Landfill) [c]	Range [d]
COD	mg/L	29,500 ± 1470	24,600 ± 1230	23,300 ± 1160	23,300–29,500
BOD	mg/L	4530 ± 1380	3880 ± 660	4860 ± 830	3880–4860
pH	-	6.14 ± 0.06	6.30 ± 0.06	8.14 ± 0.08	6.14–8.14
TFA	mg/L	1.98 ± 0.10	1.74 ± 0.09	1.45 ± 0.07	1.45–1.98
TDS	mg/L	72,600 ± 4360	88,700 ± 5320	45,800 ± 2750	45,800–88,700
NH_4^+	mg/L	2460 ± 120	2550 ± 130	2250 ± 110	2250–2550
N_{org}	mg/L	390 ± 20.0	380 ± 20.0	340 ± 20.0	340–390
$CaCO_3$	mg/L	26,000 ± 1300	30,000 ± 1500	24,000 ± 1200	24,000–30,000
Na^+	mg/L	18,900 ± 380	22,000 ± 440	12,500 ± 250	12,500–22,000
Ca^{2+}	mg/L	9800 ± 490	133,00 ± 660	2320 ± 120	2320–13,300
Mg^{2+}	mg/L	6620 ± 130	5640 ± 110	530 ± 10.0	530–6620
Mn^{2+}	mg/L	20.6 ± 0.41	9.90 ± 0.20	0.25 ± 0.01	0.25–20.6
Fe^{2+}	mg/L	317 ± 6.34	129 ± 2.58	9.50 ± 0.19	9.50–317
Cl^-	mg/L	14,000 ± 700	28,000 ± 1400	11,000 ± 550	11,000–28,000
SO_4^{2-}	mg/L	400 ± 10.0	980 ± 20.0	770 ± 20.0	400–980
PO_4^{3-}	mg/L	0.30 ± 0.01	71.0 ± 1.42	0.08 ± 0.00	0.08–71.0
Cr^{3+}	mg/L	1.00 ± 0.02	0.21 ± 0.00	0.89 ± 0.02	0.21–1.00
Cd^{2+}	mg/L	0.60 ± 0.01	0.09 ± 0.00	0.01 ± 0.00	0.01–0.60
Pb^{2+}	mg/L	0.70 ± 0.01	0.80 ± 0.02	0.86 ± 0.02	0.70–0.86
Zn^{2+}	mg/L	37.4 ± 0.75	0.50 ± 0.01	<0.01 [b]	<0.01–37.4

[a] Sampling dates: 8, 16, and 24 February 2021; [b] Sampling dates: 7, 15, and 23 February 2021; [c] 1, 6, and 10 March 2020; [d] based on the minimum and maximum mean values obtained in the three zones investigated in Cairo; [b] below detection limit; COD: Chemical oxygen demand; BOD: Biological oxygen demand; TFA: trifluoroacetic acid; TDS: total dissolved solids; NH_4^+: ammonium; $N_{org:}$ organic nitrogen; PO_4^{3-}: phosphate; CaCo3: Calcium carbonate and it expresses total alkalinity of leachate; Cl^-: chloride; SO_4^{2-}: sulfate; Na^+: sodium; Mg^{2+}: magnesium; Ca^{2+}: calcium; Zn^{2+}: zinc; Mn^{2+}: manganese; Fe^{2+}: iron; Cd^{2+}: cadmium; Cr^{3+}: chromium; Pb^{2+}: lead.

Chemical oxygen demand (COD) ranged between 23,300 and 29,500 mg/L, while biological oxygen demand (BOD_5) range was 3880–4860 mg/L. Thus, the BOD_5/COD ranged between 0.15 and 0.21 indicating young leachate in the landfills and dumpsite examined [46]. The COD range in Cairo was only preceded by the leachate collected from the United Kingdom and Nova Scotia, Canada ([47,48]; Tables 6 and 7). Similarly, the BOD_5 was higher than all leachates presented in Tables 6 and 7, except for that reported by [47] in the United Kingdom. This high BOD_5 value might indicate relatively higher organic constituents in the leachate in Cairo, or deficiency in the leachate collection system in the landfills examined [49].

The leachate samples collected from the Shabramant dumpsite (Giza), and the 15th May landfill (Southern and Western Cairo) were slightly acidic (pH= 6.14–6.30), while the leachate samples collected from El-wafaa & El-amal landfill (Northern and Eastern Cairo) were slightly basic (pH = 8.14). These values reflected the landfill age (Shabramant dumpsite: fresh leachate collected from the waste mass; 15th May landfill: 3 years; El Wafaa & El-Amal: 16 years) with lower pH values for relative new landfills (pH = 4.5–7.5) and relative higher pH values (pH closer to 9) for relatively old landfills [50,51].

The concentration range of macro inorganic constituents (Table 5) was higher than the typical ranges for MSW landfills indicated by [43]. For instance, the concentration of ammonium (NH_4^+) was 2250–2550 mg/L (typical values: 50–2200 mg/L), sodium (Na^+) was 12,500–22,000 mg/L (typical values: 70–7700 mg/L), Calcium (Ca^{2+}) was 2320–13,300 mg/L (typical values: 10–7200 mg/L), and chloride was 11,000–28,000 mg/L (typical values: 150–4500 mg/L). Similar high concentrations of Ca^{2+} were reported for a landfill in Riyadh, Saudi Arabia [52] and Nova Scotia, Canada [48] as presented in Tables 6 and 7. The concentration of chloride in the leachate samples collected in Cairo (11,000–28,000 mg/L; current study) and other samples from another Egyptian mega-city, Alexandria (11,400 mg/L; [53]) were far higher than counterparts presented in Tables 6 and 7 with the exception for the leachate collected from landfills in Germany [6,54].

The heavy metals concentrations detected in the leachate were 9.5–317 mg/L (iron; Fe^{2+}), 0.01–0.60 mg/L (cadmium; Cd^{2+}), 0.21–1.0 (chromium; Cr^{3+}), and <0.01–37.4 (zinc; Zn^{2+}). These values were higher than the typical values that could be encountered in an MSW landfill young leachate [55]. These typical values are 1 mg/L (Cr^{3+}), 0.1 mg/L (Cd^{2+}), 1 mg/L (Pb^{2+}), and 0.01 mg/L (Zn^{2+}). These findings are common in developing countries due to the uncontrolled disposal of industrial and electronic waste in MSW streams [56]. More important these findings showed the positive impact of intermediate processing of waste, either in a transfer station or a recycling plant, on the reduction of heavy metals concentration in leachate. This was obvious from the higher heavy metals concentration in leachate collected from Shabramant, Giza (waste directly disposed from source to the dumpsite) compared to leachate collected in the landfills located at Northern and Eastern Cairo; Southern and Western Cairo and was subjected to intermediate processing. For example, the concentration of Fe^{2+} was 317 $\pm$ 6.34 (Table 5) compared to 9.50 $\pm$ 0.19 (El-Wafaa & El-Amal landfill) and 129 $\pm$ 2.58 (15th May landfill). Similarly, the concentration of Zn^{2+} was 37.4 $\pm$ 0.75 at Shabaramant dumpsite, 0.50 $\pm$ 0.01 (15th May landfill), and <0.01 (below detection limit; El- wafaa & El-amal landfill). Furthermore, the highest Cd^{2+} concentration among the leachates presented in Tables 6 and 7, was detected in the leachate collected from Shabramant dumpsite (0.60 $\pm$ 0.01 mg/L; current study), followed by leachates collected from two sites in Zhejiang, China (0.24–0.60 mg/L; [57]), then the leachate collected from Alexandria, Egypt (0.09 $\pm$ 0.03 mg/L; [53]). These high values might indicate a disposal of electronic waste in the MSW stream at these locations [58].

Table 6. Chemical composition of municipal solid waste leachate collected from landfills in various regions/countries; digits are rounded to three significant digits.

City or Region Country		Site 1 Zhejiang China	Site 2 Zhejiang China	Site 3 Zhejiang China	Site 1, Central area of Taiwan	Site 2, Central area of Taiwan	Site 3, Central area of Taiwan	Tsuen-Wan Hong Kong	Sai-Kung Hong Kong	Sulaibiyah Kuwait	Jaleeb AlShiookh Kuwait	Nova Scotia Canada	Ouled Fayet Algeria
Parameter	Unit	[57]			[59]			[60]		[61]		[48]	[62]
Study date	-	NA	NA	NA	Feb. 2001–July 2003			March 1990–Jan. 1991		May–Oct.2000		NA	2006
pH	-	8.01	7.75	7.66	7.03–8.50	7.30–8.40	6.82–8.37	7.20–8.00	7.20–8.40	6.90–8.20	7.82–8.06	5.10	8.27
BOD	mg/L	1000	876	834	12–97	26.0–492	16.0–312	-	-	30–600	210–345	-	980
COD	mg/L	1490	1100	1900	320–1340	400–4300	840–4200	489–1670	147–1590	158–9440	6400–8800	11,6000	3790
$CaCO_3$	mg/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	85.8
NH_4^+	mg/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	-
N_{org}	mg/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	58.2
PO_4^{3-}	mg/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
Cl^-	mg/L	1430	819	3150	NA	NA	NA	464–1340	140–1100	NA	NA	3720	4570
SO_4^{2-}	mg/L	NA	NA	NA	NA	NA	NA	-	-	NA	NA	-	3060
Na^+	mg/L	NA	NA	NA	320–1340	297–3530	431–3140	484–1190	132–743	NA	NA	3800	NA
Mg^{2+}	mg/L	NA	NA	NA	27.8–103	23.0–163	15.7–157	35.0–63.0	9.00–26.0	5.20–20.8	86.0–268	1020	NA
Ca^{2+}	mg/L	NA	NA	NA	47.2–137	67.2–133.7	15.9–61.0	NA	NA	5.60–67.6	52.0–122	6300	NA
Zn^{2+}	mg/L	17.2	533	1330	0.04–1.61	0.003–0.56	0.03–0.66	0.24–2.55	0.13–0.39	0.00–0.20	0.20–4.80	13.5	NA
Mn^{2+}	mg/L	0.54	2.39	5.98	0.18–5.27	0.02–0.74	0.02–0.75	0.05–0.24	0.05–1.30	NA	NA	51.0	0.41
Fe^{2+}	mg/L	1.94	15.5	38.6	0.26–5.44	0.26–15.3	0.39–28.0	1.14–3.25	1.26–5.00	0.30–18.1	1.40–54.6	297	8.23
Cd^{2+}	mg/L	0.01	0.24	0.60	<0.15	<0.01	<0.01	<0.01	<0.02	NA	NA	0.02	NA
Cr^{3+}	mg/L	0.17	0.31	0.78	0.01–0.18	0.12–0.52	0.04–1.26	0.03–0.15	0.02–0.23	NA	NA	0.40	0.20
Pb^{2+}	mg/L	0.23	4.56	11.4	<0.02	<0.01–0.09	0.02–0.18	0.03–0.12	<0.10	0–0.10	NA	0.81	3.49

Table 7. Chemical composition of municipal solid waste leachate collected from landfills in various regions/countries; digits are rounded to 3 significant digits.

City or Region Country		Riyadh Saudi Arabia	USA	Italy	Germany	UK	Southern Italy	Thessaloniki Greece	Site 1 South Africa	Site 2 South Africa	Hong Kong	New Zealand	Alexandria Egypt	Cairo Egypt
Parameter	Unit	[52]		[6]		[47]	[63]	[64]			[65]		[53]	Current study
Study date	-	Feb.–May 2008	1972–1979	1987	1991	Jan.–March 2000	NA	NA	1999–2003		1990–1991	1986–1987	NA	March 2020–March 2021
pH	-	5.94–6.32	5.10–6.90	6.00–8.50	5.70–8.10	6.70	8.20	7.90	7.50	8.20	7.80	7.00	7.00–7.80	6.14–8.14
BOD	mg/L	NA	13400	2130–10,400	400–45,900	18,600	2300	1050	170	550	117	737	10,824 ± 95	3880–4860
COD	mg/L	13,900–22,400	1340–18,100	7750–38,500	1630–63,700	36,800	10,500	5350	760	4560	873	1700	15,600 ± 206	23,300–29,500
$CaCO_3$	mg/L	NA	NA	NA	NA	7250	21,500	4950	2420	9650	4940	NA	NA	24,000–30,000
NH_4^+	mg/L	NA	NA	NA	NA	922	5210	940	435	1550	1160	NA	321 ± 68.0	2250–2550
N_{org}	mg/L	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA	340–390
PO_4^{3-}	mg/L	NA	NA	NA	NA	5.00	32.0	8.80	1.40	13.0	22.2	NA	NA	0.08–71.0
Cl^-	mg/L	NA	180–2260	1870–3650	1490–21,700	1810	4900	4120	1690	4630	821	973	11,400 ± 119	11,000–28,000
SO_4^{2-}	mg/L	NA	NA	NA	NA	676	NA	210	NA	NA	NA	1.00	596 ± 87	400–980
Na^+	mg/L	4140–7770	160–1380	1300–1400	NA	1370	3970	NA	590	2830	217	429	NA	12,500–22,000
Mg^{2+}	mg/L	693–2610	233–410	830–1470	100–270	384	24.1	140	80.0	195	18.0	160	NA	530–6620
Ca^{2+}	mg/L	5300–8600	354–2300	70.0–290	130–4000	2240	15.7	NA	105	198	22.0	NA	NA	2320–13,300
Zn^{2+}	mg/L	0.11–0.23	18.8–67.0	5.00–10.0	NA	17.4	0.16	NA	0.17	NA	0.90	1.65	0.75 ± 0.24	<0.01–37.4
Mn^{2+}	mg/L	9.25–13.2	NA	NA	NA	32.9	0.04	NA	0.86	NA	NA	6.56	0.84 ± 0.17	0.25–20.6
Fe^{2+}	mg/L	134–190	4.20–1190	47.0–330	8.00–870	654	2.70	16.2	18.8	9.35	7.80	0.89	6.31 ± 1.83	9.50–317
Cd^{2+}	mg/L	<0.002	NA	NA	NA	0.02	NA	NA	NA	NA	NA	0.02	0.09 ± 0.03	0.01–0.60
Cr^{3+}	mg/L	0.21–0.34	NA	NA	NA	0.13	2.21	1.91	0.08	NA	NA	0.07	0.06 ± 0.04	0.21–1.00
Pb^{2+}	mg/L	<0.04	0.00–0.46	NA	NA	0.28	NA	NA	NA	0.02	NA	0.15	0.02 ± 0.01	0.70–0.86

NA: not available; COD: Chemical oxygen demand; BOD: Biological oxygen demand; NH_4^+: ammonium; Norg: organic nitrogen; PO_4^{3-}: phosphate; $CaCo_3$: Calcium carbonate and it expresses total alkalinity of leachate; Cl^-: chloride; SO_4^{2-}: sulfate; Na^+: sodium; Mg^{2+}: magnesium; Ca^{2+}: calcium; Zn^{2+}: zinc; Mn^{2+}: manganese; Fe^{2+}: iron; Cd^{2+}: cadmium; Cr^{3+}: chromium; Pb^{2+}: lead.

In short, the strength of leachate collected from three sites in Cairo was high but not exceptional compared to leachate quality in other countries (Tables 6 and 7). The high concentrations of sodium, iron, magnesium, manganese, chloride, and the organic constituent expressed by BOD_5 were significant in comparison with other leachates presented in Tables 6 and 7. The practical implications of these high concentrations, their effect on the environment, and methods of mitigations will be discussed later in Section 5.

4. Variation of Leachate Quality with Time

Leachate characteristics vary with time, and after passing through a leachate collection system due to the interaction between leachate and the granular soil particles of the leachate collection system. This section presents a comparison between the leachate quality from the same landfill (El-wafaa & El-amal; Northern & Eastern Cairo) in 2006 and 2020 (Table 8). The landfill understudy is located in Eastern Cairo, and it serves about four million residents with a capacity of 8.8 million tons of waste that was disposed of directly to the landfill without intermediate processing such as recycling or composting. The landfill was built in 2004 and it was one of the earlier engineered landfills in Egypt with baseliners and a leachate collection system. The landfill was closed in 2018 with clear signs of failure in the leachate collection system (Figure 3) implied by the leachate pond formed beside the landfill and side slopes failure probably caused by leachate seepage force acting on the slopes (Figure 4). Two-year-old leachate samples were collected from the end of the leachate collection system in 2006 [66], and other samples were collected in 2020 (sixteen-year-old) from the end of the leachate collection system (current study). The variations in the concentration of leachate quality among the two-year-old and sixteen-year-old specimens are presented in Figure 5. The ammonia concentration decreased from 12,100 ppm (2006) to 2250 (2020), while the chloride concentration increased extensively from 325 ppm to 11,000 pm during the same period (Table 8). Similarly, higher concentration was observed for sodium (301 ppm in 2006; 12,520 ppm in 2020), calcium (137 ppm in 2006; 2320 ppm in 2020), magnesium (104 ppm in 2006; 530 ppm in 2020), phosphate (33.5 ppm in 2006; 80.0 ppm in 2020), and chromium (2.26 ppm in 2006; 890 ppm in 2020). In contrast, the concentration of lead remained constant at 855–860 ppm. The leachate became more alkaline with pH increased from 8.10 to 8.90 mostly due to the 3200% increase in the concentration of the soluble inorganic load represented by chloride. Additionally, the remarkable increase in COD from 7350 mg/L in 2007 to 23,250 mg/L in 2020 could be attributed to the 1600% increase in the insoluble fraction of inorganic loading represented by calcium, besides a possible increase in the organic loading in the leachate. The BOD_5 value decreased from 18,630 mg/L (two-year-old leachate; 2006) to 4860 mg/L (sixteen-year-old leachate; 2020) probably due to the biodegradation of the organic component of the waste [65]. The ratio of BOD_5/COD was 2.5 in 2006 indicating that the leachate was young leachate in the acetogenic phase ($BOD_5/COD > 0.4$; [10]) and decreased to 0.21 in 2020 indicating old leachate in the methanogenic phase. The changes in concentration of various leachate and key parameters mentioned earlier could be attributed to various causes; some are engineering, and others are relevant to socioeconomic changes in the surrounding districts served by this landfill. Firstly, the engineering reason was the failure of the leachate collection system at the time of collecting the sixteen-year-old sample, which subsequently resulted in the leachate mounding and formation of leachate ponds surrounding the landfill cell. Thus, the high concentration of calcium in the analyzed sixteen-year-old sample was not consumed by deposition in the leachate collection system [45]. The socioeconomic reason could be attributed to the noticeable expansion of the nearby districts accompanied by an increase in the population served by the landfill. More importantly, the increased number of commercial and administrative facilities in nearby districts could influence the waste stream disposed of at that landfill and subsequently change the leachate quality.

Table 8. Variation in municipal solid waste leachate quality with time in Northern and Eastern Cairo (Al Wafaa & Al Amal landfill); digits are rounded to three significant digits.

Parameter	Units	2006 [a] (LCS)	2020 [b] (Sump)
COD	mg/L	7350	23,300 ± 1160
BOD_5	mg/L	18.6	4900 ± 830
pH	-	8.10	8.90 ± 0.08
TFA	mg/L	NA	1.45
TS	mg/L	NA	45,800
TDS	mg/L	32,900	54,000
N_{org}	mg/L	NA	340 ± 20
NH_4^+	mg/L	12,100	2300 ± 110
Na^+	mg/L	301	12,500 ± 250
Ca^{2+}	mg/L	137	2300 ± 120
Mg^{2+}	mg/L	104	530 ± 10
Mn^{2+}	mg/L	NA	0.25 ± 0.01
Fe^{2+}	mg/L	NA	9.50 ± 0.19
Cl^-	mg/L	325	11,000 ± 550
SO_4^{2-}	mg/L	NA	770 ±20
TA	mg/L	NA	24,000 ± 1200
PO_4^{3-}	mg/L	33.5	80.0 ± 0.0
Cr^{3+}	mg/L	2.26	890 ± 20
Cd^{2+}	mg/L	NA	10.0 ± 0.00
Pb^{2+}	mg/L	855	860 ± 20

[a] mean value cited from Eid et al., (2009); [b] mean ± standard deviation estimated in the current study.

Figure 3. Signs of failure of the leachate collection system in El- Wafaa & El- Amal landfill located in Eastern Cairo in 2020 after landfill closure (sixteen-year-old).

Figure 4. El-wafaa & El-amal landfill (Eastern Cairo) cell side slope failure due to seepage of mounding leachate after leachate collection system failure. The photo was taken in 2020 after landfill closure (sixteen-year-old).

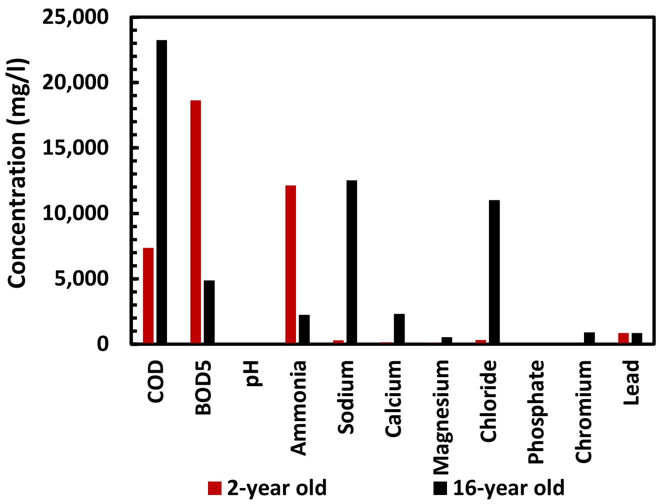

Figure 5. Variations in the concentration of leachate quality in El-wafaa & El- amal landfill (Eastern Cairo). The two-year-old leachate quality was reprinted/adapted with permission from Ref. [64]. 2003, the Authors, while the sixteen-year-old sample was analyzed in the current study.

5. Practical Implications

The outputs of this study revealed a need for increasing the collection coverage and building a national waste tracking information system to avoid misuse of some waste components such as medical waste (e.g., paper masks and syringes, especially in times of pandemic), and hygiene waste. Further use of such items might have drastic effects on public health. Moreover, developing a waste tracking database and a good identification of waste management scenarios in various cities in Cairo will help with proper identification of waste streams disposed of at a landfill that serves a certain district. Hence, a more sustainable design for various components of a landfill can be achieved.

The waste composition analysis that has been done in this study indicated that recycling had a positive impact on reducing the concentration of some key contaminants in the leachate such as iron, while the concentration of other contaminants was not reduced such as chloride, since the chloride concentration is mainly attributed to the type of waste disposed of and cannot be reduced by recycling activities [67]. For instance, the chloride concentration in the leachate collected from the landfill in the Southern and Western parts of Cairo was 28,000 ppm compared to 14,000 ppm in the dumpsite in Giza (Table 5). However, the earlier landfill receives waste from a recycling plant, and the later dumpsite receives landfill from the source. This variation implies that recycling the waste did not result in a lower chloride concentration acknowledging the difference in the waste stream. In the meantime, the recycling had resulted in a reduction in the iron concentration in the leachate collected from the 15th May landfill (129 ppm; Table 5; Southern and Western Cairo) compared to that detected in the leachate collected from the dumpsite (317 ppm; Northern and Eastern Cairo). This reduction in iron concentration due to recycling might result in better long-term performance for a leachate collection system [68]. Moreover, the waste processing before disposal in the landfills either in a recycling plant or by scavengers in a transfer station resulted in the reduction of Cd^{2+} concentration from 0.60 mg/L at Shabramant dumpsite (direct waste disposal from source) to 0.01–0.09 mg/L in 15th May and El-wafaa and El-amal landfills. In short, intermediate waste processing before the disposal of the waste directly into the landfill resulted in a reduction of the concentration of heavy metals (Table 5) such as iron and cadmium in the leachate, and subsequently better protection for the environment since these elements have an adverse effect on the environment associated with their bioaccumulation and long lifetime [69].

The leachate samples collected at the end of the leachate collection system from landfills in Cairo had a high concentration of ammonia (2400 mg/L) which was defined as a primary source of toxicity of MSW landfill leachate [5]. Thus, the leachate treatment method must reduce the ammonia to an acceptable level. Two options could be adopted, either an aerobic biological treatment with extended aeration or subsequent nitrification and denitrification of the leachate [70]. Additionally, the BOD_5/COD of the leachate samples analyzed in this study were mostly $\leq$0.2 indicating biologically stable leachate that is difficult to degrade [71,72]. Therefore, it is recommended to treat leachate using phsico-chemical treatment techniques that introduce chemicals to alter the physical state of the colloidal particles in the leachate [73].

The concentration of contaminants in leachate influences the selection of a landfill barrier system configuration and subsequently the design of various components of this barrier system. For instance, the thickness and hydraulic conductivity of a compacted clay liner along with the thickness of the geomembrane shall be estimated to limit the concentration of contaminants in an aquifer within the allowable limits of drinking water. The chemical analysis of MSW leachate in the Cairo metropolitan area revealed a far higher concentration of chlorides of 17,700 mg/L compared to 1000–4500 mg/L for leachates analyzed in landfills in other countries (Tables 6 and 7); this concentration is much higher than drinking water allowable values [74]. Furthermore, chloride mobility in leachate is one of the highest [75], and 100–150 years are needed before chloride in MSW leachate can be directly released without attenuation to the environment [76]). Consequently, a high-density polyethylene (HDPE) geomembrane base liner shall be implemented in MSW landfills in Cairo because the non-polar matrix of polyethylene reduces the diffusibility of inorganic salts into the geomembrane [67,77,78]. Specifically, the diffusion of chloride into the HDPE geomembrane is extremely low [75].

The service life of geomembrane (GMB) base liners is dependent on the concentration of various elements in leachate [78,79] along with other factors including the GMB thickness, polymer resin, ambient temperature, antioxidant/stabilizer package, surface condition (white coated, smooth or textured), production residual stresses, and strains induced in the GMB [6,80–87]. The time to nominal failure of various high-density polyethylene geomembranes reported by [86] ranged between 100 and >2000 years at a temperature range of 5–20 °C when exposed to municipal solid waste leachate whose fewer salt concentrations compared to the MSW leachate in Cairo. For instance, the concentration range of calcium and magnesium ions for leachate samples in Cairo was 2300–13,300 mg/L and 530–6630 mg/L, respectively, compared to 732 mg/L (calcium) and 395 mg/L (magnesium) for the MSW leachate adopted by [86] and was simulating the leachate of Keele Valley landfill in Ontario [88,89]. Calcium and magnesium function as catalysts for the auto-oxidative degradation of a polymer [78], therefore a geomembrane exposed to leachate with higher calcium and magnesium concentrations will most likely suffer faster chemical degradation.

This might imply that for two identical geomembranes, theoretically speaking, the service life for one installed in a landfill in Cairo could have a shorter service life compared to a counterpart in Ontario, assuming all other factors are the same (temperature, stresses, and barrier system configuration).

The rate of accumulation of chemical precipitates and small particles (e.g., silt and sand) and buildup of a biofilm inside leachate collection system pipes are influenced by the leachate characteristics, besides the leachate flow rate and configuration of the leachate collection system [45,67]. The faster rate of the clogging of drainage gravel and a geotextile wrapped around a leachate collection system is associated with higher COD expressing volatile fatty acids, and inorganic elements especially calcium [90], besides the leachate flow rate [91]. Thus, special attention is needed for designing the leachate collection system elements in Cairo (geotextiles, drainage gravel, and pipes) because of the noticeably high concentration of calcium (2320–13,300 mg/L) in leachate compared to leachate from other regions (Tables 6 and 7), and the COD higher than the most of leachates presented in Tables 6 and 7.

In summary, the high concentrations observed for inorganic and organic constituents, and heavy metals in leachate samples collected from Cairo could be mitigated by adopting the following waste management scenarios: (i) construction of recycling plant(s) along with a new landfill that serves certain districts, (ii) HDPE base liners shall be used in all landfills currently in the design phase in Cairo either alone or combined with compacted clay liner or geosynthetic clay liner to contain the MSW leachate with significantly high chloride concentration, and (iii) leachate collection system compatible with the leachate in Cairo shall be investigated and designed.

6. Conclusions

The municipal solid waste composition was identified at different locations in the Cairo metropolitan area, namely, Northern and Eastern Cairo, Southern and Western Cairo, and the city of Giza. The effect of various waste disposal scenarios on waste composition was investigated by sorting the waste in the source, transfer stations, recycling plants, a dumpsite, and landfills. Furthermore, chemical analysis was performed for leachate samples collected from 3–16 year-age dumpsites or landfills covering the aforementioned regions of Cairo. The following conclusions were reached for the conditions examined at the time of the study:

1. The main components of municipal solid waste in Cairo were organics (58–75%) and plastics (19–28%).
2. The percentage of organics was higher in the waste disposed of in the landfills examined compared to the dumpsite since landfilling was accompanied by the recycling process that consumes plastics and paper/cardboard components.
3. The leachate analyzed at different locations in Cairo contained ammonia concentrations higher than most of the values reported for MSW leachate from other countries. Hence, aerobic biological treatment of leachate with extended aeration is needed.
4. The chloride concentration detected in the MSW leachate in Cairo is high but not exceptional. HDPE geomembrane base barrier shall be mandatory in landfills planned in Cairo since it has excellent resistance to chloride diffusibility.
5. The high, but not exceptional, COD (23,250–24,570 mg/L) and BOD (3880–4860 mg/L) values of the MSW leachate examined in this study might indicate clogging in the leachate collection system of the two landfills examined. Consequently, the grain size distribution of the leachate collection system used in MSW landfills in Cairo shall be investigated.
6. The relatively high concentration of Calcium (8470 mg/L) and magnesium (4260 mg/L) suggests an expected shorter service life for HDPE geomembranes used as baseliners in MSW landfills in Cairo, assuming every other factor is kept the same, compared to values reported in the literature.

7. The concentration of the soluble inorganic load, alkalinity, and COD of an MSW leachate in Cairo increased with time. For instance, the concentration of chloride for the two-year-age leachate analyzed was 325 ppm compared to 11,000 ppm for the sixteen-year-old specimen.

This study has shown the effect of waste management scenarios on the waste composition and subsequently the leachate quality. A further study is needed to monitor the leachate quality effluent from various waste streams with different organic components under controlled conditions (e.g., bioreactors in a laboratory) to mimic various recycling levels and, hence, better understanding of the outcomes of various waste management scenarios.

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