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Assessment of Selected Physico-Chemical Properties of Leachate at Kenkombe Dumping Site, Mbarara City and Modelling of Surface Water Quality of Rwentondo Stream

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Abstract. The leachate from municipal solid waste landfills is a highly concentrated "chemical soup" – so concentrated that small amounts of leachate can pollute large amounts of ground and surface waters leaving it unsuitable for domestic use. The people of Rwentondo, a small village neighboring Kenkombe dumping site, have always raised complaints about the leachate making its way to the stream of Rwentondo, whose water they consume. This work was aimed at quantifying selected physicochemical parameters in both the leachate and surface water samples, and later compare their levels to the threshold values for leachate and surface water monitoring as stated by NEMA. Using a multiparameter photometric technique, the concentrations of lead, copper, iron, phosphates, sulphates, nitrates, and the electrolytic conductivity of both the leachate and surface water samples were assessed. Specified standardized meters were used to measure pH, total dissolved solids, and temperature. The saturation indices (SI) and chemical ion species in surface water were predicted using PHREEQC software in order to reveal the interaction and distribution of the aquatic ion species. In the leachate samples, the mean levels of each of the parameters were higher than the corresponding values recorded in surface waters. On comparison of the obtained results with the NEMA threshold limits for each of the parameters, most of the values from surface water analysis, except for pH, TDS, and Cu, lie outside the acceptable ranges. All the results from leachate analysis surpassed the threshold levels. It was observed that Rwentondo stream had SI>0 for metal complexes: hematite, vivianite, goethite, iron (III) hydroxide, anglesite. Speciation modelling predicted that the dominant species of iron was $FeSO_4$ with a molality of 1.846 e^{-01} m. The dominant species of lead was $PbSO_4$ with a molality of 1.586e-^{02} m while that of copper was $CuSO_4$ with a molality of 3.120e^{-3} m. The higher levels of each of the analyzed parameters in the samples pose a strong threat to the environment, people and animals of Kenkombe that consume the surface water of Rwentondo stream.

Key Words: Leachate, Surface Water, Multiparameter Photometer, PHREEQC

Introduction

Solid waste management is one of the greatest challenges facing urban authorities in Africa. The volumes of wastes generated are reportedly exceeding the cities' technical and financial capacity to ensure proper and adequate management (Edokpayi, Durowoju, & Odiyo, 2018; Water Aid Uganda, 2011). In Uganda, much in line with the broader picture seen across cities in Sub-Saharan Africa, and many other similar developing countries across the globe, municipal solid waste (MSW) management systems are severely getting strained because of the rapid localized urbanization rates and population growth (Water Aid Uganda, 2011). Considering an example of Mbarara City in Uganda, the generation and collection of solid waste per day is reported to have risen from 30 tons in 2005 to 200 tons in 2018, accounting for about 566.7% significant increase in generation and collection of MSW in a space of only thirteen years (Gumisiriza & Kugonza, 2020).

Unfortunately, unlike their counterparts in the developed parts of the world, cities and towns like Mbarara that are situated in the developing countries, are faced with a comparably huge challenge of MSW management particularly because they have fewer technologically advanced and effective mechanisms for waste management. These cities have since adopted less sophisticated strategies of waste management like burial of wastes in landfills and open dumping sites (Gumisiriza & Kugonza, 2020; Christensen et al., 2014). A case in point, Mbarara city has a nonengineered dumping site in Kenkombe which is an equivalent of 114-acre piece of land located in Rwentondo cell just 7 km from Mbarara city center (Gumisiriza & Kugonza, 2020). This area was gazetted as a dumping site for municipal solid waste generated from the divisions of Mbarara district.

Although this kind of dumping site is cheaper to manage, it is most likely characterized by environmental problems like liquid percolations called leachates. As the leachates percolate through the wastes, they pick up suspended and soluble materials that originate from within or are byproducts of the solid wastes' decomposition processes (Kjeldsen et al., 2002). Regrettably, in most cities of the developing countries, including Uganda, the facilities for leachate collection and treatment are often not part of the design of dumping or landfill sites. This increases the likelihood of emerging social, health and economic effects as a result of the migration of toxicants and contamination of ground and surface water by the leachate percolations (National Environmental Management Authority, 2020; Parvin & Tareq, 2021).

The effects the leachates exert are dependent on its composition. The composition of a leachate is a function of the type, age of waste deposited, the prevailing physicochemical conditions, the microbiology and the water balance of the landfill (Kjeldsen et al., 2002). Major components of leachates are dissolved organic compounds, inorganic macro compounds, heavy metals such as copper, lead, iron etc. Complex organic compounds which are released from industrial effluents like perfluorooctanoic acid and benzothiazole can also be found in many leachates (Salam & Nilza, 2021). Exposure to any of these toxicants through any dietary intake of the waters from the stream could result into adverse health effects to the population.

This study was therefore aimed at assessing the selected physico-chemical characteristics of the leachate generated at Kenkombe dumping site and its effect on the quality of surface water of Rwentondo stream by measuring the selected indicator parameters as prescribed by the National Environment (Standards for Discharge of Effluent into Water or Land) Regulations (2020). The parameters assessed include: heavy metals (such as copper, iron, lead), electrolytic conductivity, pH and ions present (sulphates, phosphates, and nitrates) which are some of the criteria indicators classified by NEMA for water pollution (National Environmental Management Authority, 2020; Ibe et al., 2019). The results obtained for both samples were then compared to the limit or environmentally accepted values as set by the regulatory body (National Environmental Management Authority, 2020; The National Environment, 2020). The data obtained from surface water analysis was then subjected to a robust hydrochemical model, PHREEQC (Parkhurst & Appelo, 2013) to predict the saturation indices and metal ion species present in the surface waters.

Study Area

The study area is Kenkombe dumping site. It is located in Rwentondo cell, Kakoba ward, 7 km from Mbarara town center. It is a 114-acre piece of land owned by the city council on which all municipal solid waste generated from the divisions of Mbarara district is dumped. It was instituted in 2005, after Mbarara Municipality then, became one of the beneficiaries of a US$ 300,000 National Environmental Management Authority–World Bank Solid Waste Compositing Plant Project meant to convert organic waste into composite manure. According to the terms of this project, all the municipal solid waste generated in Mbarara Municipality was supposed to be dumped at Kenkombe dumping site (Gumisiriza & Kugonza, 2020). The nearby surface water is the Rwentondo stream from which some of the people and animals in the community of Kenkombe get their water for consumption. (Gumisiriza & Kugonza, 2020).

Figure 1. Image of Kenkombe dumping site

Materials and Methods

Reagents and Materials

Beakers, volumetric flasks, measuring cylinders, pipettes, burettes, conical flasks, droppers, retort stand and clamps, Test tube heater, cuvettes, Amino Acid, Ascorbic Acid (prepared by dissolving 0.1 g ascorbic acid in water and make up to 100 mL in a volumetric flask), Buffer reagent (prepared by dissolving 136 g sodium acetate, $NaC_2H_3O_2.3H_2O$, in water, followed by 40 mL of 1 $molL^{-1}$ acetic acid and made up to 1 litre); phenantrolene (prepared by dissolving 0.1 g of 1,10-phenanthroline in 30 mL of distilled water, Sigma-Aldrich, Germany); Bicinchoninate solution, Ferrous sulphate (95% v/v, Sigma-Aldrich, Germany), A multiparameter bench photometer (HI 83200 2008 Series) with specifications (Light Source: 4 tungsten lamps with narrow band interference filters at 420/525/575/610 nm; Light Detector: 4 Silicon Photocells; Power Supply built-in rechargeable batteries or 12 Vdc adapter; Auto-off after 10 minutes of non-use Logging 200 data points; Computer Interface: USB; Environment: 0 to 50°C (32 to 122°F), RH max 90% non-condensing; Dimensions: 230 x 200 x 110 mm (9 x 7.9 x 4.3"); Weight 900 g (32 oz.)); Membrane filter (47 mm diameter, 0.45 µm pore size); EDTA solution (95% v/v, Merck, Germany); Potassium Chloride (anhydrous); Distilled water; Weighing Balance; 1000 mL volumetric flask; 1000 mL bottle container; Temperature measuring Device.

Sampling Criteria

Twelve white plastic sampling bottles of 500 mL were thoroughly washed with liquid soap, rinsed in distilled water and left to dry. Three samples were taken from the leachate tank. Composite and homogenous samples were made for analysis by gentle shaking. For the surface water samples, nine samples were collected from 3 different regions along the stream i.e., midstream which was 100 m apart from both the downstream and upstream on either side.

After sample collection, tests for pH, EC, TDS and temperature were conducted on site and then samples were stored in a cool box to avoid influence of temperature on the samples which could alter certain parameters before laboratory analysis.

Methods

Sample Digestion for Metal Analysis

The test tube heater was turned on and the control set at 105°C. The safety shield was placed in position and then the heater heated up to the set temperature. Sample tube was prepared by removing the cap of the Metaltube Digest. The sample (5 mL) was added using a standard laboratory pipette. The cap was then replaced tightly and the tube inverted to mix contents. The tube was then placed in the test tube heater. The contents of the tube were then digested for 60 minutes, then removed and transferred to a test tube rack. The tube was allowed to cool in cold water for approximately 10 minutes (APHA, 1995).

Determination of Fe, Cu, and Pb in Leachate and Surface Water Samples

Prior to sample analysis, a blank was prepared and run on the photometer by filling the Reagent tube to the graduation line (10 mL) with deionized water to minimize interferences. Specific reagents (2 mL) for each metal (bicinchoninate solution for copper, phenanthroline for iron, calmagite for magnesium) were added to each of the tubes using a standard laboratory pipette. The cap was replaced tightly and inverted gently to mix the contents until the tube became hot. The tube was allowed to cool for approximately 10 minutes. The metals for analysis were selected each at a time from the photometer layout. The cuvette was filled with unreacted sample (10 mL) one at a time up to the mark and the cap replaced. The cuvette was then placed into the holder, the lid was closed and the zero-key pressed and followed by "Run" key. The results were displayed on the photometer in mg/L (APHA, 1995).

Measurement of Electrolytic Conductivity in the Two Sample Types

The instrument was turned on and the setup menu option selected to enter standard solution value. A standard reading of 1.413mS/m was entered and cursor moved to Cal menu option to perform calibration. The conductivity cell is then immersed into the prepared standard until end point symbol appeared. Enter key was pressed to calibrate and then later the exit option was pressed (APHA, 1995). The probe was then rinsed with deionized water and the calibration re-checked. Deionized water (50 mL) was added into a beaker, and probe immersed in it. The blank was stirred until the instrument gave stable reading. Similarly, sample (50 mL) was added to a beaker and procedure repeated and measurement was read off directly from the meter's screen in *µs/m* (APHA, 1995).

Measurement of pH, DO and TDS of Leachate in the Two Sample Types

TDS. The multimeter was reset by pressing the *zero* button and the rod was cleaned with distilled water. The TDS option on the multimeter was pressed and TDS was read off directly from the screen in *ppm* (APHA, 1995).

DO. Using the DO meter, the meter was turned on and zeroed by pressing the *zero* button the DO test rod was then dipped into the beaker containing 50 mL of sample. The DO reading was recorded off directly from the screen in *mg/L* (APHA, 1995).

pH. Using the pH meter, removing the cover off the meter and rod exposed. The instrument was switched on via the start button and the rod at the bottom of the meter was dipped into 50 mL of sample. The pH was read off and recorded directly from the screen (Sim & Leong, 2011).

Measurements of COD Level

Two samples (16 mL) of the potassium dichromate (reagent sample) were added into a measuring cylinder. Deionized water (2 mL) was added into one of the reagent samples and leachate sample (2 mL) in the other reagent and shaken gently. The reagent sample was then placed into the COD reactor at 150℃, and left to digest for about 2 hours. The samples were then cooled for about 10 minutes. The reagent sample with deionized water was placed into the photometer cuvette and zero button pressed followed by the "read" button. The COD reading was taken off directly from the screen at a wavelength of 600 nm. The procedure was repeated for the reagent sample containing the leachate and surface water samples one at a time (APHA, 1995).

Results and Discussion

After carrying out the different tests on each sample, the average values were calculated for the upstream, midstream and downstream samples of water and the three samples of leachate to come up with the mean ranges of the values in both the surface water and leachate. When a non-parametric independent samples Mann-Whitney U test was subjected to the data, it was found that the distribution of each of the variables was the same across both sample types (P value>0.05). The graphs for the parameters in each of the samples were represented in Figure 2 and Figure 3 with the corresponding error bars.

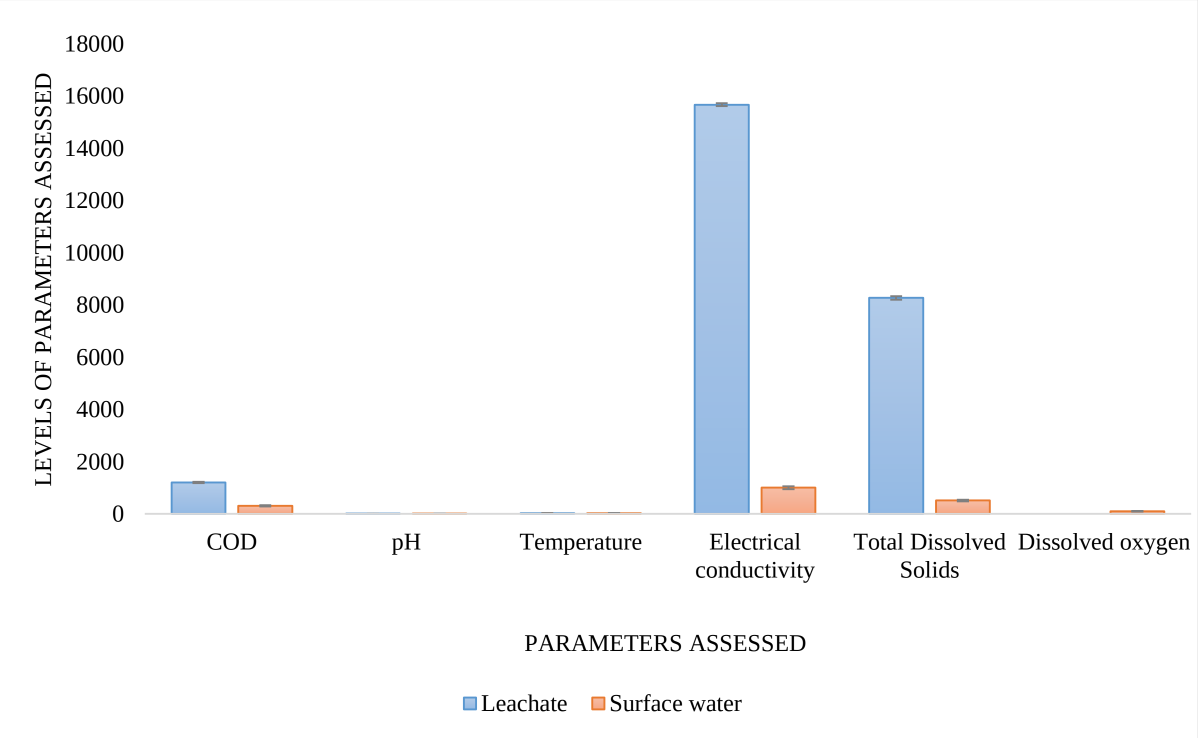

Figure 2. COD, DO, pH, temperature, EC, TDS in leachate and surface water samples

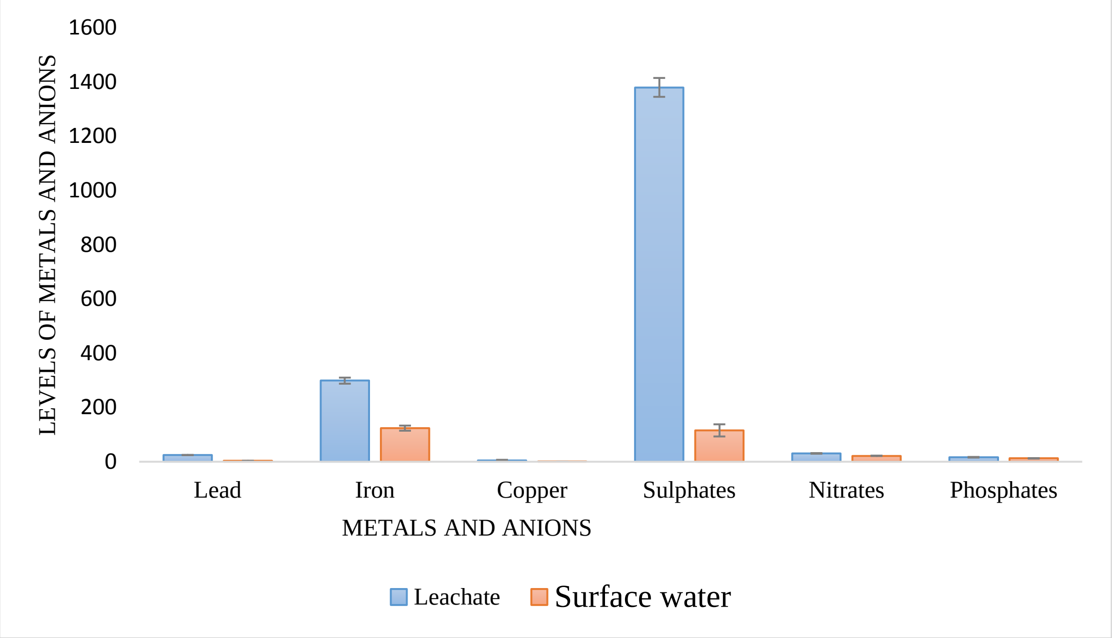

Figure 3. Pb, Fe, Cu, SO_4^{2-} , NO_3^-, PO_4^{3-} in leachate and surface water samples

Table 1. PHREEQC Simulated Saturation indices (SI)

Phase	**SI**	**Formula**
Anglesite	2.28	$PbSO_4$
$Fe(OH)_3(a)$	3.81	$Fe(OH)_3$
Goethite	9.64	FeOOH
$H_2(g)$	-21.05	H_2
$H_2O(g)$	-1.55	H_2O
Hematite	21.27	Fe_2O_3
Melanterite	-1.29	$FeSO4{:}7H_2O$
$O_2(g)$	-41.81	O_2
$Pb(OH)_2$	1.04	$Pb(OH)_2$
Vivianite	10.93	$Fe_3(PO4)_2{:}8H_2O$

Table 2. PHREEQC simulated Chemical Ion Speciation

Species	**Molality (m)**
H^+	$4.387e\text{-}^{05}$
OH^-	$5.505e\text{-}^{10}$
H_2O	$5.551e^{+01}$
Cu(1)	$2.784e^{-05}$
Cu^+	$2.784e^{-05}$
Cu(2)	$4.572e^{-03}$
$CuSO_4$	$3.120e^{-03}$
Cu^{+2}	$1.452e^{-03}$
$CuOH^+$	$1.346e^{-07}$
$Cu(OH)_2$	$2.636e^{-09}$
$Cu_2(OH)_2^{+2}$	$1.044e^{-09}$
$Cu(OH)_3$-	$7.387e^{-18}$
$Cu(OH)_4^{-2}$	$2.687e^{-26}$
Fe(2)	$2.993e^{-01}$

$FeSO_4$	$1.846e^{-01}$
Fe^{+2}	$1.000e^{-01}$
$FeH_2PO_4^+$	$1.454e^{-02}$
$FeHPO_4$	$7.687e^{-05}$
$FeHSO_4^+$	$5.767e^{-05}$
$FeOH^+$	$2.455e^{-07}$
$Fe(OH)_2$	$1.925e^{-14}$
$Fe(OH)_3^-$	$6.564e^{-20}$
Fe(3)	$1.645e^{-07}$
$Fe(OH)^{2+}$	$4.330e^{-08}$
$Fe(SO_4)^{2-}$	$3.862e^{-08}$
$FeSO_4+$	$3.053e^{-08}$
$FeH_2PO_4^{+2}$	$3.022e^{-08}$
$FeOH^{+2}$	$2.153e^{-08}$
Fe^{+3}	$2.795e^{-10}$
$Fe(OH)_3$	$5.568e^{-11}$
$FeHPO_4^+$	$1.346e^{-11}$
$FeHSO_4^{+2}$	$7.660e^{-13}$
$Fe(OH)_4^-$	$4.369e^{-15}$
$Fe_2(OH)_2^{+4}$	$1.276e^{-17}$
$Fe_3(OH)_4^{+5}$	$1.638e^{-23}$
$FeH_2PO_4^+$	$1.454e^{-02}$
$FeHPO_4$	$7.687e^{-05}$
$PbSO_4$	$1.586e^{-02}$
$Pb(SO_4)_2^{-2}$	$8.621e^{-03}$
Pb^{+2}	$2.170e^{-04}$
$PbOH^+$	$2.205e^{-07}$
Pb_2OH^{+3}	$5.317e^{-10}$
$Pb(OH)_2$	$1.752e^{-12}$
$Pb_3(OH)_4^{+2}$	$4.115e^{-17}$
$Pb(OH)_3^-$	$9.355e^{-19}$
$Pb(OH)_4^{-2}$	$3.907e^{-26}$
$Pb(SO_4)_2^{-2}$	$8.621e^{-03}$
$CuSO_4$	$3.120e^{-03}$
SO_4^{-2}	$1.159e^{+00}$

From Figure 2, the mean temperatures for the surface water and leachate samples ranged between 23.8^{o}C± 0.1^{o}C to 23.17± 0.2^{o}C. These values are consistent with temperature in typical tropical regions. The mean pH values for the leachate sample and surface water are 4.5±021 and 6.5± 0.23 respectively. The pH of the surface water lies within the NEMA's recommended threshold limit of 5.0-8.5 while that of the leachate lies below the limit. The low value of pH (below 7) in the leachate samples is an indication of an acid producing phase during the wastes' decomposition processes. It is also likely that the acidic leachate percolates through the soil to the underground water, and ultimately affects the pH of the nearby surface waters. The results obtained are in agreement with the observation made by Fatta, Papadopoulos, and Loizidou (1999) that the initial period of leachate formation is characterized by very low pH values. pH usually affects the speciation of metals in solutions with most metals easily speciated to their toxic forms in acidic pH below the value of 4, while some precipitate out of the solution at alkaline pH values.

There is an observed significant difference in the levels of COD between surface water and leachate. The COD was higher in the leachate than the surface waters. The COD values in both samples were higher than NEMA's threshold limit of 70-100 mg/L. The difference in the COD value of the two samples is indicative of the disparities in the degree of chemical activity in the two samples. The high values obtained for COD in leachate are due to chemical oxidation processes and decomposition in the leachate (Ehrig, 1989; Christensen et al., 1994; Agbozu & Nwosisi, 2015).

The concentration of nitrates was higher in the leachate than surface water. However, in both, the levels were higher than the recommended threshold by NEMA of 10 mg/L. Elevated nitrates levels in the leachates certainly find their way to ground and surface waters which increases the extent of exposure by the locals to these contaminants especially those who use the stream as a source of potable water. According to Fatta, Papadopoulos, and Loizidou (1999), nitrates are conservative contaminants as they are not affected by biochemical processes and natural decontamination processes in the site or waters. Therefore, they could correctly be characterized as key priority pollutants. Nitrates are a particular health concern in the body because they reduce the amount of oxygen that the blood can carry (methemoglobinemia) especially in children as a result of drinking water contaminated with elevated nitrates.

The other anions analyzed were sulphates and phosphates. The levels of each of the anions were higher in leachates than surface waters. The levels of sulphates could be attributed to the oxidation processes taking place in the dump site for example, the oxidation of iron sulphide present in the dump. High concentration of sulphate in water is dangerous as it causes dehydration and diarrhea in children (Longe & Balogun, 2010). The presence of phosphates in both the leachate samples and surface water sample should be a matter of concern because its presence in water increases eutrophication and subsequently promotes an algal bloom which may blanket surface water. This, in a long run, could result into a deterioration in the amount of dissolved oxygen in the waterbodies, thereby affecting the life of other aquatic organisms.

The electrolytic conductivity was higher in leachate (15,666.67 ±51.2) than surface water (1,000.8 ±51.5). In both cases, the levels were higher than 1000 µS/cm as recommended by NEMA. Electrical conductivity is generally due to the presence of inorganic charged particles such as chlorides, sulphates and others. Since leachate samples have more of these ions, their conductivities were higher. Conversely, conductivity is oftentimes used as a surrogate for total dissolved solids (Longe & Balogun, 2010). The reported figures are in agreement with the results reported from a landfill in Columbia (22,000 µS/cm) and Morocco (26,000 µS/cm) (Abd El-Salam & Abu-Zuid, 2015; Chofqi et al., 2004; Olivero-Verbel, Padilla-Bottet, & De la Rosa, 2008). However, the values are lower than those reported by Rahim et al. (2010) (31.68 µS/cm) for landfill leachate in Malaysia.

The total dissolved solids were higher in the leachate (8266.67 ±62.6) than surface water (511 ±31.2). The TDS levels can be attributed to the bedrock materials around the vicinity of the dumping site. According to WHO (2011), high level of TDS may be responsible for reduction in the palatability of water, inflict gastrointestinal inconveniences in human, may cause laxative effect particularly upon transits and may be objectionable to consumers.

The dissolved oxygen was fairly high in surface water. However, it was undetected in the leachate. The level of dissolved oxygen content of water is influenced by the chemical or biological processes taking place in the water system. Leachates experience high chemical oxidation processes, and so depleting the dissolved oxygen.

From Figure 3, variable levels of heavy metals were detected in the leachate and the surface water. For each metal, the highest levels were detected in leachate than in surface water. On average, the metals are present in the following order of concentration: Fe>Pb>Cu. The presence of these metals can be attributed to both the presence of these metals-containing wastes in the dumping site and their relative abundance on Earth. The presence of the metals in the surface water is also as a result of the continuous migration of the salts from leachate into both the ground and surface water sources. This could in turn result into an increased level of these metals in the river and groundwater aquifers. Notably, all the metals analyzed in leachates were present in concentrations higher than the normal wastewater discharge guideline (National Environmental Management Authority, 2020; The National Environment, 2020).

As observed from the simulation results in Table 1, all the metal complexes were insoluble. The sulphates combined with Pb^{2+} to form an insoluble anglesite. The phosphates, and peroxide, oxygen, and hydroxide combined with Fe^{2+} to form vivianite, hematite, goethite and iron (III) hydroxide respectively which are insoluble. The order of precipitation is: Hematite > Vivianite > Goethite > Iron (III) hydroxide > Anglesite. This partly explains the decrease in the level of the metal ions in the surface waters.

From Table 2, the speciation modelling predicted that the dominant species of iron was $FeSO_4$ with a molality of 1.846 e^{-01} m. The dominant species of lead was $PbSO_4$ with a molality of 1.586e-^{02}m while that of Cu was $CuSO_4$ with a molality of 3.120e^{-3}m. Many other complex ions for each metal were present but in very low concentrations. These results are important as inorganic complexes tend to decrease the concentration of free aqua metal ionic species. Effectively, this leads to a decrease in bioavailability and consequently, a decrease in toxicity levels. However, due to the presence of some free ions, their dispersibility in surface water could increase their dispersibility in the entire waterbody and contribute to the toxicity of the water system to the unsuspecting end users.

Conclusion and Recommendations

Conclusion

The pH, levels of TDS, and those of copper in the surface waters, lie within NEMA's permissible range. The rest of the analyzed parameters were outside the environmentally acceptable range. For the leachate, all the analyzed parameters were found to be of higher concentrations and surpassed NEMA's threshold values.

The saturation indices in Rwentondo stream as revealed by PHREEQC, were greater than zero (SI>0) for the following metal complexes: hematite, vivianite, goethite, iron (III) hydroxide, and anglesite. The speciation modelling predicted that the dominant species of iron was $FeSO_4$ with a molality of 1.846 e^{-01} m. The dominant species of lead was $PbSO_4$ with a molality of 1.586e-^{02} m while that of copper was $CuSO_4$ with a molality of 3.120e^{-3} m. The metal precipitations could have contributed significantly to the lowering of the total level of minerals ions in surface waters as compared to the leachate samples.

Therefore, the toxic leachate generated at Kenkombe landfill, possibly makes its way to the nearby stream of Rwentondo and alters the conditions of this surface water. This ultimately has a direct impact on the wellbeing of the people of Rwemigyina who domestically use this water and definitely to the environment as a whole.

Recommendations

Since the water of Rwentondo stream is consumed by the people and animals of Rwentondo and Kenkombe, we advise the responsible authorities in charge of this dumping site to devise better ways of managing (collecting and treating) this leachate to stop it from finding its way into the stream.

Whereas it is preferable to keep monitoring the dumpsite to ensure adherence to regulatory limits, we recommend that the Kekombe dumping site is fully upgraded to a well-engineered sanitary landfill by the stake holders in collaboration with relevant government agencies.

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Authors' Contribution

Derick Muloogi participated in laboratory work, data analysis, and writing of the manuscript. Collins Ruhabwa, Mollen Ampiire, and Ruth Arinwamukama participated in the data collection, laboratory work, and drafting of the research manuscript.

Conflict of Interest

The authors declare no conflict of interest.

Ethical Consideration

Since no human or any other animal was considered in this particular study, no ethical requirements were considered.

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