Fuzzy logic-based modeling of the impact of industrial activities on the environmental status of an industrial estate in Nigeria

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Fuzzy logic-based modeling of the impact of industrial activities on the environmental status of an industrial estate in Nigeria

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Industrial growth is being attributed with adverse environmental effects and has necessitated stricter environmental management policies. Formulating such policies is limited by the difficulty in understanding the trends of monitoring data. This study is aimed at the application of fuzzy comprehensive assessment (FCA) to integrate environmental contaminants in Agbara industrial estate, Nigeria, to measure the extent of impact of industrial activities on the host community. Samples of water, plants (Pteridium aquilinum, Sacciolepis africana, and Panicum maximum), soil, and sediments were collected within the estate. Water samples were analyzed for quality parameters using standard methods. Metals (Co, Cr, Cd, Cu, and Mn) were investigated in all the samples using an atomic absorption spectrophotometer. The data were modeled with FCA. The results showed Cr as the major contaminant (34–252 μgL−1). High phosphate contributed to large plant growth in the area. FCA results showed that water samples were in the pristine classification; sediment samples were extremely impacted. The vegetation growth and the sediment precipitation were responsible for the cleaning-up of the pollutants discharged downstream. The FCA of the plants indicated high metal bioaccumulation and not only showed the plants’ phyto-remediation potential but also that the metals may pose threats to human health through the food web. The activities in the estate are contributing contaminants to the environment with potential negative effects.

Keywords: fuzzy comprehensive assessment; industrial activities; biomonitoring; modeling; environment; health

Introduction

Industrial activities have caused lot of damages to the receiving environmental media because industries generate wastes, which contain hazardous organic chemicals, particulates, radionuclide, and toxic metals. These toxic chemicals are collected into plant and animal tissues and harm those living things along the food chain including humans. In developed economies, industries are the greatest sources of pollution, accounting for more than half the volume of all water pollution and for the most deadly pollutants (Pandey 2005). The situation is not different in the developing countries, where there is usually weak monitoring and enforcement efforts in the developing nations compared to the developed. Therefore, it is important to conserve and continuously monitor environmental
media, especially in developing nations, to ensure a safe ecosystem. However, environmental quality observations have little significance by themselves. A pollution parameter which has a specific value is usually meaningful only in the context of knowledge of natural background levels, regulatory standards, and combined matrix with other pollutants. Conventional environmental quality regulations contain classes which use crisp sets and the limits between different classes have inherent imprecision (Silvert 2000). An environmental quality monitoring data at the boundary of regulatory criteria is classified as belonging to only one class by real data set as against two classes by fuzzy set theory.

Fuzzy comprehensive assessment (FCA) of an environment for contaminants is a fuzzy logic-based model that can overcome the inherent imprecision and provide an overall understanding of environmental condition. This assists in establishing priorities for management purposes in terms of environmental prediction and policy formulation. Fuzzy logic is a mathematical model, designed to interpret sophisticated statements from natural language into a mathematical formalism (McNeil and Thro 1994). FCA is an aspect of this quantitative logic that provides description of environmental quality (Elmas 2003). Its application is essential because in all environmental quality assessments there is vagueness or fuzziness in environmental quality classification due to inconsistency in regulatory limits for each pollutant. A small increase or decrease in pollutant data, near its boundary value, will change its class. The fuzziness has led some environmental researchers to investigate advanced assessment methods based on fuzzy logic (Fisher 2003), such as fuzzy synthetic evaluation and fuzzy cluster analysis based on fuzzy set theory introduced by Zadeh (1965). Fuzzy logic and set theory was designed to interpret the uncertainties of real situations. The concept is gaining relevance in environmental modeling in recent years (Lu, Lo, and Hu 1999; Chang, Chen, and Ning 2001; Onkal-Engin, Demir, and Hiz 2004; Icaga 2007; Adebowale, Agunbiade, and Olu-Owolabi 2008) after its main application by researchers in electronics and engineering. The method evaluates comprehensively the contributions of various pollutants according to predetermined weights, and decreases the fuzziness by using membership functions to increase sensitivity.

Therefore, to understand the extent of impact of the increase in urbanization and industrialization in developing countries like Nigeria and the trend of their effects on the ecosystem, there is need for monitoring and ensuring good basis for policy formulation on conserving the quality of the environment. These have not been fully achieved by conventional approaches that have been widely documented, due to the fact that the ecosystem is a very complex system. But, modeling concepts such as fuzzy logic can help in representing, understanding, and exploring natural systems. The aim of this study therefore is to conduct a survey of the effects of industrial activities on the overall environment of Agbara industrial estate and to model the degree of impact using FCA approach.

**Materials and method**

**Site description**

Agbara industrial estate in Ogun state, Nigeria, is a typical example of an industrialized society which may pose threat to the host environment. The estate is the foremost private initiative in New Town development in Nigeria. It is a model integrated town development on 454.1 hectares of land. It is situated approximately 31 km west of Lagos on the Lagos-Badagry expressway on high ground above the Owo River. The industrial areas
constitute 42% (188.290 hectares) of the whole estate and provide sites for several multinational conglomerates, operating some of their most modern purpose built factories in the country. The estate has a waste treatment plant (WTP), which collects the effluents from the factories and domestic effluents. The effluents are treated at the WTP to reduce the level of contamination before their discharge into a nearby stream. This study identified seven sampling sites labeled AG01–AG07. Site AG01 is a drainage by the Agbara industrial estate WTP, which leads into a nearby stream (Figure 1a). This drainage collects effluents from the WTP and the residential area. Industries within the estate and sampling sites include different pharmaceutical and personal care products industries, glass industries, chemical industries, food and beverage industries, among others. Site AG02 is a stream (near a dump-site) into which the AG01 discharges its content (Figure 1b). Burning of domestic and commercial wastes like tyres, bottles, plastics, etc., occur at this dumpsite. Site AG03 is a swampy area downstream site AG02, with flourishing vegetation grown on a stream that receives effluents from the treatment plant (Figure 1c). Flourishing vegetation was observed on the stream which may be due to the result of nutrients from the discharged effluents. Site AG04 is within the swampy area downstream of AG03. Site AG05 is a portion of the stream receiving discharge from the WTP, where some of the dwellers swim, have their bath, wash their clothes and farm implements. Site AG06 is in the vicinity of a multinational industrial conglomerate’s factory while site AG07 is in the neighborhood of a chemical manufacturing factory. Sites AG01–AG05 are within the Agbara industrial estate WTP premises and are water-based, while the other two are within the vicinity of factories.

**Sampling and sample preservation**

The choice of sampling containers, pretreatment of sampling vessels, preservatives, storage time, and methods of analysis were carried out as described by APHA (1995). Before sampling, the sampling tools were pretreated as recommended by APHA (1995). They were washed with detergent that is free of metals and rinsed with deionized water. A liter of water sample was collected at each of the five water-based sites for physicochemical parameters and stored at 4°C, using high-density polyethylene (HDPE) bottles.
Likewise, a liter each of water sample was collected at these sites for metal analysis in a HDPE bottle, preserved by the addition of 2 mL of conc. HNO₃ per liter to reduce the pH below 2. The temperature and the pH of water samples were determined on site. Water samples for oil and grease were kept in amber-colored glass and preserved with HCl. Sediment samples were collected by using Van veen grab sampler and stored in polyethylene bags. The sediment samples were air-dried before analysis. Finally, plant samples (Sacciolepis africana, Pteridium aquilinum, and Panicum maximum) were collected at sites to biomonitor metals. The plants were identified at University of Ibadan, Botany Department. The chosen plants are weeds that can be involved in the food web and may have potential to phytoremediate pollutants in the environment.

Chemical analysis

The methods used for water sample analysis for physical and aggregate properties; inorganic non-metallic components, aggregate organic components, and metals were based on classifications and recommendations of Standard Method for Examination of Water and Waste Water (APHA 1995). Metal components in sediment samples were determined after air drying, grounding, and sieved to particle size <200 μm. One gram of air-dried sediment was then treated with 20 mL of 0.5 mol L⁻¹ HNO₃ at room temperature for 12 h and filtered to access the labile bioavailable metals. The filtrate was then made up to mark in a 50 mL standard flask. Plant samples were separated into roots, stems, and leaves. They were dried and ground before digestion. Aliquots of 0.5 g of each were weighed and treated with 20 mL H₂O₂ : HNO₃ (1 : 3) at about 80°C for 4 h. The resulting clear solution was made up to mark with deionized water in a 50 mL standard flask. Metals Co, Cr, Cd, Cu, and Mn were investigated in digested samples using Flame Atomic Absorption Spectrometer (AAS) Buck Scientific 205 Model with direct air–acetylene flame method. The quality assurance steps were taken to ensure the integrity of the data obtained. This includes the use of analytical grade reagents and deionized-distilled water, analysis of blank samples to correct for any external contribution, assessment of the reproducibility of sampling, and analytical procedures by analyzing replicate samples. Choice of analytical methods was based on their detection limits and sensitivity of methods.

Data analysis and treatment

Evaluation of metals indices

The partitioning of each metal ($K_d$) between the sediment phase and water phase was determined by the modification of the equation proposed by Ball (1988) while the plant’s enrichment factor (EF) was calculated by the comparison of each tested metal concentration in plant samples to that in the host environment. The translocation of the metals from the plant root to the shoot and leaves was calculated with translocation factor (TF) based on the ratio of each tested metal concentration in the stem and leaf to that in the root.

Principles of fuzzy comprehensive assessment

The concept of FCA is a mathematical discipline based on fuzzy logic and fuzzy set theory and expresses multiple levels process among [0, 1] instead of two levels process among (0, 1)
Fuzzy logic incorporates a simple rule-based approach to solve a control problem rather than attempting to model a system mathematically. FCA is a subdivision of fuzzy synthetic evaluation method. It involves the formulation of fuzzy membership functions which are arranged into evaluation matrix and are subjected to weighting average method of fuzzy reasoning. The mathematical expression of FCA is as follows:

\[
k_j = \sum_{i=1}^{n} w_i \mu_{ij}
\]

where \(\mu_{ij}\) are membership function and \(w_i\) is the weight associated with each parameter, and \(k_j\) is the product of each membership function and the weight.

In the application of FCA for environmental monitoring, the selection of important parameters that could reliably and accurately assess the contamination status and represent effectively the local environment is the foundational step. These parameters constitute the members of the universal set of function:

\[
\mathbb{U} = \{\mu_1, \mu_2, \mu_3, \ldots, \mu_n\}
\]

where \(\mu_1, \mu_2, \mu_3, \ldots, \mu_n\) are the parameters (e.g., organic pollutants, metals, or water quality parameters). This is followed by the establishment of classification criteria or limits for the parameters which are based on regulatory standards or by a consideration of background concentration of such pollutant natural to that environment or by expert knowledge. The criteria are defined into another set function:

\[
B = \{b_1, b_2, \ldots, b_n\}
\]

where \(b_1, b_2, \ldots, b_n\) are the classifications of the parameters and \(n\) is the total number of classification.

After the quality criteria have been established, the water, plant, soil, and sediment quality evaluation data will be classified into membership function of the quality criteria. Three levels of classifications used in this study are: I – Pristine condition; II – Moderately enriched condition, and III – Extremely impacted condition. This is based on general literature documented approach for studying water, sediment, and soil pollution and in relation to background information on the environment.

The criteria limits for each metal in samples (water, sediments, soil, and plants) are presented in Table 1 and criteria limit for water quality parameters in Table 2. The three classifications used for this study are presented as Classifications I, II, and III corresponds to limits \(b_1, b_2,\) and \(b_3\), respectively. The limits of each classification were established based on regulatory standards for each metal. The observed concentration of each metal was then used in relation to these limits to formulate fuzzy membership function based on
Table 1. Quality criteria limits of metals for formulating membership function sediments and plants.

<table>
<thead>
<tr>
<th>Metals</th>
<th>Water (mg L(^{-1}))</th>
<th>Sediments/plants (mg kg(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>0.05 1.00</td>
<td>0.10 10.0</td>
</tr>
<tr>
<td>Cr</td>
<td>0.05 1.00</td>
<td>0.10 5.00</td>
</tr>
<tr>
<td>Cd</td>
<td>0.01 0.50</td>
<td>0.05 1.00</td>
</tr>
<tr>
<td>Cu</td>
<td>1.00 20.0</td>
<td>2.00 40.0</td>
</tr>
<tr>
<td>Mn</td>
<td>0.50 50.0</td>
<td>1.00 100</td>
</tr>
</tbody>
</table>

Note: The classification \(b_1\), \(b_2\), and \(b_3\) correspond to I, II, and III classes which are defined as pristine, moderately enriched, and extremely impacted, respectively.

Table 2. Quality criteria limits of some water quality parameters for formulating membership function.

<table>
<thead>
<tr>
<th>Parameters in water</th>
<th>Units</th>
<th>(b_1)</th>
<th>(b_2)</th>
<th>(b_3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphate</td>
<td>mg L(^{-1})</td>
<td>0.20</td>
<td>0.50</td>
<td>1.00</td>
</tr>
<tr>
<td>Chloride</td>
<td>mg L(^{-1})</td>
<td>100</td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>Sulfate</td>
<td>mg L(^{-1})</td>
<td>100</td>
<td>250</td>
<td>500</td>
</tr>
<tr>
<td>TSs</td>
<td>mg L(^{-1})</td>
<td>250</td>
<td>500</td>
<td>1000</td>
</tr>
<tr>
<td>Temp</td>
<td>°C</td>
<td>20</td>
<td>25</td>
<td>27.5</td>
</tr>
<tr>
<td>pH ≥ 7</td>
<td></td>
<td>7.0</td>
<td>7.5</td>
<td>8.0</td>
</tr>
<tr>
<td>pH &lt; 7</td>
<td></td>
<td>7.0</td>
<td>6.5</td>
<td>6.0</td>
</tr>
<tr>
<td>Nitrate</td>
<td>mg L(^{-1})</td>
<td>0.2</td>
<td>0.5</td>
<td>1.0</td>
</tr>
</tbody>
</table>

Note: The classification \(b_1\), \(b_2\), and \(b_3\) correspond to I, II, and III classes which are defined as pristine, moderately enriched, and extremely impacted, respectively.

Equations (6)–(8).

\[
\mu_1(y) = \begin{cases} 
1 & \text{if } y \leq b_1 \\
\frac{(b_2 - y)}{(b_2 - b_1)} & \text{if } b_1 < y < b_2 \\
0 & \text{if } y \geq b_2 
\end{cases} \tag{6}
\]

\[
\mu_2(y) = \begin{cases} 
1 \mu_1(y) & \text{if } y \leq b_1 \\
\frac{(b_3 - y)}{(b_3 - b_2)} & \text{if } b_1 < y < b_2 \\
0 & \text{if } b_2 < y < b_3 
\end{cases} \tag{7}
\]

\[
\mu_3(y) = \begin{cases} 
0 & \text{if } y \leq b_1 \\
1 - \mu_2(y) & \text{if } b_2 < y < b_3 \\
1 & \text{if } y \geq b_3 
\end{cases} \tag{8}
\]
where $y$ is the observed data from chemical analysis of the parameters used in the assessment, $\mu_1(y)$, $\mu_2(y)$, and $\mu_3(y)$ are the fuzzy membership functions corresponding to I, II, and III, respectively.

The membership functions of the observed monitoring data obtained from the expressions (6)–(8) are arranged into an evaluation fuzzy matrix $X_k$ which is

$$
X_k = \begin{bmatrix}
\mu_{11} & \mu_{12} & \cdots & \mu_{1m} \\
\mu_{21} & \mu_{22} & \cdots & \mu_{2m} \\
\vdots & \vdots & \ddots & \vdots \\
\mu_{n1} & \mu_{n2} & \cdots & \mu_{nm}
\end{bmatrix}
$$

where $\mu_{ij}$ is the degree of membership of a classification obtained for $j$th number of parameters and $i$th number of limit classification. Thus, $i = 1, 2, \ldots, n$ and $j = 1, 2, \ldots, m$ where $n$ is the number of parameters investigated and $m$ is the number of criteria classifications (3) and $X_k$ is the fuzzy matrix at $k$th site.

Another critical step in the application of FCA is the allocation of appropriate weight to each parameter. The choice of weight influences the outcome of the assessment and several methods have been used. For this study, allocation of weight for metals will be based on the ratio of the contribution of the observed data for each metal to the overall weight which has been mathematically expressed by Shen et al. (2005) and Adebowale, Agunbiade, and Olu-Owolabi (2008) as

$$
a_{i(k)} = \frac{C_{i(k)}}{S_i} \quad (10)
$$

$$
w_{i(k)} = \frac{a_{i(k)}}{\sum_{i=1}^{n} a_{i(k)}} \quad (11)
$$

where $C_{i(k)}$ is the concentration of each metal number $(i)$ in monitoring site $(k)$ and $S_i$ is the average limits formulating the membership function for each parameter. The values obtained from Equation (10) are substituted in Equation (11) to obtain the weight ($w_{i(k)}$) of each parameters per site. The weight obtained can then be arranged as weight matrix $P_k$.

$$
P_k = \begin{bmatrix}
w_{1(k)} \\
w_{2(k)} \\
\vdots \\
w_{n(k)}
\end{bmatrix}
$$

where $n$ is the number of investigated parameters. The weight matrix ($P_k$) formulation for the assessment of water quality was based on the Analytical Hierarchy Procedure (AHP) (Ocampo-Duque et al. 2006).

The final step in FCA application involves the use of fuzzy algorithm which is computed from the product of the fuzzy matrix (Equation 9) and the weight matrix (Equation 12). The product moment of the fuzzy matrix $X_k=(\mu_i)_{n\times m}$ and the weight matrix $P_k=(w_{i(k)})_{1\times n}$ gives the matrix index as expressed in Equation (1) and the $k_j$ classifies the degree of contamination of the sites into any of the classes while the max $k_j$ is the state to which the environmental media belong as earlier presented in Equation (3).
The product of the matrix gives

$$X_k P_k = \begin{bmatrix} k_1 \\ k_2 \\ \vdots \\ k_j \end{bmatrix}$$

(13)

### Results and discussion

#### Status of heavy metals in water samples

The concentrations of the metals and other quality parameters in water samples at the water based sampling sites in Agbara industrial estate are presented in Table 3. Cd was below detection limit in all the sites. Mn concentrations were found to be the highest compared to other metals in each of the sites, which indicate that Mn may be abundant in our area of study. Cr followed Mn in concentration except for site AG02 where Cu concentration was found to be higher than Cr. High Cu in this site may due to the result of domestic and commercial wastes containing copper deposited on the dumpsite near the sampling site AG02, which after long time of burning and other chemical reactions may have been leached into the water sample. Also, Cu concentration at AG02 was found to be the highest among all the other sites. Therefore, the dumpsite may be a point source of Cu to the studied environment.

Metal concentrations reduced from AG01 to AG02 down to AG03, except for Cu. This trend suggests AG01 as the likely distribution pathway of metals discharge to other sites. Site AG01 is drainage near Agbara industrial estate WTP and may receive waste water and disperse such into other sites investigated. Metal concentrations between AG03 and AG04 were found to be relatively similar. Cr concentration was observed to increase at AG05 than at AG04, which suggests Cr contamination at AG05.

Other water quality parameters indicate that the water is slightly acidic which will enhance the availability of the metals in their more toxic ionic state in the water system. Phosphate and sulfate concentration were high in site. This high phosphate and sulfate

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Units</th>
<th>AG01</th>
<th>AG02</th>
<th>AG03</th>
<th>AG04</th>
<th>AG05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phosphate</td>
<td>mg L$^{-1}$</td>
<td>45.82 ± 3.5</td>
<td>50.73 ± 7.2</td>
<td>5.39 ± 0.45</td>
<td>5.32 ± 0.73</td>
<td>5.30 ± 0.58</td>
</tr>
<tr>
<td>Chloride</td>
<td>mg L$^{-1}$</td>
<td>9.8 ± 1.1</td>
<td>11.2 ± 0.8</td>
<td>10.4 ± 0.6</td>
<td>11.8 ± 1.2</td>
<td>11.5 ± 0.9</td>
</tr>
<tr>
<td>Sulfate</td>
<td>mg L$^{-1}$</td>
<td>149.2 ± 4.9</td>
<td>409.58 ± 8.8</td>
<td>37.1 ± 1.7</td>
<td>28.54 ± 2.5</td>
<td>28.75 ± 3.8</td>
</tr>
<tr>
<td>TSs</td>
<td>%</td>
<td>0.32 ± 0.12</td>
<td>0.58 ± 0.01</td>
<td>1.56 ± 0.08</td>
<td>1.36 ± 0.02</td>
<td>0.44 ± 0.01</td>
</tr>
<tr>
<td>Temperature</td>
<td>°C</td>
<td>30</td>
<td>31</td>
<td>28</td>
<td>27.5</td>
<td>28</td>
</tr>
<tr>
<td>pH</td>
<td></td>
<td>6.6 ± 0.1</td>
<td>6.6 ± 0.3</td>
<td>6.6 ± 0.2</td>
<td>6.3 ± 0.2</td>
<td>6.7 ± 0.3</td>
</tr>
<tr>
<td>Oil and grease</td>
<td>mg L$^{-1}$</td>
<td>98.0 ± 1.7</td>
<td>1.40 ± 0.1</td>
<td>2.3 ± 0.3</td>
<td>4.00 ± 0.5</td>
<td>96.0 ± 3.2</td>
</tr>
<tr>
<td>Alkalinity</td>
<td>mg CaCO$_3$ L$^{-1}$</td>
<td>19.5 ± 2.8</td>
<td>19.5 ± 1.7</td>
<td>19.5 ± 2.1</td>
<td>15.2 ± 3.7</td>
<td>19.5 ± 4.2</td>
</tr>
<tr>
<td>Co</td>
<td>μg L$^{-1}$</td>
<td>31 ± 3</td>
<td>22 ± 1</td>
<td>8 ± 0.5</td>
<td>9 ± 0.4</td>
<td>10 ± 0.6</td>
</tr>
<tr>
<td>Cr</td>
<td>μg L$^{-1}$</td>
<td>252 ± 7</td>
<td>131 ± 4</td>
<td>34 ± 1.6</td>
<td>33 ± 2</td>
<td>73 ± 5</td>
</tr>
<tr>
<td>Cd</td>
<td>μg L$^{-1}$</td>
<td>Nd</td>
<td>Nd</td>
<td>Nd</td>
<td>Nd</td>
<td>Nd</td>
</tr>
<tr>
<td>Cu</td>
<td>μg L$^{-1}$</td>
<td>91 ± 3.0</td>
<td>205 ± 12</td>
<td>13 ± 1.1</td>
<td>15 ± 0.9</td>
<td>14 ± 1.1</td>
</tr>
<tr>
<td>Mn</td>
<td>μg L$^{-1}$</td>
<td>940 ± 11</td>
<td>755 ± 13</td>
<td>160 ± 7</td>
<td>110 ± 8</td>
<td>90 ± 5</td>
</tr>
</tbody>
</table>

Note: Nd – not detectable.
concentration in AG01 and AG02 dropped significantly in AG03–AG05. It may be inferred that the WTP is discharging nutrient-enriched effluents which are responsible for the wide vegetation growth around discharge area (Figure 1c). The total solid (TS) had an opposite trend to the trend observed for all other parameters thus far reported. The TS increased from site AG01 to AG04 but reduced at AG05. The chloride content and the total alkalinity of the water system were moderate.

**FCA of quality parameters in water samples**

To assess the degree of contamination of the water system in the study area relative to regulatory standards and with composite effects of all parameters measured, FCA was carried out. Water sample fuzzy matrix was formulated using the following parameters determined in the samples and arranged in the order Co, Cr, Cd, Cu, Mn, phosphate, chloride, sulfate, TSs and pH at sites AG01, AG02, AG03, AG04, and AG05. Each column represents the parameters in the order presented above while each row represents the quality classification (the first row being pristine classification, second moderately enriched, and the third being the extremely impacted class). The results are represented as matrices $X_1$, $X_2$, $X_3$, $X_4$, and $X_5$, respectively each representing the sites as presented below:

$$X_1 = \begin{bmatrix} 1.00 & 0.00 & 1.00 & 1.00 & 0.12 & 0.00 & 1.00 & 0.67 & 0.00 & 0.20 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.88 & 0.00 & 0.00 & 0.33 & 0.00 & 0.80 \\ 0.00 & 1.00 & 0.00 & 0.00 & 0.00 & 1.00 & 0.00 & 0.00 & 1.00 & 0.00 \end{bmatrix},$$

$$X_2 = \begin{bmatrix} 1.00 & 0.00 & 1.00 & 1.00 & 0.49 & 0.00 & 1.00 & 0.00 & 0.00 & 0.20 \\ 0.00 & 0.69 & 0.00 & 0.00 & 0.51 & 0.00 & 0.00 & 0.36 & 0.00 & 0.80 \\ 0.00 & 0.31 & 0.00 & 0.00 & 0.00 & 1.00 & 0.00 & 0.64 & 1.00 & 0.00 \end{bmatrix},$$

$$X_3 = \begin{bmatrix} 1.00 & 1.00 & 1.00 & 1.00 & 0.00 & 1.00 & 1.00 & 0.00 & 0.00 & 0.20 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.80 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00 & 0.00 & 0.00 & 1.00 & 0.00 \end{bmatrix},$$

$$X_4 = \begin{bmatrix} 1.00 & 1.00 & 1.00 & 1.00 & 0.00 & 1.00 & 1.00 & 0.00 & 0.00 & 0.00 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.60 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00 & 0.00 & 0.00 & 1.00 & 0.40 \end{bmatrix},$$

$$X_5 = \begin{bmatrix} 1.00 & 0.54 & 1.00 & 1.00 & 1.00 & 0.00 & 1.00 & 1.00 & 0.00 & 0.40 \\ 0.00 & 0.46 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 0.60 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 & 1.00 & 0.00 & 0.00 & 1.00 & 0.00 \end{bmatrix}.$$

The mean values of parameters in water samples used for the formation of the fuzzy matrix are presented in Table 3 while the criteria limits used are presented in Tables 1 and 2. The fuzzy membership function ($\mu_i$) obtained for parameters were in the order stated above. The matrix expressed that the phosphate and TSs were in the extremely impacted classification for all the sites. This further revealed that the industrial and domestic wastes discharged into this environment contribute to the high phosphate
content in the environment and the effect is blooming of vegetation around the area. The heavy growth of vegetation at these sites is evident of the high impact of phosphate (which is a trace element essential for plant growth), a condition called eutrophication. Cr was also in the extremely impacted contamination class at site AG01 but fell into the moderately impacted state at AG02 and further into the pristine classification in sites AG03–AG04. This revealed that Cr contamination is likely discharged through site AG01 and is being introduced to the ecosystem. It is however being managed by the prevailing biogeochemistry of the environment. Therefore, policies that will reduce Cr contamination may be needed to conserve the ecosystem and not over-labor the favorable biogeochemistry presently managing its reduction and dispersion into the area. Co, Cd, Cu, and chloride ranked absolutely at the pristine range in the water system for all the sites. Mn has higher membership in moderately impacted range than the pristine membership classification at sites AG01 and AG02. In sites AG03–AG05, Mn is in the pristine classification. Sulfate has high membership in the pristine level at all the sites except for site AG02. pH was in the moderately impacted classification for all the sites.

The weight contributed by phosphate to the total contaminant load is very high, this makes the adoption of AHP necessary to better represent these sites. To formulate the final aggregate, weight matrix \( P_k \) was formulated with the use of AHP (Ocampo-Duque et al. 2006) and the results presented in the weight matrix \( P_k \) are in the same order as the evaluation matrix \( X_i \) above:

\[
P_k = \begin{bmatrix}
0.0624 \\
0.0866 \\
0.1525 \\
0.0445 \\
0.0445 \\
0.2062 \\
0.1122 \\
0.0655 \\
0.0764 \\
0.1492
\end{bmatrix}.
\]

From the weight matrix also phosphate and TSs were the major contaminants among the parameters studied in the water samples. The fuzzy algorithms \( (X_i P_k) \) for water samples in the five water-based sampling sites are presented in the following matrices:

\[
X_1 P_1 = \begin{bmatrix} 0.4507 \\ 0.1801 \\ 0.3692 \end{bmatrix}, \quad X_2 P_2 = \begin{bmatrix} 0.4232 \\ 0.2254 \\ 0.3514 \end{bmatrix}, \quad X_3 P_3 = \begin{bmatrix} 0.5980 \\ 0.1194 \\ 0.2826 \end{bmatrix},
\]

\[
X_4 P_4 = \begin{bmatrix} 0.5682 \\ 0.0895 \\ 0.3423 \end{bmatrix}, \quad X_5 P_5 = \begin{bmatrix} 0.5880 \\ 0.1294 \\ 0.2826 \end{bmatrix}.
\]

The maximum \( k_j \) determines the class to which the environment belongs. From the fuzzy matrices it is clear that the water system of the estate is in the pristine state. Result of fuzzy algorithms show that the degree of contamination of water samples can be classified within the range of 42.32%–59.8% pristine, 8.95%–22.54% moderately impacted, and
28.26%–36.92% extremely impacted. Although site AG01 was classified as pristine, it has the highest membership in the extremely impacted classification compared to other sites. This supports the view that AG01 is an entry point of contaminants into other sites.

### Status of metals in sediment samples

Concentrations of metals in sediment samples are presented in Table 4. Similar to the trends in water samples, Mn concentrations were found to be highest in each site compared to all other metals tested for. High concentrations of Mn in sediment samples had also been reported by Adebowale, Agunbiade, and Olu-Owolabi (2008) and were related to geological structure of the environment. Though Cd was not detected in water samples, it was detected in sediment samples from the sites except site AG05. Cu ranked next to Mn in concentration and was also highest at AG02 as in water sample. Cu had second highest concentration in sediment samples as against Cr in water samples. This implies that the partitioning ($K_d$) of these metals between the sediment phase and water phase will vary from metal to metal and will not be constant for all metals. Metal concentrations in sediment samples were several magnitudes higher than those in the corresponding water samples. This results in the ability of the sediment to serve as sinks for precipitated metals over a long time (Rowlatt and Lovell 1994; Mucha, Vasconcelos, and Bordalo 2003; Agunbiade, Olu-Owolabi, and Adebowale 2010).

The $K_d$ obtained for the metals between water and sediments from Agbara industrial estate are presented in Table 5. Higher $K_d$ values indicate higher metal concentration in sediment sample compared to water sample. The $K_d$ for Cd was not calculated because Cd was not detected in the water sample. Cu gave the highest $K_d$ compared to other metals in all the sites. This presented Cu as a fast sinking metal. Precipitation, coagulation, adsorption, and bioaccumulation of Cu are some of the reactions or conditions that favor the partitioning of metals into the sediment phase (James 2002). This result presents Cu as being partitioned by any of these reactions and as a main contaminant in the sediment phase of this area. Co gave the lowest average $K_d$ for the sites. Therefore, Co may not be a significant contaminant in this area. The $K_d$ of Cr was next to Co in increasing order. Cr partitioning in sites AG03 and AG04 were significantly higher than the other sites. There must be some favorable environmental conditions or biogeochemical reactions demobilizing the Cr from the water system into the sediment phase. As a result of the cleaning up of the Cr by reactions in AG03 and AG04, the $K_d$ value for Cr was the lowest at site AG05 compared to other sites. This trend of significant increase in $K_d$ at sites AG03 and AG04 and subsequent drop at site AG05 was witnessed for all the metals. It may be concluded that the prevailing biogeochemical reactions in sites AG03 and AG04 are managing the

<table>
<thead>
<tr>
<th>Elements</th>
<th>AG01</th>
<th>AG02</th>
<th>AG03</th>
<th>AG04</th>
<th>AG05</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co (mg kg(^{-1}))</td>
<td>1.40 ± 0.11</td>
<td>1.70 ± 0.23</td>
<td>1.95 ± 0.21</td>
<td>1.40 ± 0.17</td>
<td>Nd</td>
</tr>
<tr>
<td>Cr (mg kg(^{-1}))</td>
<td>7.75 ± 0.56</td>
<td>12.4 ± 0.08</td>
<td>20.0 ± 1.09</td>
<td>17.4 ± 1.31</td>
<td>1.25 ± 0.31</td>
</tr>
<tr>
<td>Cd (mg kg(^{-1}))</td>
<td>0.90 ± 0.03</td>
<td>3.35 ± 0.71</td>
<td>2.20 ± 0.41</td>
<td>3.10 ± 0.23</td>
<td>Nd</td>
</tr>
<tr>
<td>Cu (mg kg(^{-1}))</td>
<td>24.3 ± 1.87</td>
<td>43.6 ± 2.97</td>
<td>41.6 ± 2.19</td>
<td>42.15 ± 2.69</td>
<td>13.80 ± 0.98</td>
</tr>
<tr>
<td>Mn (mg kg(^{-1}))</td>
<td>49.5 ± 3.11</td>
<td>104.5 ± 4.91</td>
<td>85.5 ± 4.77</td>
<td>79.0 ± 3.86</td>
<td>7.50 ± 0.82</td>
</tr>
</tbody>
</table>

Note: Nd – not detectable.
metals discharged into the ecosystem by partitioning it from the mobile water phase into the less mobile sediment phase, which is regarded as favorable. The implication of this is that metals discharged into this environment are managed by precipitation into sediments and/or bioaccumulation into plants. This is the reason why the sediment phase of AG05 is the least affected by metals contamination.

Contrary to the trend of metal concentrations in water samples, metal concentrations in sediment samples increased from AG01 through AG02 to AG03. This increment lends more credence to the claim that biogeochemical reactions within the sites are demobilizing the metals into the sediment phase from the water phase, thus managing the metal discharge into the sediment column. The most significant metal reduction was observed in sediments from AG04 to AG05. This occurred because the metal load has been reduced by the holding capacity of the sediment phase. The demobilization of the metals by the sediment earlier discussed, makes the sediment phase act as a purifying agent, i.e., self-purification capability of nature. The possibility of a reverse trend that will release the metals from the sediment phase cannot be ruled out through the discharge of low pH effluent or other conditions. Therefore, condition that may reverse the trend must be guided against while metal content in the discharge must also be controlled.

**FCA of heavy metals in sediment samples**

Further understanding of the degree of sediment contamination and impact of industrial activities on sediment was elicited with FCA. The sediments fuzzy matrix for metals at sites AG01, AG02, AG03, AG04, and AG05 are represented as $X_1$, $X_2$, $X_3$, $X_4$, and $X_5$, respectively, and their corresponding weight matrix as $P_1$, $P_2$, $P_3$, $P_4$, and $P_5$ are presented. The trend adopted was Co, Cr, Cd, Cu, and Mn for each column and each of the three classifications (pristine, moderately enriched, and extremely impacted) are represented by the following each row:

$$
X_1 = \begin{bmatrix}
0.96 & 0.00 & 0.20 & 0.79 & 1.00 \\
0.04 & 0.45 & 0.80 & 0.21 & 0.00 \\
0.00 & 0.55 & 0.00 & 0.00 & 0.00
\end{bmatrix}
$$

$$
X_2 = \begin{bmatrix}
0.92 & 0.00 & 0.00 & 0.00 & 0.00 \\
0.08 & 0.00 & 0.41 & 0.94 & 0.99 \\
0.00 & 1.00 & 0.59 & 0.06 & 0.01
\end{bmatrix}
$$

<table>
<thead>
<tr>
<th>Elements</th>
<th>AG01</th>
<th>AG02</th>
<th>AG03</th>
<th>AG04</th>
<th>AG05</th>
<th>Mean $K_d$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Co</td>
<td>45.16</td>
<td>77.27</td>
<td>243.75</td>
<td>155.56</td>
<td>0.000</td>
<td>104.35</td>
</tr>
<tr>
<td>Cr</td>
<td>30.75</td>
<td>94.27</td>
<td>588.24</td>
<td>526.76</td>
<td>17.12</td>
<td>250.83</td>
</tr>
<tr>
<td>Cu</td>
<td>266.48</td>
<td>212.68</td>
<td>3200</td>
<td>2810</td>
<td>985.71</td>
<td>1495.0</td>
</tr>
<tr>
<td>Mn</td>
<td>52.66</td>
<td>138.41</td>
<td>534.38</td>
<td>718.18</td>
<td>83.33</td>
<td>305.4</td>
</tr>
</tbody>
</table>
The mean values of metal concentrations in sediment samples used for the formation of the fuzzy matrix are presented in Table 4. The fuzzy membership function (\( \mu_i \)) obtained for metals are arranged in the above evaluation matrices in the order stated earlier. From the fuzzy matrices, it is evident that Cr is the main contaminant in the sediments, with high membership in the extremely impacted level followed by Cd that has only 20% membership of pristine level at AG01, and at the three other sites has high membership between moderately enriched level and extremely impacted level. These two elements have been implicated as toxic to lives and have been classified by USEPA as priority pollutants and potentially carcinogenic (USEPA 1999; Pekey 2006)

This environment is free from Co pollution because Co has high membership in the pristine class in all the five sites. Cu and Mn also have high membership in the pristine level in AG01 but were moderately impacted in sites AG02, AG03, and AG04. At site AG05, all the metals were at the pristine class. Thus, AG05 is not impacted with the metals investigated. The weight matrices (\( P_i \)) confirmed Cr as the main contaminant and contributor at AG01 (contributing 42%), AG03 (contributing 48%), and at AG04 (contributing 41%) to the total contaminant weight. Cd was the highest metal contributor at AG02 and Cu at AG05. Co is the least contributor at all the sites which confirms that the site is free of Co pollution. Thus, metals of focus for management and control are Cr and Cd.

The fuzzy algorithm results (\( X_kP_k \)) for the sediments are

\[
X_3 = \begin{bmatrix}
0.89 & 0.00 & 0.00 & 0.00 & 0.29 \\
0.11 & 0.00 & 0.70 & 0.97 & 0.71 \\
0.00 & 1.00 & 0.30 & 0.03 & 0.00 \\
0.96 & 0.00 & 0.00 & 0.00 & 0.42 \\
0.04 & 0.00 & 0.48 & 0.96 & 0.58 \\
0.00 & 1.00 & 0.52 & 0.04 & 0.00
\end{bmatrix},
\]

\[
X_4 = \begin{bmatrix}
1.00 & 0.94 & 1.00 & 1.00 & 1.00 \\
0.00 & 0.06 & 0.00 & 0.00 & 0.00 \\
0.00 & 0.00 & 0.00 & 0.00 & 0.00
\end{bmatrix},
\]

\[
P_1 = \begin{bmatrix}
0.038 & 0.021 & 0.024 & 0.016 & 0.000 \\
0.420 & 0.304 & 0.483 & 0.406 & 0.373 \\
0.244 & 0.412 & 0.265 & 0.362 & 0.000 \\
0.164 & 0.134 & 0.125 & 0.123 & 0.515 \\
0.134 & 0.129 & 0.103 & 0.092 & 0.112
\end{bmatrix},
\]

\[
P_2 = \begin{bmatrix}
0.038 & 0.021 & 0.024 & 0.016 & 0.000 \\
0.420 & 0.304 & 0.483 & 0.406 & 0.373 \\
0.244 & 0.412 & 0.265 & 0.362 & 0.000 \\
0.164 & 0.134 & 0.125 & 0.123 & 0.515 \\
0.134 & 0.129 & 0.103 & 0.092 & 0.112
\end{bmatrix},
\]

\[
P_4 = \begin{bmatrix}
0.038 & 0.021 & 0.024 & 0.016 & 0.000 \\
0.420 & 0.304 & 0.483 & 0.406 & 0.373 \\
0.244 & 0.412 & 0.265 & 0.362 & 0.000 \\
0.164 & 0.134 & 0.125 & 0.123 & 0.515 \\
0.134 & 0.129 & 0.103 & 0.092 & 0.112
\end{bmatrix},
\]

\[
P_5 = \begin{bmatrix}
0.038 & 0.021 & 0.024 & 0.016 & 0.000 \\
0.420 & 0.304 & 0.483 & 0.406 & 0.373 \\
0.244 & 0.412 & 0.265 & 0.362 & 0.000 \\
0.164 & 0.134 & 0.125 & 0.123 & 0.515 \\
0.134 & 0.129 & 0.103 & 0.092 & 0.112
\end{bmatrix},
\]

The fuzzy algorithm results (\( X_kP_k \)) for the sediments are

\[
X_1P_1 = \begin{bmatrix}
0.349 \\
0.420 \\
0.231 \\
0.054 \\
0.346 \\
0.599
\end{bmatrix},
\]

\[
X_2P_2 = \begin{bmatrix}
0.019 \\
0.424 \\
0.556 \\
0.978 \\
0.022 \\
0.000
\end{bmatrix},
\]

\[
X_3P_3 = \begin{bmatrix}
0.051 \\
0.383 \\
0.566
\end{bmatrix},
\]

\[
X_4P_4 = \begin{bmatrix}
0.054 \\
0.346 \\
0.599
\end{bmatrix},
\]

\[
X_5P_5 = \begin{bmatrix}
0.022 \\
0.000
\end{bmatrix}.
\]
Overall, the obtained fuzzy indices classified the degree of contamination of sediments contamination within the range of 0–60% as extremely impacted, 2–42% as moderately enriched, and 2–98% pristine. The result revealed that AG01 sediment is moderately impacted with the metals studied. Sites AG02, AG03, and AG04 sediments were extremely impacted by metals, while site AG05 sediment is at the pristine state. At AG01, the sediment layer is thin and thus has low demobilizing ability. This is because the drainage has a concrete slab at the bottom. The sediment profile is an indicator of pollutant deposited over a long time being that sediment serves as sink. The trend at site AG01 also implies that metals discharged are not localized into this site but dispersed into the others sites, downstream of AG01, where they were demobilized into the sediment phase. This explains the increase in FCA index of sediments at AG02, AG03, and AG04 into the extremely impacted class. Their classification into extremely impacted class confirmed that there are some environmental reactions in sites AG02–AG04 that are partitioning the metals into the sediment phase. Furthermore, the close range in the FCA results of sediments of AG02, AG03, and AG04 is an indication that sediment contamination degree does not vary sharply over time and space. AG05 sediment had the lowest degree of contamination (97.8% at pristine level). This is because site AG05 is downstream of sites AG02–AG04 and the sediments of these preceding sites have demobilized most of the metals before getting to site AG05. It is evident from the results that the sediment in the area reported in this study is impacted with metals discharged from anthropogenic activities and have accumulated over some period.

Status of heavy metals in plant samples

Three plant species (S. africana, P. aquilinum, and P. maximum) were used to biomonitor metal accumulation in the environment of Agbara industrial estate. The results of the metal concentrations in their root, stem, and leaves are presented in Figures 2–4. In S. africana plant samples (Figure 2), metal concentrations were found to be highest in the roots compared to those in the stems and leaves. This indicates that S. africana has a poor translocation capacity of metals into its shoots. Mn concentration was found to be highest...
in all the plant parts and sites, due to the richness of Mn in the sites. The root at site AG03
gave the highest concentration of Mn (222 mg kg$^{-1}$).

Cd concentrations were not detected in all parts of the plant samples. The fact that
some sediment samples had Cd concentrations might suggest that the Cd is present in the
environment, but is beyond the reach of plant roots. The low level of Cd concentration in
the sediment samples and non-presence in water samples may be responsible for the
non-detection of Cd in the plant as against the plants’ inability to accumulate Cd in their
tissues. Literature has reported affinity of plants such as *Eichhornia crassipes* (Agunbiade,
Olu-Owolabi, and Adebowale 2009); *C. odorata* (Agunbiade and Fawale 2008), water
spinach (Gothberg et al. 2004), among others for Cd metal.

*Pteridium aquilinum* had lower affinity for metal than *S. africana*, as reflected by lower
metal concentration in its tissues (Figure 3). Comparing metal concentrations between
the plant’s parts showed that highest concentrations were found in the leaves than against root
in *S. africana*. This implies that *P. aquilinum* has a good translocation ability of metals into
its shoot and leaves. Mn was also the most abundant metal in this plant while Co was the lowest beside Cd that was not detected.

Status of metals in *P. maximum* is presented in Figure 4. Its affinity for metals was higher than the affinity of *S. africana* but lower than the affinity of *P. aquilinum* except for some few metals. It also translocated a significant portion of the metals accumulated into its stems and leaves. *Panicum maximum* samples were also collected from two soil-based sampling sites (AG06 and AG07) with relatively higher metal concentration (especially at AG07) than the water-based sites. Mn content in this site was much higher in the plant than all other sites studied. This is because of richness of Mn in the geological (soil) structure of the site. The assessment of the affinity of these plants for metals and their translocation abilities can be carried out with the consideration of their enrichment and TFs.

### Enrichment and TFs of plant samples

The EF measures the transfer of metals from the host community (soil, sediment, or water samples) to the plant samples. This transfer is possible because of the bioavailability and mobility of a good fraction of the metals (Adriano et al. 2001). The calculated EFs for the three plant samples used for the biomonitoring at specific sites are presented in Table 6.

For *S. africana*, the highest EF was found at AG05, which corresponds to Co transfer to this plant sample. In each of the sites, Co transfer was found to be the highest, except at site AG03. Mn ranked next to Co in metal transfer in sites AG03 and AG05 but Cr was transferred next to Co in AG02 and AG04. The least transferred metal into the tissues of *S. africana* in all the site was Cu. Generally, the EFs of all the metals at all sites were above unity (1), which signifies that the plants were accumulating the metals from their host environment. In the literature it is referred to that, plants with EF of 1 can be used for phytoremediation of heavy metal-polluted environments (Wei, Zhou, and Koval 2006; Wei et al. 2009). Therefore, the plants used in this study may be considered for the phytoremediation purposes.

Whole plant sample of *P. aquilinum* was obtained only at site AG05 due to the shallow nature of this site. EF value of metals in *P. aquilinum* were in the order of Co > Mn > Cr > Cu. The EF of Co in the site AG05 was significantly high, as was observed for Co in *S. africana* of the same site. The small quantity of Co released into the environment is being preferentially and significantly transferred and accumulated into the plants rather than the sediment phase. This may be the reason for not detecting Co in the sediment of site AG05.
Furthermore, the EF of *P. maximum* at sites AG01, AG06, and AG07 revealed that Cr was the most significantly transferred metal into the plant with the highest EF compared to other metals. High transfer of Cr into the tissues of *E. crassipes* was earlier reported by Agunbiade, Olu-Owolabi, and Adebowale (2009). It may be inferred that these plants have higher affinity for Cr followed by Co. Generally, the EF of Cu in most of the sites was the least of all the three-plant samples. This indicates that Cu at the studied sites were mostly not available for plant uptake. Rather, the very high $K_d$ value of Cu, as presented above, confirms that the Cu is rather precipitated and adsorbed into the sediment phase than into the plant tissues.

The TF on the other gives a measure of plant ability to transport the absorb metals from its root to the shoot and leaves. The TF values for *S. africana*, *P. aquilinum*, and *P. maximum* are presented in Table 7. TF values obtained for *S. africana* were generally less that unity ($< 1$) except for few cases. It implies that the plant is a poor phytoextractor. The TFs of *P. maximum* were greater than 1 except for Cu in site AG01 and AG07. Cu was the least translocated metal (except in few instances), being also the least transferred into the plant tissues. Plants that will be effective as phytoextractors in phytoremediation technology must have TF above 1 (Baker and Brooks 1989; Zhou, Wei, and Zhang 2006). In *P. aquilinum* tissue the TF values were considerably higher than unity compared to those in *S. africana*, especially for the site AG05. The TF of *P. aquilinum* for Mn in site AG05 ranked highest (7). Overall, the TF values for Mn, Cr, and Co were above 1 except for Co in *S. africana*. Therefore, these plants may be investigated further for application as a phytoremediator of these metals.

### FCA of metals in plant samples

The degree and trend of accumulation of metals into the plant samples were further analyzed with FCA based on predetermined weights similar to the ones used to model metal accumulation in sediments (Table 1). The concentration values of metals in plant samples were formatted into membership functions and arranged into a fuzzy evaluation matrix which is then aggregated and thus discussed.

#### Sacciolepis africana

The fuzzy membership function and the order of metal arrangement used is the same as that of sediment samples (i.e., Co, Cr, Cd, Cu, and Mn). The fuzzy matrices (X) and the
corresponding weight matrices (P) for S. africana are

\[
X_2 = \begin{bmatrix}
0.00 & 0.00 & 1.00 & 0.00 & 0.00 \\
0.90 & 0.00 & 0.00 & 0.68 & 0.74 \\
0.10 & 1.00 & 0.00 & 0.32 & 0.26 \\
0.42 & 0.00 & 1.00 & 0.00 & 0.00 \\
0.58 & 0.00 & 0.00 & 0.55 & 0.31 \\
0.00 & 1.00 & 0.00 & 0.45 & 0.69
\end{bmatrix}
\]

\[
X_3 = \begin{bmatrix}
0.00 & 0.00 & 1.00 & 0.00 & 0.00 \\
0.62 & 0.00 & 0.00 & 0.69 & 0.82 \\
0.38 & 1.00 & 0.00 & 0.32 & 0.10 \\
0.54 & 0.00 & 1.00 & 0.38 & 0.00 \\
0.46 & 0.00 & 0.00 & 0.62 & 0.56 \\
0.00 & 1.00 & 0.00 & 0.00 & 0.44
\end{bmatrix}
\]

\[
P_2 = \begin{bmatrix}
0.082 \\
0.654 \\
0.000 \\
0.111 \\
0.153
\end{bmatrix}, \quad P_3 = \begin{bmatrix}
0.051 \\
0.506 \\
0.000 \\
0.136 \\
0.307
\end{bmatrix}, \quad P_4 = \begin{bmatrix}
0.070 \\
0.767 \\
0.000 \\
0.074 \\
0.089
\end{bmatrix}, \quad P_5 = \begin{bmatrix}
0.070 \\
0.442 \\
0.000 \\
0.111 \\
0.378
\end{bmatrix}
\]

From the above fuzzy matrices results it is obvious that Cr (from AG02 to AG05) is the major contaminant in this plant sample. This result is similar to what was obtained for the sediment samples. This result trend corroborates the submission that reactions in sites AG02–AG04 manage the metals discharged. Cr has an absolute membership classification in the extremely impacted range, whereas Cd has an absolute membership classification in the pristine range. Therefore, Cd is not a priority contaminant in S. africana in these sites. This is an indication that the Cd at these sites is being precipitated into sediment and is not available to bioaccumulate in this plant sample, since Cd was present in sediment samples. Thus, Cd may not pose immediate threat to lives in the estate, but Cr may. The degree of bioaccumulation of Cr in S. africana may be an indicator to its applicability in phytoremediating Cr contamination.

Cobalt existed in the sites in the moderately impacted classification except in AG05 where Co had 54% membership in the pristine range. Thus, Co is being accumulated into the plant tissues and if the trend is not controlled, it may cause poses some threat to lives in the area. The accumulation of Co in this plant is increasing beyond the range that is not harmful to humans and need to be managed. Also, it may be inferred that S. africana exhibit affinity for the accumulation of Co. Copper has membership classifications in moderately enriched range for the sites. Thus, the Cu in the environment exists in the bioavailable forms and is being accumulated into the plant tissues. Mn ranked between moderately enriched and extremely impacted classes. The accumulation of Mn is higher than the accumulation of Co and Cu.

From the weight matrices, it is confirmed that Cr is the major contributor to the entire metal contamination load. Mn had the next contribution weight after Cr but its
contribution dropped significantly in site AG04. Cd has no weight contribution in all these sites because it was not detected in the plant tissue. Fuzzy algorithms for *S. africana* are

\[
X_2P_2 = \begin{bmatrix}
0.000 \\
0.263 \\
0.738
\end{bmatrix}, \\
X_3P_3 = \begin{bmatrix}
0.021 \\
0.200 \\
0.779
\end{bmatrix}, \\
X_4P_4 = \begin{bmatrix}
0.000 \\
0.167 \\
0.833
\end{bmatrix}, \\
X_5P_5 = \begin{bmatrix}
0.080 \\
0.313 \\
0.608
\end{bmatrix}.
\]

The overall aggregate of metal contamination and accumulation express by the fuzzy algorithm results revealed that *S. africana* is extremely impacted with metals contributed mainly by Cr but with additional effects of other metals except Cd. These fuzzy indices obtained from the product moments classified the degree of contamination of this plant sample within the range of 60.8–83.3% as extremely impacted, 16.7–31.3% as moderately enriched, and 0–8% as pristine. These results imply that the metals that are in the water phase and those that ought to be partitioned into the sediment phase are rather accumulating into the plant. These accumulations coupled with the precipitation of some of the metals into the sediment phase are the likely biogeochemical reactions that are managing the metal contaminants in the environment and may be responsible for the less effect observed in the downstream site AG05. It however implies that the consumption of the plant by lower animals can cause biomagnifications of the metal into human. Thus, the level of metal contamination, as expressed in this plant, may pose threat to human life because these metals may find its way into the food chain.

**Pteridium aquilinum**

The fuzzy matrices \(X_k\) and the corresponding weight matrices \(P_k\) of metals in *P. aquilinum* that are in the same arrangement order as the earlier presented samples are presented below:

\[
X_3 = \begin{bmatrix}
0.93 & 0.03 & 1.00 & 1.00 & 0.44 \\
0.07 & 0.97 & 0.00 & 0.00 & 0.56 \\
0.00 & 0.00 & 0.00 & 0.00 & 0.00
\end{bmatrix}, \\
X_4 = \begin{bmatrix}
0.51 & 0.00 & 1.00 & 1.00 & 0.00 \\
0.49 & 0.00 & 0.00 & 0.00 & 0.63 \\
0.00 & 1.00 & 0.00 & 0.00 & 0.37
\end{bmatrix}, \\
X_5 = \begin{bmatrix}
0.87 & 0.00 & 1.00 & 1.00 & 0.00 \\
0.13 & 0.00 & 0.00 & 0.00 & 0.89 \\
0.00 & 1.00 & 0.00 & 0.00 & 0.11
\end{bmatrix},
\]

\[
P_3 = \begin{bmatrix}
0.0696 \\
0.4261 \\
0.3391
\end{bmatrix}, \\
P_4 = \begin{bmatrix}
0.0900 \\
0.4433 \\
0.0550
\end{bmatrix}, \\
P_5 = \begin{bmatrix}
0.0472 \\
0.5365 \\
0.1073 \\
0.3090
\end{bmatrix}.
\]

From the matrices, it is evident that *P. aquilinum* is phytoextracting Cr just as the earlier presented plant. Thus, Cr was absolutely in the extremely impacted class in the sites, except in site AG03 where Cr had 97% membership in moderately enriched range. This suggested that *P. aquilinum* is mainly impacted by Cr compared to other metals studied which are more in the pristine class except Mn. Cd was also not detected, therefore
it occurred absolutely in the pristine classification just as was the case in *S. africana*. This confirmed that the Cd from their environment was non-bioavailable based on the prevailing biogeochemistry of the area. Cu occurred absolutely in the pristine class just like Cd. Co ranked between pristine and moderately enriched classes.

From the weight matrices, Cr contributed the highest weight to the entire metal load in the sites, at AG03 Cr contributed 42.61%, at AG04 it contributed 44.33%, and at AG05 53.65%. This further suggests that the plants are phytoremediating this metal by accumulation making other environmental compartment of this area clean. Mn ranked next to Cr in weight which was followed by Cu. The weight contribution of Cu dropped in site AG04. Fuzzy algorithms for *P. aquilinum* are

\[ X_3 P_3 = \begin{bmatrix} 0.392 \\ 0.608 \\ 0.000 \end{bmatrix}, \quad X_4 P_4 = \begin{bmatrix} 0.101 \\ 0.304 \\ 0.596 \end{bmatrix}, \quad X_5 P_5 = \begin{bmatrix} 0.148 \\ 0.281 \\ 0.571 \end{bmatrix} . \]

These classified the degree of accumulation of metals of this plant sample in the range of 10.1–39.2% as pristine, 28.1–60.8% moderately enriched, and 0–59.6% as extremely impacted. *Pteridium aquilinum* from site AG03 moderately accumulated the metals, but the accumulation and metal uptake is high in sites AG04 and AG05. This trend is similar to that of *S. africana* and suggests that the reactions in these sites favor the availability and uptake of metals by plants. It is evident that *P. aquilinum* is capable of extracting metals from this site (AG05) despite a reduced level of contamination compared to other sites studied. The potential of these metals to enter into the food chain and cause damage necessitate that management guidelines and practice that will help in harvesting and proper disposal of this plant must be employed.

**Panicum maximum**

The fuzzy matrices \( X_k \) and the corresponding weight matrices \( P_k \) of metals in *P. maximum* are presented below in the order consistent with format reported earlier:

\[
X_1 = \begin{bmatrix} 0.20 & 0.00 & 1.00 & 0.00 & 0.56 \\ 0.80 & 0.00 & 0.00 & 0.98 & 0.44 \\ 0.00 & 1.00 & 0.00 & 0.02 & 0.00 \end{bmatrix},
X_6 = \begin{bmatrix} 0.46 & 0.00 & 1.00 & 0.40 & 0.00 \\ 0.54 & 0.00 & 0.00 & 0.60 & 0.12 \\ 0.00 & 1.00 & 0.00 & 0.00 & 0.88 \end{bmatrix},
X_7 = \begin{bmatrix} 0.24 & 0.00 & 1.00 & 0.00 & 0.00 \\ 0.76 & 0.00 & 0.00 & 0.74 & 0.00 \\ 0.00 & 1.00 & 0.00 & 0.26 & 1.00 \end{bmatrix},
\]

\[
P_1 = \begin{bmatrix} 0.052 \\ 0.836 \\ 0.000 \\ 0.066 \\ 0.460 \end{bmatrix}, \quad P_6 = \begin{bmatrix} 0.027 \\ 0.727 \\ 0.037 \\ 0.209 \end{bmatrix}, \quad P_7 = \begin{bmatrix} 0.016 \\ 0.593 \\ 0.028 \\ 0.363 \end{bmatrix}.
\]
From the matrices, the trend of metals accumulation is similar to other plants evaluated in the site. Cr is also the major contaminant in *P. maximum* in all these sites, with absolute membership function in the extremely impacted classification. Thus, Cr occurs in soluble, bioavailable form which is readily taken up by these plants. A more pragmatic way of assessing metals that will pose treat to human life is by evaluating them in tissues of plants. Metals that occur in soluble forms can bioaccumulate easily and as a result of this they enter the food chain readily. Cd did not impact or accumulate in this plant also. Co ranks between pristine and moderately enriched classes, but have higher membership classification in the moderately enriched range, with 80% in AG01, 54% in AG06, and 76% in AG07. Cu has the highest membership in the moderately enriched range with 98% at AG01, 60% at AG06, and 74% at AG07 in *P. maximum*, unlike the case in *P. aquilinum*, but similar with that obtained for *S. africana*. This result presents Poaceae plant family as a better Cu extractor. The trend of weigh contribution is similar to other plants. Cr contributes the highest weight to the entire metal load. The fuzzy algorithm products for *P. maximum* are

\[
X_1 P_1 = \begin{bmatrix} 0.036 \\ 0.127 \\ 0.837 \end{bmatrix}, \quad X_6 P_6 = \begin{bmatrix} 0.027 \\ 0.062 \\ 0.911 \end{bmatrix}, \quad X_7 P_7 = \begin{bmatrix} 0.004 \\ 0.033 \\ 0.963 \end{bmatrix}.
\]

It is very evident that *P. maximum* (giant grass) is extremely impacted by metals. This plant is a valuable for pasture and grazing. The plant had membership of 83.7–96.3% in the extremely impacted classification which is the highest of all the plants investigated. The metal concentration values in this plant were higher than the concentration reported in their corresponding host environment. The extreme level of accumulation is worrisome, because giant grass is largely consumed by ruminant animals that serve as source of protein to man, exposing man to the metals. It is also a strong evidence of the potential of *P. maximum* in phytoremediating metals.

**FCA of soil samples at AG06 and AG07**

The fuzzy evaluation matrices $X_k$ and corresponding weight matrices $P_k$ of metals in soil samples taken from sites 6 and 7 are presented below.

\[
X_6 = \begin{bmatrix} 0.82 & 0.86 & 1.00 & 1.00 & 0.00 \\ 0.18 & 0.14 & 0.00 & 0.00 & 0.01 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.90 \end{bmatrix}, \quad X_7 = \begin{bmatrix} 1.00 & 0.09 & 1.00 & 1.00 & 0.36 \\ 0.00 & 0.91 & 0.00 & 0.00 & 0.64 \\ 0.00 & 0.00 & 0.00 & 0.00 & 0.00 \end{bmatrix}.
\]

\[
P_6 = \begin{bmatrix} 0.050 & 0.022 \\ 0.058 & 0.445 \\ 0.000 & 0.000 \end{bmatrix}, \quad P_7 = \begin{bmatrix} 0.024 & 0.140 \\ 0.868 & 0.393 \end{bmatrix}.
\]
The FCA of soil was determined to evaluate the soil quality in the studied area. The membership function and the order of metal arrangement used is the same as that reported for others samples. The concentrations of the metals in soil samples used for the formation of the Fuzzy matrix are presented in Figure 5.

From the concentration presented in Figure 5 and the fuzzy matrix for AG06 it can be deduced that soil is enriched with Mn. The Mn is contributed from the geological structure of the area than from any contamination source. It is therefore the only metal at the extremely impacted level and the major weight contribution of the entire metal load in site AG06. In site AG07, Cr and Mn belong to the moderately impacted classification while all other metals were at pristine levels. Cd was not detected in the soil samples also. The weight matrix at AG07 showed Cr as the highest metal contributor followed by Mn. Though the contribution of Mn is natural, the contribution of Cr is not natural and will require control. Cu contributed 14% and Co contributed 2.2% metal load. It may be inferred from the results that site AG07 (near a Chemical Manufacturing Industry) may serve as source input of Cr into the environment. Fuzzy algorithm for the soil samples are

$X_6 P_6 = \begin{bmatrix} 0.115 \\ 0.104 \\ 0.781 \end{bmatrix}, \quad X_7 P_7 = \begin{bmatrix} 0.344 \\ 0.656 \\ 0.000 \end{bmatrix}.$

The fuzzy index obtained from the product moments classified AG06 soil degree of contamination as 11.5% pristine, 10.4% moderately enriched, and 78.1% extremely impacted. The highest classification at the extremely impacted level resulted from the high values of Mn in the fuzzy matrix at the extremely impacted level (90%) and in the weight matrix contributing 86.8% to the total metal load. Thus, Mn had a tremendous effect on the overall classification of the soil sample. Since Mn is natural to our area of study and less toxic, this classification might not be worrisome.

For soil sample from site AG07, $X_k P_k$ shows 34.4% pristine level, 65.6% moderately enriched level, and 0% extremely impacted level memberships. This indicates that AG07 soil is moderately impacted with metals studied. This degree of contamination is
attributable to Cr concentration in the site. Therefore, caution must be taken to prevent further increase and remediation methods that will cater for Cr should be considered.

**Conclusion**

The environmental status of the host community of Agbara industrial estate in Nigeria was modeled with FCA. The water system was in the pristine state. It was affected by phosphate which is aiding the growth of plants that are serving as accumulators and for the remediation of other pollutants. The sediment phase has higher metal concentration than the water phase and was extremely impacted with metals, especially in the downstream sites of the discharge point. The metals were observed to bioaccumulate more into the plant tissues than their portioning into the sediment. They were predominantly in the extremely impacted classification except few instances where they belong to moderately impacted classification. This may cause exposure risk to human through the food chain/web. Cr was the major contaminant of concern in all the environmental compartments, while Cd was not detected in the environment except in sediment. It is evident that the biogeochemical reactions in the environment downstream reduce metals from the highly mobile water phase to the less mobile sediment and plant phase. The accumulation pattern of the metals into *S. africana*, *P. aquilinum*, and *P. maximum* are indicators of the phytoremediation potential that need to be investigated further. The activities in the estate are contributing contaminants to the host environment with potential adverse effects and the existing WTP is not very effective in managing contaminant discharge.

**References**


