Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2020.25982

197 (2020) 319–327
September

Spatial variability in surface water quality of lakes and ex-mining ponds in Malacca, Malaysia: the geochemical influence

Isa Baba Koki[a,b,*], Kah Hin Low[a], Sharifuddin Md Zain[a], Hafizan Juahir[c], Amina Salihi Bayero[b], Azman Azid[d], Munirah Abdul Zali[e]

[a]*Department of Chemistry, Faculty of Science, University of Malaya, Kuala Lumpur 50603, Malaysia, Tel. +2348039092875; email: isakoki@yahoo.com (I.B. Koki), Tel. +60 3 7967 7022 Ext. 2543; email: lowkayin@um.edu.my (K.H. Low), Tel. +60 3 7967 4442; mail: smzain@um.edu.my (S.M. Zain)*

[b]*Department of Chemistry, Yusuf Maitama Sule University Kano, PMB 3220 Kano, Nigeria, Tel. +2348051147245; email: aminasalihib@yahoo.com (A.S. Bayero)*

[c]*East Coast Environmental Research Institute (ESERI), Universiti Sultan Zainal Abidin, Kuala Terengganu, Malaysia, Tel. +60 19 365 8971; email: hafizanjuahir@unisza.edu.my (H. Juahir)*

[d]*Faculty of Bioresources and Food Industry, Universiti Sultan Zainal Abidin, Besut Campus, 22200 Besut, Terengganu, Malaysia, Tel. +60 13 980 4319; email: azman.azid@gmail.com (A. Azid)*

[e]*Environmental Health Division, Department of Chemistry Malaysia, Jalan Sultan, 46661 Petaling Jaya, Selangor, Malaysia, email: munirah@kimia.gov.my (M.A. Zali)*

Received 17 August 2019; Accepted 16 April 2020

ABSTRACT

A surface water quality assessment was carried out to explore the spatial variations between lakes and ex-mining ponds in Malacca with the aid of chemometrics tools. The physio-chemical data included pH, dissolved oxygen, total dissolved solids, electrical conductivity, biological oxygen demand, and ammoniacal nitrogen, which were measured *in situ*. Meanwhile, the elemental concentrations were determined by inductively coupled plasma mass spectrometry. Hierarchical cluster analysis of the water quality dataset revealed a clustering pattern that was strongly associated with their underlying geochemical variations. A similar trend was also demonstrated in the principal component analysis which suggested that the variability in the water quality depended mainly on the nature of ponds/lakes, whereby the dominance of Ca, Mg, electrical conductivity, and total dissolved solid could plausibly be linked with the dissolution of rocks; and part of the variation was originated from their current uses. Based on the linear discriminant analysis model, the ex-mining ponds were characterized with As, Ca, Mg, and Mn concentrations whereas Na, Fe, pH, and ammoniacal nitrogen levels were associated with the lakes. Despite the inherent variability characteristics between both water sources, the corresponding metal index revealed no significant As a threat. But, in most cases, Fe exceeded the reference limit, which was attributed to its natural abundance. Therefore, these surface water sources could be considered as potential reservoirs for potable supply after conventional treatment.

Keywords: Chemometrics; Drinking water; Geochemistry; Metal; Pattern recognition

* Corresponding author.

1. Introduction

The need for adequate and safe drinking water is increasing globally due to urban expansion and an increase in human population [1]. The quality of water is a major factor of consideration to maintaining a healthy ecosystem due to the reported effects of water pollutants to humans, animals, and plants [2,3]. Many countries depend on surface water such as lakes and rivers, canals, and underground sources for daily human consumption and other domestic needs [4–6]. Rainfall is also used to support drinking water supplies and agricultural activities; this expanded the idea and need for rainwater harvesting [7,8]. Many other sources of water can be explored for daily water supply, and to meet up with the public demand.

Malacca experiences seasonal water shortages, and thus this causes limited water availability and potential issues of water quality. Therefore, there is an urgent need to search for other supporting sources. Malacca experienced the worst water crisis in 1991 due to a very low water level from its major reservoirs; the Durian Tunggal Lake (LDT) and Jus Dam (JD). These water sources are not enough to cater for the three districts of Jasin, Alor Gajah, and Malacca Tengah, and thus larger portion of the daily water supply in Malacca is imported from Muar River in Johor [9]. Furthermore, the authorities in Malacca have identified additional potable water sources to complement the public needs [10].

Surface water quality is greatly influenced by a myriad of factors among which is mineral exploration such as mining [11]. In most developing countries, mining is associated with lack of proper environmental laws and monitoring [12,13], thereby resulting in surface and underground water pollution [14–16]. The pollutants of concern are toxic metals which are not easily removed from the environment, and increase in organic matter usually associated with crushing and other mining operational processes [17,18]. The acidic medium generated is due to oxidation of metal ores which increases the metal levels in ex-mining water by liberating more metals into the solution [19–21]. However, a basic medium is observed when the basement or host rocks neutralize the acidity produced due to buffering processes, resulting in low metal levels [22,23]. Therefore, a detailed understanding of the geology and geochemical characteristics is pertinent in evaluating the levels of hazardous metals in the catchments [15].

In this study, chemometric techniques which included hierarchical cluster analysis (HCA), principal component analysis (PCA), and linear discriminant analysis (LDA) were applied to evaluate the water quality dataset collected from selected ex-mining ponds and lakes in Malacca, in addition to the conventional metal index approach. The multivariate models were aimed to unveil the underlying variations in metal concentrations and physico-chemical parameters with respect to the geological influences and to characterize the water samples from both sources.

2. Materials and methods

2.1. Study area

Malacca is a state situated in the southwestern part of Malaysia which borders Negeri Sembilan to the north and west, and Johor to the south. The estimated population of Malacca is 913,210, with major land use as agricultural activities. Its small size and annual volume of rainfall result in limited water resources as compared to other Malaysian states [24]. Mining operation started in the 1820 s and expanded widely into the 1870 s until now. Tin mining is dominantly practiced with the resulting tailing which contains sand (80%), slime (20%), and sandy slime [12]. The geology of Malacca is mostly influenced by phyllite. However, there is sufficient quantity of limestone in Jasin district with substantial alluvium and schist sand extended up to Johor state [25]. Similar earlier findings by Schwartz and Askury [26] reported a sequence of limestone and pelitic deposits in Malacca with granite abundance, which is less evolved in terms of chemical composition. The largest surface of ex-mining land (356 ha) is found in Jasin District, where most ex-mining ponds in this study are located (Fig. 1). The ex-mining ponds in Malacca are mostly utilized for recreational activities, such as picnics, surfing, and fishing; while the lakes are used for agricultural purposes and water supply as listed in Table 1. Agricultural activities around the studied sites are mostly rubber and palm oil cultivations with the largest rubber plantation industry in Malaysia, covering over 1,200 ha [27,28].

2.2. Materials

All reagents used were of analytical grade or better. Deionized water was obtained by using ELGA® PURELAB® UHQ II system (UK); HNO_3 Suprapur® grade from Merck (Germany); multi-elemental calibration standard solution was from Agilent Technologies (Newcastle); certified reference material for trace elements in freshwater (SRM1643f) from National Institute of Science and Technology (USA). The plasticware involved were soaked in 15% HNO_3 (v/v) and rinsed at least twice with UPW.

2.3. Sampling

By using Wildco water sampler, nine sub-samples were collected per site from a depth of 25 cm in October 2016 which usually records low rainfall [17,31]. The samples drawn were immediately preserved to determine the total metals by the addition of concentrated HNO_3 (Suprapur®, Merck) to pH < 2 before being transported to the laboratory in acid pre-clean polyethylene bottles conserved at 4°C [32].

2.4. On-site measurement

The physico-chemical parameters, that is, pH, electrical conductivity (EC), dissolved oxygen (DO), ammoniacal nitrogen (AN), and total dissolved solids (TDS) were analyzed by using YSI Pro multi-parameter portable water quality meter (professional series); and the biological oxygen demand (BOD) was determined via portable water meter (s/no 005) to minimize temporal changes due to bacterial concentration.

2.5. Elemental analysis

The preserved water samples obtained from the study sites were filtered via 0.45 μm polytetrafluoroethylene

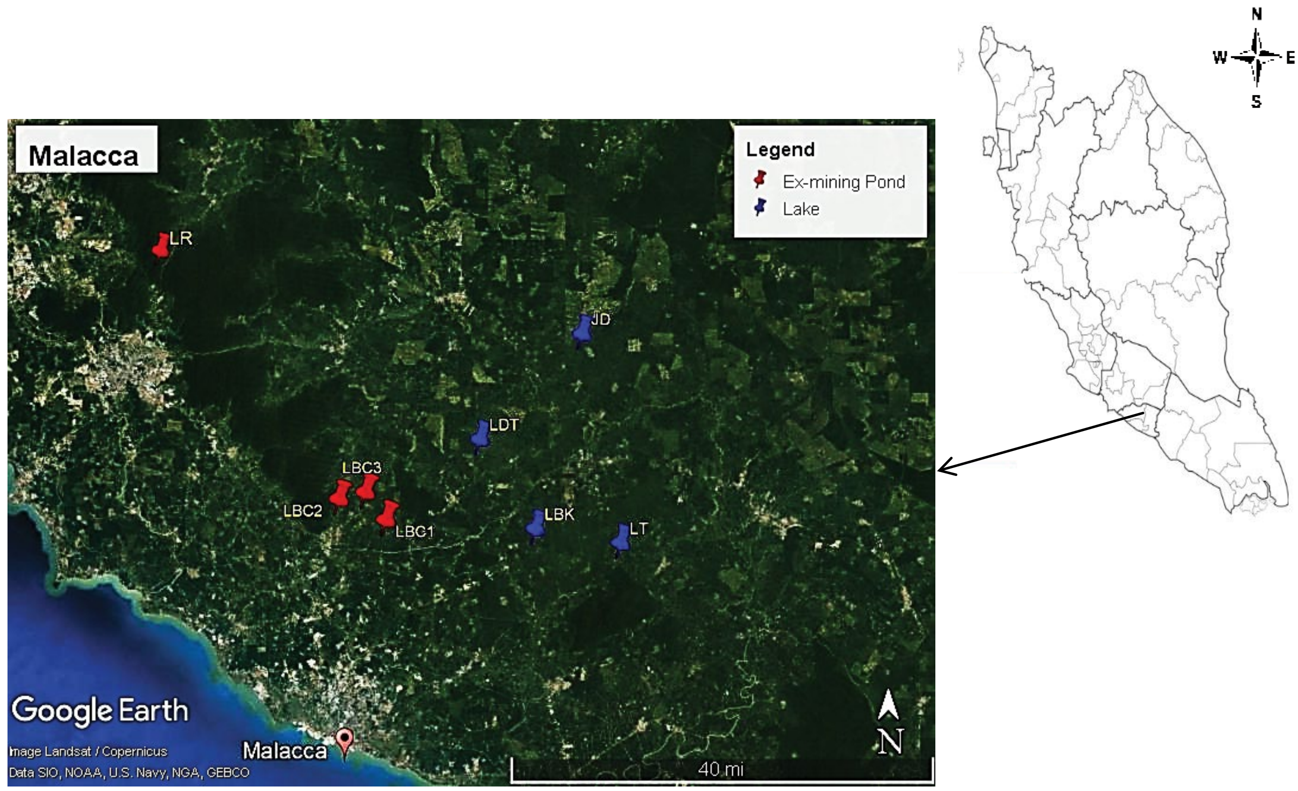

Fig. 1. Map of sampling sites.

Table 1
Details of sampling sites

Type	Coordinate	Sites	Code	Uses	Estimated size (Km^2)	Reference
Ex-mining	2.5168°N 101.9633°E	Lake Rantau	LR	Agriculture	1.98	[17]
	2.2705°N 102.4881°E	Lake Biru Chinchin 1	LBC1	Recreation	1.96	[29]
	2.2711°N 102.4939°E	Lake Biru Chinchin 2	LBC2	Recreation	0.89	[29]
	2.2743°N 102.4931°E	Lake Biru Chinchin 3	LBC3	Recreation	1.26	[29]
Lake	2.4440°N 102.4000°E	Jus Dam	JD	Reservoir	5.5	[24]
	2.3532°N 102.2989°E	Lake Durian Tunggal	LDT	Recreational and Reservoir	0.91	[30]
	2.2772°N 102.4850°E	Lake Tebat	LT	Agriculture	0.68	[30]
	2.2752°N 102.3022°E	Lake Bukit Katil	LBK	Agriculture	0.59	[30]

(PTFE) membrane filters prior to the analysis of metals and metalloids by using an Agilent 7500ce (USA) inductively coupled plasma-mass spectrometer (ICP-MS). The concentrations of dissolved As, Ca, Cd, Fe, Mg, Mn, Na, and Pb were determined under the operating conditions as listed in Table 2, which was verified via SRM1643f [15]. For quality assurance, the validity of the process was inspected for every 10 samples by using quality control samples prepared from appropriate dilution of the reference solution.

2.6. Metal index

Metal index (MI) conveys the overall water quality by taking in to account the potential health effects related to the presence of metals and metalloids [33]. The basis of evaluation entails comparison between the measured concentrations against reference values, which can be expressed as below [34]:

$$\mathrm{MI} = \sum \frac{C_i}{(\mathrm{MAC})_i} \tag{1}$$

where C_i and $(\mathrm{MAC})_i$ are, respectively, the mean concentration for *i*th element and its maximum permissible level derived from the Malaysian Interim National Water Quality Standards (INWQS) of 50, 100, and 1,000 μg/L for As, Mn, and Fe, respectively [35]. The higher the ratio of C_i with respect to $(\mathrm{MAC})_i$, the more deteriorated the quality of the water is. Therefore, MI > 1 is a threshold of warning which signifies a potential threat [33,36,37].

Table 2
ICP-MS operating conditions

Parameter	Setting
Plasma RF powers, W	1,600
Reflected powers, W	<15
Plasma gas flow, L/min	12
Carrier gas flow, L/min	0.9
Makeup gas flow, L/min	0.25
Collision gas	Helium
Collision gas flow, L/min	3–5

2.7. Multivariate analyses

The water quality dataset was preprocessed with Microsoft® Excel 2010, and the respective method detection limits were adopted for those non-detected cases. Pattern recognition techniques, that is, HCA, PCA, and LDA, were applied by using SAS® JMP Pro 12.

2.8. Hierarchical cluster analysis

HCA was performed on the standardized dataset to illustrate the spatial relation between the water samples by a dendrogram. The hierarchical linkages were constructed according to Ward's method, whereby dissimilarities were expressed in terms of Euclidean distance [16,38]. The hierarchical sequence of the selected water quality variables was further expanded via two-way clustering [39].

2.9. Principal component analysis

PCA was applied to the correlation matrix to explore the inherent pattern in the water quality dataset based on orthogonal transformation. This was achieved by summarizing the original variation through a manageable number of uncorrelated principal components [40]. The score, z_{ij}, corresponding to ith PC of jth sample is given by linear combinations of m number of original water quality variables, X_{mj}, which be written as:

$$z_{ij} = a_{i1}X_{1j} + a_{i2}X_{2j} + a_{i3}X_{3j} + \ldots + a_{im}X_{mj} \tag{2}$$

where a_{im} reflects the loadings where the number of extracted PCs was depended on those with eigenvalue > 1.

2.10. Linear discriminant analysis

LDA was applied to infer the spatial classification of water samples (i.e., ex-mining pond and lakes) based on the relative similarities of the between-group and within-group [15]. The canonical score, z_{jk}, corresponding to jth discriminant function for kth water sample is expressed as:

$$z_{jk} = w_0 + w_1X_{1k} + w_2X_{2k} + w_3X_{3k} + \ldots + w_nX_{nk} \tag{3}$$

where w_0 is an intercept, w is the discriminant weight, and X is the water quality variable.

3. Results and discussion

3.1. Quality assessment and quality control

The accuracy of ICP-MS measurement was checked as shown in Table 3 with mean recoveries that ranged between 90% and 107% (whereby coefficients of determinant $R^2 > 0.999$, in all cases; which demonstrated the fitness in the determination of those elements in freshwater with a certain degree of confidence [41,42]. The detection limits of the metals under consideration are 0.0002, 0.0001, and 0.6 mg/L, respectively, for As, Mn, and Fe.

3.2. Surface water quality

3.2.1. Physico-chemical characteristics

The physical-chemical measurements of the water catchments (Table 4) were found to be within the Drinking Water Quality Standard for raw water and Malaysia's INWQS [35,43]. The pH of all sampling sites ranged between 6.5 and 8.5, except LR (10.3 ± 0.1) which was located in Negeri Sembilan state near Malacca with a more basic rock basement [44]. Similarly, LR that surrounded by much greenly vegetation has recorded the highest DO of about 9.16 mg/L, whereas less than 5 mg/L (the recommended level) were observed in both LT and LBK. The low dissolved oxygen levels might be associated with the low water level at LT, whereby the imbalance between oxygen supply from the surface waters and removal of oxygen from bottom water, as well as the organic matter corresponding to residential discharges into LBK [45,46].

3.3. Metal index

The water quality status of the ex-mining ponds and lakes are listed in Table 5, which revealed a notable variation. According to literature reports, high metal concentrations including As are commonly related to ex-mining ponds [16,17,47–50]. For instance, elevated metal levels were reported in ex-mining ponds located in Pahang, Malaysia. However, such a trend was not apparent, whereby As was the only toxic element that was detected in all sampling sites [20]. The low metal concentrations observed could plausibly be explained by the buffering of waterbody due to dissolution of limestone host rocks. The acidic solution produced due to oxidation of metal ores liberated more metals in the solution, but the acidity is neutralized by the influence of limestone basement in the study area [51], thereby lowering the metal levels [21,52–54].

Among the metals only As, Mn, and Fe are considered in the MI computation so as to minimize the possible additive effects from other essential elements [34,55,56]. Moreover, the reference value for Ca is not even specified under the Malaysian drinking water standards INWQS [35,43]. As shown in Table 5, LT is a popular fishing lake with an overall MI of 2.71. Such value gives a negative impression on the corresponding water quality as it exceeded the reference limit of 1, which suggests potential health risks associated with its use [57]. The noticeable contributions could be linked with the arsenical pesticides used to preserve wooden boats [58,59], in addition to the natural

Table 3
Performance of ICP-MS on SRM1643f

Element	Certified value (μg/L)	Measured value (μg/L)	Recovery (%)
As	57.4 ± 0.4	57 ± 2	98 ± 5
Ca	(29.4 ± 0.3) × 10^3	(27.8 ± 0.2) × 10^3	95 ± 3
Cd	5.9 ± 0.1	6.0 ± 0.6	102 ± 9
Fe	93.4 ± 0.8	101 ± 1	107 ± 2
Mg	(7.45 ± 0.06) × 10^3	(6.77 ± 0.08) × 10^3	91 ± 11
Mn	37.1 ± 0.6	39.2 ± 0.3	105 ± 1
Pb	18.48 ± 0.08	17 ± 2	90 ± 9

Table 4
Physico-chemical characteristics of water samples from lakes and ex-mining ponds

Type	Ex-mining				Lake			
Site	LBC1	LBC2	LBC3	LR	JD	LDT	LT	LBK
DO	5.1 ± 0.2	6.1 ± 0.1	5.0 ± 0.2	9.2 ± 0.3	4.9 ± 0.1	6.1 ± 0.5	4.6 ± 0.3	3.7 ± 0.1
BOD	0.90 ± 0.01	1.15 ± 0.02	1.16 ± 0.02	1.96 ± 0.01	1.25 ± 0.03	1.09 ± 0.01	2.12 ± 0.01	1.50 ± 0.01
pH	7.2 ± 0.1	7.3 ± 0.1	7.0 ± 0.1	10.3 ± 0.1	8 ± 1	7.2 ± 0.1	7.1 ± 0.1	6.9 ± 0.1
TDS	47.5 ± 0.1	59.0 ± 0.3	55.9 ± 0.1	77.0 ± 0.9	44.9 ± 0.1	61 ± 1	26.7 ± 0.1	48.0 ± 0.3
AN	0.02 ± 0.01	0.07 ± 0.01	0.07 ± 0.01	0.22 ± 0.02	0.28 ± 0.04	0.17 ± 0.01	0.03 ± 0.01	0.09 ± 0.01
EC	82.3 ± 0.1	102.3 ± 0.1	97.5 ± 0.1	136.0 ± 0.5	77.4 ± 0.1	107.6 ± 0.1	46.0 ± 0.1	80.0 ± 0.4

Electrical conductivity in μs/cm, pH (no unit), other physico-chemical parameters in mg/L.

Table 5
Metal index corresponding to water samples from lakes and ex-mining ponds

Type	Ex-mining				Lake			
Site	LBC1	LBC2	LBC3	LR	JD	LDT	LT	LBK
As	0.19	0.13	0.14	0.05	0.01	0.03	0.21	0.09
Mn	0.23	0.51	1.12*	1.32*	1.28*	0.20	1.07*	1.70*
Fe	0.01	0.07	0.31	0.34	0.19	0.11	1.44*	0.86
MI	0.43	0.71	1.57*	1.71*	1.49*	0.33	2.71*	2.65*

The concentration of Cd and Pb were less than the limit of detection, and metal indices were <0.03 and <0.002, respectively.
*Metal and overall MI > 1.

abundance of Fe and Mn in the soils and earth's crust [60]. In this context, both Fe and Mn have considerably lower toxicity [61,62]; they can be significantly removed during the aeration stage of water treatment process [63–65]. Therefore, the impacts of Fe and Mn in LBC3, LR, JD, LT, and LB (MI > 1) should not be of health concern.

The MAC of the metals under consideration especially As (50 μg/L) is similar to that in Georgia, but much higher than European union and World Health Organization values of 10 μg/L [66]. Similarly, MAC for Mn is 400 μg/L [56], which is higher than INWQS of Malaysia. The differences in MACs result in variations in MI values, whereby larger MAC accommodates higher metal concentrations [57]. The MAC for Fe is 1,000 μg/L in all reference standards. Unless introduced in extreme quantities, iron does not cause any human health or other ecotoxicological risks [43,55,56].

The study findings on low metal concentrations in ex-mining ponds agreed with literature reports on the geological analysis of Malacca ex-mining lands which showed little or no influence of metallic elements [29]. The variations in metal concentrations could be due to the natural percentage abundance and geological background. Therefore, it is imperative to analyze and monitor the presence and levels of metals in water so as to identify the possible risk associated with its usage [67].

3.4. Hierarchical cluster analysis

The clustering patterns of the sampling sites with respect to surface water quality were examined by using HCA. The sites could reasonably be grouped into two main clusters, reflecting the variability in water quality characteristics as outlined in the two-way dendrogram (Fig. 2). Due to the similarities in underlying geological features and water chemistry, the catchments located in Jasin District formed a major cluster that partitioned from LR sited at the neighboring state [15,22,68]. Under similar circumstances, the Jasin cluster could be further subdivided based upon the background and/or uses of the catchment sites where the ex-mining ponds (LBC1, LBC2, and LBC3) were clustered and distanced from other lakes. Despite the division due to background differences, the attributions from similarities in the land use helped the agglomeration, for instance, those ex-mining ponds that were reclaimed for recreational activities were linked with a recreational lake (LDT). Such clustering results suggested that the variability in surface water quality was strongly associated with the spatial pattern of catchment characteristics. In this regard, the variations of As, Mn, Fe, and BOD levels in catchments provided a reflection of the land use, as shown in Fig. 2.

3.5. Principal component analysis

The natural variations in the water characteristic between the samples from ex-mining ponds and lakes were explored with PCA, whereby the first two PCs described 46.2% and 23.6% of the total variance which mainly originated from the geological difference and land-use. As shown in Fig. 3, the PC1 loading with major components, that is, EC, DO, TDS, and Ca was indicative of the dissolution of rocks that corresponded to weathering/leaching [15]. In a similar context, the strong loadings of Mn, Fe, and BOD on PC2 could be attributed to the natural background concentrations and/or imbalance caused by the low water level of the sites. Low water levels could result in elevated concentrations of metals, especially with natural abundance. This is because, at low water level, there is a higher rate of metal exchange between the water column and bottom sediments. The extent of metal migration is influenced by its occurrence in the sediment, pore solutions in the bottom sediments, and the physico-chemical properties or states which emerge at the water/sediment boundary [69–71]. Similarly, low DO and high BOD are associated with the bottom water in the aquatic ecosystem due to the imbalance between oxygen supply from surface waters and the removal of oxygen from bottom water [45,46].

Period of low water levels was also reported to be characterized by high EC [72]. Ex-mining pond LR was clearly separated from all other studied sites along PC1 with higher component loading, which could be due to differences in land use and natural geological background. JD that is used as a reservoir is located around the origin; however, ex-mining ponds LBC and LDT which are utilized for recreational activities, showed deviation from the origin and were loaded with As, Mg, and Na. Similarly, LT and LBK utilized for agricultural purposes deviated from the origin along PC2 and loaded with Fe, Mn, and BOD.

3.6. Linear discriminant analysis

LDA was successfully applied to examine the discriminating features between the lakes and ex-mining ponds. Under such circumstances, ex-mining ponds are commonly associated with high metal levels as compared to lakes due to the impact of acidic pH [16]. The catchments of ex-mining ponds are commonly found in acidic nature

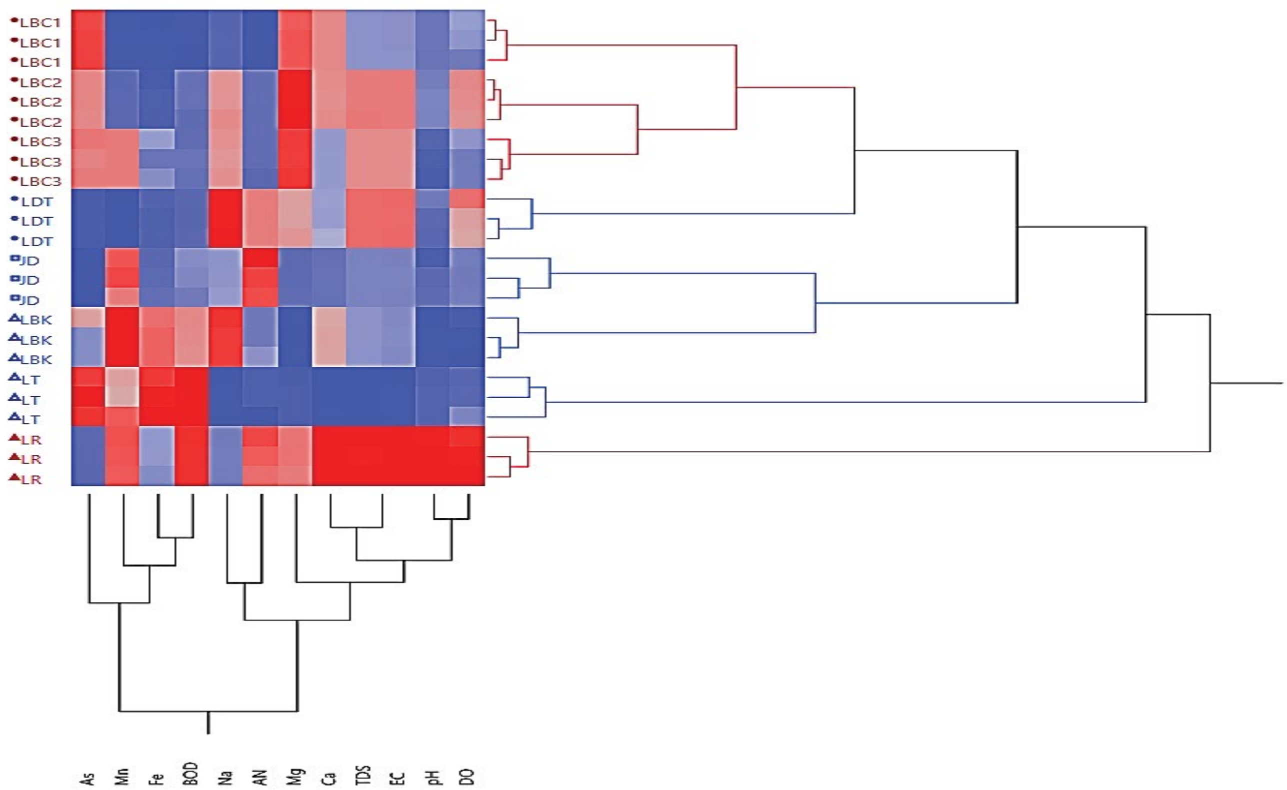

Fig. 2. Two-way clustering of lakes and ex-mining ponds in Malacca.

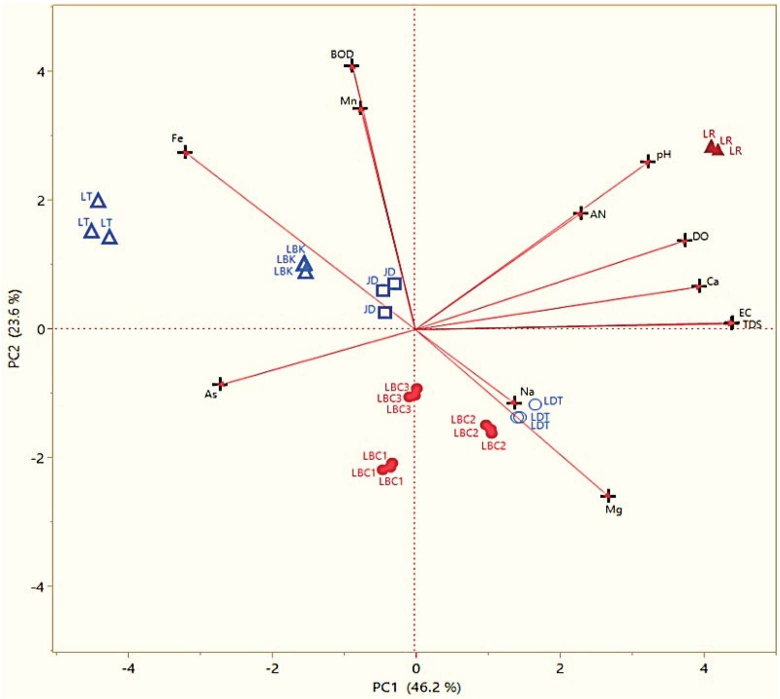

Fig. 3. PCA biplot of metals and physico-chemical parameters in lakes and ex-mining ponds in Malacca.

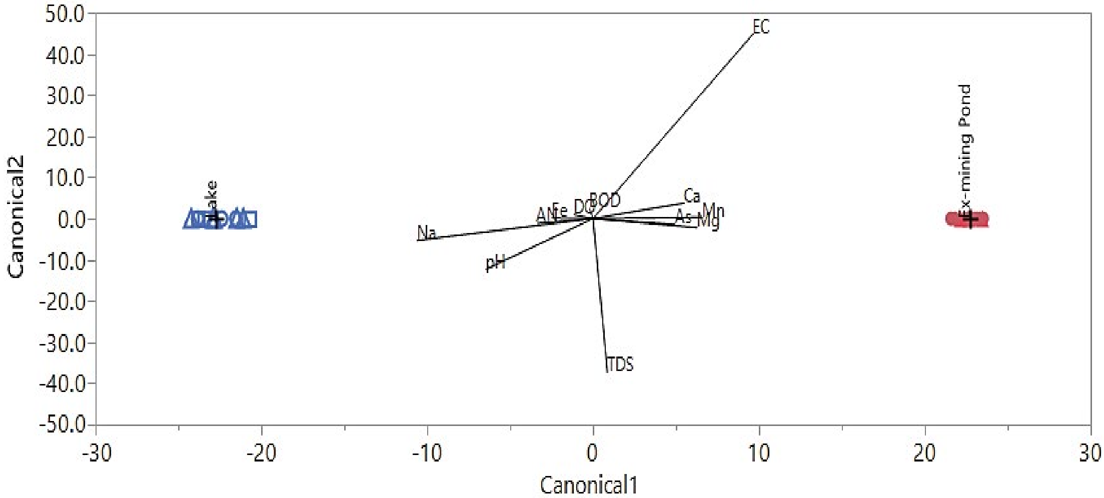

Fig. 4. Canonical plot for the discrimination of water samples from lakes and ex-mining ponds.

as the oxidation consequence of the parent ore. However, geological variations may lead to a basic pH to a certain extent. In a similar context, high EC is associated with an increased level of dissolved metals from crushed rocks by the ex-mining activities [16,73,74]. Therefore, As, Mn, Ca, Mg, and EC are the parameters associated with ex-mining ponds, whereas pH and Na are associated with lakes (Fig. 4). Such outcomes support that weathering and dissolution of rocks are the main sources of metals in the ex-mining ponds. For instance, weathering of host rocks and mine tailing were found associated with high metal levels in mines and adjacent rivers [75,76].

4. Conclusion

This work revealed the spatial variations in quality parameters between lakes and ex-mining ponds in Malacca. The results demonstrated that the quality of surface water could not be judged solely based on the historical identity of the sites because the impacts of geochemistry and current land-use are more crucial. The outcomes of multivariate analyses suggested the major variations in the water quality were derived from the dissolution of underlying rocks and current anthropogenic inputs, such as agricultural and recreational activities instead of ex-mining.

Since the contribution of As was relatively low, the overall MI suggested that those sources could be considered as the potential reservoirs for potable supply after conventional treatment processes.

Acknowledgments

The authors acknowledged the financial support of University of Malaya [PG147-2014B] and [RP017A-14AFR] for the successful completion of this research work.

References

[1] M.A. Hoaghia, O. Cadar, G.G. Hognogi, E. Levei, C. Moisa, C. Roman, Quality and human health risk assessment of metals and nitrogen compounds in drinking water from an urban area near a former non-ferrous ore smelter, Anal. Lett., 52 (2019) 1268–1281.
[2] N. Darrall, The effect of air pollutants on physiological processes in plants, Plant Cell Environ., 12 (1989) 1–30.
[3] G. Pandey, S. Madhuri, Heavy metals causing toxicity in animals and fishes, Res. J. Anim. Vet. Fishery Sci., 2 (2014) 17–23.
[4] M. Abdel-Hamid, Y. El-Amier, E. Abdel-Aal, G. El-Far, Water quality assessment of El-Salam canal (Egypt) based on physicochemical characteristics in addition to hydrophytes and their epiphytic algae, Int. J. Ecol. Dev. Res., 3 (2017) 028–043.
[5] N. Al-Ansari, N. Adamo, V. Sissakian, S. Knutsson, J. Laue, Water resources of the Tigris River catchment, J. Earth Sci. Geotech. Eng., 8 (2018) 21–42.
[6] M. Miclean, O. Cadar, L. Levei, L. Senila, A. Ozunu, Metal contents and potential health risk assessment of crops grown in a former mining district (Romania), J. Environ. Sci. Health., Part B, 53 (2018) 595–601.
[7] C.R. Fonseca, V. Hidalgo, C. Díaz-Delgado, A.Y. Vilchis-Francés, I. Gallego, Design of optimal tank size for rainwater harvesting systems through use of a web application and geo-referenced rainfall patterns, J. Cleaner Prod., 145 (2017) 323–335.
[8] N. Li, C. Zhou, X. Sun, J. Jing, X. Tian, L. Wang, Effects of ridge tillage and mulching on water availability, grain yield, and water use efficiency in rain-fed winter wheat under different rainfall and nitrogen conditions, Soil Tillage Res., 179 (2018) 86–95.
[9] MWA, Malaysian Water Association, Indah Water Konsortium Sdn Bhd, Kuala Lumpur, Malaysia, 2008.
[10] A.F. Azzlan, C.B. Cheong, K.L. Lau, Sustainable water management for water supply efficiency: a case study at Syarikat Air Melaka Berhad, J. Technol. Manage. Bus., 3 (2016) 01–21.
[11] Z. Shi, P. Pan, Y. Feng, Z. Kan, Z. Li, F. Wei, Environmental water chemistry and possible correlation with Kaschin-Beck Disease (KBD) in northwestern Sichuan, China, Environ. Int., 99 (2017) 282–292.
[12] G. Balamurugan, Tin mining and sediment supply in Peninsular Malaysia with special reference to the Kelang River basin, Environmentalist, 11 (1991) 281–291.
[13] H. Zakir, M. Islam, M. Arafat, S. Sharmin, Hydrogeochemistry and quality assessment of waters of an open coal mine area in a developing country: a case study from Barapukuria, Bangladesh, Int. J. Earth Sci., 1 (2013) 20–44.
[14] M.A. Acheampong, J. Adiyiah, E.D. Ansa, Physico-chemical characteristics of a gold mining tailings dam wastewater, Indian J. Environ. Health, A2 (2013) 469–475.
[15] N. Atanacković, V. Dragišić, J. Stojković, P. Papić, V. Živanović, Hydrochemical characteristics of mine waters from abandoned mining sites in Serbia and their impact on surface water quality, Environ. Sci. Pollut. Res. Int., 20 (2013) 7615–7626.
[16] I.B. Koki, K.H Low, J. Hafizan, A. Azman, Assessment of water quality of man-made lakes in Klang Valley (Malaysia): the impact of mining, Desal. Water Treat., 74 (2017) 125–136.
[17] I.B. Koki, K.H. Low, H. Juahir, M.A. Zali, A. Azid, S.M. Zain, Consumption of water from ex-mining ponds in Klang Valley and Melaka, Malaysia: a health risk study, Chemosphere, 195 (2018) 641–652.
[18] R. Tiwary, Environmental impact of coal mining on water regime and its management, Water Air Soil Pollut., 132 (2001) 185–199.
[19] O.C. Modoi, C. Roba, Z. Török, A. Ozunu, Environmental risks due to heavy metal pollution of water resulted from mining wastes in NW Romania, Environ. Eng. Manage. J., 13 (2014) 2325–2336.
[20] M.N. Saviour, Environmental impact of soil and sand mining: a review, Int. J. Environ. Sci. Technol., 1 (2012) 125–134.
[21] N. Woo, M. Choi, Arsenic and metal contamination of water resources from mining wastes in Korea, Environ. Geol., 40 (2001) 305–311.
[22] A.C. Berger, C.M. Bethke, J.L. Krumhansl, A process model of natural attenuation in drainage from a historic mining district, Appl. Geochem., 15 (2000) 655–666.
[23] J. Shamshuddin, N. Mokhtar, S. Paramananthan, Morphology, mineralogy and chemistry of an ex-mining land in Ipoh, Perak, Pertanika, 9 (1986) 89–97.
[24] S. Shirazi, H. Imran, S. Akib, Z. Yusop, Z. Harun, Groundwater vulnerability assessment in the Melaka State of Malaysia using DRASTIC and GIS techniques, Environ. Earth Sci., 70 (2015) 2293–2304.
[25] S.M. Shirazi, M. Adham, N.H. Zardari, Z. Ismail, H.M. Imran, M.A. Mangrio, Groundwater quality and hydrogeological characteristics of Malacca state in Malaysia, J. Water Land Dev., 24 (2015) 11–19.
[26] M.O. Schwartz, A. Askury, Geologic, geochemical, and fluid inclusion studies of the tin granites from the Bujang Melaka pluton, Kinta Valley, Malaysia, Econ. Geol., 84 (1989) 751–779.
[27] P.P. Courtenay, The plantation in Malaysian economic development, J. Southeast Asian Stud., 12 (1981) 329–348.
[28] K.H. Leong, L.B. Tan, A.M. Mustafa, Contamination levels of selected organochlorine and organophosphate pesticides in the Selangor River, Malaysia between 2002 and 2003, Chemosphere, 66 (2007) 1153–1159.
[29] R.M. Osman, L.C. Siong, Geospatial Analysis of the Ex-Mining Land of Melaka, In: Paper presented at the National Geoscience Conference Kuching, Malaysia, 2012.
[30] Z. Sharip, A.T. Zaki, M.A Shapai, S. Suratman, A.J. Shaaban, Lakes of Malaysia: water quality, eutrophication and management, Lakes Reservoirs Res. Manage., 19 (2014) 130–141.
[31] D. MacDougall, W.B. Crummett, Guidelines for data acquisition and data quality evaluation in environmental chemistry, Anal. Chem., 52 (1980) 2242–2249.
[32] S. Sadeghi, M.K. Harchegani, H. Younesi, Suspended sediment concentration and particle size distribution, and their relationship with heavy metal content, J. Earth Syst. Sci., 121 (2012) 63–71.
[33] G. Bakan, H.B. Özkoç, S. Tülek, T.H. Cüce, Integrated environmental quality assessment of the Kızılırmak River and its coastal environment, Turk. J. Fish. Aquat. Sci., 10 (2010) 453–462.
[34] G. Tamasi, R. Cini, Heavy metals in drinking waters from Mount Amiata (Tuscany, Italy). Possible risks from arsenic for public health in the Province of Siena, Sci. Total Environ., 327 (2004) 41–51.
[35] DOE, Department of Environment Malaysia: Environmental Quality Act Report, Ministry of Science, Technology and the Environment, Putrajaya, Malaysia, 2012.
[36] S. Li, Q. Zhang, Spatial characterization of dissolved trace elements and heavy metals in the upper Han River (China) using multivariate statistical techniques, J. Hazard. Mater., 176 (2010) 579–588.
[37] USEPA, Risk Assessment Guidance for SUPERFUND, Human Health Evaluation Manual (Part A), Office of Emergency and Remedial Response, EPA/540/1–89/002, Washington, DC, 1989.
[38] H. Juahir, S.M. Zain, M.K. Yusoff, T.T. Hanidza, A.M. Armi, M.E. Toriman, M. Mokhtar, Spatial water quality assessment of Langat River Basin (Malaysia) using environmetric techniques, Environ. Monit. Assess., 173 (2011) 625–641.

[39] N.S.U. Idris, K.H. Low, I.B. Koki, A.F. Kamaruddin, K.M. Salleh, S.M. Zain, *Hemibagrus* sp. as a potential bioindicator of hazardous metal pollution in Selangor River, Environ. Monit. Assess., 189 (2017) 220–234.
[40] A. Mustapha, A.Z. Aris, H. Juahir, M.F. Ramli, N.U. Kura, River water quality assessment using environmentric techniques: case study of Jakara River Basin, Environ. Sci. Pollut. Res. Int., 20 (2013) 5630–5644.
[41] E. Bulska, E. Krata, M. Kałabun, M. Wojciechowski, On the use of certified reference materials for assuring the quality of results for the determination of mercury in environmental samples, Environ. Sci. Pollut. Res. Int., 24 (2017) 7889–7897.
[42] J. Taylor, Quality Assurance of Chemical Measurements, Routledge, New York, NY, 2018.
[43] MOH, National Standard for Drinking Water Quality, Ministry of Health Malaysia, Document D1, 2004.
[44] A. Ghani, M. Azirun, R. Ramli, R. Hashim, Geochemical contrast between Beroga (Kuala Kelawang pluton) and Semenyih (Kuala Lumpur pluton) granites in Kuala Kelawang area, Negeri Sembilan, Bull. Geol. Soc. Malaysia, 54 (2008) 71–47.
[45] D.L. Breitburg, T. Loher, C.A. Pacey, A. Gerstein, Varying effects of low dissolved oxygen on trophic interactions in an estuarine food web, Ecol. Monogr., 67 (1997) 489–507.
[46] D. Seitaj, F. Sulu-Gambari, L.D. Burdorf, A. Romero-Ramirez, O. Maire, S.Y. Malkin, C.P. Slomp, F.J. Meysman, Sedimentary oxygen dynamics in a seasonally hypoxic basin, Limnol. Oceanogr., 62 (2017) 452–473.
[47] F.Y. Alshaebi, W.Z. Yaacob, A.R. Samsudin, E. Alsabahi, Risk assessment at abandoned tin mine in Sungai Lembing, Pahang, Malaysia, Electron. J. Geotech. Eng., 14 (2009) 1–9.
[48] M.A. Ashraf, M.J. Maah, I. Yusoff, Analysis of physio-chemical parameters and distribution of heavy metals in soil and water of ex-mining area of Bestari Jaya, Peninsular Malaysia, Asian J. Chem., 23 (2011) 3493–3499.
[49] M.A. Ashraf, M.J. Maah, I. Yusoff, Study of water quality and heavy metals in soil and water of ex-mining area Bestari Jaya, peninsular Malaysia, Int. J. Basic Appl. Sci., 10 (2010) 7–27.
[50] K.U. Orji, N. Sapari, K.W. Yusof, R. Asadpour, E. Olisa, Water quality assessment of ex-mining lakes in Perak, Malaysia as alternative source of water supply, Appl. Mech. Mater., 567 (2014) 177–182.
[51] J.B. Scrivenor, The geology of Malacca, with a geological map and special reference to laterite, J. Malayan Branch R. Asiatic Soc., 5 (1927) 278–287.
[52] W.K. Fletcher, P. Dousset, Y. Bin Ismail, Behaviour of Tin and Associated Elements in a Mountain Stream, Bujang Melaka, Perak, Malaysia, Southeast Asia Tin Research and Development (SEATRAD) Centre, Malaysia, 1984.
[53] S. Paikaray, Arsenic geochemistry of acid mine drainage, Mine Water Environ., 34 (2015) 181–196.
[54] M. Palmer, J. Galloway, H. Jamieson, R. Patterson, H. Falck, S. Kokelj, NWT Open File 2015–06, The Concentration of Arsenic in Lake Waters of the Yellowknife Area, Northwest Territories, Canada, 2016.
[55] WHO, Guidelines for Drinking-Water Quality, 3rd ed., Vol. 1, Recommendations, World Health Organisation, Geneva, 2008.
[56] WHO, Guidelines for Drinking-Water Quality, World Health Organization, Geneva, 2011.
[57] K.H. Low, N.S.U. Idris, S.M. Zain, A.F. Kamaruddin, K.Md. Salleh, Evaluation of elemental distributions in wild-caught and farmed *Pangasius* sp. using pattern recognition techniques, Int. J. Food Prop., 19 (2016) 1489–1503.
[58] L. Edwin, S.N. Thomas, Wood Preservation for Marine Application, 2001, pp. 01–08. Available online at: http://hdl.handle.net/123456789/1321
[59] A. Sreeja, Chromated Copper Arsenate (CCA) Treatment for Rubber Wood Preservation and Its Impact on the Aquatic Biota, Cochin University of Science and Technology, 2008.
[60] W. Xing, G. Liu, Iron biogeochemistry and its environmental impacts in freshwater lakes, Fresenius Environ. Bull., 20 (2011) 1339–1345.
[61] B.S. Caruso, M. Mirtskhulava, M. Wireman, W. Schroeder, B. Kornilovich, S. Griffin, Effects of manganese mining on water quality in the Caucasus Mountains, Republic of Georgia, Mine Water Environ., 31 (2012) 16–28.
[62] P.D. Howe, H. Malcolm, S. Dobson, Manganese and Its Compounds: Environmental Aspects, Concise International Chemical Assessment Document, World Health Organisation, Geneva, 2004.
[63] P. Mouchet, From conventional to biological removal of iron and manganese in France, J. Am. Water Works Assoc., 84 (1992) 158–167.
[64] S. Kouzbour, N. El Azher, B. Gourich, F. Gros, C. Vial, Y. Stiriba, Removal of manganese(II) from drinking water by aeration process using an airlift reactor, J. Water Process Eng., 16 (2017) 233–239.
[65] T.J. McGhee, E.W. Steel, Water Supply and Sewerage, McGraw-Hill, New York, NY, 1991.
[66] S.S. Withanachchi, G. Ghambashidze, I. Kunchulia, T. Urushadze, A. Ploeger, Water quality in surface water: a preliminary assessment of heavy metal contamination of the Mashavera River, Georgia, Int. J. Environ. Res. Public Health, 15 (2018) 621.
[67] H. Boyacioglu, Development of a water quality index based on a European classification scheme, Water SA, 33 (2007) 101–106.
[68] M.A. Caraballo, J.M. Macías Nieto, C. Ayora, Long term fluctuations of groundwater mine pollution in a sulfide mining district with dry Mediterranean climate: implications for water resources management and remediation, Sci. Total Environ., 539 (2016) 427–435.
[69] J. Mwamburi, F.N. Oloo, The distribution and concentration levels of trace metals in water and sediments of Lake Victoria, Kenya, Afr. J. Trop. Hydrobiol. Fish., 7 (1996) 37–48.
[70] M.M. Ali, M.L. Ali, M.S. Islam, M.Z. Rahman, Preliminary assessment of heavy metals in water and sediment of Karnaphuli River, Bangladesh, Environ. Nanotechnol. Monit. Manage., 5 (2016) 27–35.
[71] P.M. Linnik, I.B. Zubenko, Role of bottom sediments in the secondary pollution of aquatic environments by heavy-metal compounds, Lakes Reservoirs Res. Manage., 5 (2000) 11–21.
[72] Z. Sharip, F. Yusoff, A. Jamin, Seasonal water quality and trophic status of shallow lentic waters and their association with water levels, Int. J. Environ. Sci. Technol., 16 (2019) 4851–4862.
[73] M. Navarro, C. Pérez-Sirvent, M. Martínez-Sánchez, J. Vidal, P. Tovar, J. Bech, Abandoned mine sites as a source of contamination by heavy metals: a case study in a semi-arid zone, J. Geochem. Explor., 96 (2008) 183–193.
[74] J.S. Ogola, M.V. Mitullah, M.A. Omulo, Impact of gold mining on the environment and human health: a case study in the Migori gold belt, Kenya, Environ. Geochem. Health, 24 (2002) 141–157.
[75] L. Fanfani, P. Zuddas, A. Chessa, Heavy metals speciation analysis as a tool for studying mine tailings weathering, Plant Cell Environ., 58 (1997) 241–248.
[76] P.J. Favas, J. Pratas, M.E. Gomes, V. Cala, Selective chemical extraction of heavy metals in tailings and soils contaminated by mining activity: environmental implications, J. Geochem. Explor., 111 (2011) 160–171.