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Sludge characterization of an industrial water treatment plant, Iran

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ABSTRACT

Slurry and cake sludges from an industrial water treatment plant (WTP) were analyzed regarding their physicochemical characteristics and their disposal options. Experiments were carried out in the wet and dry seasons. *t*-test, Mann–Whitney U-test, and one sample *t*-test were applied to analyze the obtained data. The results showed that Al, Ca, Cr, Fe, Na, Pb, Se, turbidity, COD and total organic carbon in slurry sludge were significantly higher in wet season than cake sludge. On the other hand, Al, Cr, total solids (TS), FSS, and total suspended solids (TSS) were significantly higher in wet season than dry season. It was also found that in both wet and dry seasons As, Cd, Cr, Na, and Pb were higher in slurry sludge than cake sludge. Moreover, TS, TSS, VSS, and FSS in both seasons were significantly higher in cake sludge than slurry sludge. Canadian soil quality guidelines (CSQG), Florida department of environmental protection soil cleanup target levels (FDEPSCTLs) and land disposal restriction (LDR) of RCRA were used to discuss the disposal fate of the generated sludge. It was found that generated sludge compared with CSQG is not suitable for residential/parkland, agricultural, commercial, and industrial applications. But compared with FDEPSCTLs, it was found that it was just As with higher concentration. Using LDR of RCRA for deciding on the nature of studied sludge indicated that Se concentration is significantly higher than this restriction, indicating that it should be disposes in RCRA Subtitle C class landfill.

Keywords: Water treatment plant sludge; Sludge disposal; Sludge reuse; Landfill; Sludge characterization; Sludge quality

1. Introduction

Majority of water treatment sludge (WTS) is generated in chemical process involved in portable and service water treatment plants and its properties depend typically on the quality of raw water and treatment method [1,2]. Therefore, this sludge contains mineral and organic compounds in solid, liquid, and gaseous forms [2]. Precipitated form of raw water

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(e.g. pathogens, organohalogens) together with the residuals of chemicals used as coagulant (e.g. aluminum and iron) and coagulant aids (e.g. organic polymers) are materials which would be found in WTS [2,3]. Heavy metals are nonbiodegradable and hazardous materials that are discharged into water bodies by industrial streams or agricultural runoffs [4,5] and can be accumulated in the sludge during water treatment process. Thus, inappropriate disposal of sludge can be a risk for human health and environmental protection.

In order to dispose WTP sludge, it can be discharged into surface water, discharged into sanitary sewers, regenerated, reused and land filled [2]. There are various works, depending upon the physical and chemical quality, at using WTP sludge as a component in the manufacture of several materials such as concrete, cement, bricks [1,6,7], as a potential for use in agriculture [8] as a recovery source of coagulants [9] and for phosphorous reduction during wastewater treatment [10]. Such reuse methods beside their advantages of WTP sludge including economic savings on over all treatment plant operation costs and environmental sustainability offer some disadvantages such as complexity of the method and problems that can be caused by pollutants existed in the sludge [3].

The aim of this study is to determine the physical and chemical properties of the slurry and cake sludges from an industrial water treatment plant in southwestern Iran. A comparison of the heavy metal concentrations with Canadian soil quality guidelines (CSQG) for the Protection of Environmental and Human Health [11], Florida department of environmental protection soil cleanup target levels (FDEPSCTLs) [12] and land disposal restrictions (LDR) of RCRA [13] was conducted. Finally, some of disposal methods were discussed.

2. Materials and methods

2.1. Study site

The studied industrial water treatment plant located in southwestern of Iran. The raw water is collected from Karun River. Seven operational and processing units of this WTP are pretreatment unit, reverse osmosis unit, demineralization water unit, condensed water unit, drinking water unit, fire water unit, and cooling towel and blow down system. The pretreatment process is consisting of coagulation, flocculation, sedimentation and filtration. Ferric chloride (Fe_2Cl_3), polyelectrolyte (anionic polymer) and NaOH are used as coagulant, coagulant aid and pH adjuster, respectively. The other units use this pretreated water with or without further purification for their consumptions. Sludges from the pretreatment unit and the other units are concentrated using cationic polymer before its dewatering. Concentrated sludge is dewatered (70%) by passing a belt filter press and cake sludge is produced (80–100 tons per year). Cake sludge disposed every day somewhere out of the WTP, without any analysis on its component and any consideration of public health and environmental sustenance.

2.2. Sampling

Since water quality and quantity can change in different seasons, 48 sludge samples, including 24 slurry sludge and 24 cake sludge samples were collected biweekly, in wet season (November 2009–April 2010) and dry season (September–October 2009 plus May–July 2010). Slurry samples were collected before dewatering and cake samples were collected after dewatering operation, both in grab sampling manner. Samples transportation and storage were according to Standard Methods for the Examination of Water and Waste water [14].

2.3. Analytical methods and instruments

Total solids (TS), total suspended solids (TSS), total dissolved solids (TDS) (dried at 103–105˚C), fixed and volatile suspended solids (FSS and VSS) (ignited at 550˚C), pH (pH meter Metrohm, Switzerland), conductivity (conductivity meter Metrohm, Switzerland), turbidity (Nephelometric method, Hach 2100P, US) and total organic carbon (TOC) (TOC-VCSH, SHIMADZU, Japan) were determined. COD were also measured using a thermo reactor and a spectrophotometer (DR4000Hach, US). Metal content (Al, As, Cd, Co, Cr, Cu, Fe, Mn, Ni, Pb, Se, Zn, Ca, Mg and, Na) were determined by an ICP-OES VARIAN (VISTA-MPX) in the sludge samples.

Metals content and COD were determined using ASTM [15] and other parameters were measured according to Standard Methods for the Examination of Water and Waste Water [14].

All chemicals used in this study were of analytical grade and were purchased from Merck Chemical Company (Germany) except for $HgSO_4$, which were ACROS Company production (US).

2.4. Statistical analysis

In order to analyze data, first of all Explorer command and stem and leaf graph were used to exclude outlier data. Then Kolmogorov–Smirnov Z analysis was performed to assess the normality of the data. After that independent *t*-test (for normal data) and Mann–Whitney U-test (for non- normal) were used to compare the data for each sludge in each season with the others. One sample *t*-test was applied to compare metals concentration with the standard values. Since, there are no standards, regulations, or legal restrictions available for soil clean-up levels in Iran, CSQG, FDEPSCTLs, and LDR of RCRA were used for this purpose.

3. Results and discussion

3.1. The slurry and cake sludge samples

Table 1 shows the result of physicochemical characteristics and statistical results of slurry and cake sludges in both wet and dry seasons. As this table shows the number of samples for some parameters are less than 12, which is due to omission of outlier data. The results of Kolmogorov–Smirnov Z test introduced distributions of Cu, TOC, and TDS for slurry sludge, and Na and Zn for cake sludge as non-normal. So, Mann–Whitney U-test was used for them. Other parameters were normal and were analyzed using independent *t*-test (see Table 1).

According to our results, Al, Ca, Cr, Fe, Na, Pb, Se, in slurry sludge, and Al and Cr in cake sludge were significantly decreased in dry season compared with wet season. The higher concentration of metals observed during wet season could be attributed to the rainfall and subsequent river runoff, bringing much industrial and land derived materials along with domestic, municipal, and agricultural wastes, which include residues of heavy metal containing pesticides [16]. Thus, heavy metals could be removed through water treatment processes and be accumulated in the sludge.

Zn in slurry sludge and Mg and Zn in cake sludge were increased significantly in dry season compared with wet season (Table 1). Increase in water salinity in dry season can decrease the mobility of metals accumulated in the sludge. Thus, these metals cannot be released from sludge to water [17]. So, it causes high concentration of Zn in both sludges and Mg in cake sludge.

For those metals that their concentration in slurry or cake sludge in the wet and dry seasons did not have significant difference, the reason can be the close effects of both increase in heavy metal load (in wet season) and increase in water salinity (in dry season) on their concentration in sludge.

TS, TSS, and FSS in cake sludge were the parameters that significantly decreased in dry season compared with wet season, which can be due to higher quantity and turbulence of water in wet season, which compared with dry season, enters more TS, TSS, and FSS into the WTP and finally in the sludge.

Turbidity, COD and TOC in slurry sludge in the samples of wet season were significantly higher than that of dry season samples. On the other hand, pH, TDS, and VSS were parameters that increase significantly in dry season compared with wet season.

Increase in water quantity and turbulence in wet season can cause more suspended solids in water that enter into WTP and finally can increase turbidity of the slurry sludge. Organic materials transmit to the aqueous ecosystems through surface runoffs in wet season can increase its COD and TOC compared with dry season.

pH is the most important factor that can affect the chemistry of metals in soil and their uptake by organism [17]. pH of the sludge in the both wet and dry seasons was alkaline, but it was significantly higher in the dry season than wet season. Acid precipitation enters in water bodies in wet seasons can decrease their pH compared with dry season. Alkaline nature of the sludge can be due to NaOH (20%) that was added in the first section of flocculation chamber.

Less precipitation and high evaporation in dry season can cause the increase in TDS amounts in slurry sludge. Conductivity of the slurry sludge did not change significantly in wet and dry seasons. It can be due to precipitation in the wet season and increase in TDS in dry season can have almost similar effects on the conductivity of slurry sludge.

3.2. Comparing slurry and cake sludges in wet and dry seasons

To investigate whether slurry and cake sludges are different in their contents during two mentioned seasons, the mean values of the studied parameters were compared in both slurry and cake sludges in wet and dry seasons. The results of Kolmogorov–Smirnov Z showed that in wet season slurry and cake sludges were distributed normally. So, *t*-test was conducted for these data. According to Kolmogorov–Smirnov Z test, *t*-test should be used for all the data obtained in dry season except for Cd, Co, TS, and FSS data, which did not distribute normally and Mann–Whitney U was used for them. The statistical results of comparing slurry and cake sludges in wet and dry seasons were summarized in Table 2.

Our results indicated that in the wet season, the metals concentration in the slurry sludge is higher than those in the cake sludge. Although, according to Table 2 and in the wet season, among the metals, As, Cd, Cr, Na, Ni, Pb, and Se concentrations in the slurry sludge were significantly higher than those in the cake

Table 1
Physicochemical characteristics and statistical results of slurry and cake sludge in wet and dry seasons

Parameter/unit	Season	Slurry sludge					Cake sludge				
		Number of Samples	Mean ± SD	Statistical tests		PV*	Number of Samples	Mean ± SD	Statistical tests		PV*
				t	Mann-Whitney				*t*	Mann-Whitney	
Al (mg $kg^{-1}{}_{dry\ solid}$)	Wet	12	3,463 ± 1,520	2.815	–	0.01	11	3,233 ± 1,379	2.897	–	0.009
	Dry	12	1,975 ± 1,020				12	1,764 ± 1,041			
As (mg $kg^{-1}{}_{dry\ solid}$)	Wet	10	256.60 ± 159.90	−0.426	–	0.674	11	89.50 ± 49.50	0.055	–	0.957
	Dry	12	290.17 ± 201.42				12	87.92 ± 82.92			
Ca (mg $kg^{-1}{}_{dry\ solid}$)	Wet	12	349,030 ± 126,123	3.597	–	0.002	12	308,120 ± 87,109	1.245	–	0.228
	Dry	12	188,570 ± 89,274				10	270,500 ± 42,348			
Cd (mg $kg^{-1}{}_{dry\ solid}$)	Wet	12	20.58 ± 7.70	1.273	–	0.216	10	8.02 ± 2.90	1.020	–	0.320
	Dry	12	15.45 ± 11.65				11	6.82 ± 2.49			
Co (mg $kg^{-1}{}_{dry\ solid}$)	Wet	11	28.45 ± 9.12	−1.117	–	0.285	12	19.79 ± 13.20	1.049	–	0.306
	Dry	12	39.38 ± 32.51				12	15.21 ± 7.41			
Cr (mg $kg^{-1}{}_{dry\ solid}$)	Wet	12	51.33 ± 29.07	3.19	–	0.004	12	25.33 ± 14.65	2.876	–	0.009
	Dry	12	22.08 ± 14.14				12	11.47 ± 8.02			
Cu (mg $kg^{-1}{}_{dry\ solid}$)	Wet	11	24.64 ± 20.67	–	52.00	0.580	11	15.23 ± 9.29	0.894	–	0.382
	Dry	11	26.68 ± 26.42				11	11.73 ± 9.08			
Fe (mg $kg^{-1}{}_{dry\ solid}$)	Wet	10	26,615 ± 3,972	2.392	–	0.029	11	24,563 ± 5,720	1.006	–	0.326
	Dry	9	23,067 ± 2,094				12	22,125 ± 5,888			
Mg (mg $kg^{-1}{}_{dry\ solid}$)	Wet	11	36,998 ± 15,889	−0.320	–	0.752	10	27,733 ± 10,712	−4.012	–	0.001
	Dry	11	38,771 ± 9,232				11	43,046 ± 6,458			
Mn (mg $kg^{-1}{}_{dry\ solid}$)	Wet	10	126.30 ± 30.10	−0.492	–	0.629	11	124.95 ± 22.20	1.784	–	0.091
	Dry	10	131.30 ± 11.20				12	102 ± 38			
Na (mg $kg^{-1}{}_{dry\ solid}$)	Wet	12	13,455 ± 9,841	3.630	–	0.004	12	3,942 ± 3,227	–	34.00	$^{-1}$0.028
	Dry	12	3,105.50 ± 837.50				12	1,541 ± 579			
Ni (mg $kg^{-1}{}_{dry\ solid}$)	Wet	10	95.30 ± 41.30	0.238	–	0.814	11	51.00 ± 17.00	0.139	–	0.891
	Dry	11	88.91 ± 74.92				11	49.54 ± 30.18			
Pb (mg $kg^{-1}{}_{dry\ solid}$)	Wet	11	139.09 ± 38.71	2.478	–	0.023	11	56.73 ± 16.49	0.363	–	0.721
	Dry	10	98.90 ± 35.30				12	53.08 ± 29.32			
Se (mg $kg^{-1}{}_{dry\ solid}$)	Wet	10	291.40 ± 57.20	2.281	–	0.034	12	173.62 ± 112.88	0.022	–	0.982
	Dry	11	208.36 ± 101.18				12	172.67 ± 96.03			
Zn (mg $kg^{-1}{}_{dry\ solid}$)	Wet	11	61.91 ± 39.61	−3.359	–	0.005	10	56.7 ± 8.27	–	27.50	0.032
	Dry	12	192.92 ± 128.59				12	179.67 ± 133.16			
TS (%w)	Wet	12	11.61 ± 3.18	−0.814	–	0.427	12	45.01 ± 4.06	4.507	–	0.001
	Dry	11	12.47 ± 1.59				12	38.54 ± 2.86			

(*Continued*)

Table 1 (*Continued*)

Parameter/unit	Season	Slurry sludge					Cake sludge				
		Number of Samples	Mean ± SD	Statistical tests		PV*	Number of Samples	Mean ± SD	Statistical tests		PV*
				t	Mann-Whitney				*t*	Mann-Whitney	
VSS ($mg\ l^{-1}$)	Wet	12	7.13 ± 3.38	−3.266	–	0.006	10	28.01 ± 2.62	−1.650	–	0.114
	Dry	11	10.50 ± 1.10				12	29.98 ± 2.92			
FSS ($mg\ l^{-1}$)	Wet	12	106.96 ± 28.26	−0.079	–	0.938	12	418.79 ± 41.13	4.931	–	0.001
	Dry	11	107.66 ± 10.86				12	346.10 ± 30.30			
TSS ($mg\ l^{-1}$)	Wet	12	114.09 ± 30.68	−0.965	–	0.345	12	446.63 ± 40.71	4.709	–	0.001
	Dry	12	124.80 ± 23.20				12	376.07 ± 32.21			
TDS ($mg\ l^{-1}$)	Wet	12	1.79 ± 2.21	–	34.50	0.030	–	–	–	–	–
	Dry	12	5.92 ± 5.44				–	–			
pH (–)	Wet	12	9.66 ± 0.15	−4.215	–	0.001	–	–	–	–	–
	Dry	9	9.87 ± 0.07				–				
Conductivity ($\mu s\ cm^{-1}$)	Wet	12	1,700 ± 420	0.179	–	0.860	–	–	–	–	–
	Dry	12	1669.80 ± 407.10				–				
$Turbidity_{(0.4\%\ solution)}$ (NTU)	Wet	10	391.80 ± 44.10	2.279	–	0.034	–	–	–	–	–
	Dry	12	322.92 ± 86.41				–				
TH ($mg\ kg^{-1}$)	Wet	9	91,618 ± 9,089	−0.367	–	0.717	–	–	–	–	–
	Dry	12	91,611 ± 2,421				–				
$COD_{(1\%\ solution)}$ ($mg\ l^{-1}$)	Wet	12	33.83 ± 5.73	3.079	–	0.005	–	–	–	–	–
	Dry	12	27.08 ± 4.98				–				
$TOC_{(1\%\ solution)}$ ($mg\ l^{-1}$)	Wet	10	1.07 ± 0.61	–	27.5	0.030	–	–	–	–	–
	Dry	12	0.28 ± 0.26				–				

*P-value <0.05 is considered as significant.

sludge. In the dry season, As, Cd, Co, Cr, Mn, Na, and Pb concentrations in the slurry sludge were significantly higher than those in the cake sludge (p-value < 0.05) and Ca was the only metal that had significantly higher concentration in cake sludge than the slurry sludge.

It can be due to the type and the higher concentration of responsible ligands for metals adsorption in the slurry sludge than cake sludge. For those metals that their concentration in slurry and cake sludges in wet or dry seasons did not have significant difference, the reason can be the similarity in the type and concentration of these ligands' in the both seasons.

Table 2 represents that TS, TSS, VSS, and FSS in the cake sludge compared with the slurry sludge, in the both season, were significantly higher. Such results were expected, because after dewatering process the remained sludge would be more concentrated.

3.3. WTP sludge disposal

Large amount of TP sludge is generated every day, which is raising concerns over their disposal and associated costs. Table 3 represents the statistical results of comparing the investigated heavy metals with the standards determined by CSQG, FDEPSCTLS, and LDR of RCRA.

The result of our study indicates that compared with CSQG and FDEPCTLs, and As have significantly high concentration in both slurry and cake sludges in both seasons for all land usages. Other parameters have significantly lower concentration compared with FDEPCTLs for soil direct exposure in both residential and industrial applications and in both slurry and cake sludges in the both seasons.

Slurry sludge in the both wet and dry seasons had higher concentration than Cd guideline assigned for residential land use by CSQG. But it was Cd concentration in the slurry sludge and wet season that was significantly high. Cd concentration for agricultural application was significantly high in all samples. Cd was high, but not significantly, in slurry sludge in both seasons. For cake sludge samples concentration of Cd were low for both commercial and industrial applications.

Comparing our results with CSQG showed that Cr and Cu concentration was significantly low in all samples for residential, agricultural, commercial and industrial applications, except for Cr concentration in slurry sludge in wet season, which is not significantly low.

Ni concentration was high for all applications except for cake sludge in dry season that were low. Compared with CSQG, slurry sludge in wet and dry seasons were significantly high in their Pb concentration for agricultural applications but cake sludge had low concentration for Pb, especially in wet season that its concentration was significantly low. Pb concentration for residential/parkland, commercial and industrial applications was significantly low in all samples, except for slurry sludge in wet season, which was not significant. Compared with CSQG, Se, and Zn concentrations in all samples were significantly high and low, respectively. Zn concentration in the both slurry and cake sludges in dry season was not significantly low for their residential/parkland and agricultural uses.

Considering these results some constructive approaches toward WTP sludge management are discussed below.

3.3.1. Discharge to wastewater systems

WTP sludge can be used as a coagulant or as an adsorbent for pollutants and metals in wastewater. Basibuyuk and Kalat, were used an iron-based WTP sludge as a coagulant in the treatment of vegetable oil refinery wastewater and obtained excellent removal efficiencies. They noted that the iron sludge was as efficient as using alum or ferric chloride, and removal was further enhanced when combined with ferric chloride [18]. Chu also reported the use of WTP sludge for the treatment of textile wastewaters and various dyestuffs and satisfactory removal efficiencies for colors as compared with the use of original coagulants [19].

Phosphorous is one of the major pollutants in wastewater, and thus, there are a number of studies were implemented based on phosphorous absorbance using WTP sludge [10,20,21]. WTP sludge was also preliminarily studied as a potential adsorbent for the removal of lead and Copper in wastewaters [22].

Beside all these advantages, it should be noted that chemical nature and volume of sludge and extra load of solids need to be considered because it can affect the solid capacity of waste water units and increase operational and maintenance costs. A large amount of sludge produced every day in WTP of FPCC 220–275 kg/d and it is impossible for WWTP to handle this amount. Moreover, both slurry and cake sludges have high levels of some heavy metals. Therefore, discharging to the wastewater system is not a suitable option for this study.

3.3.2. Coagulants recovery from WTP sludge

Compared to CSQG for commercial and industrial applications As, Ni, and Se in the both slurry and cake sludges were significantly high, indicating that

Table 2
Statistical results of comparing slurry and cake sludges in wet and dry seasons

Parameter/unit	Sludge	Wet season			Dry season				
		Mean ± SD	t	PV*	Mean ± SD	t	Median	Mann-Whitney U	PV*
Al (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	3463.20 ± 1520.57	0.380	0.710	1975.30 ± 1020.03	0.501	–	–	0.621
	Cake	3232.60 ± 1379.66			1764.50 ± 1041.18		–		
As (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	256.60 ± 159.93	3.303	0.004	290.17 ± 201.42	3.217	–	–	0.006
	Cake	89.50 ± 49.53			87.92 ± 82.92		–		
Ca (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	349,030 ± 126,123	0.925	0.365	188,570 ± 89,274	−2.656	–	–	0.015
	Cake	308,120 ± 87,109			270,500 ± 42,348		–		
Cd (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	20.58 ± 7.70	4.860	0.001	–	–	14.54	35.5	0.05
	Cake	8.02 ± 2.90			–		9.23		
Co (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	28.45 ± 9.12	1.814	0.084	–	–	16.29	26.5	0.008
	Cake	19.79 ± 13.19			–		8.71		
Cr (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	51.30 ± 29.10	2.767	0.011	21.58 ± 14.10	0.501	–	–	0.042
	Cake	25.30 ± 13.20			11.47 ± 8.03		–		
Cu (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	24.64 ± 20.67	1.377	0.190	26.68 ± 26.43	3.217	–	–	0.101
	Cake	15.23 ± 9.29			11.73 ± 9.08		–		
Fe (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	26,615 ± 3,973	0.945	0.357	23,067 ± 2,094	−2.656	–	–	0.616
	Cake	24,563 ± 5,720			22,124 ± 5,888		–		
Mg (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	36,998 ± 15,889	1.550	0.138	38,771 ± 9,232	0.501	–	–	0.223
	Cake	27,733 ± 10,712			43,046 ± 6,458		–		
Mn (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	126.30 ± 30.10	0.117	0.908	131.30 ± 11.20	3.217	–	–	0.025
	Cake	124.95 ± 22.20			102 ± 38		–		
Na (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	13,455 ± 9,842	3.182	0.007	3105.50 ± 837.50	−2.656	–	–	0.001
	Cake	3,942 ± 3,227			1540.70 ± 578.70		–		
Ni (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	95.30 ± 41.30	3.268	0.004	88.91 ± 74.93	0.501	–	–	0.122
	Cake	51.00 ± 17.00			49.55 ± 30.18		–		
Pb (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	139.09 ± 38.71	6.492	0.001	98.90 ± 35.30	3.217	–	–	0.003
	Cake	56.73 ± 16.49			53.08 ± 29.32		–		
Se (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	291.40 ± 57.20	3.159	0.006	208.36 ± 101.18	−2.656	–	–	0.395
	Cake	173.62 ± 112.87			172.67 ± 96.03		–		
Zn (mg $kg^{-1}{}_{dry\ solid}$)	Slurry	61.91 ± 39.62	0.426	0.678	192.92 ± 128.59	0.501	–	–	0.806
	Cake	56.70 ± 8.30			179.67 ± 133.17		–		
TS (%w)	Slurry	11.59 ± 3.18	−22.418	0.001	–	–	6.00	0.001	0.001
	Cake	45.01 ± 4.07			–		17.50		

(Continued)

Table 2 (*Continued*)

Parameter/unit	Sludge	Wet season			Dry season				
		Mean ± SD	*t*	PV*	Mean ± SD	*t*	Median	Mann-Whitney U	PV*
TSS (mg l^{-1})	Slurry	114.09 ± 30.68	−22.597	0.001	124.80 ± 23.16	−2.656	–	–	0.001
	Cake	446.63 ± 40.71			376.07 ± 32.20		–		
VSS (mg l^{-1})	Slurry	71.33 ± 33.76	−15.935	0.001	10.50 ± 1.10	−21.44	–	–	0.001
	Cake	28.01 ± 2.62			29.98 ± 2.29		–		
FSS (mg l^{-1})	Slurry	106.96 ± 28.26	−21.645	0.001	–	–	60.00	0.001	0.001
	Cake	418.79 ± 41.13			–		175.00		

*P–value <0.05 is considered as significant.

this accumulated heavy metals can contaminate the recovered coagulant. Because it is possible that other metals, in addition to Fe or Al, also being solubilized and causing coagulant contamination [3]. Although ion exchange can be used for improving the purity of recycled coagulant, but due to high cost of ion-exchange process and the large amount of produced sludge per day, recycling the coagulant in this study it is not a cost-effective option.

3.3.3. Using as building and construction materials

WTP sludge has been studied as a building and concentration materials. For example Ramadan, used WTP sludge for the production of brick [6] and Kaosal, used WTP sludge to produce concrete blocks [1]. However, despite the obvious beneficial, these approaches are yet to be fully accepted in the industry. Final product made from WTP sludge is variable because of its variable physicochemical characteristics, which considered as a problem, even when such products wholly conform to industry standards [3]. For example, none of mentioned researches considered heavy metal concentration in their studied sludges, as it was showed in the present study, there is a pollution potential of WTP sludge that restricts its application as building and construction material.

However, FDEP guidance document allows the blending of sludge with uncontaminated soils in order to reduce the potential public health threat from exposure to the sludge, provided that the resulting mixture is still appropriate for beneficial use. If sludge is to be blended with available soils, FDEP is recommended Eq.1 be used to determine the appropriate blend ratio (ratio of blend material to sludge) to use for lowering the concentrations of a contaminant contained in the sludge [12]:

$$\text{Blend ratio} = \frac{(A - B)}{(B - C)} \tag{1}$$

where A = concentration of contaminant in the sludge, mg kg^{-1}, B = target concentration of the blended material, mg kg^{-1}, C = concentration of contaminant in the material used for blending, mg kg^{-1}.

3.3.4. Agricultural application

Disposal of sludge on land can cause an increase in pollution load in the soil with lots of environmental consequences. Cd, Zn, Cu, Pb, and Ni in sludge are the elements of primary concern, which when applied to the soil in a large amount, can decrease plant yields or degrade the quality of food or fiber products.

Table 3
Statistical results of comparing the investigated heavy metals with the standards determined by CSQG, FDEPSCTLS and LDR of RCRA

Heavy metal	Sludge	Season	CSQG								FDEPSCTLS				LDR of RCRA	
			Residential/ parkland		Agricultural		Commercial		Industrial		Soil direct exposure					
											Residential		Industrial			
			Standard ($mg\,kg^{-1}$)	PV*	Standard ($mg\,kg^{-1}$)	PV*	Standard ($mg\,kg^{-1}$)	PV*	Standard ($mg\,kg^{-1}$)	PV*	Standard ($mg\,kg^{-1}$)	PV*	Standard ($mg\,kg^{-1}$)	PV*	Standard ($mg\,l^{-1}$)	PV*
Al	S	W	–	–	–	–	–	–	–	–	80,000	<0.0001$^{\downarrow}$	–	–	–	–
		D		–		–		–		–		<0.0001$^{\downarrow}$		–		–
	C	W		–		–		–		–		<0.0001$^{\downarrow}$		–		–
		D		–		–		–		–		<0.0001$^{\downarrow}$		–		–
As	S	W	12	0.001$^{\uparrow}$	12	0.001$^{\uparrow}$	12	0.001$^{\uparrow}$	12	0.001$^{\uparrow}$	2.1	0.001$^{\uparrow}$	12	0.001$^{\uparrow}$	5	0.001$^{\downarrow}$
		D		0.001$^{\uparrow}$		0.001$^{\uparrow}$		0.001$^{\uparrow}$		0.001$^{\uparrow}$		<0.0001$^{\uparrow}$		0.001$^{\uparrow}$		0.004$^{\downarrow}$
	C	W		0.002$^{\uparrow}$		0.002$^{\uparrow}$		0.002$^{\uparrow}$		0.002$^{\uparrow}$		0.001$^{\uparrow}$		0.002$^{\uparrow}$		<0.0001$^{\downarrow}$
		D		0.009$^{\uparrow}$		0.009$^{\uparrow}$		0.009$^{\uparrow}$		0.009$^{\uparrow}$		0.004$^{\uparrow}$		0.009$^{\uparrow}$		<0.0001$^{\downarrow}$
Cd	S	W	10	0.001$^{\uparrow}$	1.4	<0.0001$^{\uparrow}$	22	0.537$^{\downarrow}$	22	0.537$^{\downarrow}$	82	<0.0001$^{\downarrow}$	1,700	<0.0001$^{\downarrow}$	1	<0.0001$^{\downarrow}$
		D		0.133$^{\uparrow}$		0.002$^{\uparrow}$		0.077$^{\downarrow}$		0.077$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$
	C	W		0.059$^{\downarrow}$		<0.0001$^{\uparrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$
		D		0.002$^{\downarrow}$		<0.0001$^{\uparrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$
Cr	S	W	64	0.159$^{\downarrow}$	64	0.159$^{\downarrow}$	87	<0.0001$^{\downarrow}$	87	<0.0001$^{\downarrow}$	210	<0.0001$^{\downarrow}$	470	<0.0001$^{\downarrow}$	5	<0.0001$^{\downarrow}$
		D		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$
	C	W		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$
		D		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$
Cu	S	W	63	0.004$^{\downarrow}$	63	0.004$^{\downarrow}$	91	<0.0001$^{\downarrow}$	91	<0.0001$^{\downarrow}$	150	<0.0001$^{\downarrow}$	89,000	<0.0001$^{\downarrow}$	–	–
		D		0.05$^{\downarrow}$		0.05$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–
	C	W		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–
		D		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–
Fe	S	W	–	–	–	–	–	–	–	–	53,000	<0.0001$^{\downarrow}$	–	–	–	–
		D		–		–		–		–		<0.0001$^{\downarrow}$		–		–
	C	W		–		–		–		–		<0.0001$^{\downarrow}$		–		–
		D		–		–		–		–		<0.0001$^{\downarrow}$		–		–
Mn	S	W	–	–	–	–	–	–	–	–	3,500	<0.0001$^{\downarrow}$	43,000	<0.0001$^{\downarrow}$	–	–
		D		–		–		–		–		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–
	C	W		–		–		–		–		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–
		D		–		–		–		–		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–
Ni	S	W	50	0.007$^{\uparrow}$	50	0.007$^{\uparrow}$	50	0.007$^{\uparrow}$	50	0.007$^{\uparrow}$	340	<0.0001$^{\downarrow}$	35,000	<0.0001$^{\downarrow}$	–	–
		D		0.116$^{\uparrow}$		0.116$^{\uparrow}$		0.116$^{\uparrow}$		0.116$^{\uparrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–
	C	W		0.850$^{\uparrow}$		0.850$^{\uparrow}$		0.850$^{\uparrow}$		0.850$^{\uparrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–
		D		0.961$^{\downarrow}$		0.961$^{\downarrow}$		0.961$^{\downarrow}$		0.961$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–
Pb	S	W	140	0.939$^{\downarrow}$	70	<0.0001$^{\uparrow}$	260	<0.0001$^{\downarrow}$	600	<0.0001$^{\downarrow}$	400	<0.0001$^{\downarrow}$	1,400	<0.0001$^{\downarrow}$	5	<0.0001$^{\downarrow}$
		D		0.005$^{\downarrow}$		0.029$^{\uparrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$
	C	W		<0.0001$^{\downarrow}$		0.023$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$
		D		<0.0001$^{\downarrow}$		0.071$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$

(*Continued*)

Table 3 (*Continued*)

Heavy metal	Sludge	Season	CSQG Residential/parkland Standard ($mg\,kg^{-1}$)	CSQG Residential/parkland PV*	CSQG Agricultural Standard ($mg\,kg^{-1}$)	CSQG Agricultural PV*	CSQG Commercial Standard ($mg\,kg^{-1}$)	CSQG Commercial PV*	CSQG Industrial Standard ($mg\,kg^{-1}$)	CSQG Industrial PV*	FDEPSCTLS Soil direct exposure Residential Standard ($mg\,kg^{-1}$)	FDEPSCTLS Soil direct exposure Residential PV*	FDEPSCTLS Soil direct exposure Industrial Standard ($mg\,kg^{-1}$)	FDEPSCTLS Soil direct exposure Industrial PV*	LDR of RCRA Standard ($mg\,l^{-1}$)	LDR of RCRA PV*
Se	S	W	1	<0.0001$^{\uparrow}$	1	<0.0001$^{\uparrow}$	2.9	<0.0001$^{\uparrow}$	2.9	<0.0001$^{\uparrow}$	440	<0.0001$^{\downarrow}$	11,000	<0.0001$^{\downarrow}$	1	<0.0001$^{\uparrow}$
		D		<0.0001$^{\uparrow}$		<0.0001$^{\uparrow}$		<0.0001$^{\uparrow}$		<0.0001$^{\uparrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		0.005$^{\uparrow}$
	C	W		<0.0001$^{\uparrow}$		<0.0001$^{\uparrow}$		<0.0001$^{\uparrow}$		<0.0001$^{\uparrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		0.045$^{\uparrow}$
		D		<0.0001$^{\uparrow}$		<0.0001$^{\uparrow}$		<0.0001$^{\uparrow}$		<0.0001$^{\uparrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		0.024$^{\uparrow}$
Zn	S	W	200	<0.0001$^{\downarrow}$	200	<0.0001$^{\downarrow}$	360	<0.0001$^{\downarrow}$	360	<0.0001$^{\downarrow}$	26,000	<0.0001$^{\downarrow}$	630,000	<0.0001$^{\downarrow}$	–	–
		D		0.852$^{\downarrow}$		0.852$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–
	C	W		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–
		D		0.607$^{\downarrow}$		0.607$^{\downarrow}$		0.001$^{\downarrow}$		0.001$^{\downarrow}$		<0.0001$^{\downarrow}$		<0.0001$^{\downarrow}$		–

*P-value <0.05 is considered as significant.

$^{\uparrow}$ and $^{\downarrow}$ indicate that measured amounts are higher and lower than standards, respectively.

Therefore, sludge needs to be analyzed for its elements before applying on land [23].

Our results showed that As, Cd, Ni, and Se in the both slurry and cake sludges compared with CSQG for agricultural application had higher concentration. Thus, none of the slurry or cake sludges is suitable for agricultural applications. Lombi et al. reported that WTP sludge due to its capability of adsorbing phosphorous can cause decrease in plants growth. They also mentioned that Al and Cu in plants were increased after applying WTP sludge [8].

FDEP recommends that if the approach is to blend the sludge into the top six inches of soil at the land application site, then Eq. (2) should be used to calculate the allowable application rate in tons per acre [12]:

$$\text{Application rate} = (10.89\rho_s)\frac{(B-C)}{(A-B)} \tag{2}$$

where ρ_s = density of soil in the top 6 inches, $lb\,ft^{-3}$, A = concentration of contaminant in the sludge, $mg\,kg^{-1}$, B = target concentration of the blended material, $mg\,kg^{-1}$ and C = concentration of contaminant in the material used for blending, $mg\,kg^{-1}$.

3.3.5. Land filling

Based on its toxicity, sludge generated by WTPs is characterized as hazardous or nonhazardous. This can be assessed by the toxicity characteristic leaching procedure (TCLP). If contaminant concentrations in the TCLP leachate are in excess of those listed in the LDR of RCRA, the sludge is classified as hazardous [24]. Table 3 indicates that all the metals considered in this study were significantly lower than the amounts regulated by LDR of RCRA, except for Se concentration that was significantly high in the slurry and cake sludges in the both seasons. Thus, the studied sludge must be disposed in a RCRA subtitle C class landfill, which shows that current practice of disposing sludge should be abandoned. Vijay and Sihorwala, reported that Cr, Zn, Mn, Fe, Ni, Co, and Cu in sludge generated from metal pickling and electroplating industries compared to TCLP regulatory limits given by USEPA and Germany Leachate Quality Standards are in their higher side and its handling, treatment, recovery and disposal should be managed carefully [25].

4. Conclusion

The aim of this study was to characterize the WTP sludge in two slurry and cake sludges and in two wet and dry seasons. The measured parameters were compared according to their type and season, and the results were reported. Compared with CSQG, the investigated sludge was polluted for residential/parkland, agricultural, commercial and industrial land use. According to FDEPSCTLs, it was just as with significantly higher concentration for residential and industrial applications. FDEP also recommend that blending of sludge with uncontaminated soil can make it suitable for its different applications. Moreover, using TCLP for the understanding of sludge characteristics and comparing its results with LDR of RCRA, showed that because of high concentration of Se, the sludge can be considered as hazardous material. Thus, it has to be disposed in a RCRA subtitle C class landfill. It should be noted that there are another parameters in CSQG, FDEPSCTLs, and LDR of RCRA than those investigate in this study including different organic and inorganic compounds, and it would be better that these parameters be considered in future studies.

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