# Physico-chemical Characteristics of Municipal Sludge Produced at Three Major Cities of the Eastern Province of Saudi Arabia

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**Abstract.** Due to uncontrolled dump of dried municipal sludge and its use by farmers as soil conditioner and/or fertilizer, an extensive research was conducted in order to determine the physical and chemical characteristics of municipal sludges produced at three major cities, namely, Qateef, Dammam and Khobar in the Eastern Province of Saudi Arabia between April 2000 and February 2001. Sludge samples were collected, from sand drying beds, twice a season for one year and were analyzed for certain potential parameters such as total solids, oil and grease, nitrogen compounds and heavy metals. The results indicated that total solids concentration in dried sludge samples collected from the three cities was found to reach 87%, which was higher than that reported in literature and that volatile solids were within those reported internationally. Dried sludge samples collected from Dammam were found to contain an oil and grease concentration of 8.66%t which is the highest when compared to other cities that was attributed to the industrial activities in that city. With respect to sludge fertilizer value, sludge samples collected from the three cities were found to be deficient in nitrogen, where TKN concentration was between 0.66 and 1.25%. With respect to heavy metals, sludge samples collected from the three cities were found to contain concentrations that are within ranges reported in literature. Arsenic, cadmium, chromium, lead and mercury concentrations were 10, 40, 67, 3.3 and 0.3 mg/l, respectively.

## Introduction

Wastewater treatment facilities across the Kingdom of Saudi Arabia have been, or are being, expanded to provide higher degree of wastewater treatment and to cope with the increasing quantities of wastewater being delivered to the treatment facilities. This, of course, translates into increased volumes of produced wastewater sludges, which must be managed properly. In the Eastern Province of Saudi Arabia, sludge is not being characterized by the concerned authority and is mainly disposed by a land spreading technique at sites outside the cities of Dammam, Khobar and Qateef. Furthermore, farmers are utilizing municipal sludge as a fertilizer or soil conditioner after an uncontrolled drying period and without proper characterization or treatment. This practice may result in crops that are polluted with pathogens, toxic organics, and heavy metals. Consequently, serious health hazards are expected if consumers continue to bio-accumulate toxicants through this practice. Accordingly, the issue of municipal sludge should be fully investigated to help decision makers become familiarized with the characteristics of those sludges, the possibilities of treatment, and the consequences of the aforementioned fertilizing practices on public health.

Characteristics of sludge, to be measured, are strongly related to its ultimate fate. For example, if the sludge is to be thickened by gravity, then settling and compaction characteristics are important. The first characteristic, solids concentration, is perhaps the most important variable in defining the volume of sludge to be handled. Table 1 shows solids concentration in various municipal sludges, while the physical characteristics of sludge from different treatment processes are given in Table 2 (Droste, 1997; Kiely, 1997).

**Table 1. Solids concentration in various sludge types (Droste, 1997)**

| Sludge type | Solids concentration % |
| --- | --- |
| Primary sludge | 5-8% |
| Waste activated sludge | 0.5-2.0% |
| Fixed film waste sludge | 3-10% |
| Primary and waste activated sludge | 2.5-4% |
| Primary and fixed film sludge | 3-5% |
| Aerobically digested sludge (thickened) | 1-2% |
| Anaerobically digested sludge (thickened) | 6-12% |

**Table 2. Physical characteristics of sludge (Kiely, 1997)**

| Parameter | Primary sludge | Secondary sludge | Dewatered sludge |
| --- | --- | --- | --- |
| Dry solids | 2-6% | 0.5-2% | 15-35% |
| Volatile solids | 60-80% | 50-70% | 30-60% |
| Sludge specific gravity | 1.02 | 1.05 | 1.1 |
| Solids specific gravity | 1.4 | 1.25 | 1.2-1.4 |
| Shear strength (kN/m2) | <5 | <2 | <20 |
| Energy content (MJ/kg VS) | 12-22 | 12-20 | 25-30 |
| Particle size (90%) | <200 μm | <100 μm | <100 μm |

The chemical characteristic of sludge is of great importance for several reasons. The characteristics of sludge that affect its suitability for beneficial use include organic content (usually measured as volatile solids), nutrients, pathogens, metals, and toxic organics. The fertilizer value of the sludge, which should be evaluated when sludge is to be used as a fertilizer or soil conditioner, is dependent primarily on the availability of N, P and K, as well as trace elements. Table 3 shows mean concentrations of several elements in different sludge types, while typical nutrient values of sludge as compared to commercial fertilizers are reported in Table 4 (Kiely, 1997; Metcalf and Eddy, 2003). Moreover, Table 5 gives a range of typical chemical compositions of different sludges (Kiely, 1997). In fact, measurement of pH, alkalinity, and organic acid content is important in the process control of anaerobic digestion.

**Table 3. Concentrations of several elements in different sludge types (Kiely, 1997)**

| Parameter | Mean concentration (% of dry solids) | | |
| --- | --- | --- | --- |
| | Anaerobic | Aerobic | All |
| K | 0.52 | 0.46 | 0.4 |
| Na | 0.7 | 1.1 | 0.57 |
| Ca | 5.8 | 3.3 | 4.9 |
| Mg | 0.58 | 0.52 | 0.54 |
| Ba | 0.08 | 0.02 | 0.06 |
| Fe | 1.6 | 1.1 | 1.3 |
| Al | 1.7 | 0.7 | 1.2 |

**Table 4. Comparison of nutrient levels in commercial fertilizers and wastewater sludge (Metcalf and Eddy, 1991)**

| | Nutrients, % | | |
| --- | --- | --- | --- |
| | Nitrogen | Phosphorous | Potassium |
| Fertilizers for typical agricultural use | 5 | 10 | 10 |
| Typical values for stabilized sludge | 3.3 | 2.3 | 0.3 |

**Table 5. Typical chemical composition of sludges (Kiely, 1997)**

| Parameter | Primary sludge | Anaero-bicaly digested sludge | Aero-bically digested sludge |
| --- | --- | --- | --- |
| pH | 5-8 | 6.5-7.5 | |
| Alkalinity (mg/l $CaCO_3$) | 500-1500 | 2500-3500 | |
| Nitrogen (N% of TS[a]) | 1.5-4 | 1.6-6 | 0.5-7.6 |
| Phosphorous ($P_2O_5$% of TS) | 0.8-2.8 | 1.5-4 | 1.1-5.5 |
| Fats, grease (% of TS) | 6-30 | 5-20 | |
| Protein (% of TS) | 20-30 | 15-20 | |
| Organic acids (mg/l as HAc[b]) | 6800-10000 | 2700-6800 | |

[a]TS = Total Solids; [b]HAc = Hydrogen Acetate

Trace elements in sludge are those inorganic chemical elements that, in very small quantities, can be essential or detrimental to plants and animals. Actually, concentrations of heavy metals vary widely, as indicated in Table 6 (Metcalf and Eddy, 2003).

**Table 6. Concentrations of heavy metals in sludge (Metcalf and Eddy, 1991)**

| Metal in Dry Sludge (mg/kg) | Range | Median |
| --- | --- | --- |
| Arsenic | 1.1-230 | 10 |
| Cadmium | 1-3410 | 10 |
| Chromium | 10-99000 | 500 |
| Cobalt | 11.3-2490 | 30 |
| Copper | 84-17000 | 800 |
| Iron | 1000- 154000 | 17000 |
| Lead | 13-26000 | 500 |
| Manganese | 32-9870 | 260 |
| Mercury | 0.6-56 | 6 |
| Molybdenum | 0.1-214 | 4 |
| Nickel | 2-5300 | 80 |
| Selenium | 1.7-17.2 | 5 |
| Tin | 2.6-329 | 14 |
| Zinc | 101-49000 | 1700 |

(Laschka and Nachtwey, 1995) measured platinum concentration in wastewater and sludge of two large wastewater treatment plants in dry and rainy weather periods. They found that platinum concentrations and loads increased in primary sludge during rainfall compared to dry weather conditions. (Sonmez and Bozkurt, 2006) evaluated the effects of sewage sludge, manure and humic acid applications on soil properties and element concentrations of soil and plants. They reported that the addition of sewage sludge increased the levels of N, P, K and Mg to the same extent. Leaf Cd concentration was also found to increase in sludge treated plots. Furthermore, sewage sludge applications increased organic matter, electrical conductivity, total N, available P, exchangeable K, total Cu and Ni, extractable Mn, Cu, Fe, Cr, Zn and Cd concentrations of topsoil. (Afyuni *et al.*, 2006) performed a four-year field experiment in which the uptake of heavy metals from a sludge-amended soil by lettuce and spinach was investigated. Single applications were found to increase the extractable concentrations of Cu, Zn and Pb and that Cd concentrations increased only after two or three consecutive applications. The results also showed that in subsequent years with no further sludge applications, extractable metal concentrations in soil showed a decreasing trend, but even after four years, metal concentrations were still significantly higher in plots that had received more than 45 mg per hectar sludge than in control plots. (Muchuweti *et al.*, 2006) studied heavy metal concentrations in crops irrigated with sewage sludge. The crops analyzed in this study are heavily contaminated with the four regulated elements: Cd, Cu, Pb and Zn. This contamination is at its highest in two of the staple dietary crops maize and tsunga. Furthermore, the concentrations observed in this study were higher than those reported by other workers who have examined vegetation from other contaminated sites. This study highlights the potential risks involved in the cultivation and consumption of vegetables on plots irrigated with sewage sludge, a practice which may place at risk the health of the urban population who consume these vegetables. (Garrido *et al.*, 2005) evaluated the physicochemical interactions between soil treated with biosolids and compost from municipal residual waters, and the nutritional parameters of broad bean seeds. The parameters determined for biosolids, compost, and soil were: pH, electrical conductivity (EC), organic matter (OM), total nitrogen, available phosphorus, cation exchange capacity (CEC), exchangeable cations (Ca, Mg, Na and K), total and available heavy metals (Cd, Cr, Cu, Ni and Zn). Total concentrations of Cr, Zn, Ni and Cu in soil presented significant differences between treated soil and the control, Cd was not detected. (Gasco *et al.*, 2005) conducted a column study to assess the potential Cr, Ni, Cu, Zn, Cd and Pb movement through a reconstructed soil to which surface composted sewage sludge was applied. The results showed that metal balance accounted for over 97% of metals were retained in the first 100 mm of the column. The maximum metal concentration in leachate was lower than the limit value for irrigation water, but metal concentrations exceeded the drinking water levels for Pb and Ni in all treatments. Thus, harmful health effects may result from the application of sewage sludge.

Based on the above discussion. The main objective of the study is to determine the physical and chemical characteristics of municipal sludge produced in three main cities of the Easter Province, Saudi Arabia. Recommendations on the utilization and/or disposal of the sludge will be also formulated.

## Materials and Methods

Sludge samples collected between April 2000 and February 2001 from sand drying beds at Khobar, Dammam, and Qateef wastewater treatment plants were characterized by determining their physico-chemical properties, as shown in Table 7. It is worth mentioning that sludge samples were kept in a cold storage at 4°C prior to analysis.

**Table 7. Physico-chemical parameters**

- Moisture Content
- Total Solids
- Total Volatile Solids
- pH
- Total Alkalinity
- Total Kjeldahl Nitrogen
- Ammonia Nitrogen
- Organic Nitrogen
- Nitrate ($NO_3$)
- Nitrite ($NO_2$)
- Oil and Grease
- Heavy Metals:
- Hg, B, Cd, Pb, Zn
- Cr, Cu, Ni, As Fe

Sludge sampling was carried out twice per season (twice in each three months). When the drying period was seven days, as in the case of Dammam and Khobar, samples were collected at the intervals of 0, 1, 2, 4 and 7 days. However, when the drying period was 14 days, as in the case of Qateef, samples were collected at the intervals of 0, 2, 5, 10 and 14 days.

Five core samples were collected from pre-assigned beds; four from each corner and one from the middle. The five core samples were then homogenized in order to constitute one representative sludge sample.

Standard methods were implemented in the sample analysis (APHA, 1998). It is worth mentioning that collected sludge samples were analyzed in triplicates.

## Results and Discussion

In this section, seasonal data obtained on sludge physico-chemical characteristics for samples collected from Dammam, Khobar and Qateef are presented and discussed. Due to similarities in result patterns obtained on individual parameters, only one set of the results are presented graphically and discussed. However, statistical analysis of the data obtained on all physic-chemical parameters together with the seasonal effect on total solids in dried sludge samples are also presented and discussed.

### Water content

Figure 1 shows the percentage of the sludge water content over the drying period for Qateef, Dammam, and Khobar during the first session of the spring season. The initial water contents of the sludge were about 97, 95 and 96% for Qateef, Dammam, and Khobar, respectively. The figure clearly demonstrates the continuous decrease in sludge water content with respect to the drying period. The loss in sludge water content is attributed to two main mechanisms, namely, infiltration and evaporation. At the end of the drying period, the water content of sludge reached values of about 13, 29 and 45% in Qateef, Dammam, and Khobar wastewater treatment plants, respectively. Based on the results, sludge water contents were reduced by about 78, 55, and 50% in Qateef, Dammam, and Khobar, respectively. Since the three cities are close to each other and have similar geography and weather conditions, evaporation rates are expected to be the same. Consequently, the results can be attributed to the longer drying periods adopted at Qateef when compared to those adopted at Dammam and Khobar. Moreover, the figure clearly shows that after four days of drying, a sharp decrease in sludge water content was noticed to take place in the wastewater treatment plants of the three cities. The trend of sludge water content with drying time is attributed to the types of water associated with sludge flocs, namely, unbound and bound waters. Unbound water, which comprises the largest water content, can be separated mechanically. Dewatering devices primarily remove free unbound water, some interstitial water can be removed as well, but it is likely that the major fraction of bound water is vicinal water that cannot be removed mechanically. Bound water, which contributes to the smallest water content, has the sternest physical-chemical bonding to the particles and can only be removed thermally. Based on that, the results obtained after four days of the drying period could be attributed to a combined effect of infiltration and evaporation.

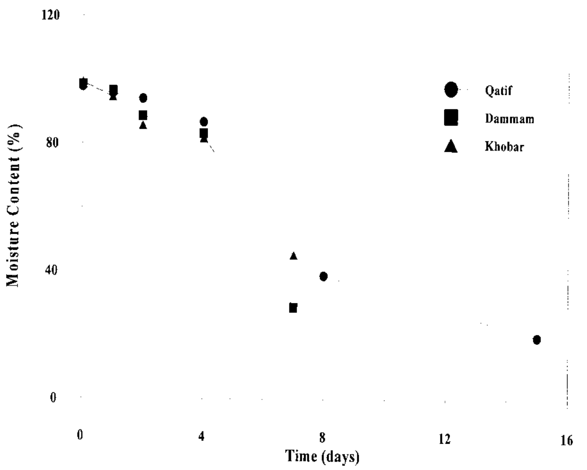


**Fig. 1. Moisture content in sludge with respect to drying time.**

### Total solids content

Regarding concentration of sludge total solids during the spring season, Fig. 2 shows that total solids concentrations were increasing with respect to the drying period in the three cities. The initial values of sludge total solids were found to be 2.2, 1.5 and 0.85% for sludge samples collected from Qateef, Dammam, and Khobar wastewater treatment plants, respectively. The solids concentration in sludge samples collected from the three cities is in agreement with those reported by (Droste, 1997). The trend of sludge total solids is attributed to the same reasons given on water content. At the end of drying periods, total solids concentrations were found to reach values of about 80, 58 and 45%, for sludges collected from Qateef, Dammam, and Khobar, respectively. The values of solid content in the dewatered sludge samples collected from the three cities is much greater than those reported by (Kiely, 1997), which could be attributed to the weather conditions of the Kingdom of Saudi Arabia.

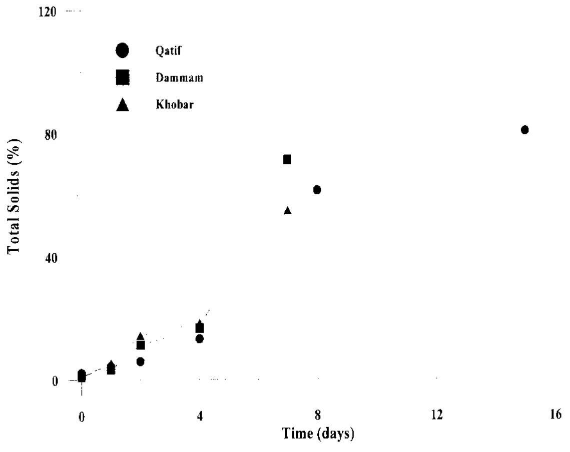


**Fig. 2. Total Solids content in sludge with respect to drying time.**

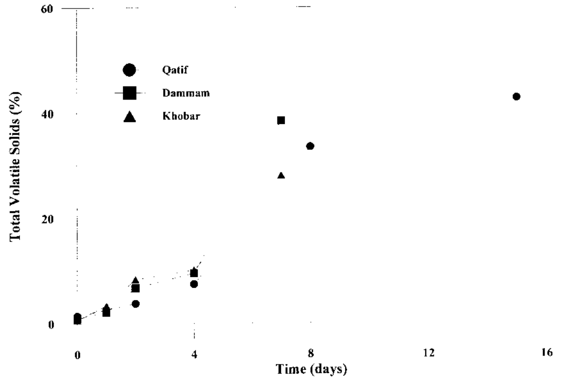


**Fig. 3. Volatile solid content in sludge with respect to drying time.**

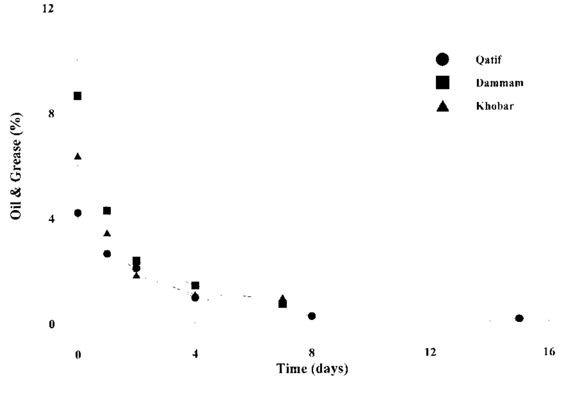


**Fig. 4. Oil and grease content in sludge with respect to drying time.**

## Volatile solids content

The concentration of the total volatile solids in sludge samples collected from Qateef, Dammam and Khobar treatment plants are shown in Fig. 3. In Qateef samples, the total volatile solids increased from 1.4 to 7.4 during the first four days of drying. A relatively sharp increase in the concentration of total volatile solids was noticed between the fourth and the eighth days, which could be attributed to the same reasons given on water content and total solids. Similar trends of increase in the concentration of volatile solids were also noticed in samples collected from Dammam and Khobar wastewater treatment plants. Total volatile solids were found to range between 51 and 65% of the total solids in dried sludge samples collected from the three cities. Moreover, the total volatile solids content, as a% of total solids, was found to decrease over the drying period. In Qateef, the total volatile solids decreased from 62 to 53%, while in Dammam and Khobar, it decreased from 64 to 54% and from 66 to 51%, respectively. This could be attributed to weathering effects and biodegradation activities. The%age of volatile solids in sludge samples collected from the three cities also agrees with that reported by (Kiely, 1997).

## Sludge pH

With respect to sludge pH, the results showed that the variations in sludge pH, for the three cities, were not significant and that the pH was shifting towards neutrality. The reasons for pH fluctuations could be attributed to several reasons such as evaporation and other weathering effects. Such effects will affect the ionic strength of the collected sludge samples, which, in turn, will affect the pH values.

## Oil and grease content

Concentrations of oil and grease in sludge samples collected from Qateef, Dammam, and Khobar are shown in Fig. 4. In general, the figure shows that oil and grease concentrations were decreasing with respect to drying time, which is attributed to infiltration and weathering effects. Moreover, the figure shows that the rate of decrease in oil and grease concentration was high at the start of the drying period and tended to slow down over the course of drying. This is attributed to the fact that at the start of the drying period, the water infiltration rate was relatively high and continued to decrease with respect to time. In sludge samples collected from Qateef, the oil and grease concentration was seen to decrease from 4.2 to 0.21% in the first eight days of drying, and by the end of the drying period, it reached 0.08%. In Dammam, which was found to contain the highest concentration among all, oil and grease decreased from 8.66 to 1.41 during the first four days

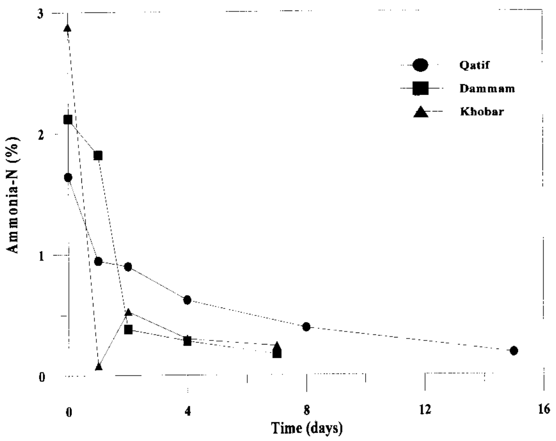


**Fig. 5. Ammonia-nitrogen content in sludge with respect to drying time.**

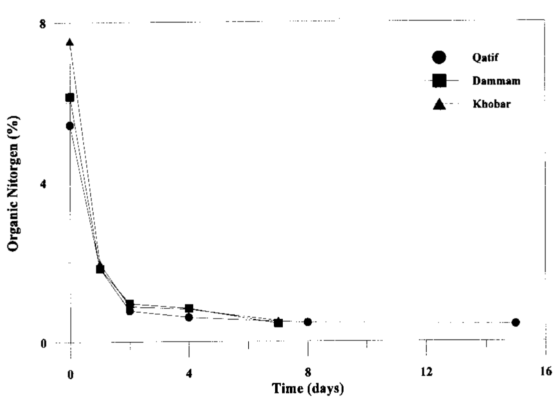


**Fig. 6. Organic nitrogen content in sludge with respect to drying time.**

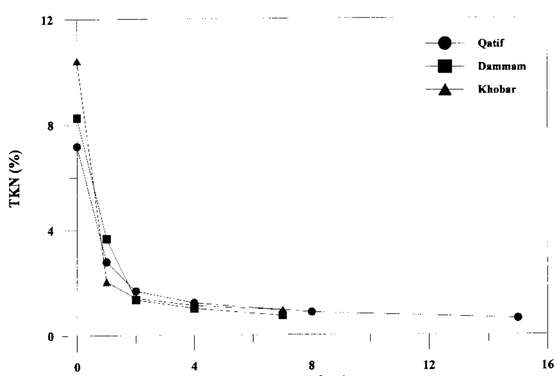


**Fig. 7. TKN content in sludge with respect to drying time.**

of drying, and by the end of the drying period it reached a value of 0.68%. Similarly, Khobar sludge was found to initially contain 6.37% oil and grease, which decreased to 1.06 and 0.92 after four and seven days of drying, respectively. The presence of high concentration of oil and grease in sludge samples collected from Dammam could be attributed to the industrial activities, in the first industrial city, which discharge their wastewater into the municipal sewer line.

## Ammonia-nitrogen content

Figure 5 shows the concentrations of ammonia-nitrogen in sludge samples collected from Qateef, Dammam, and Khobar. The results show that initially the raw sludge had a very high concentration of ammonia-nitrogen ranging from about 1.5% at Dammam to 3.9% at Khobar, based on dry weight. This high concentration may be attributed to the release of ammonia-nitrogen from the death and decay of microorganisms during the thickening process before the sludge is brought to the drying beds. It is clear that as the sludge dries off, the concentration of ammonia-nitrogen decreases rapidly. During the second session, the concentration of ammonia-nitrogen after two days of drying was reduced by about 56% and 48% of the initial values for the cities of Dammam and Khobar, respectively, and by the end of the drying period (seven days), the reduction reached about 70% and 65%, respectively. However, for the city of Qateef, the concentration was reduced by about 47% after two days of drying and continued decreasing until the end of the drying period (15 days) where the final reduction was about 70% of the initial value. The reduction of ammonia-nitrogen concentration is mainly due to water infiltration into the sand layer underneath the sludge layer. Another reason for ammonia-nitrogen decrease could be attributed to the oxidation of $NH_4$-N to $NO_3$ due to the exposure of sludge to air in the drying bed.

## Organic nitrogen and TKN contents

The relationship between the drying period and both of organic nitrogen and TKN in sludge samples collected from the three cities is shown in Figs. 6 and 7, respect-tively. The results on TKN and organic nitrogen clearly demonstrate a consistent trend when compared with other nitrogen compounds. Generally, as sludge dried, the concentrations of TKN and organic nitrogen were found to decrease rapidly in the first two days of the drying period. This is attributed to the high rate of water infiltration in the first days of the drying period. By the end of the drying period, TKN reaches values of 0.965%, 1.25% and 0.658% for sludge samples collected from Qateef, Dammam, and Khobar, respect-ively. These values are lower than those reported by Metcalf and Eddy for fertilizers and stabilized sludge (Metcalf and Eddy, 2003).

### Heavy metals contents

The concentration of heavy metals, namely arsenic, cadmium, chromium, lead and mercury, in sludge samples collected from the cities of Qateef, Dammam, and Khobar are shown in Figs. 8 to 12, respectively. The figures clearly demonstrate that the concentrations of heavy metal in dewatered sludge collected from the three cities are within or even less than those reported for municipal sludge (Metcalf and Eddy, 2003). The figures also show that the concentrations of heavy metals of sludge in drying beds of the three cities were decreasing with respect to the drying period, which could be attributed to water infiltration.

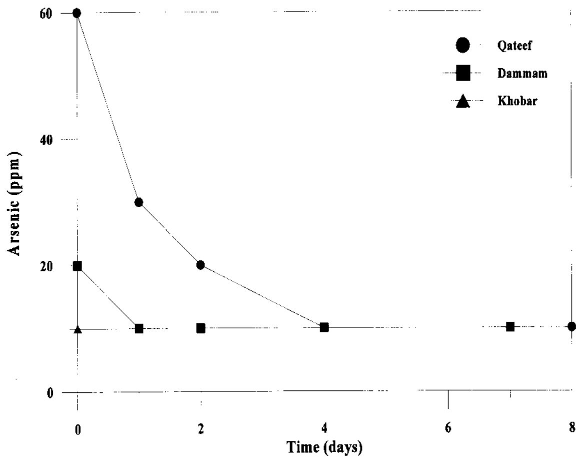


**Fig. 8. Arsenic content in sludge with respect to drying time.**

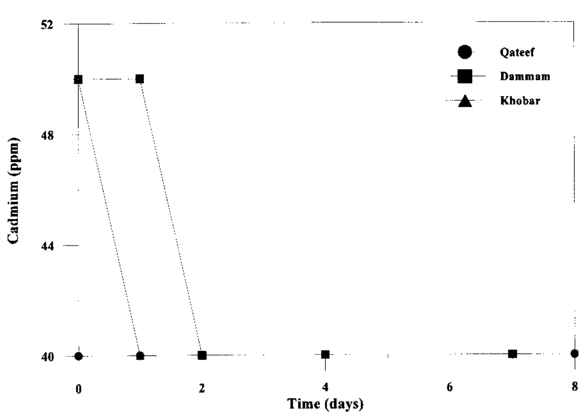


**Fig. 9. Cadmium content in sludge with respect to drying time.**

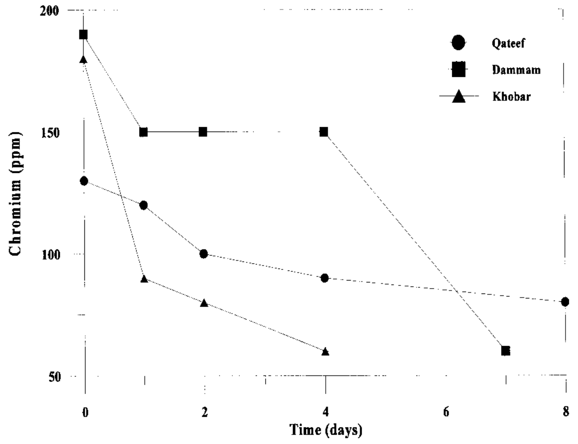


**Fig. 10. Chromium content in sludge with respect to drying time.**

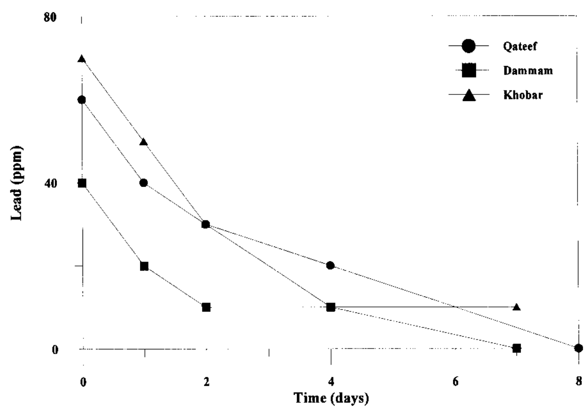


**Fig. 11. lead content in sludge with respect to drying time.**

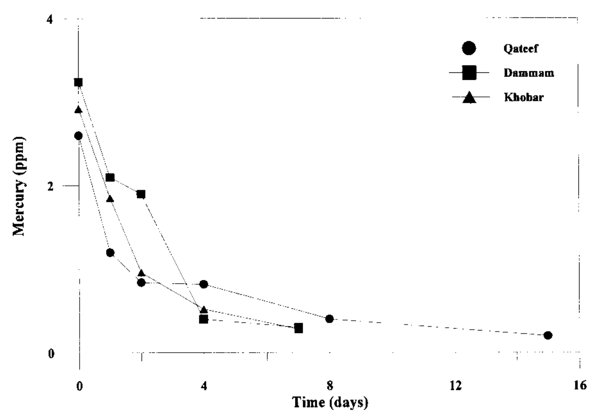


**Fig. 12. Mercury content in sludge with respect to drying time.**

### Statistical analysis of the data

In general, Tables 8, 9 and 10 show statistical analysis of the data obtained on raw and dried sludge samples collected from Qateef, Dammam, and Khobar, respectively. Minimum, maximum, and mean of all quality parameters are presented in the tables. Total dried solids were found to be 74.4, 51.8 and 47.0% for dried sludge samples collected from Qateef, Dammam, and Khobar, respectively. It is

**Table 8. Statistical analysis of data obtained on characteristics of sludge collected from Qateef**

| Parameters | Raw Sludge | | | Dried Sludge | | |
|---|---|---|---|---|---|---|
| | **Min.** | **Max.** | **Mean** | **Min.** | **Max.** | **Mean** |
| Moisture content % | 96 | 97 | 96 | 10 | 20 | 13 |
| Total solids % | 2.2 | 4.2 | 3.4 | 80 | 90 | 87 |
| Total volatile solids % | 1.6 | 2.9 | 2.3 | 43 | 55 | 50 |
| Oil and grease % | 4.2 | 5.4 | 5 | 0.1 | 0.8 | 0.53 |
| pH | 6.8 | 7.1 | 6.9 | 7.0 | 7.1 | 6.9 |
| Total alkalinity (mg/l) | 354 | 436 | 381 | 248 | 324 | 297 |
| Ammonia (mg/l) | 1 | 1.6 | 1.1 | 0.2 | 0.4 | 0.3 |
| Nitrite (mg/l) | 16 | 18 | 16 | 0.8 | 2.5 | 1.7 |
| Nitrate (mg/l) | 148 | 156 | 150 | 22 | 34 | 28 |
| Organic nitrogen % | 5.4 | 6.9 | 6.1 | 0.4 | 4.9 | 3.5 |
| TKN % | 6.8 | 7.9 | 7.3 | 0.6 | 5.3 | 3.7 |
| Arsenic (ppm) | 45 | 60 | 53 | 9 | 10 | 10 |
| Boron (ppm) | 62 | 170 | 136 | 40 | 42 | 41 |
| Cadmium (ppm) | 10 | 185 | 65 | 0 | 78 | 35 |
| Chromium (ppm) | 130 | 162 | 140 | 10 | 107 | 58 |
| Copper (ppm) | 260 | 340 | 303 | 50 | 130 | 90 |
| Iron (ppm) | 1523 | 10880 | 7188 | 1072 | 1600 | 1344 |
| Mercury (ppm) | 0.2 | 14 | 5.3 | 0.05 | 10 | 2.7 |
| Manganese (ppm) | 48 | 150 | 83 | 38 | 60 | 48 |
| Nickle (ppm) | 60 | 150 | 100 | 0 | 270 | 88 |
| Lead (ppm) | 60 | 350 | 160 | 0 | 94 | 39 |
| Zinc (ppm) | 1200 | 1500 | 1378 | 60 | 730 | 392 |

**Table 9. Statistical analysis of data obtained on characteristics of sludge collected from Dammam**

| Parameters | Raw Sludge | | | Dried Sludge | | |
|---|---|---|---|---|---|---|
| | **Min.** | **Max.** | **Mean** | **Min.** | **Max.** | **Mean** |
| Moisture content % | 94 | 99 | 96 | 29 | 51 | 42 |
| Total solids % | 1.5 | 5.9 | 4.5 | 49 | 71 | 58 |
| Total volatile solids % | 0.95 | 4.0 | 2.8 | 29 | 38 | 34 |
| Oil and Grease % | 5.0 | 8.7 | 6.4 | 0.32 | 1.9 | 0.86 |
| pH | 6.8 | 7.1 | 6.9 | 6.8 | 7.1 | 6.9 |
| Total alkanity (mg/l) | 223 | 320 | 294 | 182 | 288 | 254 |
| Ammonia (mg/l) | 1.1 | 2.1 | 1.3 | 0.2 | 0.5 | 0.4 |
| Nitrite (mg/l) | 15.3 | 32.2 | 18.7 | 3 | 6 | 4.3 |
| Nitrate (mg/l) | 132 | 152 | 143 | 19 | 38 | 32 |
| Organic Nitrogen % | 6.1 | 8.4 | 7.1 | 0.45 | 5 | 3.4 |
| TKN % | 8.1 | 9.9 | 8.4 | 0.73 | 5.5 | 3.8 |
| Arsenic (ppm) | 20 | 45 | 31 | 10 | 20 | 12 |
| Boron (ppm) | 68 | 150 | 101 | 0 | 70 | 43 |
| Cadmium (ppm) | 50 | 96 | 69 | 0 | 54 | 34 |
| Chromium (ppm) | 158 | 220 | 187 | 40 | 132 | 76 |
| Copper (ppm) | 456 | 600 | 526 | 80 | 300 | 189 |
| Iron (ppm) | 1250 | 11870 | 7079 | 940 | 5070 | 2764 |
| Mercury (ppm) | 1.8 | 26 | 9.6 | 0.3 | 20 | 6 |
| Manganese (ppm) | 54 | 190 | 97 | 22 | 70 | 37 |
| Nickle (ppm) | 40 | 244 | 124 | 0 | 224 | 78 |
| Lead (ppm) | 40 | 450 | 180 | 0 | 100 | 55 |
| Zinc (ppm) | 1116 | 6080 | 4067 | 60 | 920 | 661 |

**Table 10. Statistical analysis of data obtained on characteristics of sludge collected from Khobar**

| Parameters | Raw Sludge | | | Dried Sludge | | |
|---|---|---|---|---|---|---|
| | Min. | Max. | Mean | Min. | Max. | Mean |
| Moisture Content % | 95 | 99 | 97 | 45 | 49 | 47 |
| Total solids % | 0.85 | 5.5 | 4.0 | 51 | 55.2 | 52.8 |
| Total Volatile Solids % | 0.56 | 3.7 | 2.6 | 27.2 | 34 | 32 |
| Oil and Grease % | 4.4 | 6.5 | 5.5 | 0.3 | 1.0 | 0.62 |
| pH | 6.7 | 7 | 6.8 | 6.7 | 7.1 | 6.9 |
| Total alkanity (mg/l) | 296 | 364 | 332 | 222 | 286 | 251 |
| Ammonia (mg/l) | 1 | 2.9 | 1.4 | 0.2 | 0.5 | 0.37 |
| Nitrite (mg/l) | 15.4 | 36.3 | 20.1 | 3 | 3.7 | 3.4 |
| Nitrate (mg/l) | 112 | 184 | 140 | 26 | 46 | 35 |
| Organic Nitrogen % | 6 | 7.5 | 6.9 | 0.4 | 5.6 | 3 |
| TKN % | 7 | 10.4 | 8.3 | 0.7 | 6.1 | 3.7 |
| Arsenic (mg/l) | 10 | 50 | 24.3 | 8 | 20 | 11.1 |
| Boron (mg/l) | 50 | 100 | 75 | 0 | 70 | 39 |
| Cadmium (mg/l) | 10 | 96 | 52 | 0 | 46 | 28.4 |
| Chromium (mg/l) | 80 | 180 | 144 | 30 | 128 | 73 |
| Copper (mg/l) | 300 | 460 | 385 | 50 | 250 | 186 |
| Iron (mg/l) | 1470 | 7900 | 4817 | 800 | 4550 | 2249 |
| Mercury (mg/l) | 2.8 | 32 | 10.7 | 0.3 | 13 | 3.9 |
| Manganese (mg/l) | 66 | 130 | 86 | 20 | 50 | 35.8 |
| Nickle (mg/l) | 40 | 195 | 106 | 0 | 135 | 51 |
| Lead (mg/l) | 65 | 130 | 93 | 10 | 90 | 47 |
| Zinc (mg/l) | 1000 | 3790 | 2268 | 90 | 1034 | 664 |

**Table 11. Concentration limits on sludge quality and application (EPA, 1993)**

| Pollutant | Ceiling Concentration (mg/Kg) | Cumulative Pollutant Loading Rate (kg/ha) | Monthly Average Concentration (mg/kg) | Annual Pollutant Loading Rate (kg/yr/ha) |
|---|---|---|---|---|
| Arsenic | 75 | 41 | 41 | 2.0 |
| Cadmium | 85 | 39 | 39 | 1.9 |
| Chromium | 3000 | 3000 | 1200 | 150 |
| Copper | 4300 | 1500 | 1500 | 75 |
| Lead | 840 | 300 | 300 | 15 |
| Mercury | 57 | 17 | 17 | 0.85 |
| Molybdenum | 75 | - | - | - |
| Nickel | 420 | 420 | 420 | 21 |
| Selenium | 100 | 100 | 36 | 5.0 |
| Zinc | 7500 | 2800 | 2800 | 140 |

clear that samples collected from Qateef wastewater treatment plant contained the highest percentage of dried solids among the other cities. This could be attributed to the longer drying period (15 days) adopted at Qateef when compared to Dammam and Khobar (7 days). Another reason for the higher percentage could be the better physical condition of the drying beds at Qateef plant compared to those at Dammam and Khobar plants. In all cases, the percentage of dried solids was higher than those reported in literature (Kiely, 1997), which could be attributed to weather conditions of the Kingdom of Saudi Arabia. Volatile solids as percentage of total solids ranged between about 30 to 45%, with the highest and lowest values belonged to Qateef and Khobar, respectively. (Metcalf and Eddy, 2003) reported that activated sludge without drying contains 59 to 88% of volatile solids. Due to drying, especially in the case of Saudi Arabia's severe weather conditions, portions of the volatile solids may have been lost. However, the results on volatile solids in sludge samples are in agreement with those reported by (Kiely, 1997). Oil and grease content was found to be between 0.64 and 1.27%, with Dammam and Qateef containing the highest and lowest values, respectively. The reason for Dammam sludge contain-ing the highest oil and grease content could be attri-buted to the industrial activities in the city, where the industrial wastewater produced at Dammam first Industrial city is being discharged to the municipal sewer line. Samples of dried sludge samples were found to have pH values close to neutral (6.91 to 6.95), which is in agreement with values reported by (Metcalf and Eddy, 2003). Total nitrogen (TKN) was found to range between 3.38 and 3.83% of total solids, which also agrees with those reported by Metcalf and Eddy for activated sludge (2.4 to 5.0%) (Metcalf and Eddy, 2003).

With respect to heavy metal concentrations in dried sludge samples collected from the three cities, the tables show that arsenic concentration ranges between 9.86 and 12.28 ppm (mg/kg) of dried weight. (Metcalf and Eddy, 2003) reported that arsenic content in wastewater sludge ranges between 1.1 and 230 mg/kg with a median value of 10 mg/kg, which demonstrates that arsenic content in dried sludge samples collected from the three cities is within the range of typical wastewater sludge. Similarly, cadmium, chromium, copper, iron, manganese, nickel, lead and zinc were found to be within the range reported by Metcalf and Eddy for typical wastewater sludge (Metcalf and Eddy, 2003). Mercury content in dried sludge samples collected from the three cities was found to range between 2.39 ppm (in Qateef) and 8.43 ppm (in Khobar), which is within the range reported by (Metcalf and Eddy, 2003). However, Khobar sludge samples contain an average mercury concentration (8.43 ppm) that is higher than the median value (6 ppm). In all cases, and as depicted in Table 11, heavy metal concentrations in dried sludge samples collected from the three cities are below the ceiling and monthly average concentrations set by U.S. EPA for reuse of sludge in agricultural activities (USEPA, 1993). However, Table 12 shows that cadmium and mercury (in Dammam and Khobar samples) are higher than those set by the Canadian regulations on heavy metals in sludge to be used for land applications.

**Seasonal effect on solid content**

Seasonal effect on sludge solid content was investigated by making a comparison between results obtained over the course of the investigation on total solids content in dewatered sludge samples that were collected from the cities of Qateef, Dammam, and Khobar. Ambient minimum, maximum, and mean temperatures obtained at Dhahran station during all seasons are shown in Table 13 (PME, 2000). The table clearly shows that the mean ambient temperature recorded during spring, summer, fall and winter were 31.8, 36.8, 32 and 22.8, respectively.

Table 14 shows the seasonal effect on the contents of total solids in dried sludge samples collected from Qateef, Dammam, and Khobar. With respect to total solids in dried sludge, and beside the effect of the physical conditions of the drying beds, the table clearly demonstrates the seasonal effect on the contents of total solids. As an example, Qateef sludge was found to contain the lowest percentage of total solids during the winter season, while the highest

**Table 12. Canadian regulations on heavy metals in sewage sludge for land application (Droste, 1997)**

| Pollutant | Maximum Acceptable Concentration (mg/kg) | Cumulative Acceptable Loading (kg/ha) |
|---|---|---|
| Arsenic | 75 | 15 |
| Cadmium | 20 | 4 |
| Chromium | - | - |
| Cobalt | 150 | 30 |
| Copper | - | - |
| Lead | 500 | 100 |
| Mercury | 5 | 1 |
| Molybdenum | 20 | 4 |
| Nickel | 180 | 36 |
| Selenium | 14 | 2.8 |
| Zinc | 1850 | 370 |

**Table 13. Ambient minimum, maximum, and mean temperatures for dhahran station during the investigation**

| Season | Session | Ambient Temperature (°C) | | | Season's Mean Temperature (°C) |
|---|---|---|---|---|---|
| | | Minimum | Maximum | Mean | |
| Spring | 1 | 21.5 | 36.3 | 28.75 | 31.82 |
| | 2 | 27.7 | 42.2 | 34.9 | |
| Summer | 1 | 28.9 | 45.1 | 37 | 36.75 |
| | 2 | 29.5 | 43.5 | 36.5 | |
| Fall | 1 | 28 | 40 | 32 | 32 |
| | 2 | -- | -- | -- | |
| Winter | 1 | 17 | 24 | 21.6 | 22.8 |
| | 2 | 18 | 27 | 24 | |

**Table 14. Seasonal effect on total solids and total coliform in dried sludge**

| City | Parameters | Session | Season | | | |
|---|---|---|---|---|---|---|
| | | | Spring | Summer | Fall | Winter |
| Qateef | Total Solids % | 1 | 80.42 | 85.7 | 89.92 | 41.7 |
| | | 2 | 87.4 | 88.2 | -- | 47.4 |
| Dammam | Total Solids % | 1 | 71.2 | 55.3 | 49.1 | 27.6 |
| | | 2 | 57.7 | 59.4 | -- | 42.2 |
| Khobar | Total Solids % | 1 | 54.8 | 50.9 | 51.1 | 34.6 |
| | | 2 | 51.6 | 55.2 | -- | 31 |

percentage was obtained during summer and fall seasons. As have been shown before, the increase in ambient temperatures will result in increasing the rate of evaporation, which in turn will increase the content of total solids in sludge samples.

## Conclusions and Recommendations

Sludge samples were collected from the drying beds located at wastewater treatment plants of the cities of Qateef, Dammam, and Khobar in order to determine the physical and chemical characteristics of the sludge. The investigation showed that total solids concentration of the dewatered sludge samples collected from the three cities was much higher than those reported in the literature, which was attributed to weather conditions of the Kingdom of Saudi Arabia. Variations in sludge pH for samples collected from the three cities was found insignificant and shifting towards neutrality. With respect to oil and grease concentration in sludge, Dammam sludge was found to contain the highest concentration among other cities, which was attributed to the industrial activities taking place in Dammam. Regarding levels of nitrogen content, sludge samples collected from the three cities were found deficient in nitrogen when compared to those reported in the literature for stabilized sludge and fertilizers. Concentrations of heavy metals in dried sludge samples were found to be in the range of those reported in the literature for municipal sludge.

Based on the results of the investigation, it is strongly recommended that the improvement of the physical conditions of the drying beds, at Dammam and Khobar treatment plants, is to be taken into consideration. The presence of high oil contents in wastewater delivered to Dammam treatment plant is to be investigated and proper measures must be implemented. The concerned authority must be well equipped to facilitate the processes of characterization of sludges produced at their treatment plants routinely. It is highly recommended that the concerned authorities must establish, if not yet established, and re-enforce regulations and standards governing sludge management.

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# الخواص الفيزيائية والكيميائية للحمأة البلدية المنتجة في ثلاث مدن رئيسة من المنطقة الشرقية بالمملكة العربية السعودية

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(قدِّم للنشر في ١٦/٠٧/٢٠٠٦م؛ وقبل للنشر في ٠٥/٠٢/٢٠٠٧م)

**ملخص البحث**. بسبب الرمي غير المقيد للحمأة البلدية المجففة واستعمالها من قبل بعض المزارعين كمحسن للتربة أو كسماد، فقد تم القيام ببحث مكثف بغرض إيجاد الخواص الفيزيائية والكيميائية للحمأة المنتجة في ثلاث مدن من المنطقة الشرقية وهي القطيف، والدمام، والخبر وذلك بين إبريل عام ٢٠٠٠م وفبراير عام ٢٠٠١م. تم جمع عينات الحمأة من أحواض التجفيف الرملية مرتين خلال كل فصل ولمدة عام كامل، وتحليلها لمعرفة تركيز بعض العناصر المهمة مثل المواد الصلبة الكلية، والزيوت، ومركبات النيتروجين، والمعادن الثقيلة. وقد بينت النتائج أن تركيز المواد الصلبة بلغ ٨٧٪ وهي نسبة تعتبر عالية قياسا بالقيم المنشورة في الأدبيات، أما تركيز المواد الصلبة المتطايرة فكان ضمن القيم المنشورة دوليًّا. كما بينت النتائج بأن العينات المجموعة من مدينة الدمام احتوت على زيوت بلغ تركيزها ٨,٦٦٪ وهي الأعلى بين المدن الأخرى، وقد أرجعت هذه النتائج إلى النشاطات الصناعية في مدينة الدمام. أما بخصوص قيمة الحمأة كسماد، فقد وُجد أن عينات الحمأة التي تم جمعها من المدن الثلاث احتوت على تركيز منخفض من مركبات النيتروجين، حيث بلغ تركيز مركبات النيتروجين الكلية بين ٠,٦٦ و١,٢٥٪. وبخصوص تركيز المعادن الثقيلة فقد كانت ضمن القيم المنشورة حيث كانت تراكيز كل من الزرنيخ، والكادميوم، والكروم، والرصاص، والزئبق ١٠، و٤٠، و٦٣، و٣٣، و٠.٣ جزء بالمليون على التوالي.