Journal of Environmental Management (2002) **64**, 171–177
doi:10.1006/jema.2001.0520, available online at http://www.idealibrary.com on IDEAL®

Land application of phosphorus-laden sludge: a feasibility analysis

T. Viraraghavan*and M. Ionescu

Environmental Systems Engineering, University of Regina, Regina, Saskatchewan, Canada S4S 0A2

Received 17 November 1999; accepted 3 October 2001

An investigation was conducted to examine aerobic digestion of the phosphorus-laden sludge produced at the Regina Wastewater Treatment Plant and feasibility of land use of this sludge combined with the dewatered anaerobically digested primary sludge from this plant. Experimental studies showed that aerobic digestion can be employed for the stabilization of the chemical sludge. Results of the feasibility analysis showed that mixing the two digested sludges met the heavy metal criteria set by various guidelines for agricultural use, presented the advantage of an increased concentration of nutrients and a decreased concentration of heavy metals, and a longer useful life of the agricultural site compared to using dewatered anaerobically digested primary sludge alone. Land application of the mixed digested sludges would be a more appropriate method of sludge disposal compared to the present practice of landfilling the dewatered sludge and lagooning the chemical sludge.

Keywords: Aerobic digestion, phosphorus-laden sludge, land application, sludge management.

Introduction

Regina Wastewater Treatment Plant treats an average flow of 75 000 m^3/day and it consists of primary treatment (grit removal and sedimentation), secondary treatment (biological treatment-five aerated lagoons) and tertiary treatment (chemical phosphorus removal). Primary sludge is stabilized using two-stage high rate anaerobic digestion; the supernatant is returned to the front end of the primary plant. The digested sludge (10–14% solids) is dewatered in belt filter presses. The dewatered sludge (30–40% solids) is transported to the city landfill. The lagoon sludge is removed when necessary.

The phosphorus-laden chemical sludge is stored in a lagoon cell, and subsequently removed and stockpiled on site. Besides the primary sludge, the plant produces a considerable quantity of biological-chemical sludge resulting from the phosphorus removal stage, which has not been included in any study so far. Earlier studies (Viraraghavan and Rana, 1987; Spankie *et al*., 1992) examined only the land disposal of dewatered anaerobically digested primary sludge. The present practice of disposing of the sludge in a lagoon cell and then stockpiling it on site is not an acceptable long-term solution. An alternative is to try to include this sludge in a land application scheme since the phosphorus held in this sludge can make it valuable as a fertilizer. A comprehensive scheme of sludge management with special reference to land application can be developed considering the primary and the biological-chemical sludge either separately or in combination. In order to evaluate these possibilities, the composition and the treatment requirements of the chemical-biological sludge have to be studied. As a result of the sludge stabilization process, a significant quantity of supernatant may result. Its quality has to be analyzed in order to assess its suitability for recycling through the front end of the plant.

* Corresponding author. Email: t.viraraghavan@uregina.ca

Objectives of the study

The primary objective of this study was to examine the feasibility of land application of the chemical sludge produced at the Regina Wastewater Treatment Plant and the sludge treatment needed, in conjunction with any proposal for the agricultural use of anaerobically digested primary sludge produced at the plant. The stabilization method contemplated for the chemical sludge was aerobic digestion.

The secondary objective of this study was to assess the quality of supernatant resulting from sludge stabilization and its suitability for recycling through the plant.

Study methodology

The study methodology comprised of the following tasks:

(1) Review of the ten-year plant data (1984–1994) to obtain characteristics of the dewatered anaerobically digested sludge with respect to solids, N, P and heavy metals;
(2) Characterization of the chemical sludge at the treatment plant with respect to solids, and nutrients (nitrogen and phosphorus);
(3) Laboratory batch aerobic digestion studies to obtain the characteristics (solids, N and P, heavy metals, pH) of the digested sludge;
(4) Analysis of data to obtain the characteristics of the combined sludge (dewatered anaerobically digested sludge plus aerobically digested sludge) and to examine the suitability of such a sludge for land application; and
(5) Determination of the digested chemical sludge supernatant characteristics to examine its suitability for recycling.

Results and discussion

Based on the data provided by the City of Regina, characteristics of dewatered digested primary sludge are shown in Table 1. For an evaluation of digested primary sludge, monthly production for the year 1992 was chosen as reference, being the most recent continuous year-round period with no major perturbations in digester operation. The average production of digested primary sludge solids was 124 000 kg/month.

Characteristics of raw and aerobically digested chemical sludge

Table 2 presents the characteristics of raw and aerobically digested chemical sludge based on an average of duplicate tests. Volatile suspended solids reduction by aerobic digestion was found to be 21·5%. The digested chemical sludge had only copper and zinc concentrations slightly higher than the soil background values in the area. Cadmium was not detected by atomic absorption spectrometry; however a minimum value of 1·2 mg/kg was adopted using the value for fresh chemical sludge. The fertilizer value of the aerobically digested sludge was higher than that of the primary digested sludge (dewatered). The decrease in TKN during aerobic digestion was probably due to nitrification. Digested chemical sludge production was calculated using an average monthly flow of 45·4 ML and the results obtained from batch aerobic digestion equipments. The chemical sludge solids was 99 000 kg/month.

Characteristics of combined digested primary-chemical sludges

The characteristics of the mixed sludge were derived using monthly values for sludge production and material balance. The characteristics of the mixed sludge along with heavy metal guideline value for comparison are presented in Table 3. It may be observed from Table 3 that the addition of aerobically digested chemical sludge to the anaerobically digested and dewatered primary sludge resulted in an increase in nutrient content and a decrease in heavy metal content in the mixed sludge. The mixed sludge meets the heavy metal limits set by various guidelines.

Combined sludge application rates

Application rates can be obtained in several ways based on plant nutrient and heavy metal content of soil and sludge. For a preliminary estimate the conditions stipulated in Saskatchewan guidelines (Saskatchewan Environment, 1987) and the general methodology from USEPA design manual (USEPA, 1983) were considered. Based on available data, approximately 25% of the total nitrogen in sludge was in the ammonium form and that nitrates constituted 0·1% on a dry basis similar to the data from Ontario (OMAF/OME, 1992). Determination of application rates applying the

Table 1. Characteristics of dewatered digested primary sludge

Value	% as dry solids		mg/kg as dry solids				
	TKN	Total P	Cd	Cr	Cu	Ni	Zn
Min	0·02	0·05	0·5	5·2	180	12	260
Max	3·80	2·20	10	360	1600	130	2100
Mean	1·69	1·04	4·6	115	909	35	741
Median	1·80	1·00	4·3	100	880	32	740
Standard deviation	0·67	0·42	1·5	50	233	14	196

Table 2. Characteristics of chemical sludge

Parameter	Value	
	Raw chemical sludge	Aerobically digested chemical sludge*
pH	7·50	6.8–7.2
TKN (% on a dry basis)	4·39	2·27
Total P (% on a dry basis)	3·66	3·50
Total solids (%)	0·35	0·30
Total suspended solids (mg/L)	2510	1726
Volatile suspended solids (mg/L)	1603	1003
Supernatant BOD (mg/L)	82	42
Supernatant COD (mg/L)	844	374
Supernatant SS (mg/L)	–	460
Supernatant P (mg/L)	–	5·2
Heavy Metals (mg/kg dry basis)		
Cd		ND†
Cr		39·8
Cu		121·2
Ni		28·4
Zn		78·8

* Based on averaged results from two laboratory aerobic digestion studies (DT=15d).
† Not detected.

Table 3. Comparison of sludge characteristics with guideline requirements

Constituent sludge	(% as dry solids)		(mg/kg as dry solids)				
	TKN	Total P	Cd	Cr	Cu	Ni	Zn
Mixed digested-primary chemical	2·01	2·11	2·9	73·3	543·1	30·4	446·5
Digested primary sludge	1·8	1	4·6	100	880	32	740
Digested chemical sludge	2·27	3·5	<1·2	40	121	28	>9
Guidelines:							
Canada			20	–	–	180	1850
Ontario			34	2800	1700	420	4200
USA ('503')			39	3000	1500	420	2800

procedure from Saskatchewan guidelines yielded a figure of 9 tonnes/ha (based on dry solids) for the recommended rate. Details are provided in the Appendix.

The USEPA design manual (USEPA, 1983) outlines three basic approaches used in determining the annual application rate: (1) annual rate applies N equivalent to crop need and Cd less than regulatory limits; (2) annual rate applies Cd equal to the regulatory limit and N less than the crop N need; and (3) annual rate applies P equal to the crop need, N less than crop need and Cd less than regulatory limit.

Considering the first approach and neglecting the effects of nitrogen mineralization in subsequent years, an available nitrogen (N_p) of 7·23 kg/tonne, and a sludge application rate (S_N) of 13·1 tonnes/ha were obtained. It was found that cadmium did not limit the rate of application using USEPA, Saskatchewan, and Ontario total metal limits, copper was found limiting in all three cases. According to USEPA limits, the maximum quantity of sludge applied to one site could be 975 tonnes/ha, while with Saskatchewan and Ontario values, maximum quantity could be 209 tonnes/ha and 261 tonnes/ha respectively. The useful life of the site would be 23·2 years based on Saskatchewan guidelines. Details are provided in the Appendix.

In conclusion, the results obtained in an evaluation of application rates indicate that:

(1) Canadian guidelines are more conservative;
(2) Copper limits the maximum quantity of sludge that can be applied on the same site; and
(3) The fact that copper concentration is diminished in the combined sludge will lengthen the useful life of the site in comparison to application of primary sludge alone.

Characteristics of supernatant

The characteristics of the digested sludge supernatant are given in Table 4 and these were found to be similar to those of weak to medium municipal wastewaters, except for BOD concentration which was very low, and total suspended solids which was typical for a strong wastewater. Following the digestion process supernatant BOD and COD removals obtained varied between 26–59% and 38–77% respectively. Although the total P results were inconsistent, the small phosphorus concentrations in supernatant, together with the average sludge phosphorus content that underwent little change, did not suggest that phosphorus was released from sludge.

The first and fourth columns in Table 4 show the comparison between the case when the chemical sludge supernatant is not added and the case when it is added to the influent. The last column gives quantitative effect of changes in influent quality when the chemical sludge supernatant is added. As shown, even for the most unfavorable case the influent quality undergoes little change, thus recycling through the plant creates no additional problems.

Conclusions

Aerobic digestion in the mesophilic range can be employed to stabilize the chemical sludge produced at the Regina Wastewater Treatment Plant. Sludge volatile suspended solids reduction during aerobic digestion was 21·5%, based on the assumption that fixed solids did not change during digestion. The values were based on reduction in ratios rather than on mass balance. The digested chemical sludge was yellow green in color, had no odour, and had pH values between 6·9 and 7·4. The characteristics of the digested chemical sludge and of the digested and mixed primary-chemical showed that in either case they were suitable for agricultural use, the combined digested sludge being favored for economic reasons. The heavy metal content of the chemical sludge alone was much lower than the limits set by Canadian and various other guidelines. The concentration of potentially hazardous elements Cd, Cr, Cu, Ni and Zn, was much lower than in Ontario sludges, approaching background uncontaminated soil values. Average dry basis concentrations of 40 mg/kg chromium, 121 mg/kg copper, 28 mg/kg nickel, and 79 mg/kg zinc were measured in digested chemical sludge.

In a similar manner an analysis of the combined primary-chemical sludge showed that the mixed sludge met all guidelines/requirements and had lower heavy metal concentrations than Ontario sludges. Average dry basis concentrations of 2·9 mg/kg cadmium, 73·3 mg/kg chromium, 543·1 mg/kg copper, 30·4 mg/kg nickel and 446·5 mg/kg zinc were estimated. The fertilizer value of the digested chemical sludge was found to be higher than that of the digested primary sludge with dry basis values of 2·27% TKN and 3·5% total P as compared with 1·8% TKN and 1·00% total P for the primary sludge. The mixed primary-chemical

Table 4. Supernatant quality

Parameter	Raw wastewater	Digested chemical sludge supernatant	Digested primary sludge supernatant	Influent with chemical sludge supernatant	Influent quality change (%)
Total flow/month (ML)	2220·7	45·4	9·6	2266·1	2
TSS (mg/L)	232	460	2500	237	2
BOD (mg/L)	190	42	263	187	−1·6
COD (mg/L)	440	374	1086	439	−0·3
Total P (mg/L)	5·8	5·2	37	5·8	−0·2

sludge was estimated to contain 2·01% TKN and 2·11 % total P on a dry basis.

Annual application rates of approximately 9 tonnes/ha (using Saskatchewan draft guidelines) and 13·1 tonnes/ha (using USEPA design manual) were determined. Copper was found to be the limiting element in cumulative application of sludge for all cases examined. The lowest acceptable load was 209 tonnes/ha (USEPA design manual). The large difference reflects the more conservative limits imposed in Canadian guidelines. The supernatant BOD and COD average reductions were 46% and 56% respectively. The supernatant quality was found suitable for recycling through the front end of the plant. Mixing the two sludges would have these advantages over using the primary dewatered sludge alone: (1) higher fertilizer value; (2) lower heavy metal concentrations; (3) longer useful life of the site; and (4) a more acceptable method of disposing sludge from a technical and environmental point of view, than the present practice.

Acknowledgements

The authors would like to thank the staff at the Regina Wastewater Treatment Plant for providing the plant data and help in obtaining chemical sludge samples for digestion studies.

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Appendix: Combined sludge application rates

Application rates can be obtained in several ways based on plant nutrient and heavy metal content of soil and sludge. For a preliminary estimate the conditions stipulated in Saskatchewan draft guidelines (Saskatchewan Environment, 1987) and the general methodology from USEPA design manual (USEPA, 1983) were considered; 25% of the total nitrogen in sludge is in the ammonium form and that nitrates constitute 0·1% on a dry basis.

Determination of application rates applying the procedure from Saskatchewan guidelines is as follows:

Calculate maximum application rate (MAR) from crop nitrogen requirement assuming incorporated sludge and the plant nutrient removals for wheat:

$$\mathrm{MAR(kg/ha)} = \frac{\text{N requirement of crop (kg/ha)}}{0{\cdot}25\ \mathrm{TKN}\ (\%) + 0{\cdot}50\ \mathrm{NH_3} - \mathrm{N}\ (\%)} \qquad (1)$$

$$\mathrm{MAR} = \frac{95{\cdot}2 \times 100}{(0{\cdot}25 \times 2{\cdot}01) + (0{\cdot}5 \times 0{\cdot}5)} = 12\,651\ \mathrm{kg/ha}$$

The guidelines limit maximum loading rates to 180 kg/ha for TKN and 60 kg/ha for ammonia and nitrate nitrogen. Check if these limits are exceeded using Eq. 2 for the case when ammonia plus nitrate nitrogen is more than one third of the TKN value and Eq. 3 for the opposite case.

$$\mathrm{MAR\ (kg/ha)} = \frac{60 \times 100}{\mathrm{NH_3} - \mathrm{N}\ (\%) + \mathrm{NO_3} - \mathrm{N}\ (\%)} \qquad (2)$$

$$\mathrm{MAR\ (kg/ha)} = \frac{180 \times 100}{\mathrm{TKN}\ (\%)} \qquad (3)$$

$$\mathrm{MAR\ (kg/ha)} = \frac{180 \times 100}{2{\cdot}01} = 8955\ \mathrm{kg/ha}$$

Select the lesser value obtained from Eq. 1, 2 or 3 and calculate the loading rates of heavy metals:

$$\text{loading rate(kg/ha)} = \frac{\text{MAR} \times \text{metal concentration in sludge (mg/kg)}}{1 \times 10^6} \qquad (4)$$

Verify if any of these loading rates exceed the maximum annual loading rates

$$\text{Cd loading} = \frac{8955 \times 2{\cdot}9}{10^6} = 0{\cdot}026\ \mathrm{kg/ha} < 0{\cdot}13\ \mathrm{kg/ha}$$

in a similar manner:

$$\text{Cr loading} = 0{\cdot}099\ \text{kg/ha} < 11{\cdot}1\ \text{kg/ha}$$

$$\text{Cu loading} = 0{\cdot}119\ \text{kg/ha} < 13{\cdot}3\ \text{kg/ha}$$

$$\text{Ni loading} = 0{\cdot}03\ \text{kg/ha} < 3{\cdot}3\ \text{kg/ha}$$

$$\text{Zn loading} = 0{\cdot}298\ \text{kg/ha} < 33{\cdot}3\ \text{kg/ha}$$

$$\text{Cadmium: RAR} = \frac{0{\cdot}13 \times 10^6}{2{\cdot}9} = 44\,828\ \text{kg/ha}$$

in a similar manner:

$$\text{chromium: RAR} = 151\,432\ \text{kg/ha}$$

$$\text{copper: RAR} = 24\,489\ \text{kg/ha}$$

$$\text{nickel: RAR} = 108\,552\ \text{kg/ha}$$

$$\text{zinc: RAR} = 74\,850\ \text{kg/ha}$$

the final RAR=8955 kg/ha being the lesser value from Eqs. 1, 3, and 5.

Calculate recommended sludge application rate (RAR):

$$\text{RAR(kg/ha)} = \frac{\text{maximum annual loading rate (kg/ha)} \times 10^6}{\text{metal concentration in sludge (mg/kg)}} \quad (5)$$

the final recommended sludge application rate will be the lesser value resulting from Eqs. 1, 2, 3, and 5. A recommended application rate of 9 tonnes/ha was obtained.

The USEPA design manual (USEPA, 1983) outlines three basic approaches used in determining the annual application rate: (1) annual rate applies N equivalent to crop need and Cd less than regulatory limits; (2) annual rate applies Cd equal to regulatory limit and N less than crop N need; and (3) annual rate applies P equal to crop need, N less than crop need and Cd less than regulatory limit. Considering the first approach and neglecting the effects of nitrogen mineralization in subsequent years, the methodology consists of the following steps (all units are given on a dry basis):

calculate available nitrogen using Eq. 6

$$N_p = S[NO_3 - N + K_v(NH_3 - N) + F(N_0 - N)](10) \quad (6)$$

where:

N_p = plant available nitrogen, kg/ha

S = sludge application rate, tones/ha

NO_3 = nitrates content of sludge, %

K_v = volatilization factor, 0·5 for surface applied sludge

NH_3 = ammonia content of sludge, %

F = mineralization factor for the organic carbon in the sludge

N_0 = organic nitrogen content of the sludge, %

$N_p = (1)[0{\cdot}1 + (0{\cdot}5)(0{\cdot}5) + (0{\cdot}25)(1{\cdot}51)](10) = 7{\cdot}23$ kg/tonne

the sludge application rate required to deliver the nitrogen to the crop:

$$S_N = \frac{C_N}{N_P} \quad (7)$$

where:

S_N = sludge application rate based on nitrogen requirements, tonnes/ha

C_N = plant nitrogen requirement, kg/ha

N_p = available nitrogen as determined using Eq. 6, kg/tonne

calculate annual sludge application rates using cadmium limitation:

$$S_{cd} = \frac{C_{cd}}{N_{cd}}(1000) \quad (8)$$

where:

S_{cd} = sludge application rate based on cadmium limitation, tonnes/ha

C_{cd} = maximum annual loading rate, 0·5 kg/ha

N_{cd} = cadmium concentration in sludge, mg/kg

$$S_{cd} = \frac{0{\cdot}5}{2{\cdot}9}(1000) = 172{\cdot}4\ \text{tonnes/ha}$$

it is evident that cadmium does not limit the annual application rate.

calculate the total cumulative amount of sludge that can be applied for the life of the site:

$$S_m = \frac{L_m}{C_m}(1000) \quad (9)$$

where:

S_m = sludge total loading based on heavy metal limitation, tonnes/ha

L_m = total heavy metal limit, kg/ha

C_m = concentration of heavy metal in sludge, mg/kg

(a) according to USEPA limits

Metal	Total metal limit kg/ha	Metal content of sludge plus soil mg/kg	Calculation	Total amount of sludge allowed tonnes/ha
Cd	20	2·9+1=3·9	(20/3·9)(1000)=	5128
Cu	560	543·1+31·5=574·6	(560/574·6)(1000)=	975
Ni	560	30·4+36·5=66·9	(560/66·9)(1000)=	8371
Zn	1120	446·5+115=561·5	(1120/561·5)(1000)=	1995

(b) according to Saskatchewan limits

Metal	Total metal limit kg/ha	Metal content of sludge plus soil mg/kg	Calculation	Total amount of sludge allowed tonnes/ha
Cd	1·2	3.9	(1·2/3·9)(1000)=	308
Cr	100	57·5+73·3=130·8	(100/130·8)(1000)=	765
Cu	120	574·6	(120/574·6)(1000)=	209
Ni	30	66·9	(30/66·9)(1000)=	448
Zn	300	561·5	(300/561·5)(1000)=	534

(c) according to Ontario limits

Metal	Total metal limit kg/ha	Metal content of sludge plus soil mg/kg	Calculation	Total amount of sludge allowed tonnes/ha
Cd	1·6	3·9	(1·6/3·9)(1000)=	410
Cr	210	130·8	(210/130·8)(1000)=	1605
Cu	150	574·6	(150/574·6)(1000)=	261
Ni	32	66·9	(32/66·9)(1000)=	478
Zn	330	561·5	(330/561·5)(1000)=	588