Optimizing Color Removal for D/DBP Rule Compliance

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For compliance with the Disinfectant/Disinfection By-Product (D/DBP) Rule, utilities are implementing modified conventional processes, such as enhanced coagulation and softening, to achieve higher TOC removals. However, implementing enhanced coagulation or enhanced softening can be difficult in terms of process control. Many utilities do not have the capability of measuring TOC on-site and must send out samples to be analyzed by contract laboratories, which could cause monitoring to become quite expensive, and which would mean that data would not be immediately available for process control.

In contrast, color monitoring is common for many small utilities. The purpose of the study discussed in this article was to demonstrate that color can be effectively used as an indicator of precursor control and can accurately predict seasonal variations in TOC that could pose treatment difficulties.

The color of surface waters and surficial aquifer groundwaters in Florida has been noted to change seasonally. The first phase of the study included seasonal data collected from both surface waters and surficial aquifer groundwaters sampled in east coastal Florida. Figure 1 illustrates that color and TOC levels correlate quite well in data collected over a one-year period from the surficial aquifer, a correlation that can be attributed to the increased leaching of organic debris from top soils and the underlying aquifer lithology during wet seasons. This high variability in color, and subsequently TOC, can pose treatment difficulties, especially for precursor control.

The second phase of the study demonstrated that the use of enhanced softening at high pH ranges could effectively remove TOC by monitoring color removal. Therefore, based on the color and TOC correlation established for the surficial aquifer illustrated in Figure 1, color was used as an indicator of TOC removal in studying process optimization for compliance with the D/DBP Rule. The data was collected with both bench-scale and full-scale studies.

In addition to enhanced softening alone, the study considered the use of metal salt coagulants and polymers with enhanced softening to achieve higher color and TOC removals. Alum, ferric sulfate, and ferric chloride were used with anionic, cationic, and nonionic polymers.

The raw water used in the bench-scale study was a composite raw water collected from the surficial aquifer in Port St. Lucie, Florida. The raw water had an average total hardness of 292 mg/L as $CaCO_3$, a calcium hardness of 273 mg/L as $CaCO_3$, an alkalinity of 257 mg/L as $CaCO_3$, color of 171 color units, and an average TOC of 12 mg/L.

The full-scale data was collected at the city of Hallandale, FL lime softening plant.

Study Objectives

1. To evaluate the effectiveness of the use of color as an indicator of TOC removal.
2. To assess the effectiveness of enhanced softening for TOC removal by monitoring color removal for D/DBP Rule Compliance.
3. To quantify the effect of various metal salt coagulants and polymers in color and TOC removal during enhanced softening.

Bench Scale Study

Methods and Materials

The processes of coagulation and flocculation were simulated with a programmable Phipps and Bird mechanical stirrer using a standard 2-liter sample volume. The jar tests were performed in the manner as described by Hudson and Wagner.[1] A total of six 2-liter jars could be tested with different amounts of chemical additions in each jar for one experimental run. All treatment chemicals were added during rapid mix. The rapid mix was conducted at 300 rpm, corresponding to a mixing intensity of 200 sec^{-1}. The duration of the rapid mix was five minutes with the addition of all chemicals occurring in the first two minutes. After the rapid mixing, the samples were flocculated at 120 rpm for ten minutes and 40 rpm for another ten minutes, which yielded velocity gradients of 100 and 35 sec^{-1}, respectively.

Characterization of Hardness Removal

To obtain an optimum lime dosage for hardness removal, increasing concentrations of lime only were added to each consecutive jar test (six jar tests in one run) and the resulting hardness was determined. Lime dosages ranging from 90 to 400 mg/L as CaO resulted in a pH range from 8.14 to 11.77.

Figure 2 illustrates the levels of calcium hardness, magnesium hardness, and their sum, total hardness. The raw water composite total hardness of 292 mg/L as $CaCO_3$ is reduced to the minimum, 70 mg/L as $CaCO_3$, at the optimum lime dosage of 170 mg/L as CaO. After this optimum lime dosage, as expected, the calcium hardness (from the additional lime) will increase, thus increasing the total hardness.

At pH values above 11, magnesium hardness will precipitate out of solution as magnesium hydroxide ($Mg(OH)_2$). Figure 2 shows the optimum range of magnesium hardness removal to be between the lime dosages of 250 and 350 mg/L as CaO. Since the magnesium hardness is at a minimum in this range, the total hardness and calcium hardness curves in Figure 2 will approximate one curve. Because of the low levels of magnesium hardness in the raw water, operating at the higher lime dosages for magnesium hardness removal was not considered.

Effect of Softening on Color Removal

The effect of color removal was monitored with increasing lime dosage. Previous studies[2,3] have shown that at higher lime dosages and higher softening pH values, more TOC is removed during softening. Therefore, based on the correlation between color and TOC in Figure 1, the same trend of increasing color removal should be observed at the higher lime dosages and softening pH values. Between the lime dosages of 90 to 400 mg/L as CaO, as the lime dosage increased, the removal of color also increased. The raw water composite color of 171 color units was decreased to 12 color units at a lime dosage of 400 mg/L as CaO.

Figure 3 illustrates a trend of increasing color removal with increasing lime dosage that verifies that additional color removal and TOC removal is achieved at higher lime dosages and higher softening pH values. Therefore, if TOC cannot be readily measured, color can be used to identify this region of increased organic removal during softening.

It should be noted that the lime dosage range for high removals of color does not coincide with the optimum lime dosage for hardness removal. Referring to Figure 2, the lime dosage range cited for increased color removal is within the area of the increasing hardness due to the additional lime dosage past that of the optimum dosage for hardness removal (170 mg/L as CaO).

Lime softening can remove TOC, and the color caused by TOC via two distinct mechanisms that are a function of the lime dosage. At lower lime dosages (i.e., lime dosages for hardness removal), the removal mechanism for TOC/color is by rapid adsorption of fulvic acids onto the growing $CaCO_3$ solid.[2] This phenomenon, known as coprecipitation.[3], typically occurs during the initial moments of softening when the high surface area of the $CaCO_3$ solids and the relatively high concentration of calcium ion (Ca^{2+}) provides excellent conditions for adsorption.[2,3] The positive calcium ions from lime addition help form a bridge between the negatively charged fulvic acids and the $CaCO_3$ crystals, thereby facilitating coprecipitation. However, this removal mechanism is limited because the calcium ions quickly complex (i.e., combine) with the high levels of carbonate ions (CO_3^{2-}), therefore leaving many organics in solution. This removal mechanism is illustrated in Figure 3.

For the bench-scale data, the removal mechanism is exemplified between the lime dosages of 90 to 170 mg/L as CaO, as illustrated in Figure 4. The data points in Figure 4 illustrate that the color removal between the lime dosages of 90 and 170 mg/L as CaO is relatively constant. This data trend suggests that color removal by lime softening, at these low dosages, is limited by the rapid depletion of the calcium ions.

Lime dosages above the optimum dosage for hardness removal are characteristic of high pH values, high calcium concentrations, and low carbonate concentrations, which are the most favorable conditions for the removal of groundwater fulvic acids (i.e., color removal) during lime softening.[2] At such high lime dosages, the removal mechanisms for TOC/color are (1) increased coprecipitation due to the availability of the excess calcium ions in solution and low carbonate concentrations.[2,3], and (2) complexion (combination) of the positive calcium ions with the negative fulvic acids to form an insoluble calcium fulvate precipitate.[2]

This high pH and high calcium removal condition is illustrated in Figure 5. These removal mechanisms typically occur above the optimum lime dosage for hardness removal and result in significantly higher color removals, as illustrated in Figure 4. Above the optimum lime dosage for hardness removal of 170 mg/L as CaO, the finished water calcium levels increase from 46 mg/L to 330 mg/L at a lime dosage of 400 mg/L (see Figure 1). These extremely high calcium levels would indicate an exhaustion of the carbonate ion concentration due to $CaCO_3$ precipitation. Therefore, as theory would indicate, at the lime dosages of 180 to 400 mg/L as CaO, Figure 4 illustrates much higher color removals due to either increased coprecipitation or calcium fulvate precipitation, or both.

Coagulant Performance During Conventional Softening

The metal salt coagulants included in this optimization study were alum (aluminum sulfate), ferric sulfate, and ferric chloride. To select the performance of each coagulant during softening, increasing amounts of each type of coagulant were added to the raw water for each consecutive jar test. After 30 seconds of rapid mixing with the coagulant, 170 mg/L of lime as CaO was added to the raw water, and the rapid mixing was continued for an additional 4.5 minutes. The optimum dosage of lime for hardness removal (170 mg/L as CaO) was used during this portion of the investigation so that the effect of each coagulant on color removal could be assessed independently from the effects of higher lime dosages and higher softening pH values.

Alum, ferric sulfate, and ferric chloride all had significant color removals beyond that of conventional lime softening. An increased coagulant dosage provided increased color removal for all three coagulants. Figure 6 illustrates the color removal for each coagulant with respect to the color removal with lime softening alone. Each coagulant achieved relatively high color removals of up to 50% at relatively low dosages.

Although the color removal increased with increasing coagulant dosage, the additional color removal at coagulant dosages above the typical dosage of 30 mg/L, is not significant for the amount of additional coagulant being added (see Figure 6). This would render coagulant dosages above 30 mg/L as not cost-effective for additional color removal. All three coagulants, between the cost-effective dosages of 10 to 30 mg/L, removed color effectively.

As expected, this portion of the study verified that chemical coagulation will generally provide for additional color removal over that of conventional lime softening. Furthermore, the addition of the metal salt coagulants lowered the softening pH required for color removal. With lime addition only, a softening pH of 11.4 was necessary to achieve a finished water color of 20 color units. Using a metal salt coagulant with lime softening, a finished water color of 20 color units was achieved at a softening pH of approximately 9.0

Chemical coagulation, as expected, increased turbidity removal. The decrease in filtered water turbidity, due to chemical coagulation during conventional lime softening, is illustrated in Figure 7. Alum provided the best turbidity removals for the entire range of coagulant dosages. With the exception of ferric sulfate, an increased coagulant dose did not result in a significant increase in turbidity removal.

As illustrated in Figure 6, the metal salt coagulants provided for additional color removal at lower lime dosages and softening pH values than lime softening alone. However, higher color removals were desired to optimize for organic removal. Therefore, a combination of higher lime dosages and higher softening pH values (enhanced softening) with metal salt coagulation was evaluated in the next portion of the study.

Coagulant Performance During Enhanced Softening

Based on the preliminary results of the lime softening and lime softening/metal salt coagulation evaluations, color removal optimization was conducted for the three coagulants with the following dosages:

Alum - 25 mg/L ; Lime - 210 to 260 mg/L as CaO
Ferric Sulfate - 15 mg/L ; Lime - 180 to 260 mg/L as CaO
Ferric Chloride - 15 mg/L ; Lime - 180 to 260 mg/L as CaO

Because alum consumes less alkalinity, it could be dosed at slightly higher dosages and thus has less of an effect on the softening reactions than the iron salt coagulants. This optimization set a hardness threshold of approximately 100 mg/L as $CaCO_3$. This threshold meant that, for the given coagulant dosages, additional lime could be added (past the optimum dosage for hardness removal, refer to Figure 2) to achieve higher levels of color removal up to a finished softening hardness of approximately 100 mg/L as $CaCO_3$.

As expected, with the increase in lime addition beyond the optimum lime dosage for hardness removal of 170 mg/L as CaO, the color decreases as the hardness increases for each coagulant. For all three coagulants, the lime dosages from 170 to 210 mg/L as CaO were the optimum range for hardness removal, not color removal. Conversely, lime dosages from 230 to 260 mg/L as CaO were the optimum range for color removal, not hardness removal, for all three coagulants. Based on these ranges, the only optimization range for color removal to approximately 10 color units, resulting with acceptable hardness values around 100 mg/L as $CaCO_3$, is between the lime dosages of 210 to 230 mg/L as CaO.

For alum, at the upper lime dosage of 230 mg/L as CaO the resultant color was 11 color units and the resulting hardness was 107 mg/L as $CaCO_3$, which are acceptable values.

For ferric sulfate, at the upper lime dosage of 220 mg/L as CaO the color was 10 color units and the resulting hardness was 104 mg/L as $CaCO_3$, which are acceptable values.

For ferric chloride, when the color levels fell below 15 color units the resulting hardness approached 110 mg/L as $CaCO_3$, which is already beyond the target of 100 mg/L as $CaCO_3$. These values do not provide for any type treatment flexibility. Thus any values of color below the MCL of 15 color units will result in higher hardness levels. This is because ferric chloride addition consumes the highest amount of alkalinity of the three coagulants studied and therefore requires more lime (i.e. hardness addition) to achieve the same level of color removal.

TOC Removal Based on Color Data

Based on the previous evaluation for optimum color removal to approximately 10 color units, the following coagulant, lime, and polymer dosages were evaluated for their respective TOC removal by using color as an indicator:

For Alum Coagulation:	
Alum	25 mg/L
Lime	220 to 235 mg/L as CaO
Anionic Polymer	0.5 mg/L
Resulting Color	13 to 9 color units
Resulting Hardness	91 to 108 mg/L as $CaCO_3$
Softening pH:	10.6 to 10.8

For Ferric Sulfate Coagulation:	
Ferric Sulfate	20 mg/L
Lime	210 to 220 mg/L as CaO
Anionic Polymer	0.5 mg/L
Resulting Color	12 to 10 color units
Resulting Hardness	99 to 108 mg/L as $CaCO_3$
Softening pH	10.6 to 10.7

As expected, by using the optimum dosages identified above, the color for each sample was approximately 10 color units and the total hardness was close to 100 mg/L as $CaCO_3$. The TOC results for each sample are as follows:

Sample	*TOC (mg /L)*	*% Removal*
Raw Water Composite	11.3	n/a
Alum/Lime/Polymer A	6.32	44%
Alum/Lime/Polymer B	6.13	46%
Ferric Sulfate/Lime/Polymer A	7.02	38%
Ferric Sulfate/Lime/Polymer B	7.33	35

The bench-scale results indicate that when the color levels were reduced during softening to approximately 10 color units, between 35% and 46% TOC removal was accomplished. This percent removal exceeds the enhanced softening requirement for TOC removal of 30% in the D/DBP Rule for a source water with an alkalinity greater than 120 mg/L as $CaCO_3$ and a TOC greater than 8.0 mg/L. The data suggest that color removal was a viable indicator for TOC removal for the water used in this study for compliance with the D/DBP Rule TOC removal requirements.

These data also indicate that alum coagulation, during enhanced softening, removed as much as 10% more TOC than ferric sulfate coagulation. Based on the TOC results, it is expected that an alum-treated water would have a lower trihalomethane (THM) formation potential than a water treated with ferric sulfate.

Figure 8 illustrates that, as expected, the finished water TOC levels were quite indicative of the respective THM formation potentials. Figure 8 shows that the alum treated water resulted in the lowest TOC concentration. This water also had the lowest overall THM formation potential. It can be concluded that for an enhanced softened water, the reduction of TOC correlated to the resulting THM formation potential.

The study demonstrated that enhanced softening resulted in THM precursor reductions, which correlated to lower THM formation potentials. This can provide additional disinfection flexibility to a water utility, such as the ability to use free chlorine as a primary disinfectant.

Full-Scale Study

A full-scale enhanced softening study was conducted at the Hallandale's lime softening water treatment plant. One of the city's existing 2-MGD softening units was taken off line to be used during the study. Raw water from the Biscayne Aquifer (Broward County wellfield) was used. The raw water TOC levels exceeded 20 mg/L with color ranging from 60 to 100 color units.

In addition to verifying the color and TOC correlation identified in the bench-scale study, the full-scale study evaluated the relationship with the specific UV absorbance (SUVA). The raw water SUVA is 3.8 L/mg-m. The SUVA value indicates the relative amount of the fulvic fraction of TOC that can be readily coagulated.

In conducting enhanced coagulation, a SUVA value of 2.0 L/mg-m is considered to be optimized, and it is assumed that the remaining fraction of TOC left is primarily humic and is not readily coagulated. A goal of the full-scale study was to extend this correlation to enhanced softening and to determine whether it agreed with the TOC and color results of the bench-scale study.

The full-scale study was conducted for 12 weeks. The coagulant used was ferric chloride. After each process change the softening unit was allowed to stabilize for one week to take measurements. During the first eight weeks higher coagulant dosages were applied at the lower softening pH of 9.5 to quantify the effect of the coagulant alone for color removal. In weeks 9 through 12, softening pH values were increased incrementally from 9.5 to 11 with a fixed coagulant dose of 30 mg/L to assess the effect of excess lime (excess calcium) addition for color removal.

In Week 8, at a lime dosage of 180 mg/L, a pH of 9.5, and a coagulant dosage of 70 mg/L, the settled water color was >25 color units, the TOC removal was 20%, and the SUVA was 2.7 L/mg-m. For this low pH case, the high color levels indicated a TOC removal which does not meet the D/DBP Rule value of 30% and correlates with a SUVA value greater than 2.0 L/mg-m, which suggests that the process is not optimized and more TOC removal can occur.

In Week 11, at a lime dosage of 238 mg/L, a pH of 10.4, and a coagulant dosage of 30 mg/L, the settled water color was <15 color units, the TOC removal was 36%, and the SUVA was 2.0 L/mg-m. For this high pH case, the low color levels indicated a TOC removal that exceeded the D/DBP Rule value of 30% and correlates with a SUVA value of 2.0 L/mg-m, which suggests that the process is optimized with respect to TOC removal. These results agree very well with the bench-scale data.

The results of the full-scale study are illustrated in Figure 9. As mentioned earlier, Figure 9 illustrates that through Week 8, the higher coagulant dosages do not result in a significant increase in color removal. However, after Week 9, the higher lime dosages (excess calcium), which causes a higher softening pH, results in the increased color removal.

Test Type	Coagulant. Dosage and Type	Lime Dosage and Softening pH	Softened Water Color	Softened Water TOC Removal
Bench-Scale	Ferric sulfate 20mg/L	220 mg/L pH 10.6	10 to 12	38%
Full-Scale	Ferric Chloride 30 mg/L	238 mg/L pH 10.4	11 to 14	35%

Conclusions

The results of the bench-scale and full-scale studies demonstrate that color can be used as an indicator to assess the removal of TOC. Through the use of enhanced softening and metal salt coagulation with an anionic polymer, the treatment of the raw water was optimized to color levels of approximately 10 color units in the settled water. This corresponds to a total color removal of 95%. In achieving this color removal goal, the TOC removal ranged between 35% and 46%. This TOC removal range exceeds the enhanced softening TOC removal requirement of 30% in the proposed D/DBP Rule for a source water with an alkalinity greater than 120 mg/L as $CaCO_3$ and a TOC greater than 8 mg/L.

A summary of the full-scale results and the bench-scale results is shown in the accompanying table.

These studies demonstrated that by achieving a color removal goal, the TOC removal requirement for the D/DBP Rule was met. The full-scale test verified that in addition to indicating TOC removal, color removal can be used to indicate process optimization in producing softened water with SUVA values of approximately 2.0 L/mg-m.

The results of this study can help demonstrate to small utilities that there are cost-effective alternatives for both precursor monitoring programs and precursor removal strategies. This study can help give utilities ideas on TOC removal and monitoring that could potentially assist them in cost-effectively complying with the TOC removal requirements of the D/DBP Rule.

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Beneficial Use of Wastewater Sludge Biosolids in Russia

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I was involved with the management of research and development of standards in Russia for the treatment of sludge biosolids prior to land application. The following scientific organizations took part in the research: All-Union Research Institute of Water Supply and Sewage System, The Russian Municipal Academy, The Institute of Municipal Hygiene, The Research Institute of Hygiene, The Institute of Medical Parasitology and Tropical Medicine, The Institute of Fertilizers and Agricultural Soil, The Science Medicine Institutes, Agricultural Institutes of the Former Soviet Republics, and several wastewater treatment plants.

The studies were performed with various types of sludges, including raw sludge, aerobically digested sludge, anaerobic mesophilic and thermophilic digested sludge, mechanically dewatered sludge, and sludge dried on drying beds, from more than 100 treatment plants. Parameters analyzed included pathogenic bacteria, viruses, heavy metals, and helminth eggs.

Pathogens

Large numbers of helminth eggs were found in both raw sludge and sludge digested under mesophilic conditions. Helminths are common parasitic worms that include cestodes (tapeworms), nematodes (roundworms or ascariasis, and whipworms or *Trichuris trichura*), and trematodes (flukes). Nematodes form the main mass of eggs.

The life cycle of nematodes is typical of helminths. Larvae bore through the intestinal wall of a host, either human or animal, enter the bloodstream, and are carried to the lungs, from which they are coughed up into the mouth and returned to the intestines where they develop into adult worms. Humans are hosts to about 50 species of roundworms and, in fact, more than a third of the world's population suffers from diseases caused by roundworms (Goodman 1986).

The number of nematode eggs in 1 kg of primary sludge, activated sludge, and mixture digested in aerobic or anaerobic mesophilic conditions reached several hundred; in mechanically dewatered sludge the number reached several thousands.

A portion of helminth eggs perishes during drying on drying beds and during storage, but a large part survive for a long time, and they can transform into larva, which can survive for about five years in drying beds (Turovskiy, 1988).

During our experiments, special little bags with helminth eggs were incorporated into the sludges, which allowed a precise determination of the quantity of damaged eggs resulting from treatment. We found that helminth eggs are destroyed within 2 hours by heating at 50°C, within several minutes at 60°C, and within several seconds at 70°C.

After mechanically dewatering sludge and heating it to 60°C, inoculation on Wilson Bleaur or Ploskiryov medium, on media with different inhibitors, or on Miller, Kaufman, and others media revealed no presence of the intestinal typhoid group of bacteria. Our studies showed that because of the extreme changeability of the colon bacillus that was revealed in the process of reactivation, there should be no fear of livability or virulence of pathogenic microbes during utilization of dewatered, heated sludges.

During aerobic digestion, helminth eggs survive for a long time. In thermophilic digestion, additional equipment for disinfection may not be necessary. For pre-disinfection of mesophilic digestion, one-, two-, or multi-stage heat exchangers may be used for heating the sludge to 60°C. The temperature in the process that produces Class A sludge that meets the fecal coliform requirement has to be maintained at either 53°C for five days, 55°C for three days, or 70°C for thirty minutes (Water Quality Management Library, 1992). Those temperatures meet not only the fecal coliform requirements, but also density requirements for viruses and viable helminth ova.

In accordance with Russian Construction Standards and Regulations for disinfecting sludge, the following methods may be used:

- Thermal— heating, drying, incineration.
- Biothermal— composting.
- Chemical treatment.
- Biological — extermination of microorganisms by unicellular fungi and by soil plants.

For thermal drying, the standards require heating of the whole mass of sludge to not less than 60°C. The moisture of the thermally dried sludge is recommended to be not less than 25 to 30% because evaporation of bound water requires excessive energy to achieve a moisture less than 25%, a sludge with a moisture less than 25% becomes hygroscopic and is able to absorb water from the air, and dust is formed when drying sludge to less than 25% moisture.

Increasing the pH of raw sludge to greater than 10 removes its odor and suppresses coliform and enterococcus.

Raw sludge, treated with hydrated lime to increase its pH to greater than 10, loses its odor and coliform and enterococcus are suppressed, but there is no significant effect on helminth eggs. Hydrated lime increases temperature during hydration; 1 mole (56 gm) of calcium oxide generates 65 kilojoules of heat:

$$CaO + H_20 = Ca\,(OH)_2 + 65 \text{ kilojoules} \qquad (1)$$

During the process of hydrating 1 kg of chemically pure lime (100% CaO), 1152 kilojoules of heat is produced, requiring 320 gm of water.

The quantity of heat in kilojoules that is required for heating sludge by lime treatment may be determined by the following formula:

$$Q = (M_{SL}C_{SL} + M_LC_L)\,\Delta T \qquad (2)$$

where M_{SL} = sludge mass
M_L = lime mass in kg.
C_L = specific heat of lime in kilojoules/(Kg°C = 0.92
ΔT = difference between temperature that is necessary to heat the sludge and prime temperature of the sludge.

The specific heat of sludge may be calculated as follows:

$$C_{SL} = 1.8(1+0.85W_{SL}{}^3) \qquad (3)$$

where 1.8 = specific heat in kilojoules/(Kg°C) of dry sludge with a moisture of 5 to 10%;
W_{SL} = sludge moisture in decimals.

The heat in kilojoules produced by lime hydration, taking into consideration its activity by CaO, is:

$$Q_R = 1152A\,M_L \qquad (4)$$

where A = lime activity in decimals.

The increase of sludge temperature caused by a predetermined dose of lime may be preliminarily calculated by using the equation of material balance:

$$\Delta T_C = (1152\ A\ ML)/(M_{SL}C_{SL} + M_L C_L) \tag{5}$$

Given the required difference of temperatures, the mass of lime necessary for sludge treatment may be calculated as follows:

$$M_L = (M_{SL}C_{SL}\Delta T)/(1152A\text{-}C_L\Delta T) \tag{6}$$

The formula for calculating sludge moisture after lime addition, asssuming complete hydration of lime, is:

$$W_K = (1000\ W_{SL} - 0.32AM_L)/(M_{SL} + M_L) \tag{7}$$

where W_K = sludge moisture after lime addition, in decimals.

The amount of lime (M_L) in kg required to decrease the moisture of one metric ton of sludge to the required level may be determined from the following equation:

$$ML = (W_{SL} - WK)1000/(0.32 + W_K)A \tag{8}$$

The above formulas may be used only for approximate calculations because in reality lime is not completely hydrated. Lime consumption very much depends on the sludge moisture and, therefore, on the volume of the treated sludge. Therefore it preliminary thickening or dewatering of sludge is highly recommended.

Heavy Metals

Russian studies of the influence of biosolids on harvest, crop quality, and migration of heavy metals from biosolids into soils and from soils into plants (Goldfarb, 1983; Turovskiy, 1988) established that absorption of heavy metals by plants depends on the following factors:

1. *Mobility of heavy metals in the sludge.* Nickel, cadmium, and zinc are the most movable metals, but different methods of treatment may change the mobility of heavy metals in the sludge. When treated by lime, for instance, the major part of heavy metals does not migrate into plants.

2. *Types of soils.* In acidic soils the mobility of heavy metals is significantly higher than in alkaline soils. Organic and exchangeable cations in soils facilitate withholding of heavy metals. Until nitrogen is acting as a fertilizer, the influence of heavy metals on the growth of plants is insignificant.

3. *Types of plants.* Crops have different absorptions of metals. For instance, during the study of the mineral composition of potatoes, carrots, and garden radishes grown on lands where sludge from Kiev (Ukraine) was applied, researchers found that manganese was absorbed by all experimental crops; zinc and copper by only potatoes and carrots; iron by only carrots and garden radishes; and lead by only garden radishes. Iron and molybdenum decreased in potatoes and nickel decreased in carrots. Other elements did not change significantly.

In the grain and straw of millet grown on black soils where turf-sludge fertilizers were applied, the content of copper and nickel increased. The content of chromium, lead, titan, and molybdenum in the ash of all plants were on the level of control.

Distribution of heavy metals in plants is unequal—the greater concentration is in plants' organs (stems, leaves) and the smaller in the grain. The age of plants also affects accumulation of heavy metals; there are more heavy metals in old tissues than in young.

It was found that the conditions under which the sludge was applied affected the accumulation of heavy metals in plants. Applying sludge to soil in the spring tended to cause an increase in iron, barium, molybdenum, nickel, cobalt, and chromium in potato tubers.

Experiments to determine toxicity and migration of heavy metals in plants were conducted because of the high content of heavy metals in the thermal dried sludge at the sewage water plants of the city of Orechovo-Zuevo. The content of heavy metals in mg/kg of dry substance was as follows: lead - 200; chromium - 700; cadmium - 100; manganese - 500; copper - 200; zinc - 2500; nickel - 100. The results of the experiments are shown in the accompanying table.

As a result of the possibility of cumulating toxins in plants, it was decided to restrict the dosage of biosolids in the soil. Criteria for such restrictions were Standards for Limited Concentrations (SLC) for several heavy metals and toxins that were developed in Russia and approved by Russia's Ministry of Health. SLC in dry sludge were developed for the following metals in mg/kg : lead - 20; cadmium - 9; arsenic - 20; nickel - 50; chromium - 100; mercury - 2.1; manganese - 1500; vanadium - 150; manganese + vanadium - 1000 + 100;superphosphate ($P_2 0_5$) - 200.

The maximum rate of adding biosolids to soil is usually determined by a calculation that takes into account the possibility of embedding harmful impurities in the soil. The calculation is based on an assertion that after adding the sludge to the soil the total content of heavy metals in the soil (considering dispersion in the plowed layer) should not exceed the permissible dose of heavy metal in biosolids (PDS) in mg/kg, defined from the following equation:

$$F + D < PDS \tag{9}$$

where F = prime content of heavy metal in soil, mg/kg;
D = additional supply of the same metal into the plowed layer of soil with fertilizers in mg/kg.

The value of permissible addition to soil of one or another toxin D_{TOT} may be determined by the following formula:

$$D_{TOT} = (PDS\text{-}F)\ X\ 3{,}000 \tag{10}$$

where 3,000 = mass of plowed layer of soil in metric tons/ha recounted for dry substance.

Depending on the type of soil, the magnitude of permissible supply of harmful impurities D_{Tot} is usually decreased by the reducing factor K, that can be determined by the following formula:

$$K = K_1 * K_2 * K_3 \tag{11}$$

where K_1 =factor based on the content of humus (H) in the soil. When H = 0.5 - 1%, K_1 = 0.6; when H = 1 - 2%, K_1 = 0.8; when H = 2 - 3%, K_1 = 0.9; when H > 3%, K_1 =1.
K_2 = factor based on the mechanical composition of the soil. For sandy and sandy-loam soils, K_2 = 0.7; for loamy soils K_2 = 0.9; for all other soils K_2 = 1.
K_3 = factor based on the concentration of hydrogen ions in the soil. For soil with pH < 5 and biosolids with pH < 6, K_3 = 0.4; for soil with pH = 6.5 - 7.0 and biosolids with pH < 6, K_3 = 0.5; for soil with pH = 7.0 - 7.5 and biosolids with pH > 6, K_3 =0.8.

The average annual rate of adding biosolids to soil D_{AV} in metric tons per hectare can be calculated using the following formula:

$$D_{AV} = D_{Tot}/\ T\ C_N \tag{12}$$

where T = maximum time for adding sludge for the same site in years; C_N = concentration of the element in the biosolids in g/ton of the dry solids.

The maximum rate of adding biosolids to soil (D_{MAX}) at a frequency of one time in five years will be $5D_{AV}$ ton/ha per year dry solids.

D_{MAX} is also restricted by the level of nitrogen in the soil, which should not exceed $N_p = 300$ kg/ha per year.

Current specifications for thermally dried biosolids or compost used as a fertilizer limit the quality of the biosolids as follows:

Moisture %: <50
Content as percentage of the mass of dry substance:
Organic: >40
Nitrogen total N: >1.6
Phosphorus as P_2O_5: > 0.6
Potassium as K_2O: >0.2

Quantity of dusty fractions d<250 mkm, %, for sludge that does not contain fractions more than 30 mm: <10
Average density in kg/m^3: 500-700.

Several articles have described how to meet EPA (EPA 1993) standards (Foess and Siger, 1993; Siger, 1993; McDonald, 1995; EPA, 1995).

The requirements for heavy metals content in biosolids become less restrictive when they are used for shrubs, flowers, fast-growing trees, development of low-productive soils, reinforcement of ravines and hillsides, and planting trees and shrubs on former industrial waste sites (Land Application of Biosolids, 1997).

Content of heavy metals in plants grown with the utilization of thermally dried sludge from the city of Orechovo-Zuevo, Russia.

Analyzed sample	Content, % of mass of dry substance			Ash content
	Cu	Zn	Mn	%
Barley:				
Control	0.008	0.002	0.004	2.7
50 Metric Tons/ha TDS	0.001	0.003	0.0026	2.2
50 Metric Tons/ha TDS+N_{180}	0.002	0.004	0.005	5.4
50 Metric Tons/ha TDS+P_{120}	0.002	0.003	0.002	5.7
50 Metric Tons/ha TDS+$K1_{80}$	0.002	0.0017	0.0036	2.2
50 Metric Tons/ha TDS+N_{180}+K_{180}+P_{120}	0.0007	0.004	0.003	2.5
Oat:				
Control	0.0016	0.006	0.014	4.0
10 Metric Tons/ha TDS	0.0015	0.008	0.012	3.4
20 Metric Tons/ha TDS	0.0005	0.006	0.007	2.5
Corn:				
Control	0.01	0.016	0.005	10.5
10 Metric Tons/ha TDS	0.01	0.008	0.003	10.7
20 Metric Tons/ha TDS	0.007	0.007	0.005	10.2
Perennial herbs:				
Control	0.005	0.004	0.003	4.1
10 Metric tons/ha TDS	0.004	0.003	0.003	5.0

Notes:
1. Control = plants grown on soils without biosolids.
2. In addition to the above elements, traces of Cr and Cd were found.

Conclusions

Our research showed that several processes of sludge treatment, such as thermal, biothermal, or chemical treatment, as well as digestion, provide reduction of pathogens and vector attractions. Digestion, lime stabilization, and composting can be effective in destroying helminthes eggs.

Use of dewatered and disinfected biosolids as fertilizers can contribute to their effective, economical, and ecologically acceptable disposal, as well as transferring sewage sludge from the category of pollutants to the category of useful resources.

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