Operational performance of sludge blanket in clarification: effect of organic matter

Chihpin Huang, Tinlai Lee, Jill R Pan and Jaiwai Hon

ABSTRACT

Sludge blanket clarifiers (SBC) are presently an important unit of the water treatment process in Taiwan. Most studies concerning SBC have revolved around the treatment efficiency on turbidities. In Taiwan, most of the raw water sources for water treatment plants are contaminated with organic substances, which often interfere with the operation of SBC. In this study, the effects of organic materials on the formation of the sludge blanket and its performance were examined. Humic acid and salicylic acid were added in water to simulate natural waters polluted with organic materials of high and low molecular weights. The addition of humic acid accelerated the formation of a stable sludge blanket, however, the sludge blanket so formed contained less solid. Opposite effects were discovered with salicylic acid. Nevertheless, both organics enhanced the efficiency of turbidity removal by SBC. Large organic molecules were more easily removed by SBC. Coagulant addition had no significant effect on turbidity removal although the formation time for a sludge blanket was shortened. To successfully operate SBC, the occurrence and types of organic materials must be monitored.

Key words | coagulation, organic removal, sludge blanket clarifiers, sludge characteristics

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INTRODUCTION

Fluctuating turbidity and organics contamination of raw water are the two major challenges for water treatment in Taiwan. Because it can provide stable effluent quality, sludge blanket clarifiers (SBC) are commonly incorporated in the water treatment process to aid the traditional coagulation/sedimentation process. Currently, more than fifty percent of the water treatment plants in Taiwan practice SBC (Su *et al.* 2004). Although the operation of SBC has been studied extensively (Kawamura 1991; Masschelein 1992; Stevenson 1997), the focus has been on the removal of inorganic particles. The success of SBC depends highly on the characteristics of the raw water. As a result, the operation of SBC in Taiwan may require a different approach because of the high level of organic matters and the fluctuating turbidity of raw water (Yeh *et al.* 1993; Chang *et al.* 2000).

Conventional coagulation/flocculation produces dense flocs for easy settling. A satisfactory operation of SBC, on the other hand, requires a smooth flow of water through the blanket to avoid sludge bulking and short circuiting, which relies greatly upon the floc structure. Studies have shown that organic content affects the floc structure of the sludge. Chen *et al.* (2003) have discovered that the input of organics will bulk up the sludge blanket by forming less dense and more buoyant sludge flocs. However, few studies considered the effect of organic materials on the development of SBC and the accompanying performance of the operation.

The objective of this study was to examine the effects of organic substances on the formation and characteristics of the sludge blanket as well as its performance. Humic acid and salicylic acid were added to simulate the natural water contaminated with large and small organic compounds. Sludge blanket forming time (SBFT) of a stable SBC, floc structure and floc size distribution were determined to

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represent the sludge characteristics under various organic influences. The results were compared with the performance of the SBC.

MATERIALS AND METHODS

Preparation of raw water for sludge blanket clarification

The tap water was run through an activated carbon filter (GAC column) to remove the organic matter and to rid its residual chlorine, as shown in the first stage of the water clarifier module, as shown in Figure 1. The residual TOC was between 400 and 600 μg/L. The water was stirred and stored in the storage tank overnight. Various amounts of organic compounds, namely, humic acid and salicylic acid, and kaolin were added into the mixing tank to simulate the organic-contaminated natural water. The turbidity of the synthetic raw water was kept at around 50 NTU, while the acid content of each raw water sample was varied as presented in Table 1. The pH was then adjusted to 6.8 ± 0.2 with 0.12N $HClO_4$ and 0.25N $NaClO_4$. The conductivity of the synthetic raw water was in the range of 300 ± 50 μscm^{-1}.

Sludge blanket clarification

The coagulant, alum of 3 mg/L as Al^{3+}, was added and the suspension was mixed at 150 rpm for 1 min. The coagulated synthetic water was then fed into the bottom of the sludge blanket column and the effluent overflowed from the top of the column. The column is 8 cm in diameter and 150 cm high, as shown in Figure 1. The hydraulic retention time (HRT) was kept at 20 min, which equated to an upflow-rate of 3.51 m/hr. A blanket of sludge would form gradually and be suspended in the column. The sludge was collected at 30 cm above the bottom of the sludge blanket and the flocs were characterized. The solid concentration was calculated

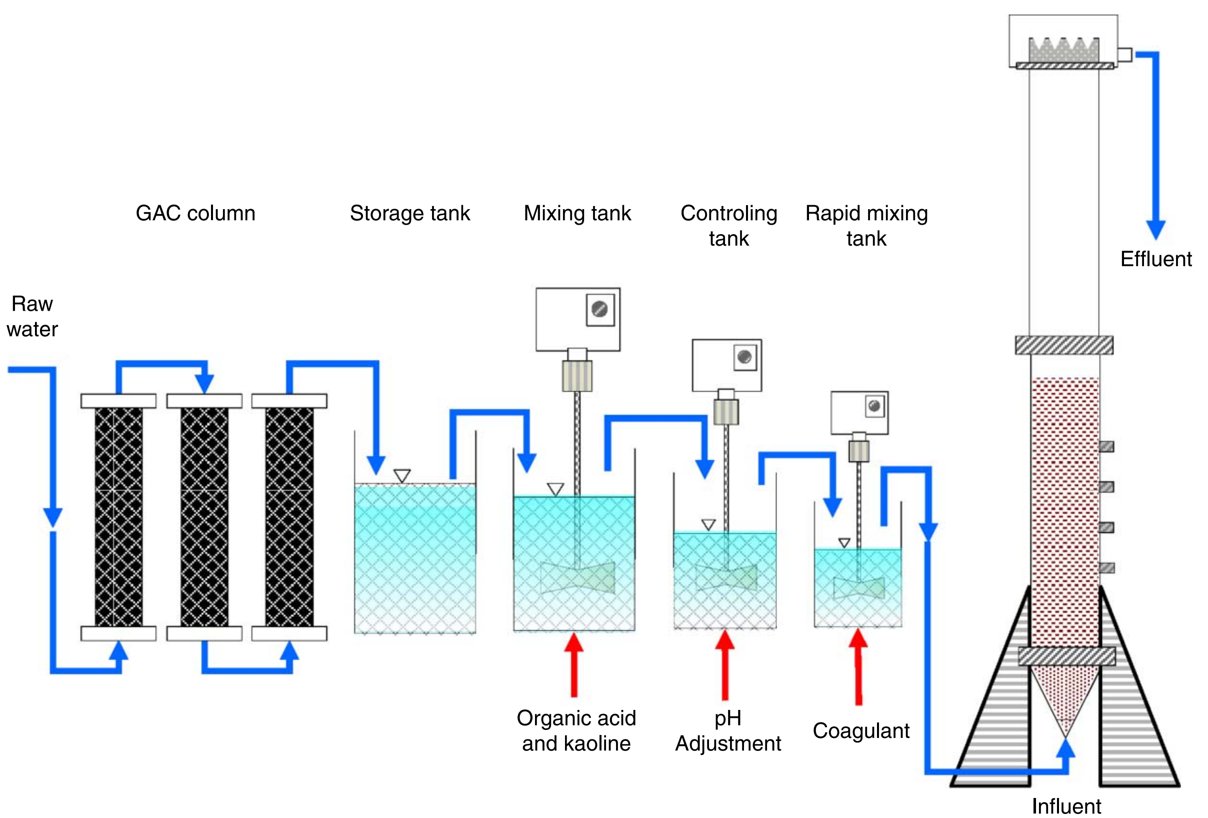

Figure 1 | Schematic diagram of the water clarifier module containing GAC column, storage tank, chemical mixing tank, pH controlling tank, coagulation tank and SBC.

Table 1 | Effect of organic content in synthetic raw water on the performance of sludge blanket clarifier

Raw water	A	B1	B2	B3	C1	C2	C3	D
Humic acid (mg/L)	0	1.02	2.14	3.45	0	0	0	1.65
Salicylic acid (mg/L)	0	0	0	0	1.58	2.18	3.54	1.55
SBFT (HRT)	21.0	16.5	22.5	33.0	110	99.0	66.0	49.5
TOC_i (mg/L)	0.443	1.02	2.14	3.45	1.58	2.18	3.54	3.20
TOC_e (mg/L)	0.577	0.408	0.843	0.716	0.79	1.81	3.44	1.55
TOC removal (%)	–	60	61	79	50	17	2.8	52
$SUVA_i$ (L/mg-m)	–	4.70	5.27	5.01	0.379	0.328	0.420	2.79
$SUVA_e$	–	1.47	2.01	3.72	0.481	0.276	0.291	0.706
Turbidity (NTU)	7.0	9.0	7.0	8.0	7.6	9.5	8.0	9.0

TOC_i: TOC of the influent.
TOC_e: TOC of the effluent.
$SUVA_i$: SUVA of the influent.
$SUVA_e$: SUVA of the effluent.
Raw water conditions: turbidity 52 ± 4 NTU; conductivity 320 ± 30 μS/cm; pH 6.8 ± 0.

as $(W_0-W_1)/W_0 \times 100\%$, in which W_0 and W_1 were the masses of the specimen before and after drying at 100°C for 25 hr.

Determination of sludge forming time

Sludge blanket forming time (SBFT) of a stable sludge blanket is recorded when the maximum solids concentration is achieved.

Characteristics of sludge flocs

The particle size of the sludge flocs was measured by Masteriszer 2000 (Malvern) and the zeta potential was determined by a Zetasizer Nano (Malvern). The Zoom 70 Optical System (OPTEM) with CCD cameras was used to detect the structure of the micro-flocs. The TOC was determined by a Carbon Analyser Schimadzu TOC-5,000. The UV absorbance at 254 nm was measured to determine the specific ultraviolet absorbance (SUVA). The SUVA (254 nm/TOC) value is an indicator of aromatic compounds and large organic molecules. The efficiency of the sludge blanket clarifier was evaluated by monitoring the TOC, SUVA and residual turbidity of the effluent.

RESULTS AND DISCUSSION

The development and characteristics of the sludge blanket were evaluated by SBFT, size and characteristics of sludge flocs, and organic content of the blanket sludge.

SBFT

Gregory (1996) has defined a stable sludge blanket as such that the maximum solid concentration of the sludge blanket is reached. Therefore, the SBFT can more or less represent the time to achieve optimum operation. The SBFT, given in the unit of HRT, with raw water of various organic compositions are shown in Table 1. Without organic addition, the forming time was 21 HRT. A small amount of humic acid (b1) shortened the forming time to 16.5 HRT. A higher concentration of humic acid, on the contrary, increased the forming time to as high as 33 HRT when 3.45 mg/L humic-acid was added. Since the TOC content of the Taiwan raw water is normally more than 2.10 mg/L, this may retard the stabilization of the sludge blanket.

The response of SBFT to salicylic acid was a totally different story. The SBFT was lengthened by approximately three to five times, also as shown in Table 1. The second observation was that the most dramatic change occurred when a small amount of salicylic acid, namely, 1.58 mg/L, was added. This effect weakened with the increasing concentration of salicylic acid. When a mixture of equal amounts of humic-acid and salicylic acid was added in the raw water, both organic compounds contributed equally toward the forming time. The result suggested that the formation of the sludge blanket could be facilitated by large organic molecules possibly through bridging.

Residual organic matter

Residual TOC in the water distribution system promotes the growth of microorganisms and induces the formation of trihalomethanes (THMs) when chlorination is the means of disinfection. As shown in streams b1 to b3 in Table 1, humic acid was effectively removed from the sludge blanket clarifier. The TOC removal remained high and fairly constant within the organic concentration studied, ranging from 60 to 80% while slightly increased with the concentration of humic acid. Table 1 also shows that the shifting in SUVA from around 5 to 2, a value denoting the aromaticity and content of large organic substances, indicated that the majority of large organic compounds, predominantly humic acid, has been removed from the water. However, traces of small molecules were still present in the effluent, as indicated by the residual TOC and the SUVA value of less than 2 L/mg-m. A different result was observed with salicylic acid addition, as seen from stream c1 to c3 of Table 1. Very little TOC was removed. The small SUVA value suggested that the effluent contained small hydrophilic organic compounds. Removal of small organic molecules such as salicylic acid depends upon two mechanisms: adsorption and entrapment. The adsorption of salicylic acid on solid particles desorbs easily when the chemical binding is not strong enough. Huang & Shiu (1996) have suggested that a five-stage coagulation to improve the removal of salicylic acid by enhancing the entrapment. However, neither of the two mechanisms can be achieved in the sludge blanket, which explains the poor removal efficiency for salicylic acid and the high TOC concentrations in the effluent of the blanket. When equal amounts of humic acid and salicylic acid were present in the influent, as seen in stream d, a 50% organic removal was observed. The lower values of SUVA indicated that the TOC in the effluent were small molecules. Edzwald & Tobiason (1999) have also pointed out that large hydrophobic molecules are easier to remove by the traditional coagulation, which suggests that a sludge blanket cannot improve organic removal any further than the coagulation. In other words, a sludge blanket is merely a clarifier for solid/liquid separation, and maximum organic removal depends upon the efficiency of the coagulation.

Turbidity removal

The most direct index to evaluate the performance of SBC is turbidity removal. The initial turbidity was 52 NTU. As shown in Table 1, the turbidity of the coagulated supernatant remained in the range of 7 to 9 NTU regardless of the organic content. It implies that the turbidity removal by sludge blanket has no direct relationship with the condition of the sludge blanket.

Solid concentration and floc density of sludge blanket

Gregory (1979) has pointed out that blanket concentration is an important factor in determining the screening efficiency of the coagulated particles. The flocs were sampled from various depths of the sludge blanket and mixed as the test samples. The solid concentrations were analyzed and are given in Figure 2. At an up-flow of 3.51 m/hr, the solid concentration of the sludge blanket decreased with the increasing amount of humic acid. On the contrary, salicylic acid increased the solid concentration of the sludge blanket, and the increase was proportional to the amount of the organic acid.

The reason for the contrasting results is that large particles like humic acid are capable of bridging and crosslinking flocs. As a result, Sung *et al.* (2005) have also observed that the presence of humic acid resulted in bulky flocs which deteriorated the performance of coagulation by PACl. Salicylic acid, on the other hand, forms dense flocs

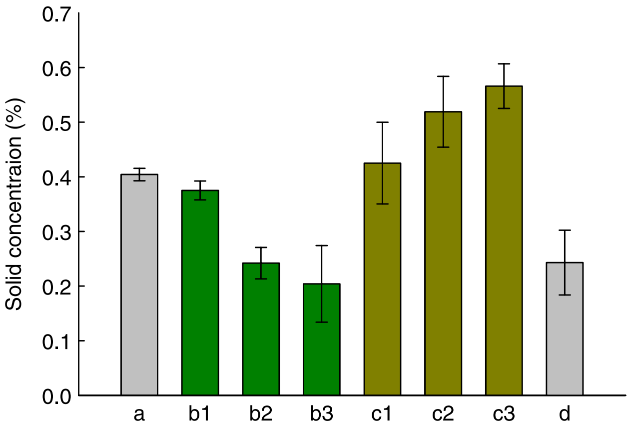

Figure 2 | Effect of type and concentration of organic compounds on solid concentration of sludge blanket.

with inorganic particles through complexation and adsorption (Hundt & O'Melia 1988). Entrapment of small organic compounds also produces dense flocs as indicated by Huang & Shiu (1996). Through these three mechanisms, the solid concentration of c-series is higher, as seen in Figure 2, and increases in proportion to the concentration of salicylic acid.

Increasing humic acid concentration had no effect on the structure of the flocs. The microphotographs of the coagulated flocs from sludge blankets a, b3, c3 and d are given in Figure 3. The flocs of humic acid-laden sludge (b3) were thinner and looser than those of salicylic acid (c3). Flocs became larger and looser structurally with increasing concentration of humic acid. Figure 3 also shows that the flocs were dense when low concentrations of salicylic acid were added. However, when high concentrations of salicylic acid were added, the flocs formed were loose and crumbled. When humic acid and salicylic acid were mixed in a 1:1 ratio (stream d of Figure 3), the sludge flocs were more like those from the humic acid-laden sludge, with a similar structure, dewatering property and low solid density. The results suggest that the property of the sludge blanket is dominated by large organic molecules.

Size analysis of the sludge flocs

Floc size is closely related to the sludge volume, settling ability and aggregation of the flocs. Gregory *et al.* (1996) has

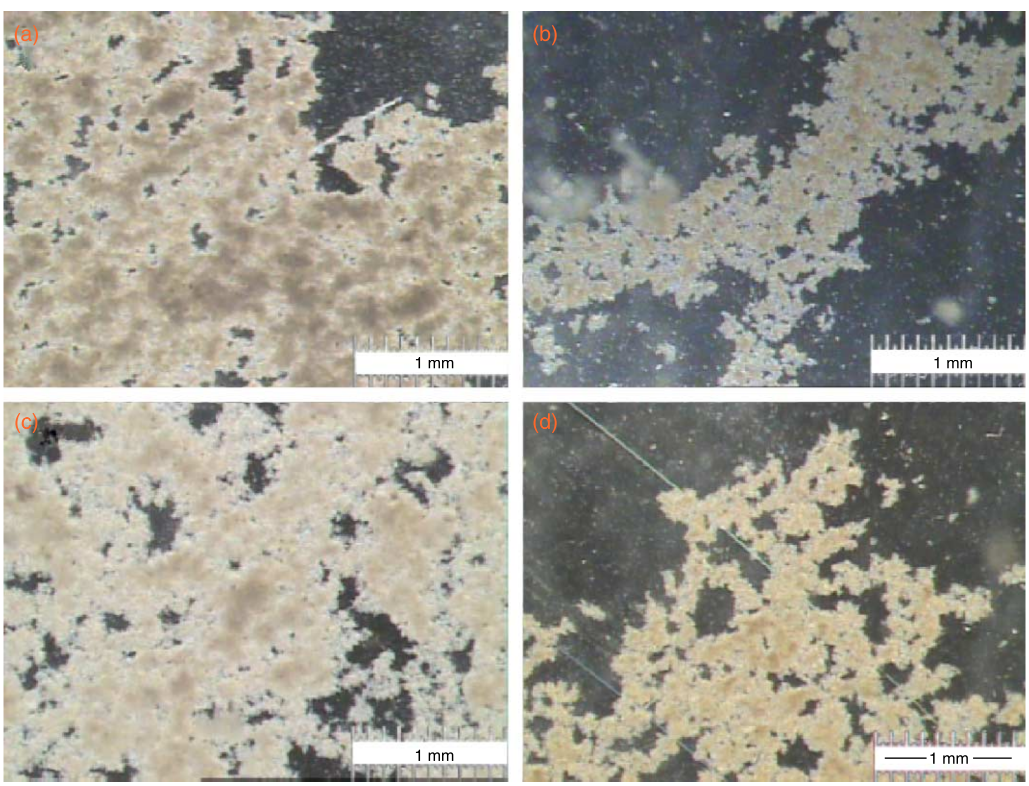

Figure 3 | Microphotographs of the coagulated flocs: (a) flocs from stream a; (b) flocs from stream b3; (c) flocs from stream c3; (d) flocs from stream d.

pointed out that after particles were coagulated, the formatting size of the floc affects the floc's volume, settling rate, and the aggregation. He has also mentioned that the formatting size also directly affected the solid concentration of the sludge blanket. In sludge blanket clarification, the flocs aggregate by means of the up-flow gradient instead of slow mixing. Therefore, the size of the flocs is the key to the formation of a stable sludge blanket. The process of particle aggregation under the influence of organic contamination is depicted in Figure 4. Results of two streams, namely, b2 for humic acid and c2 for salicylic acid, are illustrated in Figures 4a and 4b, respectively. The beginning (0 HRT) flocs size was around 1 μm. The flocs gradually shifted towards a larger size with the increase of HRT in both cases. For humic acid, after 15 HRT, the majority of flocs were in the vicinity of 1,000 μm. The shifting of mode back to 100 μm at 20 HRT suggested that a stable sludge blanket was achieved after 15 HRT, equivalent to an SBFT of 15 HRT.

A different result is observed for salicylic acid in Figure 4b. Although the same trend of size enlargement with increasing HRT was detected, the SBFT was lengthened to 50 HRT. The persistency of the two-mode curves, one around 200 μm and the other around 1,000 μm, indicates that the aggregation was hindered and the small size flocs were induced by the salicylic acid (Figure 5).

Dulin & Knocke (1989) have pointed out that the flocs size is inversely proportional to the effective density of the flocs. Because larger size flocs formed in the presence of humic acid, lower solid concentration was expected. Moreover, there were more smaller flocs in salicylic acid than in the humic acid (Figure 4). Because the small flocs could fill the pore space of large flocs salicylic acid promotes the density and the solid concentration of the sludge blanket more readily than the humic acid. On the other hand, large organic molecules enhance the aggregation of large flocs in the sludge blanket operation. The time to form large flocs (1,000 μm) was shorter under the influence of humic acid because large molecules are more efficient in particles aggregation. In low concentration, humic acid acts like a polymer to bridge the adsorbed aluminum salts and the particles, which increases the efficiency of aggregation. However, when a large quantity of humic acid was added, the organic compounds would consume the coagulant and, in turn, deprive the efficiency of coagulation.

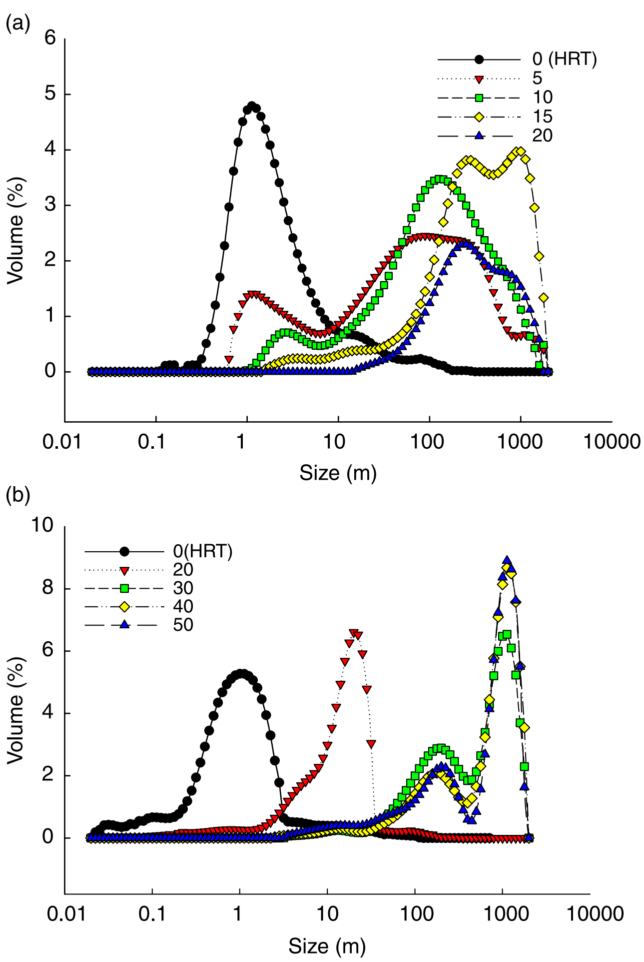

Figure 4 | Size distribution of flocs in (a) humic acid-laden blanket sludge (b2); (b) salicylic acid-laden blanket sludge (c2).

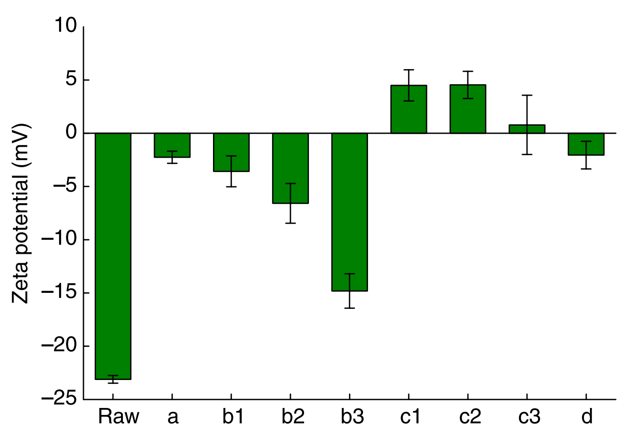

Figure 5 | Zeta potentials of sludge developed from synthetic raw water containing various types and concentrations of organic materials.

CONCLUSION

A small amount of large organic compounds can benefit the stabilization of the sludge blanket. The occurrence of small organic compounds prolongs the formation of a stabilized sludge blanket. SBC removes humic acid efficiently while leaving the majority of the salicylic acid in the effluent. Contamination of humic acid results in large loose flocs, while the addition of salicylic acid causes small dense flocs. Stable effluent turbidity can be maintained once the sludge blanket is stabilized regardless of organic contamination or inappropriate coagulant dosing.

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