NEW APPROACHES TO MINIMIZE EXCESS SLUDGE IN ACTIVATED SLUDGE SYSTEMS

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Introduction

Activated sludge production, treatment and disposal
Sludge Production

Raw Wastewater
BOD (100%) → Screens

Primary Treatment Effluent
(BOD 65%) → Bio-reactor

Primary Sludge
(35% BOD)

CO₂ + H₂O (25% BOD)

Secondary Sludge
(30% BOD)

Secondary Effluent
(BOD 10%)

Effluent to Secondary Treatment

Primary sludge:
110-170 kg dry solids /10³ m³
of wastewater treated

3 m³/10³ m³
wastewater treated

Secondary sludge:
70-100 kg dry solids /10³ m³
of wastewater treated

8 m³/10³ m³
wastewater treated

organic matter + O₂ + nutrients → CO₂ + H₂O + new cells

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Sludge Treatment

Primary sludge (5% solids)

- Gravity
- Flotation
- Centrifuge

Primary sludge + secondary sludge (3% solids)

- Anaerobic digestion
- Chemical conditioning
- Heating
- Aerobic digestion
- 7-9% solids

Secondary sludge (1% solids)

- Thickening
- Stabilization
- Conditioning
- Dewatering

- Drying bed
- Lagoon

~ 30% solids content → Reducing the sludge volume greatly

Sludge reuse or disposal
Sludge Disposal

Landfill
- The most preferred means
- Capacity is limited
- Lack of new location

Incineration
- Practiced in large municipalities
- Air pollution

Land application
- Reuse of sludge nutrient
- Soil amendment
- Sludge should be less contaminated

Ocean dumping
- Water pollution control regulations
Best solution will be reducing excess sludge production during the wastewater treatment, or recovering energy and resources from sludge.
Major Approaches of Excess Sludge Reduction
Major Approaches of Excess Sludge Reduction

1. Sludge pretreatment through thermal, mechanical, or ozone treatment
2. Restricting/limiting sludge growth in an aeration tank
Why Sludge Solubilization/disintegration can Reduce Excess Sludge Production

As a result, excess sludge can be reduced
- **Heat treatment under a high temperature up to 180°C**
  [R. T. Haugh *et al.*, 1978]

- **Mechanical pretreatment using ultrasonication, mills and homogenizers**
  [U. Basier and P. Schmidheiny, 1997]
  - Stirred Ball Mills (SBM)
  - High Pressure Homogenizers (HPH)
  - Ultrasonic Homogenizers (UH)
  - Mechanical Jet Smash Technique (MJS)
  - High Performance Pulse Technique (HPP)
  - Lysat-Centrifugal-Technique (LC)

- **Ozonation**
  [H. Yasui and M. Shibata, 1994], [E. Egemen *et al.*, 2001]
[1] Specific energy consumption with various pretreatment methods [J. Müller, 2000]

![Graph showing specific energy consumption with various pretreatment methods.](image)
## [1] Comparison of various sludge pretreatment methods

<table>
<thead>
<tr>
<th>Sludge pretreatment method</th>
<th>Sludge reduction efficiency</th>
<th>Energy requirement</th>
<th>Operational cost</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thermal</td>
<td>Low</td>
<td>High</td>
<td>High</td>
<td>Produce non-biodegradable organic matter at high temperature Odor generation</td>
</tr>
<tr>
<td>Mechanical</td>
<td>High</td>
<td>High</td>
<td>High</td>
<td>High cost Suitability of the machines for practical application is major concern</td>
</tr>
<tr>
<td>Ozonation</td>
<td>High</td>
<td>Relatively low</td>
<td>Relatively low</td>
<td>Poor sludge settling Odor generation</td>
</tr>
</tbody>
</table>
[2] Restricting/limiting sludge growth in an aeration tank

A significant reduction in sludge production could be achieved by restricting/limiting sludge growth under the following conditions:

1. at high temperatures [P. Coultate and K. Sundaram, 1975], [I. Nioh and C. Furusaka, 1968]
2. with the presence of metabolic inhibitory substances [G.H Chen et al., 2000];
3. with nutrients limitation [S. P. Tsai, 1990]
4. with the presence of higher forms of microorganisms such as protozoa and metazoa [C. H. Ratsak et al., 1994]; [J. H. Rensink et al., 1997]
5. with a long SRT as in an extended aeration process and MBR process [S. Chaize and A. Huyard, 1993].
[2] Concept of restricting/limiting sludge growth through futile cycle or energy uncoupling

Conditions to induce futile cycle:
- Extreme or unfavorable environment
- Limitation of nutrients
- Presence of certain chemicals
### Sludge Pretreatment vs Sludge Growth Restriction

<table>
<thead>
<tr>
<th>Sludge Pretreatment</th>
<th>Sludge Growth Restriction</th>
</tr>
</thead>
<tbody>
<tr>
<td>60-100% excess sludge reduction</td>
<td>50-80% excess sludge reduction</td>
</tr>
<tr>
<td>High energy input</td>
<td>Lower energy input</td>
</tr>
<tr>
<td>Require modification of treatment plant</td>
<td>Little modification of treatment plant</td>
</tr>
</tbody>
</table>
Major Shortcomings of the Present Methods

- Poor Sludge Settling
- Higher Oxygen Requirements
- Reduced Nutrient and Substrate Removal
- Alternative method for reducing excess sludge production, which is feasible and cost-effective, is necessary
New Approaches to Reduce Excess Sludge
Studied at HKUST

1. Chemically stimulated futile cycle
2. Chlorination pretreatment of sludge
3. Oxic-Settling-Anaerobic (OSA) process
4. Autotrophic denitrification
Ideal Chemicals to Stimulate Futile Cycle

- Low cost
- High efficiency
- Low toxicity
- Less impact on substrate removal capacity

3, 3’, 4’, 5-tetrachlorosalicyanide (TCS)
A chemical compound, 3,3′,4′,5-tetrachlorosalicylanilide (TCS) can stimulate futile cycle in *Streptococcus bovis*.

One of the formulations of soaps, rines, polishes, shampoo, deodorants.
Work Scope

✓ to investigate the effect of TCS on sludge growth rate and substrate utilization rate

✓ to find out an appropriate TCS dosage to induce excess sludge reduction

✓ to examine the response of microbial activity to the TCS dosage
Methodology:

- pure culture of E.Coli
- batch and continuous mixed cultures cultivated with and without TCS
- endogenous decay coefficient study
Effect of TCS on the observed growth yield ($Y_{obs}$) of *E. coli* at different TCS concentration
Change of ATP content in *E. coli* at different TCS concentrations

<table>
<thead>
<tr>
<th>TCS concentration (ppm)</th>
<th>∆ATP content (µg/mg SS)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>-1.59</td>
</tr>
<tr>
<td>0.02</td>
<td>-1.62</td>
</tr>
<tr>
<td>0.05</td>
<td>-1.77</td>
</tr>
<tr>
<td>0.1</td>
<td>-1.90</td>
</tr>
<tr>
<td>0.2</td>
<td>-1.88</td>
</tr>
<tr>
<td>0.4</td>
<td>-2.16</td>
</tr>
</tbody>
</table>
Effect of TCS on Sludge Growth Rate and Substrate Removal Rate

Continuous aeration

Significant effect on sludge growth when TCS > 0.4 ppm

Significant effect on substrate uptake rate when TCS > 0.4 ppm
TCS reduces the $Y_{obs}$

A shape drop of $Y_{obs}$ is detected between 0.4 and 0.6 ppm TCS introduction.

TCS reduces both the $\mu$ and $q$

The change of $\mu$ resemble that of $Y_{obs}$
Effect of TCS on Sludge Decay Rate
Effect of TCS on Cumulative Excess Sludge Production of Batch Cultures

Accumulative Excess Sludge (g SS/d)

Time (day)

- Bc 2
- Bc 1
- Bc 0

$S_0/X_0 = 0.25$

$X_0 = 2,000$ mg SS/L

$y = 3.41$ g SS/d

$y = 2.66$ g SS/d

$y = 1.94$ g SS/d
## Nomenclatures in the Results and Discussion

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bc 0</td>
<td>Batch cultivation without the presence of TCS (control)</td>
</tr>
<tr>
<td>Bc 1</td>
<td>Batch cultivation with the presence of 0.5 ppm TCS</td>
</tr>
<tr>
<td>Bc 2</td>
<td>Batch cultivation with the presence of 1.0 ppm TCS</td>
</tr>
<tr>
<td>Cc 0</td>
<td>Continuous cultivation without the presence of TCS</td>
</tr>
<tr>
<td>Cc 1</td>
<td>Continuous cultivation with the presence of 1.0 ppm TCS</td>
</tr>
</tbody>
</table>
Observed Growth Yield of Batch Cultures Cultivated with TCS at Different Dosages

![Graph showing the growth yield over time for different dosages of TCS. The x-axis represents time in days, ranging from 0 to 30, and the y-axis represents the observed growth yield (Yobs) in g SS/g COD. The graph includes lines for Bc 0, Bc 1, and Bc 2, with different symbols for each dosage.](image-url)
Effect of TCS on Cumulative Excess Sludge Production of Continuous Cultures

![Graph showing cumulative excess sludge production over time for two cultures, Cc 0 and Cc 1, with linear regression lines and equations:]

- Cc 0: $y = 3.06 \ g \ SS/d$
- Cc 1: $y = 1.90 \ g \ SS/d$
Experiments were conducted at a period of 3 hours
During the experiment, TCS was not added
**Effect of TCS on Substrate Removal Efficiency of Continuous Cultures**

![Graph showing substrate removal efficiency over time with TCS dose of 0 and 1 ppm]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>TCS dose (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mean Substrate removal (mg COD/L/d)</td>
<td>920 880</td>
</tr>
<tr>
<td>Daily Sludge Production</td>
<td>383 238</td>
</tr>
<tr>
<td>Overall yield (g SS / g COD)</td>
<td>0.41 0.27</td>
</tr>
<tr>
<td>Effluent SS conc. (mg/L)</td>
<td>35.7±15.4 43.3±23.1</td>
</tr>
</tbody>
</table>
Effect of TCS on SOUR of Batch and Continuous Cultures

### Batch Culture

<table>
<thead>
<tr>
<th>Measurement Day</th>
<th>SOUR (mg O$_2$/g SS/hr)</th>
<th>0 ppm TCS (control)</th>
<th>0.5 ppm TCS</th>
<th>1.0 ppm TCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>58.6</td>
<td>61.2</td>
<td>58.9</td>
<td></td>
</tr>
<tr>
<td>5$^{th}$</td>
<td>52.1</td>
<td>57.1</td>
<td>49.3</td>
<td></td>
</tr>
<tr>
<td>10$^{th}$</td>
<td>63.1</td>
<td>75.3</td>
<td>97.0</td>
<td></td>
</tr>
<tr>
<td>20$^{th}$</td>
<td>63.7</td>
<td>79.7</td>
<td>90.8</td>
<td></td>
</tr>
<tr>
<td>30$^{th}$</td>
<td>60.1</td>
<td>81.3</td>
<td>96.1</td>
<td></td>
</tr>
</tbody>
</table>

### Continuous Culture

<table>
<thead>
<tr>
<th>Measurement Day</th>
<th>SOUR (mg O$_2$/g SS/hr)</th>
<th>0 ppm TCS (control)</th>
<th>1.0 ppm TCS</th>
</tr>
</thead>
<tbody>
<tr>
<td>0$^{th}$</td>
<td>61.2</td>
<td>63.7</td>
<td></td>
</tr>
<tr>
<td>5$^{th}$</td>
<td>62.2</td>
<td>72.4</td>
<td></td>
</tr>
<tr>
<td>10$^{th}$</td>
<td>66.7</td>
<td>77.8</td>
<td></td>
</tr>
<tr>
<td>20$^{th}$</td>
<td>64.8</td>
<td>79.5</td>
<td></td>
</tr>
<tr>
<td>30$^{th}$</td>
<td>62.6</td>
<td>78.3</td>
<td></td>
</tr>
</tbody>
</table>

**INCREASE**
## Microbial Activity of Batch Cultures (DAPI & CTC Data)

### Table: Microbial Activity

<table>
<thead>
<tr>
<th>Day</th>
<th>Batch Culture</th>
<th>Active microbial portion (%)</th>
<th>no. of active microbes/ VSS (no./mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>Control</td>
<td>5.7</td>
<td>1.39 x 10^8</td>
</tr>
<tr>
<td></td>
<td>0.5 ppm TCS</td>
<td>10.3</td>
<td>3.45 x 10^8</td>
</tr>
<tr>
<td></td>
<td>1.0 ppm TCS</td>
<td>10.5</td>
<td>4.07 x 10^8</td>
</tr>
<tr>
<td>30</td>
<td>Control</td>
<td>3.9</td>
<td>1.09 x 10^8</td>
</tr>
<tr>
<td></td>
<td>0.5 ppm TCS</td>
<td>4.3</td>
<td>1.22 x 10^8</td>
</tr>
<tr>
<td></td>
<td>1.0 ppm TCS</td>
<td>7.6</td>
<td>2.72 x 10^8</td>
</tr>
</tbody>
</table>

*Increase*
### Microbial Activity of Continuous Culture

<table>
<thead>
<tr>
<th>Day</th>
<th>Continuous Culture</th>
<th>Active microbial portion (%)</th>
<th>no. of active microbes/VSS (no./mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>control</td>
<td>7.4</td>
<td>1.49 x $10^8$</td>
</tr>
<tr>
<td></td>
<td>1.0 ppm TCS</td>
<td>11.2</td>
<td>2.99 x $10^8$</td>
</tr>
<tr>
<td>30</td>
<td>control</td>
<td>5.6</td>
<td>1.42 x $10^8$</td>
</tr>
<tr>
<td></td>
<td>1.0 ppm TCS</td>
<td>10.1</td>
<td>2.69 x $10^8$</td>
</tr>
</tbody>
</table>

*Increase*
Proposed Mechanism: Futile Cycle Induced by TCS

Enzyme complex I, III and IV

1/2 O₂ + 2 H⁺ + 2 e⁻ \rightarrow H₂O

2 NADH + 2 H⁺ + 2 e⁻ \rightarrow 2 NAD⁺ + 2 e⁻

TCS interacts with membrane

2 NADH + 2 H⁺ \rightarrow 2 NAD⁺ + 2 e⁻

1/2 O₂ + 2 H⁺ + 2 e⁻ \rightarrow \text{H₂O}

F₀, F₁-ATP synthase

I, III, IV

ADP+Pᵢ \rightarrow ATP

MITOCHONDRIA
Figure 2-1. Membrane biological reactor (A) and chlorination setup (B) used in this study.
Chlorine dose and residual during the sludge chlorination.

<table>
<thead>
<tr>
<th>Chlorine Dose (g Cl₂ /g MLSS)</th>
<th>Free Cl₂ Residual (mg Cl₂/L)</th>
<th>Total Cl₂ residual (mg Cl₂/L)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.066</td>
<td>0.3</td>
<td>5.5</td>
</tr>
<tr>
<td>0.133</td>
<td>0.3</td>
<td>9.0</td>
</tr>
<tr>
<td>0.199</td>
<td>1.8</td>
<td>12.9</td>
</tr>
<tr>
<td>0.266</td>
<td>5.8</td>
<td>37.8</td>
</tr>
<tr>
<td>0.332</td>
<td>19.1</td>
<td>65.0</td>
</tr>
</tbody>
</table>
Figure 2-2. Sludge production rates in the continuous systems without (the reference system) and with (testing line) the chlorination treatment of excess sludge.
Figure 2-3. Variations of the COD concentration in the sludge and treated water of the testing system.

(Errors bars present the standard deviation of the COD measurement).
Figure 2-4. Change of MLSS/TS during the operation of the testing system.

Figure 2-5. Particle distribution in activated sludge
(A) prior to chlorination study;
(B) after recirculation of chlorinated excess sludge for 20 days;
(C) just after chlorination step.
Figure 2-8. Total number of cells and the number of active bacteria in both the reference and testing systems (the results represent the mean values of five independent analyses).

THMs concentrations in the treated water and sludge.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Analysis 1</th>
<th>Analysis 2</th>
<th>Analysis 3</th>
<th>Analysis 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treated water</td>
<td>&lt;200</td>
<td>&lt;200</td>
<td>&lt;200</td>
<td>&lt;200</td>
</tr>
<tr>
<td>Chlorinated sludge (just after chlorination)</td>
<td>260*</td>
<td>&lt;200</td>
<td>310</td>
<td>270*</td>
</tr>
<tr>
<td>Chlorinated sludge (after 10 min reaction)</td>
<td>&lt;200</td>
<td>230*</td>
<td>&lt;200</td>
<td>&lt;200</td>
</tr>
<tr>
<td>Sludge after NaClO addition (150 mg Cl₂/L)</td>
<td>1280</td>
<td>830</td>
<td>680</td>
<td>860</td>
</tr>
</tbody>
</table>
[3] Oxic-Settling-Anaerobic (OSA) System

- Sludge settleability and nutrient removal?
  What extent of reduction?
  What is the cause for the reduction?

- Sludge concentration
  - Longer retention time

- Important factors
  - Biomass level
  - Anaerobic sludge exposure time (SAET)
  - ORP

- Effluent

- Excess sludge

- It is relatively easy to modify conventional activated sludge process
- Neither chemical addition nor heat energy is required
- The treatment efficiency is NOT affected
- Great potential in full-scale application
Study Objectives

- To examine the capacity of OSA system in reducing excess sludge production
- To investigate the performance of an OSA system under different operating conditions
- To study the impact of the anaerobic sludge zone on bacterial activity
- To identify the cause of the reduction of excess sludge production in an OSA system
Experimental Set-up

- Working Volume = 10.0 L
- AERATION TANK
- SETTLING TANK
  - Volume = 4.0 L
  - Concentrated Sludge
  - Recirculated Supernatant
  - Effluent Overflow
  - Effluent Permeate
  - Hollow Fiber Membrane
    - Pore size 0.4 µm
    - Facilitate the precise measurement of sludge production
- Dilution Water
- Stock Solution
- Nitrogen Gas Tank
  - Working Volume = 4.5 L
- SAET 6, 10, and 12 hr
- MLSS: 7-9 g/L
- ORP: -250mV
- Wastage excess sludge

- HRT: 6 hr, MLSS: 2 g/L, DO: >2 mg/L

- ORP Electrode
- Effluent Permeate

- MLSS: 7-9 g/L
- ORP: 100, -100, and -250mV
## Observed Growth Yield at Different ORP in Sludge Holding Tank

<table>
<thead>
<tr>
<th>ORP in sludge holding tank (mV)</th>
<th>Net sludge production rate (g SS/day)</th>
<th>COD removal rate (g COD/day)</th>
<th>$Y_{obs}$ (g SS/g COD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>+ 100</td>
<td>3.90</td>
<td>12.18</td>
<td>0.32</td>
</tr>
<tr>
<td>-100</td>
<td>2.70</td>
<td>12.27</td>
<td>0.22</td>
</tr>
<tr>
<td>-250</td>
<td>2.30</td>
<td>12.77</td>
<td>0.18</td>
</tr>
</tbody>
</table>
Observed growth yield at different SAET in Sludge Holding Tank at -250 mV ORP

<table>
<thead>
<tr>
<th>SAET in sludge holding tank (hours)</th>
<th>Net sludge production rate (g SS/day)</th>
<th>COD removal rate (g COD/day)</th>
<th>$Y_{\text{obs}}$ (g SS/g COD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3.5</td>
<td>12.2</td>
<td>0.27</td>
</tr>
<tr>
<td>10</td>
<td>2.4</td>
<td>12.3</td>
<td>0.19</td>
</tr>
<tr>
<td>12</td>
<td>2.0</td>
<td>12.7</td>
<td>0.17</td>
</tr>
</tbody>
</table>
Comparisons of Performance of OSA System with Reference System under same COD Loading

Operating conditions

Reference System I

- HRT: 6 hr
- MLSS: 2 g/L
- Effluent

OSA System

- HRT: 6 hr
- MLSS: 2 g/L
- Effluent
- Influent
- Aeration Tank
- Wastage sludge
- SAET: 10 hr
- MLSS: 8 g/L
- ORP: -250 mV
- Settling Tank
- Sludge Holding Tank
- Wastage sludge

Membrane filtration was used to facilitate the precise measurement
Influent average = 330 mg/L

Effluent average (Reference system I) = 41 mg/L

Effluent average (OSA system) = 18 mg/L

Effluent average (Reference system I) = 41 mg/L

Effluent average (OSA system) = 18 mg/L
Sludge Production Rate

Excess sludge production (Reference system) @ 4.8 g/day
Excess sludge production (OSA system) @ 2.3 g/day
## Observed Growth Yield

<table>
<thead>
<tr>
<th></th>
<th>Reference System I</th>
<th>OBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net sludge production rate</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>(g SS/day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Substrate utilization rate</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>(g COD/day)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>$Y_{obs}$ (g SS/g COD)</td>
<td>0.4</td>
<td>0.2</td>
</tr>
</tbody>
</table>

50 % of reduction !!! How about the sludge settleability and bacteria activity?
Sludge Settleability

![Graph showing sludge settleability over time for different systems. The graph includes data points for two systems: Reference system I and OSA system, along with their respective mean values of SVI 180 and 110.](image)
SOUR

At temperature 20°C
Comparisons of Performance of OSA System with Reference System under same Sludge Quantity

Operating Conditions

**Reference System II**

- **HRT**: 6 hr
- **MLSS**: 7~8 g/L

**OSA System**

- **HRT**: 6 hr
- **MLSS**: 2 g/L

Higher sludge quantity will generally result in low sludge production? → is it the main cause for the OSA system for reducing the excess sludge production?
Sludge Production Rate

Reference system II
@ 2.2 g/day

OSA system
@ 2.0 g/day
COD Removal

- Influent average 330 mg/L for both systems
- Effluent average (Reference system II) = 12 mg/L
- Effluent average (OSA system) = 18 mg/L
- Sludge loading is 4 times higher
### Observed Growth Yield

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference System</th>
<th>OSA System</th>
</tr>
</thead>
<tbody>
<tr>
<td>Net sludge production rate (g SS/day)</td>
<td>2.2</td>
<td>13</td>
</tr>
<tr>
<td>Substrate utilization rate (g COD/day)</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>$Y_{\text{obs}}$ (g SS/g COD)</td>
<td>0.2</td>
<td>0.18</td>
</tr>
</tbody>
</table>

However, the operating principle of the two systems are different!

Let’s look at the other parameters...
Substrate oxidation and cell synthesis:

COHNS + O₂ + nutrients $\xrightarrow{\text{bacteria}}$ CO₂ + H₂O + NH₃ + C₂H₇O₂N (new cell tissue) + other end products

At Temperature 20°C
Endogenous respiration:

\[ \text{C}_5\text{H}_7\text{O}_2\text{N (Cells) + 5 O}_2 \xrightarrow{\text{bacteria}} 5\text{CO}_2 + \text{NH}_3 + 2\text{H}_2\text{O} \]

At Temperature 20°C
The diluted SVI (DSVI) test has been used for the reference system II since MLSS concentration in the aeration tank was very high (Wastewater Engineering 4th edition)
## Microscopic Observation

<table>
<thead>
<tr>
<th>Type of microorganism</th>
<th>OSA System</th>
<th>Reference System II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Protozoa and metazoa (counts/mL)</td>
<td>absent</td>
<td>13,750</td>
</tr>
<tr>
<td>Actinomycete (CFU/mL)</td>
<td>&lt;100</td>
<td>1,260</td>
</tr>
</tbody>
</table>

**Ciliates in Ref II**

**Actinomycete**
## Nutrients Removal

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Reference system II</th>
<th>OSA system</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Influent</td>
<td>Effluent</td>
</tr>
<tr>
<td><strong>TN (mg N/L)</strong></td>
<td>60±1</td>
<td>55±1</td>
</tr>
<tr>
<td><strong>NH₄⁺ (mg N/L)</strong></td>
<td>35±0.5</td>
<td>0.04±0.5</td>
</tr>
<tr>
<td><strong>NO₂⁻ (mg N/L)</strong></td>
<td>0</td>
<td>0.05±0.02</td>
</tr>
<tr>
<td><strong>NO₃⁻ (mg N/L)</strong></td>
<td>1.6±0.3</td>
<td>55±1</td>
</tr>
<tr>
<td><strong>PO₄³⁻ (mg P/L)</strong></td>
<td>10±1</td>
<td>9.5±0.5</td>
</tr>
<tr>
<td><strong>COD (mg/L)</strong></td>
<td>330±10</td>
<td>12±2</td>
</tr>
</tbody>
</table>
COD Balance Batch Test Set-Up

- Reactor I: ORP: -250 mV
- Reactor II: ORP: -150 mV
- Reactor III: ORP: 0~ -20 mV

Measured Parameters:
- pH and ORP
- MLSS and COD
- Nitrite, Nitrate, Phosphate, Sulfate
- Organic Carbon content in the produced gas
(a) MLSS and COD

MLSS (g/L)

Initial, 9 10% Final, 7.9
Initial, 9 4% Final, 8.7
Initial, 9 1.2% Final, 8.9

(b) COD concentration (mg/L)

Initial, 35 Final, 15
Initial, 35 Final, 147
Initial, 35 Final, 512

Reactor I (ORP at -250 mV) Reactor II (ORP at -150 mV) Reactor III (ORP at -20 mV)
Typical Results

1. Initial and final COD (soluble + particulate) was estimated, their difference gives a total COD loss.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Initial Sample</th>
<th>Reactor I</th>
<th>Reactor II</th>
<th>Reactor III</th>
</tr>
</thead>
<tbody>
<tr>
<td>MLSS (mg/L)</td>
<td>8,906</td>
<td>8,254.0</td>
<td>8,678</td>
<td>8,898</td>
</tr>
<tr>
<td>MLVSS (mg/L)</td>
<td>8,194</td>
<td>7,593</td>
<td>7,966</td>
<td>8,129</td>
</tr>
<tr>
<td>SCOD (mg/L)</td>
<td>11,640</td>
<td>11,477</td>
<td>11,128</td>
<td>11,674</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>12165.3</td>
<td>13,453.9</td>
<td>13,894.5</td>
<td>14,218.6</td>
</tr>
<tr>
<td>TSS (mg/L)</td>
<td>8,129</td>
<td>8,593</td>
<td>8,966</td>
<td>9,129</td>
</tr>
<tr>
<td>VFA (mg as COD/L)</td>
<td>32</td>
<td>46</td>
<td>144</td>
<td>0</td>
</tr>
<tr>
<td>pH</td>
<td>7.3</td>
<td>7.5</td>
<td>6.5</td>
<td>7.0</td>
</tr>
<tr>
<td>NO₂⁻-N (mg/L)</td>
<td>1.4</td>
<td>1.6</td>
<td>1.8</td>
<td>2.0</td>
</tr>
<tr>
<td>NO₃⁻-N (mg/L)</td>
<td>2.5</td>
<td>2.7</td>
<td>2.9</td>
<td>3.1</td>
</tr>
<tr>
<td>PO₄³⁻-P (mg/L)</td>
<td>7.6</td>
<td>37.8</td>
<td>32.0</td>
<td>7.9</td>
</tr>
<tr>
<td>SO₄²⁻-S (mg/L)</td>
<td>7.2</td>
<td>3.6</td>
<td>6.3</td>
<td>7.0</td>
</tr>
<tr>
<td>Organic carbon (%) in the gas</td>
<td>-</td>
<td>2.03</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

2. COD consumptions in the corresponding reactions were estimated.

3. The amount of COD released as gaseous products was estimated.

Total COD removed in Step (2) and (3) was compared with the total COD loss of the system in Step (1).
## COD Balance

### Reactor I

| COD loss $S_{To-S_{Te}}$ (mg/L) | COD consumption (mg/L) | Unaccounted COD (%)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Denitrification</td>
<td>Sulfate reduction</td>
</tr>
<tr>
<td>536.32</td>
<td>163</td>
<td>7.2</td>
</tr>
<tr>
<td>431.32</td>
<td>159.22</td>
<td>10.4</td>
</tr>
<tr>
<td>476.48</td>
<td>166.36</td>
<td>9.6</td>
</tr>
</tbody>
</table>

### Reactor II

| COD loss $S_{To-S_{Te}}$ (mg/L) | COD consumption (mg/L) | Unaccounted COD (%)
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(1)</td>
<td>(2)</td>
</tr>
<tr>
<td>210.54</td>
<td>149.86</td>
<td>1.8</td>
</tr>
<tr>
<td>215.54</td>
<td>156.99</td>
<td>0.4</td>
</tr>
<tr>
<td>214.02</td>
<td>164.13</td>
<td>1.2</td>
</tr>
</tbody>
</table>
## Expected Sludge Production under Anaerobic and Aerobic Conditions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Removal of substrate under anaerobic condition</th>
<th>Removal of substrate under aerobic condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>COD consumed (mg/L)</td>
<td>Theoretical sludge production (mg/L)</td>
</tr>
<tr>
<td></td>
<td>Y (g VSS/g COD)</td>
<td>Y (g VSS/g COD)</td>
</tr>
<tr>
<td></td>
<td>Theoretical sludge production (mg/L)</td>
<td>Theoretical sludge production (mg/L)</td>
</tr>
<tr>
<td>Denitrification</td>
<td>163</td>
<td>48.9</td>
</tr>
<tr>
<td>Sulfate reduction</td>
<td>7.2</td>
<td>1.4</td>
</tr>
<tr>
<td>Phosphorus release</td>
<td>60.4</td>
<td>10.88</td>
</tr>
<tr>
<td>Gas production</td>
<td>266.8</td>
<td>13.34</td>
</tr>
<tr>
<td>Total</td>
<td>$\sum 497.4$</td>
<td>$\sum 74.5$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\sum 251.3$</td>
</tr>
</tbody>
</table>
Influent COD = 330 mg/L  
$\text{NH}_4^+ - \text{N} = 36 \text{ mg N/L}$  
$\text{NO}_3^- - \text{N} = 2 \text{ mg N/L}$  
$\text{PO}_4^{3-} - \text{P} = 10 \text{ mg P/L}$  
Biomass = 8.8 g/L  
COD < 30 mg/L  
Sludge wastage

Achromobacter, Acinetobacter, Agrobacterium, Alcaligenes, Arthrobacter, Paracoccus etc (Payne, 1981)

Halobacterium, Methanomonas.  

Most of these bacteria are able to use oxygen as well as nitrate or nitrite and also can carry out fermentation in the absence of nitrate or oxygen.

Biomass Decay  
Soluble COD (100%)

$\rightarrow$  
Denitrification (33%)  
Sulfate reduction (2%)  
Phosphorus release (15%)  
Gas production (50%)

Overall growth yield is significantly lower as compared to aerobic oxidation.

Biomass = 8.3 g/L  
COD = 70 mg/L  

$K_a = \frac{\text{SS loss due to decay}}{\text{amount of sludge}} = \frac{5 \text{ g/day}}{39.4 \text{ g}} = 0.12 \text{ /day}$
## Economic Aspect

<table>
<thead>
<tr>
<th>Cost increase</th>
<th>Sludge holding tank construction</th>
<th>Q:25,000m³/d, HRT 10h = 10,416 m³</th>
<th>NO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sludge Treatment and disposal cost</td>
<td>Additional for sludge pumping</td>
<td>1.02×10⁷ USD/year [2,3] (40USD/ton)</td>
<td>1.6 *10⁷ USD/year [2,3]</td>
</tr>
<tr>
<td>ORP control unit</td>
<td>Yes</td>
<td>NO</td>
<td></td>
</tr>
</tbody>
</table>

### Cost saving

| Disposal capacity (Landfill) | 210 m³/d | 330 m³/d |

Calculation based on 100,000 m³/d of flow rate for two systems


Hong Kong sewage has unique characteristics due to the use of seawater in toilet flushing: sulfate level ~ 500 mg/L, COD ~ 300 mg/L, and chloride ~ 6000 mg/L.

This sulfate level enables efficient sulfidogenic reactions under anaerobic condition, thereby resulting in a very low sludge yield (0.17) and eliminating oxygen demand for carbon oxidation in the subsequent treatment steps.

If sufficiently produced sulfide, mostly in dissolved form, could be utilized by “Autotrophic Denitrification” as the electron donor, sludge production can be further reduced up to 75% as compared to conventional aerobic-anaerobic processes.

Key point is to shut out carbon source completely from heterotrophic oxidation and denitrification that feature a high sludge yield (0.4-0.5).
**REACTION I – Heterotrophic Sulfate Reduction**

\[ Y = 0.17 \quad \text{COD} + \text{SO}_4^{2-} \rightarrow \text{H}_2\text{S} + \text{HS}^- \]

\[ Y = 0.5 \quad \text{COD} + \text{O}_2 \rightarrow \text{CO}_2 + \text{H}_2\text{O} \]

---

\[ Y = 0.4 \quad \text{COD} + \text{NO}_3^- \rightarrow \text{CO}_2 + \text{N}_2 \]

\[ Y = 0.15 \quad \text{H}_2\text{S} + \text{HS}^- + \text{NO}_3^- \rightarrow \text{SO}_4^- + \text{N}_2 \]

---

**REACTION II – Autotrophic Denitrification**
Proposed New Treatment System for Hong Kong Saline Sewage

COD Removal (Low sludge yield)

Nitrification (Low sludge yield)

Autotrophic denitrification (Low sludge yield)

Up to 75% excess sludge can be reduced than conventional aerobic-anaerobic processes
Advantages of Proposed Treatment

- Integration of sulfate reduction, autotrophic denitrification, and nitrification to achieve a very low sludge yield.
- Efficient COD removal and complete nitrogen removal are possible.
- Neither chemical nor physical forces are needed, oxygen demand is also reduced greatly. Thus, a very low operation cost can be expected.
Objective of this study

• To confirm efficiency of COD removal through sulfate reduction (Phase I)
• To study efficiency of autotrophic denitrification (AD) and its affecting factors (Phase I)
• To investigate performance of the integrated system for nitrogen and COD removal and excess sludge reduction (Phase II)
• To identify SRB and ADB bacteria (Phase II)
• Pilot study of the proposed system at sewage treatment works (Phase III)
Phase I Results

Reactor I (SR Bioreactor)

- Diameter = 10 cm, Height = 40 cm
- Volume = 3L
- Feeding synthetic sewage
  (TOC ~ 100mg/L, $\text{SO}_4^-$ ~ 500mg/L)
- Reactor II (Submerged AD Bio-filter)
  - Diameter = 10 cm, Height = 30 cm
  - Volume ~ 2.15 L
  - Feeding effluent from reactor I with external nitrate source (30 N-mg/L)
### Summary of Reactor I (SRB) Performance

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Hydraulic Retention Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>4 hrs</td>
</tr>
<tr>
<td>Influent Flow Rate (L/hr)</td>
<td>0.8</td>
</tr>
<tr>
<td><strong>TOC (mg/L)</strong></td>
<td></td>
</tr>
<tr>
<td>Influent (Average)</td>
<td>95</td>
</tr>
<tr>
<td>Effluent</td>
<td>16.3 ± 4.2</td>
</tr>
<tr>
<td>TOC Removal %</td>
<td>82.4 ± 0.1</td>
</tr>
<tr>
<td><strong>Sulfate (mg/L)</strong></td>
<td></td>
</tr>
<tr>
<td>Influent</td>
<td>480.4 ± 116.7</td>
</tr>
<tr>
<td>Effluent</td>
<td>220.3 ± 110.2</td>
</tr>
<tr>
<td>Sulfate Removal</td>
<td>260.1 ± 113.4</td>
</tr>
<tr>
<td><strong>Average organic loading rate</strong></td>
<td></td>
</tr>
<tr>
<td>kg TOC/m³-day</td>
<td>0.57</td>
</tr>
<tr>
<td><strong>Sludge Yield (g VSS / g COD)</strong></td>
<td>0.17</td>
</tr>
</tbody>
</table>
Theoretical COD / SO$_4^{2-}$ ratio for sulfidogenic reaction = 0.67
Experimental COD / SO$_4^{2-}$ Ratio ~ 0.65 – 0.93
Majority of COD was utilized by sulfate reducers
**Sulfur Balance in Reactor I**

**Measured Sulfur Source**

- **Influent**
  - Sulfate ~ 154.2 mg S/L

- **Effluent**
  - Sulfate ~ 64.2 mg S/L
  - Total dissolved sulfide ~ 72.5 mg S/L

- Sulfate Reduced = 90 mg S/L

- About 80% of the sulfide produced is in the dissolved form

- The remaining sulfur may include:
  - hydrogen sulfide gas
  - biomass sulfur
  - Metal sulfide
Performance of Reactor II (SADB)

HRT = 4hrs

Nitrate (N-mg/L)

Time (days)

Influent $\text{NO}_3^-$

Effluent $\text{NO}_3^-$
## Summary of SADB Performance

<table>
<thead>
<tr>
<th></th>
<th>Influent</th>
<th>Effluent</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \text{NO}_3^- (\text{N-mg/L}) )</td>
<td>33.8</td>
<td>1.3</td>
<td>96%</td>
</tr>
<tr>
<td>( \text{SO}_4^{2-} (\text{mg/L}) )</td>
<td>259.7</td>
<td>373.2</td>
<td></td>
</tr>
<tr>
<td>( \text{SO}_4^{2-} (\text{mg S/L}) )</td>
<td>86.6</td>
<td>124.4</td>
<td></td>
</tr>
</tbody>
</table>

- TOC removal < 5mg/L
- Theoretical Ratio: \( \text{SO}_4^{2-} / \text{NO}_3^- = 1.92 - 2.51 \text{ mg S/ mg N} \)
- Experimental Ratio: \( \text{SO}_4^{2-} / \text{NO}_3^- = 2.1 \pm 1.19 \text{ mg S / mg N} \)

Sufficient \( \text{NO}_3^- \) removal in \( \text{HRT} = 4 \text{ hrs} \)
Acknowledgement

• Following organizations should be acknowledged for financially supporting our work:

Hong Kong Research Grants Council
HKUST
Vivendi Water
The end

Thank you very much for your attention and patience.
Sludge Production and Landfill Capacity
Example of Hong Kong

Projected daily sludge production from water and wastewater treatment works in Hong Kong

Sludge production and landfill assimilative capacity in Hong Kong

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Sludge quantity (ton/day)</td>
<td>510</td>
<td>1200</td>
<td>1850</td>
<td>2120</td>
</tr>
<tr>
<td>Landfill capacity (ton/day)</td>
<td>1690</td>
<td>1500</td>
<td>1800</td>
<td>2050</td>
</tr>
</tbody>
</table>