Comparison of advanced oxidation processes for emerging contaminants removal
OUTLINE

• Introduction
• Background
  • Emerging Contaminants
  • Advanced Oxidation Processes
• Analytical Methods and Techniques
• Results
  • Process Engineering Parameters
  • Environmental Parameters
  • Economic and Social Parameters
• Discussion
INTRODUCTION

• Emerging contaminants are difficult to remove using traditional water and wastewater treatment methods
  • EDCs and PPCPs are potentially harmful to humans and wildlife
  • Advanced oxidation processes have been proven successful

• Multiple parameters must be considered when choosing the best method
  • Technical competence is not the only essential element

• Various AOPs were compared by ranking numerous parameters
  • The processes with the highest average ranking indicates most rational options
EMERGING CONTAMINANTS

- Relatively unknown
- Limited regulations
- Difficult to remove from water and wastewater
- Pose threat through introduction to aquatic environments and drinking water
- Occur on ng/L to μg/L scale
ENDOCRINE DISRUPTING COMPOUNDS (EDCS)

- Effect humans and aquatic wildlife
  - Reproduction
  - Growth
  - Metabolism
- Cause birth defects and tumors
- Introduced through urban and agricultural runoff, landfill leachates, and concentrated animal feeding operations

Table 1: Examples of EDCs

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bisphenol A</td>
<td>Preservative, Plastic Component</td>
</tr>
<tr>
<td>Butylated Hydroxyanisole</td>
<td>Food Preservative</td>
</tr>
<tr>
<td>DDT</td>
<td>Pesticide</td>
</tr>
<tr>
<td>Atrazine</td>
<td>Pesticide</td>
</tr>
<tr>
<td>17β-estradiol</td>
<td>Steroid Hormone</td>
</tr>
<tr>
<td>Estrone</td>
<td>Steroid Hormone</td>
</tr>
<tr>
<td>Testosterone</td>
<td>Steroid Hormone</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Heavy Metal</td>
</tr>
<tr>
<td>Mercury</td>
<td>Heavy Metal</td>
</tr>
<tr>
<td>Lead</td>
<td>Heavy Metal</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Heavy Metal</td>
</tr>
<tr>
<td>Musk Ketone</td>
<td>Fragrance</td>
</tr>
<tr>
<td>Hexabromocyclododecane</td>
<td>Flame Retardant</td>
</tr>
<tr>
<td>Caffeine</td>
<td>Stimulant</td>
</tr>
</tbody>
</table>
PHARMACEUTICAL AND PERSONAL CARE PRODUCTS (PPCPs)

• Widespread use
• Include:
  • Pharmaceutical drugs
  • Cosmetics
  • Fragrances
  • Food supplements
• Introduced mainly through sewage effluent and hospital and animal wastes
• Effects:
  • Chronic effects unknown
  • Antibiotic resistance

Table 2: Examples of PPCPs

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acetaminophen</td>
<td>Analgesic</td>
</tr>
<tr>
<td>Ketoprofen</td>
<td>Analgesic</td>
</tr>
<tr>
<td>Carbamazepine</td>
<td>Anticonvulsant</td>
</tr>
<tr>
<td>Ibuprofen</td>
<td>Anti-Inflammatory</td>
</tr>
<tr>
<td>Triclosan</td>
<td>Antibacterial</td>
</tr>
<tr>
<td>Ciprofloxacin</td>
<td>Antibiotic</td>
</tr>
<tr>
<td>Acidine</td>
<td>Antiseptic</td>
</tr>
<tr>
<td>Bezafibrate</td>
<td>Fibrate Drug</td>
</tr>
<tr>
<td>Dilantin</td>
<td>Antiepileptic</td>
</tr>
<tr>
<td>Nicotine</td>
<td>Stimulant, Insecticide</td>
</tr>
</tbody>
</table>
ADVANCED OXIDATION PROCESSES (AOPS)

- Effective in degrading emerging contaminants
  - Theoretically broken down into harmless components
  - Must consider degradation products

- Organic compounds are oxidized into CO$_2$, H$_2$O, and mineral acids

- Production of hydroxyl radicals that react easily with organic compounds due to unpaired electron

- Common oxidants
  - Ozone (O$_3$)
  - UV
  - Hydrogen peroxide (H$_2$O$_2$)
ADVANCED OXIDATION PROCESSES (AOPS)

- $O_3$
- $H_2O_2/O_3$
- $O_3/UV$
- $H_2O_2/UV$
- TiO$_2$ photocatalysis
- Fenton reaction
In order to accurately compare each process, performance was quantified. Rankings were assigned to each process for each parameter. Higher values indicate improved performance. Rankings were then averaged across each parameter category.

Table 3: Ranking System

<table>
<thead>
<tr>
<th>Value</th>
<th>Description</th>
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</thead>
<tbody>
<tr>
<td>5</td>
<td>Very High</td>
</tr>
<tr>
<td>4</td>
<td>High</td>
</tr>
<tr>
<td>3</td>
<td>Moderate</td>
</tr>
<tr>
<td>2</td>
<td>Low</td>
</tr>
<tr>
<td>1</td>
<td>Very Low</td>
</tr>
</tbody>
</table>
RESULTS

Process Engineering
Environmental
Economical and Social
PROCESS ENGINEERING PARAMETERS
MECHANICAL RELIABILITY

- Mechanical soundness
  - Least number of “moving parts”

- Ozone
  - Ozone generator and ozone gas diffuser require routine cleaning and inspection
  - Sparger fouling

- UV
  - Lamp replacement
  - Routine inspection

- Photocatalysis, Fenton
  - High maintenance
    - pH
    - Mixing
    - TiO₂, iron

Table 4: Mechanical Reliability Ranking

<table>
<thead>
<tr>
<th>Mechanical Reliability</th>
<th>AOP</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>H₂O₂/O₃</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>O₃/UV</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>TiO₂</td>
<td></td>
<td>2</td>
</tr>
<tr>
<td>Fenton</td>
<td></td>
<td>2</td>
</tr>
</tbody>
</table>
PROCESS RELIABILITY

• Ability to consistently produce adequate effluent
• Older techniques have a proven history of reliability
• Photocatalysis and Fenton process are more modern and less tested
  • TiO₂ slurry and precipitated iron effect effluent (requires removal)

Table 5: Process Reliability Ranking

<table>
<thead>
<tr>
<th>Process Reliability</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOP</td>
<td></td>
</tr>
<tr>
<td>O₃</td>
<td>4</td>
</tr>
<tr>
<td>H₂O₂/O₃</td>
<td>4</td>
</tr>
<tr>
<td>O₃/UV</td>
<td>4</td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td>4</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2</td>
</tr>
<tr>
<td>Fenton</td>
<td>2</td>
</tr>
</tbody>
</table>
FLEXIBILITY

- Ability to adjust to influent flow rate
- Older technologies have experience in adjusting conditions
  - Factor of safety has been implemented
- Chemical dosages can easily be adjusted
- Semi-batch reactors in photocatalysis and Fenton

Table 6: Flexibility Rankings

<table>
<thead>
<tr>
<th>Flexibility</th>
<th>AOP</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>H₂O₂/O₃</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>O₃/UV</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>TiO₂</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>Fenton</td>
<td></td>
<td>3</td>
</tr>
</tbody>
</table>
# ADAPTABILITY

- Ability to adjust to influent water quality
- Turbidity can effect UV penetration
- Ozone diffusers and UV lamp sleeves are subject to scaling
- Nitrate and iron reduce degradation efficiency of UV processes
- Photocatalysis produces hydroxyl radicals quickly
- Adapts well
- Fenton process is pH sensitive

## Table 7: Adaptability Rankings

<table>
<thead>
<tr>
<th>Adaptability</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOP</td>
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</tr>
<tr>
<td>O$_3$</td>
<td>3</td>
</tr>
<tr>
<td>H$_2$O$_2$/O$_3$</td>
<td>3</td>
</tr>
<tr>
<td>O$_3$/UV</td>
<td>2</td>
</tr>
<tr>
<td>H$_2$O$_2$/UV</td>
<td>2</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>3</td>
</tr>
<tr>
<td>Fenton</td>
<td>3</td>
</tr>
</tbody>
</table>
ENERGY CONSUMPTION

• Large contributor to total cost
• Relation to resource depletion, CO$_2$ emissions
• UV lamps
  • Energy intensive
  • Can be mitigated with proper chemical additions
• Onsite O$_3$ generation
• Fenton process only includes simple pumping requirements

Table 8: Energy Consumption Rankings

<table>
<thead>
<tr>
<th>Energy Consumption</th>
<th>AOP</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$_3$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>H$_2$O$_2$/O$_3$</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>O$_3$/UV</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>H$_2$O$_2$/UV</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Fenton</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>AOT</td>
<td>Source/Water</td>
<td>Initial Concentration (μg/L)</td>
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<tr>
<td>---------------</td>
<td>------------------------------</td>
<td>------------------------------</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Geosmin</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>UV/O₃</td>
<td>Fish Farm (spiked)</td>
<td>0.0042-0.0067</td>
</tr>
<tr>
<td>UV/H₂O₂</td>
<td>Fish Farm (spiked)</td>
<td>0.0042-0.0068</td>
</tr>
<tr>
<td>TiO₂/O₃</td>
<td>Synthetic</td>
<td>126</td>
</tr>
<tr>
<td>TiO₂/UVA/O₂</td>
<td>Synthetic</td>
<td>126</td>
</tr>
<tr>
<td>TiO₂/UVA/O₃</td>
<td>Synthetic</td>
<td>126</td>
</tr>
<tr>
<td>O₃</td>
<td>Post MBR Wastewater</td>
<td>-</td>
</tr>
<tr>
<td>O₃/UV</td>
<td>Post MBR Wastewater</td>
<td>-</td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td>Post MBR Wastewater</td>
<td>-</td>
</tr>
<tr>
<td>Photocatalysis</td>
<td>Post MBR Wastewater</td>
<td>-</td>
</tr>
<tr>
<td>UV/HOCl</td>
<td>Tap Water</td>
<td>1.00</td>
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<tr>
<td>UV/Clo₂</td>
<td>Tap Water</td>
<td>1.00</td>
</tr>
<tr>
<td>UV/H₂O₂ (UV mp lamps)</td>
<td>Tap Water</td>
<td>1.00</td>
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<tr>
<td>UV/H₂O₂ w/ RO</td>
<td>MF/RO Permeate</td>
<td>-</td>
</tr>
<tr>
<td>UV/H₂O₂ w/ MF</td>
<td>MF/RO Permeate</td>
<td>-</td>
</tr>
<tr>
<td>UV/H₂O₂ w/ AC</td>
<td>MF/RO Permeate</td>
<td>-</td>
</tr>
<tr>
<td>O₃ (2 mg/L)</td>
<td>WWTP Effluent</td>
<td>0.001-0.503</td>
</tr>
<tr>
<td>O₃ (4 mg/L)</td>
<td>WWTP Effluent</td>
<td>0.001-0.503</td>
</tr>
<tr>
<td>O₃ (6 mg/L)</td>
<td>WWTP Effluent</td>
<td>0.001-0.503</td>
</tr>
<tr>
<td>Process</td>
<td>Location</td>
<td>DOC (mg/L)</td>
</tr>
<tr>
<td>--------------------</td>
<td>---------------------</td>
<td>--------------</td>
</tr>
<tr>
<td>O3 (2 mg/L)/UV 65W</td>
<td>WWTP Effluent</td>
<td>0.001-0.503</td>
</tr>
<tr>
<td>O3 (4 mg/L)/UV 65W</td>
<td>WWTP Effluent</td>
<td>0.001-0.503</td>
</tr>
<tr>
<td>O3 (6 mg/L)/UV 65W</td>
<td>WWTP Effluent</td>
<td>0.001-0.503</td>
</tr>
<tr>
<td>UV(10W)</td>
<td>Hospital WW</td>
<td>0.4</td>
</tr>
<tr>
<td>UV(2.5W)</td>
<td>Hospital WW</td>
<td>0.4</td>
</tr>
<tr>
<td>0.83 gH2O2 L^-1</td>
<td>Hospital WW</td>
<td>0.4</td>
</tr>
<tr>
<td>1.11 gH2O2 L^-1</td>
<td>Hospital WW</td>
<td>0.4</td>
</tr>
<tr>
<td>Conventional GAC</td>
<td>NF/GAC Plants</td>
<td>-</td>
</tr>
<tr>
<td>Nanofiltration</td>
<td>NF/GAC Plants</td>
<td>-</td>
</tr>
</tbody>
</table>
OVERALL PROCESS ENGINEERING RESULTS

Table 9: Process Engineering Summary

<table>
<thead>
<tr>
<th>Process Engineering Parameters</th>
<th>O₃</th>
<th>H₂O₂/O₃</th>
<th>O₃/UV</th>
<th>H₂O₂/UV</th>
<th>TiO₂</th>
<th>Fenton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Reliability</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Process Reliability</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Flexibility</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>Adaptability</td>
<td>3</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>3</td>
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<tr>
<td>Energy Consumption</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>5</td>
</tr>
</tbody>
</table>

Table 10: Process Engineering Average Rankings

<table>
<thead>
<tr>
<th>AOP</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td>3.4</td>
</tr>
<tr>
<td>H₂O₂/O₃</td>
<td>3.6</td>
</tr>
<tr>
<td>O₃/UV</td>
<td>3</td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td>3.4</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.4</td>
</tr>
<tr>
<td>Fenton</td>
<td>3</td>
</tr>
</tbody>
</table>
Figure 1: Process Engineering Parameter Summary
ENVIRONMENTAL PARAMETERS
CONTRIBUTION TO CLIMATE CHANGE

• Reduction in factors leading to climate change is essential
  • Emission of Greenhouse gases:
    • Polar melt
    • Altered wind and ocean patterns
    • Sea level rise
    • Change in seasons

• CO₂ emissions
  • Related to energy consumption
  • Also released during oxidation

• High ranking indicates low emissions

Table 11: Climate Change Ranking

<table>
<thead>
<tr>
<th>Climate Change</th>
<th>AOP</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>H₂O₂/O₃</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>O₃/UV</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td>4</td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Fenton</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
EUTROPHICATION

- Excess nutrients (nitrogen and phosphorus) can cause harmful aquatic conditions
  - Hypoxia, algal blooms
- All discussed processes do not release additional nutrients
- Preceded or proceeded by specific nutrient removal process

Table 12: Eutrophication Rankings

<table>
<thead>
<tr>
<th>Eutrophication</th>
<th>AOP</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>H₂O₂/O₃</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>O₃/UV</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>TiO₂</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>Fenton</td>
<td>5</td>
<td></td>
</tr>
</tbody>
</table>
TERRESTRIAL AND AQUATIC TOXICITY/DEGRADATION PRODUCTS

- Chemicals and degradation products can influence effluent water quality
- Ozonation produces bromate
- UV has the advantage of no chemical usage
- Photocatalysis requires catalyst removal
- The Fenton process requires iron removal
- All processes potential form degradation products

Table 13: Toxicity Rankings

<table>
<thead>
<tr>
<th>Toxicity</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOP</td>
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</tr>
<tr>
<td>O₃</td>
<td>2</td>
</tr>
<tr>
<td>H₂O₂/O₃</td>
<td>3</td>
</tr>
<tr>
<td>O₃/UV</td>
<td>2</td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td>3</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2</td>
</tr>
<tr>
<td>Fenton</td>
<td>2</td>
</tr>
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</table>
## OVERALL ENVIRONMENTAL RESULTS

Table 14: Environmental Summary

<table>
<thead>
<tr>
<th>Environmental Parameters</th>
<th>AOPs</th>
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<th></th>
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<tbody>
<tr>
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<td>O₃</td>
<td>H₂O₂/O₃</td>
<td>O₃/UV</td>
<td>H₂O₂/UV</td>
<td>TiO₂</td>
<td>Fenton</td>
</tr>
<tr>
<td>Climate Change</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>4</td>
<td>2</td>
<td>5</td>
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<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
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<td>Toxicity</td>
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<td>3</td>
<td>2</td>
<td>3</td>
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<td>2</td>
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</tbody>
</table>

Table 15: Average Environmental Rankings

<table>
<thead>
<tr>
<th>AOP</th>
<th>Average Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
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<tr>
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<td>2.75</td>
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<td>O₃/UV</td>
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</tr>
<tr>
<td>H₂O₂/UV</td>
<td>3</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.25</td>
</tr>
<tr>
<td>Fenton</td>
<td>3</td>
</tr>
</tbody>
</table>
Figure 2: Environmental Parameter Summary
• Approval of public is critical

• Newer technologies tend to be viewed more negatively than commonly used processes
  • Older processes have had the opportunity to prove success through pilot scale and full scale operations
  • Photocatalysis and the Fenton process introduce inorganic compounds (TiO₂ and iron) that may be viewed negatively

<table>
<thead>
<tr>
<th>Public Acceptance</th>
<th>Ranking</th>
</tr>
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<tbody>
<tr>
<td>AOP</td>
<td></td>
</tr>
<tr>
<td>O₃</td>
<td>4</td>
</tr>
<tr>
<td>H₂O₂/O₃</td>
<td>4</td>
</tr>
<tr>
<td>O₃/UV</td>
<td>4</td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td>4</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2</td>
</tr>
<tr>
<td>Fenton</td>
<td>2</td>
</tr>
</tbody>
</table>
EASE OF USE

Table 17: Ease of Use Rankings

<table>
<thead>
<tr>
<th>Ease of Use</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>AOP</td>
<td>4</td>
</tr>
<tr>
<td>O₃</td>
<td>4</td>
</tr>
<tr>
<td>H₂O₂/O₃</td>
<td>4</td>
</tr>
<tr>
<td>O₃/UV</td>
<td>4</td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td>4</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2</td>
</tr>
<tr>
<td>Fenton</td>
<td>2</td>
</tr>
</tbody>
</table>

- More complicated techniques introduce more opportunity for error
- Skilled personal can increase operational costs
- Commonly used processes have had time to correct problems
- Newer technologies possess level of uncertainty
- Photocatalysis also requires difficult catalyst recovery
ECONOMIC FEASIBILITY

Table 18: Cost Summary

<table>
<thead>
<tr>
<th>AOP</th>
<th>Cost $/1000 gal</th>
<th>Amortized Annual Capital Cost</th>
<th>Annual O&amp;M Costs</th>
</tr>
</thead>
<tbody>
<tr>
<td>O$_3$</td>
<td>1.2023</td>
<td>7.55E+04</td>
<td>9.16E+04</td>
</tr>
<tr>
<td>O$_3$/UV</td>
<td>38.648</td>
<td>1.12E+06</td>
<td>4.25E+06</td>
</tr>
<tr>
<td>H$_2$O$_2$/UV</td>
<td>308.482</td>
<td>2.36E+06</td>
<td>4.05E+07</td>
</tr>
<tr>
<td>TiO$_2$</td>
<td>8648.79</td>
<td>2.51E+08</td>
<td>9.51E+08</td>
</tr>
<tr>
<td>Fenton</td>
<td>14.2829</td>
<td>-</td>
<td>1.99E+06</td>
</tr>
</tbody>
</table>

Table 19: Capital Cost Breakdown

<table>
<thead>
<tr>
<th>Factors</th>
<th>Percent (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Piping, Valves, Electrical</td>
<td>30</td>
</tr>
<tr>
<td>Site Work</td>
<td>10</td>
</tr>
<tr>
<td>Engineering</td>
<td>15</td>
</tr>
<tr>
<td>Contractor O &amp; P</td>
<td>15</td>
</tr>
<tr>
<td>Contingency</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>100</td>
</tr>
</tbody>
</table>

- Plant is working for the full year (52 weeks)
- Labor rate = $80/hour
- Analytical labor rate = $200/hour
- Electricity rate = $0.08/kWh
- Amortization occurs over 30 years at a rate of 7%
- Mahamuni & Adewuyi, 2014
ECONOMIC FEASIBILITY

• Can be considered one of the most important/limiting factors
• Largely related to energy consumption
• Older methods tend to be more cost efficient
• Photocatalysis shows very poor performance
  • UV lamps, expensive catalyst, maintenance

Table 20: Economic Feasibility Rankings

<table>
<thead>
<tr>
<th>Economic Feasibility</th>
<th>AOP</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td></td>
<td>5</td>
</tr>
<tr>
<td>H₂O₂/O₃</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>O₃/UV</td>
<td></td>
<td>4</td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td></td>
<td>3</td>
</tr>
<tr>
<td>TiO₂</td>
<td></td>
<td>1</td>
</tr>
<tr>
<td>Fenton</td>
<td></td>
<td>4</td>
</tr>
</tbody>
</table>
OVERALL ECONOMIC AND SOCIAL RESULTS

Table 21: Economic and Social Summary

<table>
<thead>
<tr>
<th>Economic and Social Parameters</th>
<th>AOPs</th>
<th>O_3</th>
<th>H_2O_2/O_3</th>
<th>O_3/UV</th>
<th>H_2O_2/UV</th>
<th>TiO_2</th>
<th>Fenton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Public Acceptance</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Ease of Use</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>4</td>
<td>2</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>Economic Feasibility</td>
<td>5</td>
<td>4</td>
<td>4</td>
<td>3</td>
<td>1</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

Table 22: Average Economic and Social Rankings

<table>
<thead>
<tr>
<th>AOP</th>
<th>Ranking</th>
</tr>
</thead>
<tbody>
<tr>
<td>O_3</td>
<td>4.33</td>
</tr>
<tr>
<td>H_2O_2/O_3</td>
<td>4.00</td>
</tr>
<tr>
<td>O_3/UV</td>
<td>4.00</td>
</tr>
<tr>
<td>H_2O_2/UV</td>
<td>3.67</td>
</tr>
<tr>
<td>TiO_2</td>
<td>1.67</td>
</tr>
<tr>
<td>Fenton</td>
<td>2.67</td>
</tr>
</tbody>
</table>
Figure 3: Economic and Social Parameter Summary
## COMPREHENSIVE RESULTS

Table 23: Comprehensive Rankings and Averages

<table>
<thead>
<tr>
<th>Parameters</th>
<th>AOPs</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>O_3</td>
</tr>
<tr>
<td>Mechanical Reliability</td>
<td>4</td>
</tr>
<tr>
<td>Process Reliability</td>
<td>4</td>
</tr>
<tr>
<td>Flexibility</td>
<td>4</td>
</tr>
<tr>
<td>Adaptability</td>
<td>3</td>
</tr>
<tr>
<td>Energy Consumption</td>
<td>2</td>
</tr>
<tr>
<td>Average Engineering</td>
<td>3.4</td>
</tr>
<tr>
<td>Climate Change</td>
<td>2</td>
</tr>
<tr>
<td>Eutrophication</td>
<td>5</td>
</tr>
<tr>
<td>Toxicity</td>
<td>2</td>
</tr>
<tr>
<td>Average Environmental</td>
<td>2.25</td>
</tr>
<tr>
<td>Public Acceptance</td>
<td>4</td>
</tr>
<tr>
<td>Ease of Use</td>
<td>4</td>
</tr>
<tr>
<td>Economic Feasibility</td>
<td>5</td>
</tr>
<tr>
<td>Average Economic and Social</td>
<td>4.33</td>
</tr>
<tr>
<td>Comprehensive Average</td>
<td>3.33</td>
</tr>
</tbody>
</table>
Figure 4: Comprehensive Parameter Category Comparison
POTENTIAL FOR DISPROPORTIONATE COMPARISON

• Analysis included both novel techniques and more commonly used processes
  • Older processes often had an advantage
  • The same study completed in the future could produce different results as methods progress

• Variation in constituent matrix
  • Different studies considered different contaminants
  • Some contaminants are more difficult to degrade than others
  • This gives unequal comparison
    • One process may work well for one contaminant, which should not be compared to a process degrading a more recalcitrant contaminant

• An examination of all processes with multiple sources would be advantageous
ADDITIONAL DATA REQUIREMENTS

Further study of economic feasibility was deemed necessary
- Breakdown of O&M costs revealed that photocatalysis is significantly more expensive due to electricity costs
- Degradation products are also a concern
  - Limited information available
  - Additional research is needed

Table 24: Cost Breakdown

<table>
<thead>
<tr>
<th>AOP</th>
<th>Part Replacement</th>
<th>Labor</th>
<th>Analytical</th>
<th>Chemical</th>
<th>Electrical</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₃</td>
<td>5.10E+02</td>
<td>4.54E+04</td>
<td>4.16E+04</td>
<td>0.00</td>
<td>4.06E+03</td>
<td>9.16E+04</td>
</tr>
<tr>
<td>O₂/UV</td>
<td>1.26E+06</td>
<td>5.91E+04</td>
<td>7.28E+04</td>
<td>0.00</td>
<td>2.01E+06</td>
<td>4.23E+06</td>
</tr>
<tr>
<td>H₂O₂/UV</td>
<td>2.78E+06</td>
<td>3.89E+04</td>
<td>3.12E+04</td>
<td>3.15E+07</td>
<td>6.17E+06</td>
<td>4.03E+07</td>
</tr>
<tr>
<td>TiO₂</td>
<td>2.95E+06</td>
<td>3.88E+04</td>
<td>3.12E+04</td>
<td>1.56E+04</td>
<td>6.56E+08</td>
<td>9.51E+08</td>
</tr>
<tr>
<td>Fenton</td>
<td>0.00</td>
<td>4.77E+04</td>
<td>3.12E+04</td>
<td>1.91E+06</td>
<td>0.00</td>
<td>1.99E+06</td>
</tr>
</tbody>
</table>

Figure 5: Comparison of O&M Costs
PROPOSED RANKING SYSTEM ALTERATIONS

• All parameters were considered to have equal worth
  • Some aspects may be more important than others (economic feasibility)
  • A study using parameters weighted for importance or relevance would be more accurate
    • Importance could vary from user to user, however

• Amount of detail was limited by five point scale
  • All rankings were relatively similar due to small numerical range
  • A ten point scale would allow for further detail and a more accurate study
CONCLUSIONS

- After comparing six AOPs across three parameter categories:
  - $\text{H}_2\text{O}_2/\text{O}_3$ presented the highest average ranking (3.45)
  - TiO$_2$ photocatalysis earned the lowest ranking (2.11)
    - This was largely due to high energy consumption and electricity costs

- The ranking system revealed both strengths and weaknesses for each process

- More established processes performed better overall
  - Reinforces need for pilot scale and full scale studies

- Confirms need for studies in energy consumption and economic feasibility

- Revealed faults in ranking system