Nutrient Removal and Activated Sludge from BPR to Anammox

Central States WEA

James L Barnard
Contents

- Discovery of the Activated Sludge Process
- Eutrophication problems
- Early history of biological nutrient removal
- Available technologies
- Nutrient recovery
- What does the future hold
Ye nymphs that reign o'er sewers and sinks,  
The River Rhine, it is well known,  
Doth wash your city of Cologne;  
But tell me, nymphs! what power divine  
Shall henceforth wash the river Rhine?

Samuel Taylor Coleridge
"A great city is the most powerful of stercoraries. To employ the city to enrich the plain would be a sure success. If our gold is filth, then our filth is gold....these fetid streams of subterranean slime which the pavement hides from you, do you know what all this is? It is the flowering meadow, it is the green grass, it is marjoram and thyme and sage, it is game, it is cattle, it is the satisfied low of huge oxen at evening, it is perfumed hay, it is golden corn, it is bread on your table, it is warm blood in your veins, it is health, it is joy, it is life."
Before activated sludge
Thanks for support of Worshipful Company of Grocers
Some main points from A&L papers and discussions

- Full nitrification was considered as producing a stable effluent
- Nitrification needed longer aeration time
- Nitrifiers growth decline with lower temperature
- Nitrifiers growth decline with pH
- The disappearance of nitrogen was a mystery
- The surplus sludge was unusually rich in phosphorus
- Granular sludge was formed in the batch reactors
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**Other historical highlights**

- **Activated Sludge Studies 1920-1922 State of Illinois - A.M Bushwell**
  - Discuss mystery of vanishing nitrogen – no proof but it was believed to escape as nitrogen gas
  - Adenay & Letts treated KNO$_3$ with septage and measured N$_2$ in some experiments – doubts remain
  - Scheringa – we must conclude that there is no data in the literature showing that nitrogen gas is formed to any great extent during the reactions of sewage purification
  - When nitrites and ammonia are both present "auto-oxidation reduction" may occur reducing nitrites to nitrogen gas (Anammox?)
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Historical highlights – cont.

- Buswell and Long (1923) reported that heterotrophic organisms could use nitrate in the absence of DO for respiration.
- Sawyer & Bradney (1945) investigating sludge rising problems in secondary settling tanks (SST’s).
- Christianson et al., (1956) reported on denitrification of an industrial waste.
- Finsen & Sampson (1959) used molasses as the electron donor in an upflow attached-growth system.
- Downing et al (1964) landmark paper on nitrifier growth rate for enabling design.
P is limiting in lakes
Microcystis Poisoning – Enrichment with Phosphorus

Dr. Anthony Turton, Keynote Address CSIR RSA November 18, 2008
Nitrogen enrichment

Olympic Sailing Craft in Algae at Qingdao
In 1989, 60% all streams in the Occoquan Watershed were classified as high-quality streams.

Up to 85% of the flow to the reservoir comes from Water Purification plants.
Recent studies showed that nitrates discharged to lake has benefits – Cubas et al Wat Res, Feb. 2014
The Activated Sludge Process

RIP
JAN 1 2000

Angel blowing a horn
Nutrient Removal
Physical/Chemical Treatment

Tertiary High Lime and Ammonia Stripping

- Lake Tahoe – Right and Pretoria Left
Ion Exchange for ammonia removal
Upper Occoquan plant
Biological Nitrogen Removal
Blue Plains plant – Washington DC  16 m³/s  
Effluent Nutrient Limits - Nitrogen < 3 mg/ℓ 

Annual chemical costs

FeCl₃  <> $8,000,000
Methanol     $7,154,000

With permission from Walter Bailey, Manager
Denitrification using internal carbon sources

ANOXIC AEROBIC

Mixed liquor recycle

2-4Q

Return sludge

Waste Sludge

MBE (MLE)

NH₃ < 0.5 mg/L
NOₓ < 6 mg/L
TN < 8 mg/L
Simple “MLE” with Denitrification Filter

Considerations:
- Removes additional NO$_3$-N
- External Carbon – Methanol
- Particulate Nitrogen Removed
- Usually not applied w/ 4-stage process
- High Costs

Effluent TN 6-8 mg/L

< 3 mg/L
High percent Denitrification

ORIGINAL BARDENPHO PROCESS

Q → ANOXIC → AEROBIC → ANOXIC → AEROBIC → CLARIFIER → NH₃ < 0.5 mg/L
NOx < 1.5 mg/L
TN < 3 mg/L

Carbon optional

MIXED LIQUOR RECYCLE

RETURN ACTIVATED SLUDGE

WASTE SLUDGE
Palmetto BNR plant (First in the US)

TN < 3 mg/L
TP < 1 mg/L
Escambia, FL

- 5-year average effluent TN = 2 mg/L!!
- NH$_3$-N = 0.1 mg/L
- Org-TKN = 0.7 mg/L
- NOx-N = 1.2 mg/L
Vienna plant

SIMULTANEOUS NITRIFICATION AND DENITRIFICATION

2nd Stage of A-B Process
70% TN reduction
Dublin Bay – View towards City

11.3 m³/s 260 mgd
Phosphorus
Biological Phosphorus Removal

- **Srinath et al 1959, India**
  - Plant removed more P than required to make new biomass

- **Levin and Shapiro 1965**
  - Phostrip process

- **Milbury et al (1971)**
  - Noted release of P in plug-flow plants

- **Barnard 1974**
  - Phosphorus removal in nitrifying plant
  - Correlation between nitrate and P removal
  - Phoredox process (3 stage Bardenpho), Fermenters

- **Research in South Africa, Europe and Canada**
Phosphorus removal observed with this configuration

At this stage design underway with JHB Goudkoppies plant
Goudkoppies plant completed - 1975

60th Birthday of the activated sludge process

85% N removal
90% P Removal

Anaerobic Zones added 1974
Fuhs & Chen (1975)

Anaerobic
- Poly P
- PHB
- HAc

Aerobic
- Poly P
- PHB

PO$_4$ from wastewater

Buchan City of Johannesburg
VFA from Fermenters

A. STATIC FERMENTER
- Raw Influent
- PST
- VFA
- Anaerobic Zone
- Optional Recycle
- To Digesters

B. ACTIVATED PRIMARY
- Raw Influent
- VFA
- Anaerobic Zone
- To Digesters

C. FERMENTER THICKENER
- Raw Influent
- PST
- Anoxic
- Fermenter
- Thickener
- To Digesters

Images: Pictures of the systems described in the text.
Reduced Footprint
IFAS Example Schematic

Influent

Anoxic (No Media)

Aerobic (20-65% Media)

Aerobic (20-65% Media)

ML Recycle

Clarifier

Effluent

RAS

WAS
The Broomfield IFAS Basins
Biological phosphorus removal still possible

![Bar chart showing concentration (mg-P/L) from July to August with months on the x-axis and concentration on the y-axis. The chart indicates that concentration varies throughout the months, with peak concentrations in March and low concentrations in June and July.]
Advanced Membrane BNR

[Diagram showing a process flow with stages labeled Anaerobic, Anoxic, Aerobic, and Post Anoxic, with an inset showing a membrane tank and water sludge.]
Resource Recovery
Possible Resource Recovery

- Urine Separation
- Influent
- Protein Recovery
- BNR
- Power
- Digester
- Fertilizer
- Composting
- Cooling Towers
- Potable Water
- Irrigation
- Heat Recovery
- Protein Recovery
## Comparative Energy Costs

<table>
<thead>
<tr>
<th>Energy used for</th>
<th>kWh/c/a</th>
</tr>
</thead>
<tbody>
<tr>
<td>BNR Wastewater Treatment</td>
<td>40</td>
</tr>
<tr>
<td>Switching one lamp to LED</td>
<td>102</td>
</tr>
<tr>
<td>Pumping water from north to south of California</td>
<td>355</td>
</tr>
<tr>
<td>Household per person (2 persons)</td>
<td>14,000</td>
</tr>
</tbody>
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Most of the Energy in WWTP required for Nitrification
Nitrogen Recovery

- There is no shortage of nitrogen
- Feedstock is natural gas
- Energy cost of manufacture is \( \pm 12 \text{ kWh/kg N} \)
- Cost-effective N recovery only from return streams with concentration varying between 800 and 3000 mg/L
- Must compete with energy of nitrification/denitrification
- Anammox process made this more difficult
Clinoptilolite Ion Exchange for Ammonia Recovery
Ammonia Stripping and capture from return streams - Oslo Norway From Evans 2009

HNO₃ used for absorption
Lower portion of adsorption column

Final Product 54% NH₄ NO₃
90% nitrogen removal
Anamnox
Anammox (Kuenenia stuttgartiensis)

ANaerobic AMMonia OXidation

- Very slow growing
- Temperature sensitive
- Form granules or attach on to plastic media
- Ideal for Hi temperature, concentrated return streams
- Inhibition of NOBs important
- Some nitrate formation inevitable
- Uses <40% of energy for N/DN
- Need no COD for denitrification
- Further reduction of energy when used in Mainstream
### Anammox and Wastewater Treatment

- **NH$_4^+$**
- **N$_2$**
- **NO$_2^-$**

#### Denitrification

<table>
<thead>
<tr>
<th></th>
<th>Conventional BNR</th>
<th>Partial Nitritation / Anammox</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (kWh/kgN)</td>
<td>2.3</td>
<td>1</td>
</tr>
<tr>
<td>Methanol (kg/kgN)</td>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>Sludge Production (kgVSS/kgN)</td>
<td>0.5-1.0</td>
<td>0.1</td>
</tr>
<tr>
<td>CO$_2$ emission (kg/kgN)</td>
<td>&gt;4.7</td>
<td>0.7</td>
</tr>
<tr>
<td>Total costs ($US/kgN)</td>
<td>4.1-6.9</td>
<td>1.4-2.8</td>
</tr>
</tbody>
</table>

Data reprinted from *Biological Wastewater Treatment: Principles, Modeling and Design*
At WWTPs with centralized dewatering facilities the centrate contributes up to 40% of the total nitrogen load. Specialized anammox bacteria in separate centrate treatment can be used to take this N load off of the mainstream.
Marketed Anammox Configurations

- Sequencing Batch Reactor (SBR)
  - DEMON®
  - CLEARGreen™
- Upflow Sludge Blanket (UASB)
- ANAMMOX®
  - Moving Bed Biofilm Reactor (MBBR)
- ANITA-Mox™
Strass Austria plant energy self-sufficient

- Plant produces surplus energy
- Hi-rate/Nitrification (A-B) plant
- 60% BOD removal in primaries
- SND in second stage
- Anammox in return stream
- Digester gas power gen.
- Surplus Anammox to main stream
- Cyclones on main stream
- Adding FOG to digesters
Phosphorus Recovery
THE DISAPPEARING NUTRIENT

Phosphate-based fertilizers have helped spur agricultural gains in the past century, but the world may soon run out of them. Natasha Gilbert investigates the potential phosphate crisis.
Phosphorus is a limited resource

Together with nitrogen and potassium, phosphorus is a crucial ingredient in fertilizer. It is extracted from phosphorus-rich rock in the form of phosphate. Morocco, China, South Africa and the United States hold 83 percent of the world’s easily exploitable phosphate rock and contribute two-thirds of the annual phosphorus production (circles, below). At current rates of extraction (bars, below), the U.S. reserves are projected to last 40 years. Global availability of phosphorus remains.

Once the reserves are depleted, economical supplies may have to be replaced by expensive substitutes and market disruptions, leading despite the incentives for increased production after the price spiked up because of shortages.

From D. Vacarri “The looming phosphorus crisis” Scientific American Inc June 2009
Worse than Climate Change

Concept of Complete Phosphorus Recovery

Adapted from Petzet & Cornel 2011
Asimov on Chemistry

About Phosphorus

“We may be able to substitute nuclear power for coal power, and plastics for wood, and yeast for meat, and friendliness for isolation, but for phosphorus there is neither substitute nor replacement.”

“Our greatest responsibility is to be good ancestors."   Salk
Phosphorus recovery

Also recovers up to 20% of nitrogen

Struvite
Mg.NH₄.PO₄·6 H₂O
100% Recovery of Incinerator P
Noord-Brabant, Holland
Granular Activated Sludge
Granular Sludge

Methanogenic

Sulphate Reducing

Anammox

Aerobic

With permission Prof. Mark van Loosdrecht
With permission Prof. Mark van Loosdrecht
Granule: Biofilm or Activated Sludge

Microbiology: Biofilms
Process Engineering: Activated Sludge

With permission Prof. Mark van Loosdrecht
Pilot plant

Influent

Decant

NEREDA®
GANSBAAI SOUTH AFRICA

COD in 800-10,000 ppm → COD out < 100 ppm / N in 150-200 ppm → N out < 10 ppm
P(dissolved) in 15-25 ppm → P out < 1.0 ppm / SS out < 20 ppm

SVI< 40 mL/g
MLSS 8 g/L
SS effluent < 10 mg/L
CLOSE UP VIEW

After 3 min settling
MUNICIPAL WWTP GARMERWOLDE

- Extension of A-B system (2005)
- Extremely sensitive project with many participants over the years
- Design called for alternatives to treat 40% of plant load
- Nereda was lowest of 20 tenders considered by the consultants

Information supplied by DHV
GRANULES IN GARMERWOLDE PLANT

Photos by James L Barnard
Laboratory-scale units presently used at Lawrence and Leawood KS

- Granular sludge observed in Lawrence plant
- Very good settling in Leawood plant
- Used for proof of concept
Urine in Wastewater

Volume of Wastewater

- Yellow-water (Urine+flushwater): 80%
- Brownwater (Faeces+flushwater): 20%
- Greywater (shower, kitchen, etc): 1%

"N" Content

- 80%

"P" Content

- 40%
- 50%
Dual flush toilet
Apartments in Hong Kong

November 12-13, 2014
Backyard garden

Kampala Uganda
Do-it-yourself Fertilizer

http://www.submersibledesign.com/drinkpee/diy.html
Future vegetable gardens?
Summary

- Expect to see the activated sludge process around for some time in some form – as, IFAS, MBR, GAS or with membrane filtration for water re-use
- More emphasis on resource recovery N and P
- More emphasis on saving water as the main driver for reducing energy cost – indigenous living
- Emphasis on energy self-sufficiency but the environment is our most serious concern
- Urine separation as a means of sustainability in countries that are catching up and in new developments
- Greatly improved membranes for solids liquid separation and water recovery
Discussion