Algae Bioreactors as a Cost-Effective Approach for Enhanced Nutrient Removal – Approaching it From All Sides

Tuesday, April 29th, 2014

1:00 – 3:00 pm Eastern

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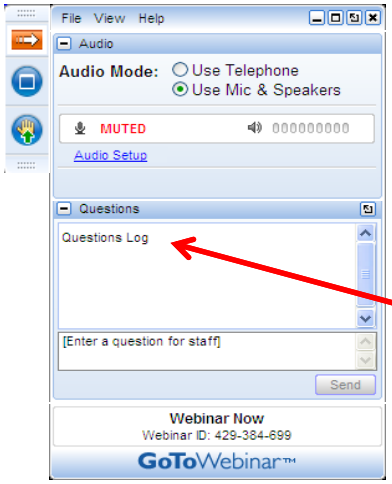

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Today's Moderator

Amit Pramanik, PhD, BCEEM
Senior Program Director, WERF

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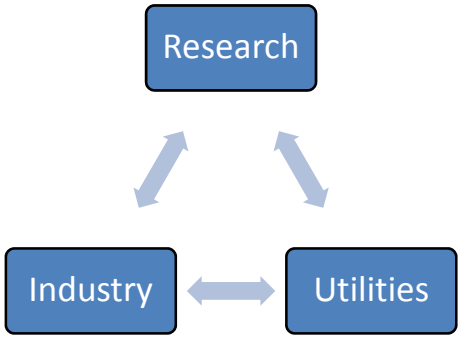
Algae Bioreactors – A Cost-Effective Approach for Enhanced Nutrient Removal

Approaching it From All Sides



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Algae Bioreactors – Approaching it from all sides

- Part I: The research side - Enhanced nutrient removal using encapsulated algae in a waste stream, *Dr. Katherine C. Filippino and Dr. Margaret R. Mulholland (Old Dominion University)*
- Part II: The engineering side - Algal nutrient removal vs conventional denitrification processes, an evaluation matrix, *Dr. Christopher Wilson (Greeley and Hansen)*
- Part III: The utility side - In-plant benefits of algal nutrient removal, *Dr. Charles Bott (Hampton Roads Sanitation District, VA)*

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Part I: The research side

Background and Introduction

Dr. Margaret R. Mulholland,
Old Dominion University

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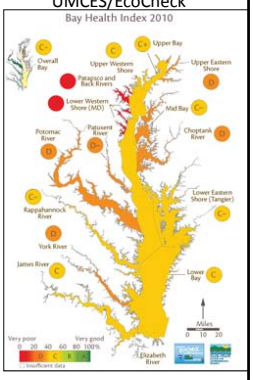
Part I: The research side

Turning a problem into an opportunity

Map courtesy UMCES/EcoCheck



Chesapeake Bay watershed getting 'pollution diet', EPA set total maximum daily loads (TMDLs)

- States creating Watershed Implementation Plans (WIP) to comply
- Sectors targeted: wastewater resource recovery facilities (WRRFs), agriculture, forest, urban/suburban stormwater runoff, on-site systems (septic), and air

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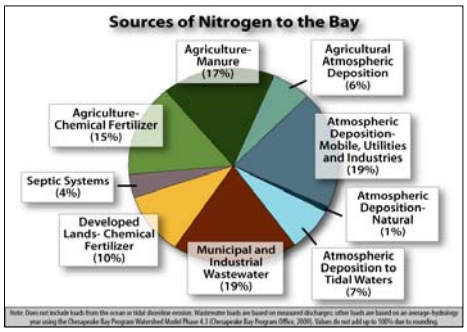
Part I: The research side

Turning a problem into an opportunity

- Point sources like WRRFs are easier to target for nutrient reductions compared to non-point sources (urban, suburban, agricultural run-off)
- WRRFs are regulated point sources with discharge permits already in place



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Turning a problem into an opportunity

- Eutrophication of water ways leads to unbalanced algal growth
- Algae need nitrogen and phosphorus to grow

$$106\ CO_2 + 16\ HNO_3 + H_3PO_4 + 78\ H_20 \rightleftarrows C_{106}H_{175}O_{42}N_{16}P + 150\ O_2$$

- Rather than bringing the nutrients to the algae, bring the algae to the nutrients

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State of Existing Technology & Current Research

Dr. Katherine C. Filippino,
Old Dominion University

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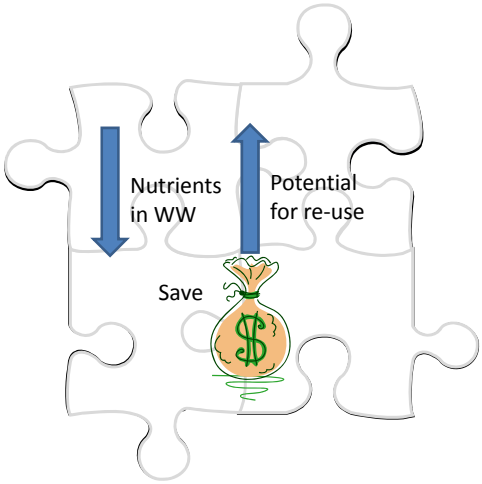
Part I: The research side

State of Existing Technology



Part I: The research side

State of Existing Technology

- Aquaculture, agriculture, livestock, and small community wastewater facilities have used algal nutrient removal

Existing technologies:

- Algal ponds
  - Advanced Integrated Wastewat Pond Systems (AIWPS) = Settlin ponds + High rate algal ponds (HRAPs)
  - AIWPS + Rotating biological contactors (RBCs)
  - Focus on removal of ammonium (NH_4^+)
  - Require space and sunlight

State of Existing Technology

- Biofuels sector – significant advancements in bioreactor development, no strict focus on nutrient removal
  - Photo-bioreactors – open or closed

- Immobilization techniques developed for variety of purposes
  - Alginate, carrageenan, PVA gels
  - Beads, screens, biofilms

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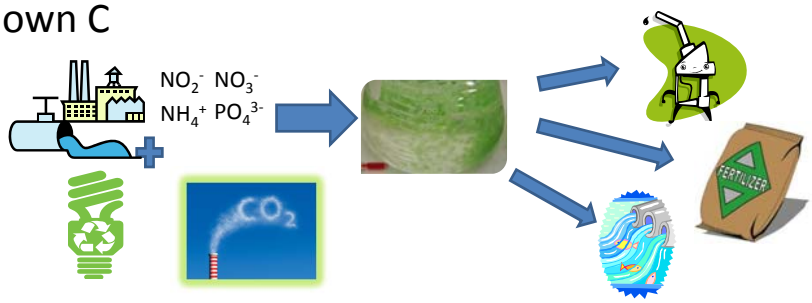
State of Existing Technology

- Algae grow fast, use N in high quantities, use many forms of dissolved N and P, and make their own C



- **Municipal wastewater treatment - potential for enhancing or replacing traditional bacterial post-denitrification processes**

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Phycoremediation - Challenges

- WRRF footprint
  - Existing WRRF reactors are large and deep = light limitation for algal growth
- Natural temperature and pH fluctuations in WRRFs
- Prevent "wash out" of algal biomass – Growth > HRT
- Separation and/or harvesting of algae and treated WW

Research Solutions

- Identify algae – fast growing, high rates of N and P removal
- Immobilize algae to facilitate separation
  - Natural polymers – sodium alginate
  - Apply as a biofilm
- Optimize light availability
  - Surface vs submerged

Research Solutions

- Monitor pH
  - Introduce inorganic C source to ensure no C limitation
  - Could come from in-plant source
- Monitor temperature
- Monitor N:P ratios
  - Algae grow best when N:P ≈ 16, is this flexible?
  - Could help relax upstream P reductions
- Grow under continuous flow conditions

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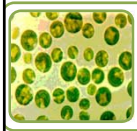
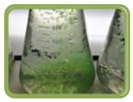
Research Approach



Algal Selection

- Mixed algal suspension from WRRF
- *Chlorella* spp.
- *Desmodesmus* spp.



Algal Immobilization

- Embed as beads, strands, or layers in sodium alginate
- Attach to biofilm carriers

Optimization

- Temperature 15, 20, 25, 30˚C
- Light supply – surface, submerged wavelength specific LEDs, side-emitting fiber optics
- Mixing/aeration
- pH/CO_2 concentrations Important
- P requirements N:P varied

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Parameters Measured

- Doubling time
  - Growth of algae via fluorescence, exponential fit
  - DT (d) = ln(2) / gr (d^{-1})
- Nutrient removal efficiency
  - Nutrients measured on Astoria Pacific AA
  - Removal efficiency calculated as % based on the rate of decrease over time
- pH monitored using meter
  - CO_2 bubbled in automatically to maintain pH between 7 and 7.5

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Preliminary Results

- First experiments focused on growth of algae on effluent in 'batch' mode (no flow)
- Followed by encapsulating algae in sodium alginate beads
  - Doubling times ~ 2 – 4 d, N removal measured in days
- Continuous flow experiments – modulated HRT, light, CO_2, N:P, bead:effluent

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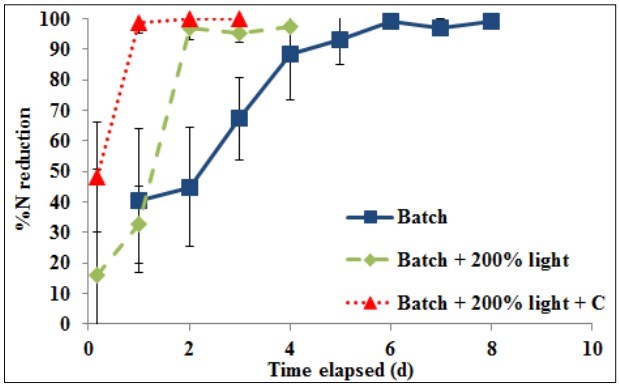
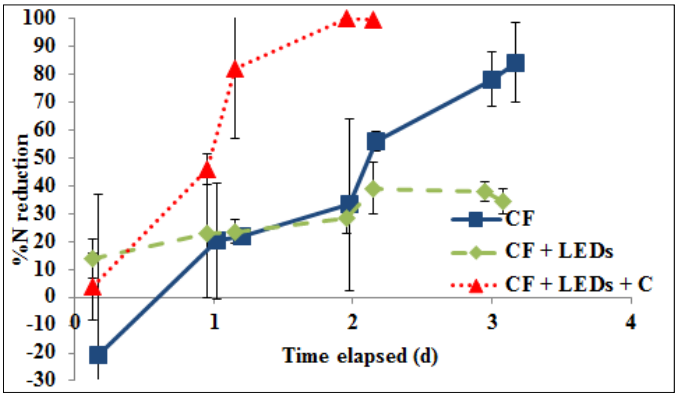
Results: Batch, encapsulated algae



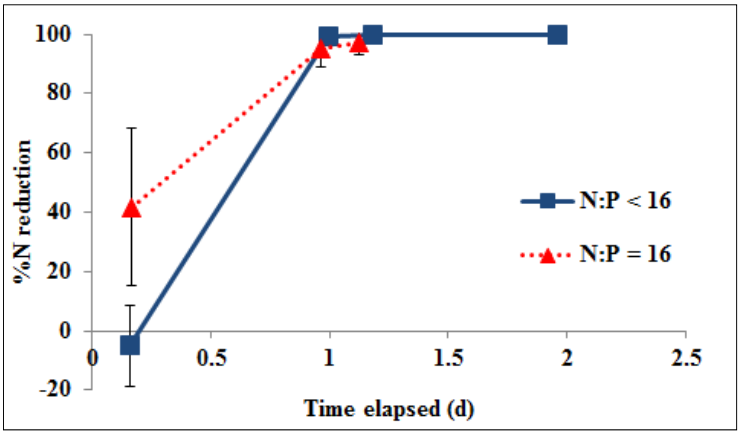
- Batch + 200% light + C yields highest % N removal

Results: Continuous flow



- Continuous flow (CF) + LEDs + C yields highest % N reduction (HRT = 12 h)

Results: Continuous flow



- Have high % reduction with decreased HRT (6.5 h), NO_3^-+NO_2^- : PO_4^{3-} ratio can be flexible

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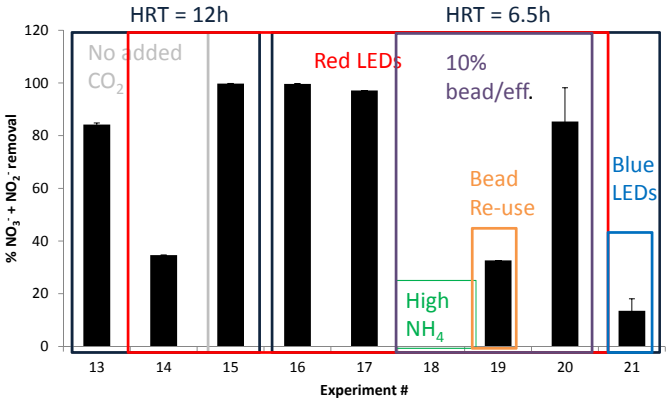
Research Findings



Optimal parameters = red LEDs, + CO_2, no bead re-use, 10 - 32% bead:eff, N:P can vary

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Research Findings

- *Chlorella* is versatile
  - Grows fast at a range of temperatures (15-30°C)
  - Grows on all forms of N, N:P must be evaluated, but always had growth with large range of N:P (2 – 100)
- Successful N removal (100%) at HRTs of 6.5 - 12 h
- Improve N removal by adding wavelength specific submersible LEDs

Part I: The research side

Research Findings

- Controlling pH important, optimal range = 7 – 7.5
  - Prevent CO_2 limitation of algal growth
  - Could be a good use of plant CO_2
- Scale-up designs must consider all variables for successful N removal
- Pilot-scale is the next stop, must take into consideration the engineering side…

Engineering Evaluation

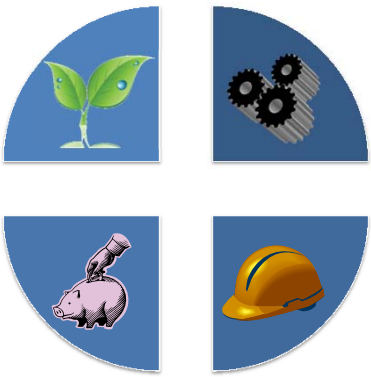
Dr. Chris Wilson,
Greeley and Hansen

The purpose of a comparative evaluation matrix for innovative technologies

- How does a utility justify investigating a high potential innovative technology that may pose higher perceived risk than a well-proven one?
- We a strategy to comparatively assess technologies at various levels of development based on inherent strengths and weaknesses
  - Technologies have similar purposes in WRRF
  - Need to acknowledge:
    - Potential of Innovative technologies relative to status quo
    - Risk of innovative technologies relative to status quo
- Focus on communication rather than decision making

Development of the comparative evaluation matrix – Multi-attribute Utility Analysis

- Technologies analyzed on 4 key bases:
  - Technical Basis
  - Operational Basis
  - Financial Performance
  - Sustainability



Technical basis criteria assess technology performance risks and implementation

- Technical basis categories:
  - Physical process issues
  - Scientific validation
  - Technological maturity
  - Technological verification
  - Project team requirements
  - Performance

Operational basis criteria assess suitability to WRRF environment

- Operational basis categories:
  - Compatibility with wastewater
  - Process control requirements
  - Maintenance requirements
  - › Labor specialization requirements
  - › Health and safety considerations

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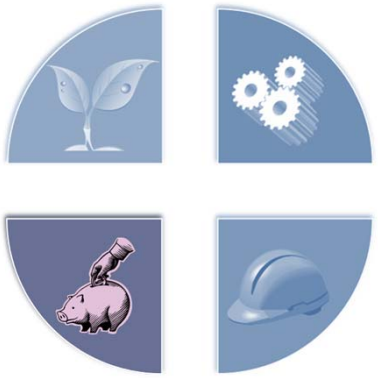
Financial performance criteria assess life-cycle cost factors

- Financial basis categories:
  - Operating cost elements
  - Capital cost elements
  - Cost risk factors
  - › Development cost mitigation
  - › Cost recovery opportunities



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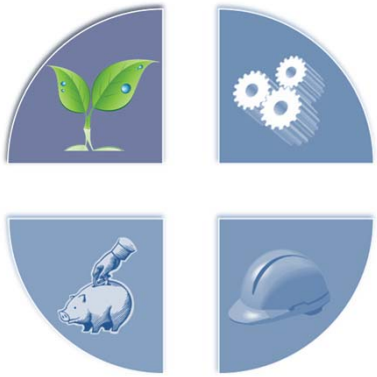
Sustainability criteria assess opportunities for net resource minimization

- Sustainability categories:
  - Carbon footprint
  - Resource efficiency
  - Beneficial product reuse



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Each criterion is assessed collaboratively on a 5 point (qualitative) scale

- For example, proven technologies may rank higher on technical basis criteria
- For example, under *Technical Basis* -

Denitrification Filters with MeOH

C. Technological Maturity	1	2	3	4	5
Level of Development	Well developed theory or concept, but no physical process available	Proof of concept achieved using bench-scaled or demonstration units	Mature technology proposed to transfer from another field	First generation technology having undergone operational or in-field mechanical optimization	Second or later generation technology with full-scale experience and optimization
Ability to Apply Risk Assessment	No information of risks available for this or similar technologies	Documentation of risk assessment for one or more similar technologies is available	Risks well understood for technology, but no framework exists for quantifying	Risks well understood for technology and quantified	Risk mitigation strategies developed leading to technical optimization

Naturally Immobilized Algae

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Each criterion is assessed collaboratively on a 5 point (qualitative) scale

- For example, novel technologies may rank higher on sustainability criteria
- For example, under *Sustainability* -

Denitrification Filters with MeOH

C. Beneficial Product Reuse	1	2	3	4	5
Nutrient Recycling	Converts nutrients to a form and releases them in way that is detrimental to the environment	Converts nutrients to a benign form that is released to the environment	Sequesters a fraction of nutrients into a beneficially reusable form while releasing a fraction in a benign form	Sequesters nutrients in a form that requires additional processing prior to beneficial use	Sequesters nutrients in a form that is directly usable as a nutirent source such as feed or fertilizer
Generation of High Value Chemical Feedstocks	Produces no beneficial byproducts that may be recovered	Produces byproducts that have limited market value or potential for beneficial use out of the WWTP	Produces precursors to valued chemcial feedstocks that require additional conversion prior to use	Produces valued chemical feedstocks that require cleanup and separation prior to use	Produces valued chemical feedstocks that are directly usable

Naturally Immobilized Algae

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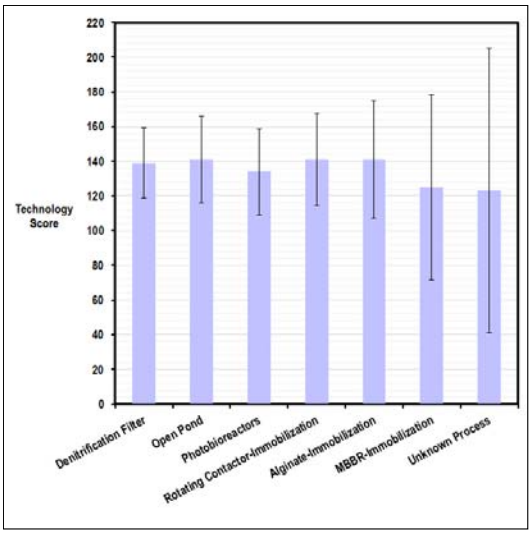
Overall Technology



- Standard error reflects relative uncertainty for each process (Unknown Process)
- Denit. Filters rate well because they are at a higher level of development
- Algal techniques rate high also because of sustainability factors

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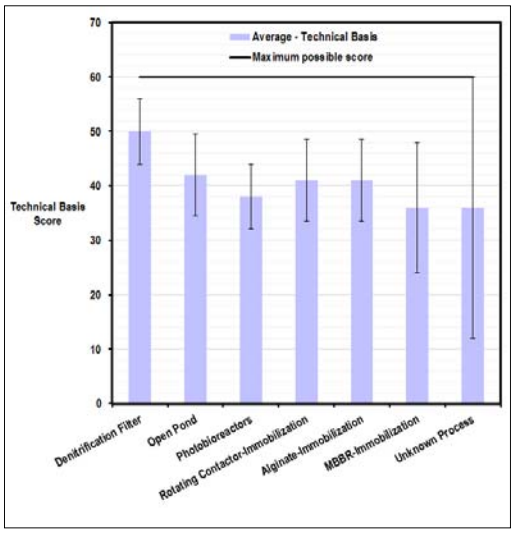
Evaluation Matrix



Technical

- Denitrification rated highest, less unknowns
- Open pond, RBCs, & alginate immobilization – equal scores
- Immobilization has benefit of small footprint, integration with existing WRRFs, scale-up potential, effluent quality, and nutrient removal efficiency

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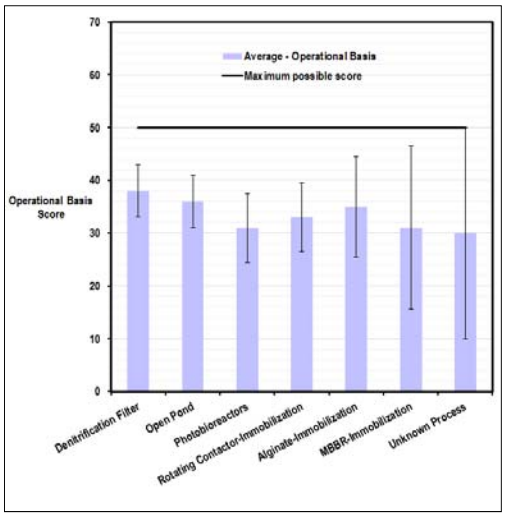
Part II: The engineering side

Evaluation Matrix



Operational

- Highest scores with denit., open ponds, and algal immobilization
- High marks for immobilization due to availability of parts and equipment, and low-levels of hazardous exposure

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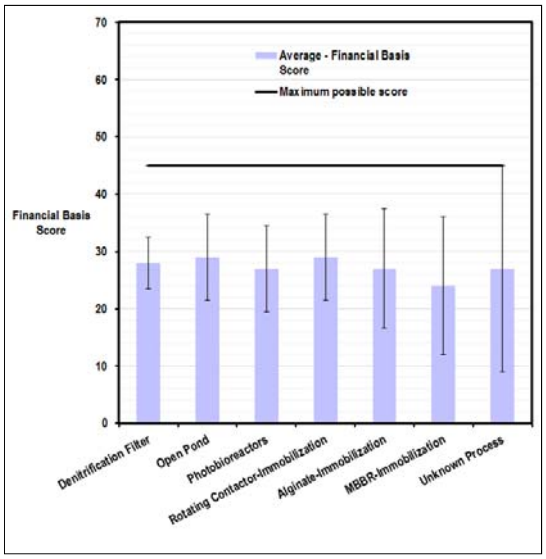

Financial

- Very similar rankings, larger error with unestablished, bench-scale technologies
- Greatest costs for alginate scale-up: LEDs (but use less energy than fluorescent), alginate (could be re-usable)

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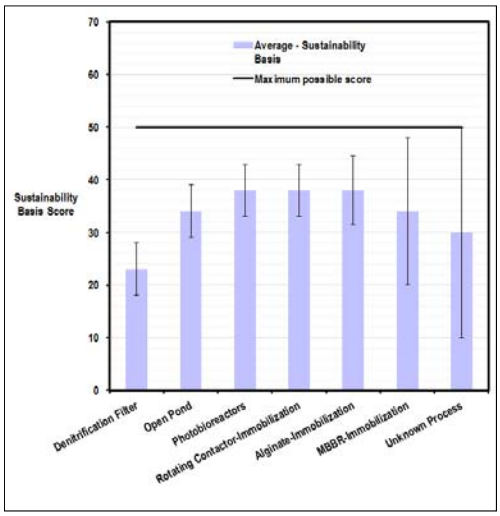
Part II: The engineering side

Evaluation Matrix



Sustainability

- Highest for photobioreactors, RBCs, and alginate immobilization
- Algal technologies can have net C sequestration, low CO_2 emissions, potential for renewable energy production, sequester nutrients, produce precurors to valued chemical feedstock

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Evaluation Matrix: Conclusions

- Denitrification filter rates highest
  - ➢The most established technology
- Algal technologies rate high
  - ➢Because of their sustainability

    - C emissions, energy consumption, potential for renewable energy production, and opportunity to re-use and recycle algal biomass
  - ➢Need piloting and development at larger scales of operation

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Part II: The engineering side

Scale-up requires targeted research where risks or outstanding questions exist

- Expansion to pilot scale technology at full-scale WRRF

Parameter	Target	Requirements	Monitoring	Costs	Benefits
HRT	Algal growth rate ≥ HRT at 100% nutrient removal	Continuous flow system	Flow rate, biomass in waste stream (washout), nutrient concentrations	Maintenance	Flexibility
pH	pH = 7 – 7.5	CO_2, or other inorganic C source	pH, algal growth, nutrients	Gas transfer issues	C consumption and in-plant C recycling
N:P	N:P = 16	Additional P (if necessary)	N and P concentrations relative to algal growth	Adding P	Relax upstream P removal if applicable
Light	Algal growth rate ≥ HRT at 100% nutrient removal	Submersible LEDs	Algal growth rates, nutrients	Start-up costs for lights, maintenance	Use of large, deep tanks, minimum energy requirement
Algae separation	No algae present in final effluent	Screens/separation technology	Biomass in waste stream	Maintenance	Nutrient recovery
Drying techniques	Dried biomass	Heat and/or ambient temperatures	Dried biomass	Energy demand necessary for drying	Final product valuable for nutrient recovery

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Part III: The utility side

Utility Perspective

Dr. Charles Bott, *Hampton Roads Sanitation District, VA*

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Part III: The utility side

Utility Perspective

- Most algae research has considered:
  - Large scale algae culture
  - Biofuel production
  - Ponds, Raceways, photo-bioreactors
  - Lots of land…
- Must also consider:
  - Urban setting - no change in WRRF footprint
  - Permit compliance – reliability
  - Good process engineering – treatment is the first priority

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Considerations…

- Possible use for polishing
- Relax P removal upstream
- Re-route CO_2 emissions
  - Incinerator
  - power plant
  - upstream bacterial process
- Provide appropriate light source…
- Reactor must be reasonable in size…
- O&M costs must be competitive with conventional post-denitrification process

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Pilot Testing…

- Size = 50 – 200 gal
- HRT < 6 hrs
- Traditional bioreactor designs
- Consider alginate beads and algae growing as biofilm
- Evaluate harvesting, drying, and nutrient recovery options
- Investigate light scale-up

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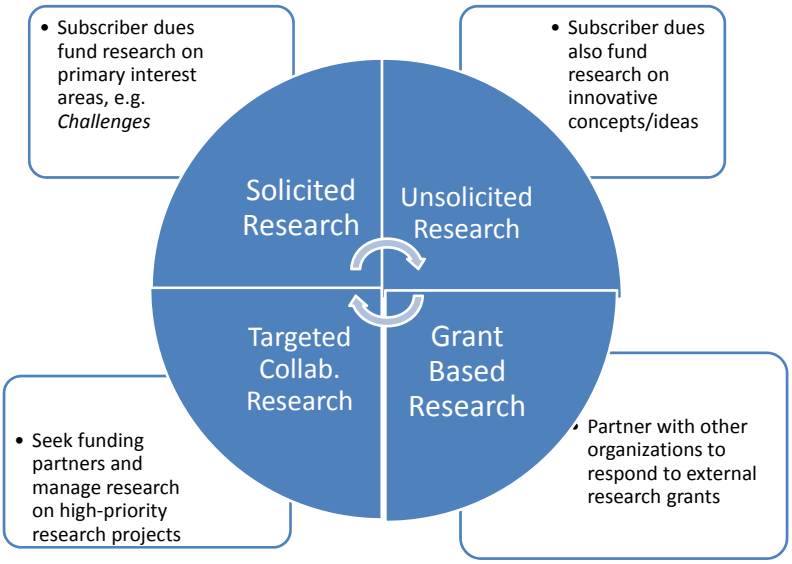
WERF Research Funding



- Subscriber dues fund research on primary interest areas, e.g. *Challenges*
- Subscriber dues also fund research on innovative concepts/ideas
- Seek funding partners and manage research on high-priority research projects
- Partner with other organizations to respond to external research grants

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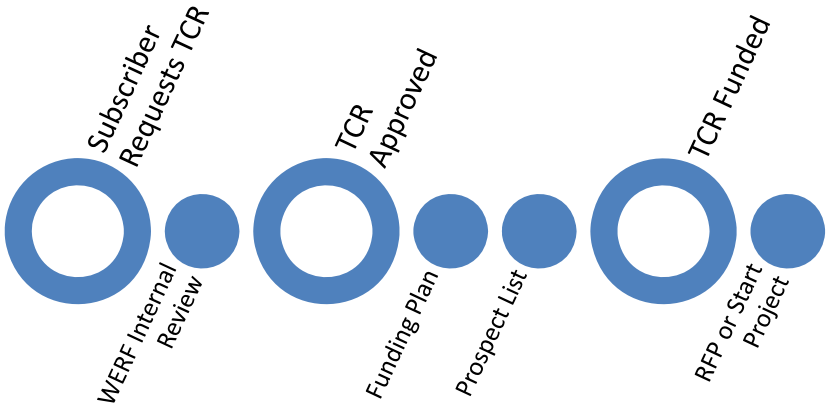
Targeted Collaborative Research



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Questions?

Acknowledgements: Mulholland laboratory, WERF, WEF, HRSD, Greeley-Hansen, Chris Schweitzer, Shalni Kumar

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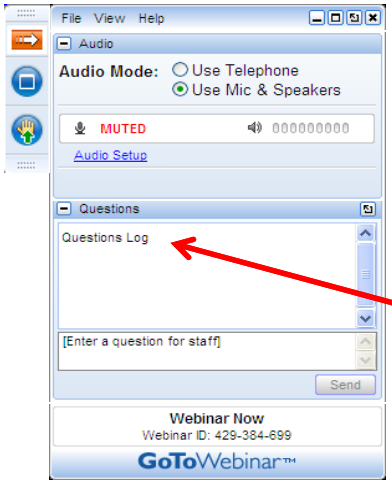

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