Growing Duckweed to Recover Nutrients from Wastewater and for Biofuel Production

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Municipal Wastewater
Agricultural Wastewater
Global Oil Consumption

Since 1990, the US & China alone have increased oil consumption by over 7 million barrels per day.
Oil Production Prediction


- Total: 101 Quadrillion BTU
- Fossil Fuel: 86 Quadrillion BTU
- Nuclear: 8.2 Quadrillion BTU
- Renewable: 6.6 Quadrillion BTU

- Total: 6.6 Quadrillion BTU
- Hydroelectric: 2.7 Quadrillion BTU
- Biomass: 3.3 Quadrillion BTU
- Geothermal: 0.34 Quadrillion BTU
- Solar: 0.07 Quadrillion BTU
- Wind: 0.18 Quadrillion BTU
Conversion of Animal Wastewater for Energy Production
Animal Wastewater

• High strength wastewater:
  COD:  4,000 – 40,000 mg/l
  TKN:  200 – 2,000 mg/l
  Total P:  50 – 600 mg/l

• Typical treatment systems:
  Anaerobic lagoons or digesters
  Cropland irrigation

• Environmental concerns:
  Ammonia and other gas emission
  Potential contamination to water resources
  Odor emission
Concept of Systems Approach

- Biogas
- Animal Wastewater
- Anaerobic Digester
- Anaerobic Effluent
- Duckweed Pond
- Cleaner Water
- Harvested High-Starch Duckweed
- Fuel Ethanol
- Saccharification Fermentation
- Bioreactor
What is duckweed?

Duckweed Pond

Duckweed Fronds
Duckweed Size

- *Wolffia brasiliensis*
- *Wolffiella denticulata*
- *Spirodea punctata*
- *Lemna minor*
Why using duckweed?

- Extremely high growth rate
- High rate of nutrient (N, P, and minerals) uptake
- Tolerance to high nutrient levels (e.g. *Spirodea polyrrhiza*: 1,000 mg/l N & 1,500 mg/l P)
- Growing at a wide variety of climate conditions
- High protein (15-45% dry weight) or high starch (up to 70% dry weight)
- Covering water surface to greatly reduce odor and ammonia emission
- Easy to harvest
Goal

To develop a duckweed-based system for animal wastewater treatment (remove and utilize the nutrients from the wastewater) and fuel ethanol production
Objectives

- To identify superior duckweed strains for nutrient recovery from anaerobically treated swine wastewater
- To determine duckweed nutrient uptake rate, its growth rate, and their relationship
- To understand the mechanism of nutrient uptake by duckweed and nutrient transport in duckweed pond
- To investigate the production of high-starch duckweed biomass for fuel ethanol production
Lab Screening

Worldwide Collection:
> 1,000 Strains
Spirodela, Lemna, Wolffia, Wolfiella

Maintaining Records

Faster Growers:
41 Strains

In vitro screening using artificial swine wastewater

Highest Protein Producers:
6 Strains: Spirodela puntata (2) Lemna gibba Lemna minor Lemna obscura Lemna aequinoctialis
Greenhouse Selection

Highest Protein Producers:
6 Strains:  *Spirodea puntata* (2)
            *Lemna gibba*
            *Lemna minor*
            *Lemna obscura*
            *Lemna aequinoctialis*

Greenhouse test using anaerobically treated swine wastewater

Three Top Candidates:
*Spirodea puntata* 7776
*Lemna gibba* 8678
*Lemna minor* 8627
Lab Tests on N and P Removal from Artificial Animal Wastewater by Growing Duckweed
In Vitro Test

Duckweed:  *Spirodela punctata* 7776  
           *Lemna minor* 8627

Medium:  Artificial swine wastewater

Temperature:  23°C

Photon flux density:  40 umol/m²-s

Photoperiod:  16 hours/day
In Vitro Test

*Spirodea punctata*

Nutrient uptake in artificial swine wastewater
Development of Models for N Removal and Duckweed Growth
Nutrient (N) Transport Model

- Duckweed takes up N ($\text{NH}_4^+$) for its growth at water surface
- $\text{NH}_4^+$ transfer from bulk to duckweed at surface
- N transfer at surface = N uptake by duckweed

Sun Light

Duckweed

$\text{NH}_4^+$

Duckweed Pond
Model Development

Governing Equation:
\[
\frac{\partial c}{\partial t} = D \cdot \frac{\partial^2 c}{\partial z^2}
\]

Boundary Conditions:
\[
D \cdot \frac{\partial c}{\partial z} (z = L, t) = -k \cdot c^\gamma (z = L, t)
\]
\[
\frac{\partial c}{\partial z} (z = 0, t) = 0
\]

Initial Condition:
\[
c(z, t = 0) = c_0
\]
Pilot Tests in Outdoor Duckweed Tanks
Duckweed Preparation in Greenhouse
Outdoor Pilot Test Set-up

Parameters:

- Temperature
- Light
- N concentration
- P concentration
- Duckweed mass
Pilot Test Results:

Temperature and Light Intensity

Graph a: Temperature, °C
- Summer Test
- Fall Test

Graph b: Light, umol/m²-s
- Summer Test
- Fall Test

Dates:
- 6/12/00
- 7/10/00
- 8/7/00
- 9/4/00
- 10/2/00
- 10/30/00

Date

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Pilot Test Results:

Nutrient Removal and Duckweed Growth

Fall Test
Growing High-Starch Duckweed for Fuel Ethanol Production
Duckweed Growth Model

rate = -28.35 mgNH$_3$-N/L/d
$R^2 = 0.999$

rate = -7.72 mgPO$_4$-P/L/d
$R^2 = 0.979$
N and P Contents in Duckweed Biomass

**Nutrient Content in Biomass, mg/g**

- **N Content in Full Strength SAM**
- **P Content in Full Strength SAM**
- **N Content in Half Strength SAM**
- **P Content in Half Strength SAM**

**Time, d**

- **N\textsubscript{min} = 16.5 mg/g**
- **P\textsubscript{min} = 6.3 mg/g**
Major Composition of Duckweed

Grown on Animal Wastewater:

- Proteins: 30-40%
- Starch: 15-18%
- Others: Fiber, Lipids, Carbohydrates, Minerals

In a nutrient limiting environment:

- Proteins: Down
- Starch: Up
High-Starch Duckweed

45.8% starch (dry base)
Saccharification

Reducing Sugars Production:

509 mg per gram of Dry Duckweed
Ethanol Fermentation

Ethanol Yield:

258 mg per gram of Dry Duckweed Biomass
Nutrient removal in duckweed system:
- N: 1.3 - 2.3 g/m²/d;  
- P: 0.2 – 0.5 g/m²/d

Duckweed growth gate:
- 15 – 30 g (dry)/m²/d

Models for N removal and duckweed growth

Starch content in dry Duckweed: ~46%

Average annual starch production: 28 tons/hec/yr
- Corn starch yield: ~5.0 tons/hec/yr

Ethanol yield: 258 mg/g dry duckweed

Easy for saccharification

No need for additional nutrients in Fermentation
Duckweed Harvesting
Duckweed Harvesting
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