Development of Renewable Microbial Polyesters for Cost Effective and Energy-Efficient Wood-Plastic Composites

PI: David N. Thompson (Idaho National Lab.)
R&D Partners: Washington State University
University of California-Davis

Industry Partners: NewPage Corporation
Eco:Logic Engineering, Inc.
Strandex, Incorporated
Wood-Plastic Composites

- Wood-plastic composites markets for durable applications are growing at 38% annually (16.9 billion lb in 2002)
- The 30-50 wt% of plastic in these materials represents a significant embodied energy derived from petroleum
- Utilizing bio-based plastics can potentially decrease the annual energy costs by as much as 0.31 Quads by 2020

**Project Goal:** Develop wood-plastic composites derived from biobased plastics produced onsite at pulp mills from mill wastes
Polyhydroxyalkanoates (PHAs)

- Potential alternative to 50% of current polymers used
- **Highly versatile family:**
  - Hydrolytically stable
  - Biodegradable
  - Form excellent films
  - Excellent UV stability
- **Current applications:** Niche markets, biodegradable products
- **Future applications:** Construction, Automotive, Agricultural
- **Challenges:**
  - Substitute broadly for petro-polymers
  - Meet economic and technical requirements
- **Needs:**
  - Reduce material costs
  - Optimize application
  - Realize waste-econ advantages
Our Solution

- **Reduce Material Costs**
  - Manufacture wood-thermoplastic composites using unpurified renewable plastic feedstocks
  - Pulp & paper mill wastewaters provide carbon sources and microbial consortia

- **Optimize Application Technology**
  - Refine formulations and processing technology
  - Utilize cell mass in composite applications
  - Optimize properties for building products

![Diagram showing the process of producing wood/PHA composite with cost efficiency and enhanced performance]

- Concept 1
  - Hi performance bioreactor
  - WTE Carbon source
  - PHA containing cells
  - Concentrate & lyse
  - PHA & cell debris
  - Drying

- Concept 2
  - Dry crude PHA
  - Wood fiber & additives
  - Wood/PHA composite w/ cost efficiency and Enhanced performance
Markets & Commercialization

- Based on properties, PHAs can potentially replace HDPE in durable composites
- Example is decking ($5.3 billion market)
- Residential & industrial markets for wood composites expected to saturate at 25-30% of treated lumber market, or 5.46 MM tons
- HDPE-based composites account for 90% of this total
- We assumed we could impact half of this total, or 2.46 MM tons annually
- First commercialization in 2010-2015 (est.)
## Energy Savings Per Unit-Year

<table>
<thead>
<tr>
<th>Fuel Type</th>
<th>Waste PHA/wood composites</th>
<th>HDPE/wood composites</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electricity (million kWh)</td>
<td>181.4</td>
<td>186.7</td>
</tr>
<tr>
<td>Natural Gas (million ft^3)</td>
<td>37.68</td>
<td>79.60</td>
</tr>
<tr>
<td>Petroleum (million bbl)</td>
<td>0.0680</td>
<td>0.0956</td>
</tr>
<tr>
<td>Steam Coal (million ton)</td>
<td>0.0333</td>
<td>0.0333</td>
</tr>
<tr>
<td>Black Liquor (thous. ton)</td>
<td>289.3</td>
<td>289.3</td>
</tr>
<tr>
<td>All Other (billion Btu)</td>
<td>1596</td>
<td>1596</td>
</tr>
</tbody>
</table>

- One unit-year was defined as a 1000 ton/day pulp & paper mill
- This equates to ca. 350,000 tons/yr of paper, and 960,000 tons/yr of biosolids containing 40% PHA
- **Values are for wood into mill through composite out of extrusion**
### Annual Energy Savings For Entire Market

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<tr>
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<th>HDPE/wood composites</th>
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</thead>
<tbody>
<tr>
<td>Electricity (MM kWh)</td>
<td>46,628</td>
<td>47,982</td>
</tr>
<tr>
<td>Natural Gas (MM ft³)</td>
<td>9,684</td>
<td>20,458</td>
</tr>
<tr>
<td>Petroleum (MM bbl)</td>
<td>17.5</td>
<td>24.6</td>
</tr>
<tr>
<td>Steam Coal (MM ton)</td>
<td>8.57</td>
<td>8.57</td>
</tr>
<tr>
<td>Black Liquor (thous ton)</td>
<td>73,347</td>
<td>73,347</td>
</tr>
<tr>
<td>All Other (BB Btu)</td>
<td>410,151</td>
<td>410,151</td>
</tr>
</tbody>
</table>

- Unit definition gives 257 units in the U.S.A. (paper & linerboard)
- **Values are for wood into mill through composite out of extrusion**
- If include municipal and / or other wastewaters, can easily supply the supply entire durable composites market with waste-derived PHAs
Other Benefits

- Significant reductions in $\text{SO}_2$, $\text{NO}_x$, Particulates, $\text{VOC}$, & $\text{CO}$ emissions
- New profit center for pulp and paper mills
- Utilization of mill waste effluents for PHA production reduces disposal costs
- COD, BOD and phosphates in waste effluents are sequestered into saleable building materials
- Improved and more economic PHA production and utilization for composites
- Attenuated ultimate biodegradability of the wood-PHA composite
Key Technical Barriers

- Poor understanding of the mechanical, adhesion, and thermal properties of composites produced using PHAs of widely varying compositions
- Considerable diversity of wastewater microbial consortia and metabolic abilities to accumulate PHAs
- Unknown effects of using waste carbon sources available onsite on the health and productivity of wastewater consortia
- Poorly characterized effects of integrating cell debris into composites
- Unknown effects of these variables on the large scale processing needed for commercial application
Project Strategy & Objectives

- **Task 1:** Determine preferred PHA monomer compositions, PHA/cell debris ratios, and PHA/wood ratios for the production of superior wood-PHA composites
- **Task 2:** Define feedstock compositional ranges for municipal wastewater effluents (WTE) and pulp & paper effluents (PPE) for production of PHAs meeting PHA compositions identified
- **Task 3:** Determine efficacy of supplementing PPE and WTE to improve PHA production in and from these effluents
- **Task 4:** Test the material properties of wood-PHA composites produced from waste-derived PHA made and used without extraction or purification
- **Task 5:** Produce and test wood-PHA composites made from WTE-derived PHA at the pilot-scale
<table>
<thead>
<tr>
<th>Task</th>
<th>Date</th>
<th>Milestone Description</th>
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<tbody>
<tr>
<td>1</td>
<td>9/30/05</td>
<td>Physical and rheological properties of the collected PHAs and WFRTCs are defined</td>
</tr>
<tr>
<td></td>
<td>12/30/05</td>
<td>Composite processing and mechanical properties of the purified PHA WFRTCs completed</td>
</tr>
<tr>
<td></td>
<td>1/2/06</td>
<td><strong>Decision Point #1</strong> – Wood/purified PHA composites with integrated cell debris produced having MOR $\geq$ 1500 psi and MOE $\geq$ 0.20 Mpsi</td>
</tr>
<tr>
<td>2</td>
<td>9/30/05</td>
<td>WTE survey of several waste treatment facilities completed</td>
</tr>
<tr>
<td></td>
<td>9/30/05</td>
<td>Enriched paper mill inoculum source and/or ATCC <em>Sphaerotilus</em> culture ready for testing</td>
</tr>
<tr>
<td></td>
<td>3/30/06</td>
<td>Unsupplemented PHA from PPE completed</td>
</tr>
<tr>
<td></td>
<td>4/3/06</td>
<td><strong>Decision Point #2</strong> – PHA produced from a PPE source by indigenous or inoculated laboratory cultures at $\geq$ 1 wt% of the dry cell mass</td>
</tr>
<tr>
<td>3</td>
<td>9/29/06</td>
<td>WTE supplements &amp; production criteria for pilot test defined</td>
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<td>4</td>
<td>10/2/06</td>
<td><strong>Decision Point #3</strong> - Wood/purified PHA composites with integrated cell debris produced having MOR $\geq$ 2000 psi and MOE $\geq$ 0.25 Mpsi</td>
</tr>
<tr>
<td></td>
<td>12/1/06</td>
<td>Basic processing conditions defined for pilot test</td>
</tr>
<tr>
<td></td>
<td>12/1/06</td>
<td>Formulations identified for pilot extrusions</td>
</tr>
<tr>
<td></td>
<td>7/31/06</td>
<td>Pilot test plan completed</td>
</tr>
<tr>
<td>5</td>
<td>2/28/07</td>
<td>Supplemented or unsupplemented WTE biosolids produced for pilot extrusions</td>
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Project Scope and Schedule Changes

- Milestones, decision points, and project end date were extended due to funding shortfalls
  - 31% shortfall in FY2005
  - 60% shortfall in FY2006

- Change in scope for pilot test
  - Originally planned for Eco:Logic’s municipal waste treatment facility in Lincoln, CA
  - Now planned for NewPage’s mill in Chillicothe, OH
  - Intent is to better align with ITP’s goals for the program
## Revised Milestones & Decision Points

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Commercialization Potential

**Advantages:**
- Wide range of applications
- PHAs can be competitive with HDPE in wood-plastic composites
  - Produced from “negative cost” feedstocks
  - Very little recovery/purification cost
- New profit center for pulp & paper mills
- Biodegradable; adjust processing & formulation to attenuate to desired product life
- Reduced greenhouse impacts

**Economic and technical criteria:**
- Competitive price for product
- Competitive properties for application
- Cannot interfere with normal mill operations
- Mill operators must integrate and operate the process onsite as a part of mill operations
Commercialization Plan

- **Barriers to Commercialization**
  - **Market** – Proper development of technical parameters in utilizing the materials in current production practices
  - **Regulatory** – None known … the reaction schemes would actually facilitate discharge levels in wastewater treatment facilities
  - **Patent** – Thorough search indicates no conflicting patents
  - **Other commercialization barriers** – Unknown willingness of mill operators to produce PHAs onsite as a normal part of mill operations

- **Commercialization/Technology Transfer Team**
  - INL & WSU have had significant prior successes in commercialization
  - NewPage’s Chillicothe mill is actively interested in new profit centers including composites
  - Approximately 30% of the wood plastic composites in the U.S.A. are produced under license from Strandex, Inc.
  - Eco:Logic operates several WTE facilities in California and the Southwest and supports green engineering practices
Project Partners

- **David N. Thompson (PI):** Idaho National Laboratory, Renewable resources utilization, fermentation to value-added products
- **Michael P. Wolcott:** Washington State University, Wood materials engineering, composites
- **Frank J. Loge:** University of California-Davis, Wastewater treatment, *in situ* PHA production
- **Katherine A. Wiedeman:** NewPage Corp., Pulp & paper mill wastewater management, pilot tests
- **Robert W. Emerick:** Eco:Logic Engineering, Inc., Municipal wastewater management, pilot tests
- **Alfred B. England:** Strandex Inc., Composites technology development and licensing, pilot tests
Acknowledgements


- Currently active research team members at the various facilities

  - **Idaho National Laboratory**
    - William Smith
    - William Apel
  
  - **Washington State University**
    - Jinwen Zhang
    - Karl Englund
    - Eric Coates (now at the University of Idaho)
  
  - **University of California-Davis**
    - Hsin-Ying Liu
    - Greg Mockos
  
  - **NewPage Corporation**
    - Jim Flanders
    - Natalie Bailey