



2024 FlexPack PLACE Conference

April 14-17, 2024 • San Diego, CA • Wyndham San Diego Bayside



Recycling Multilayer Plastic Packaging by Solvent-Targeted Recovery and Precipitation

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U.S. DEPARTMENT OF
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Chemical Upcycling of Waste Plastics

CUWP by the Numbers:

- \$12.5 Million 5-year center
- 6 Universities (3 US, 2 Mexico, 1 Canada)
- 1 National Laboratory
- 23 Companies
- 2 Industry Associations

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DANE COUNTY DEPARTMENT OF
WASTE & RENEWABLES



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CUWP Research Team

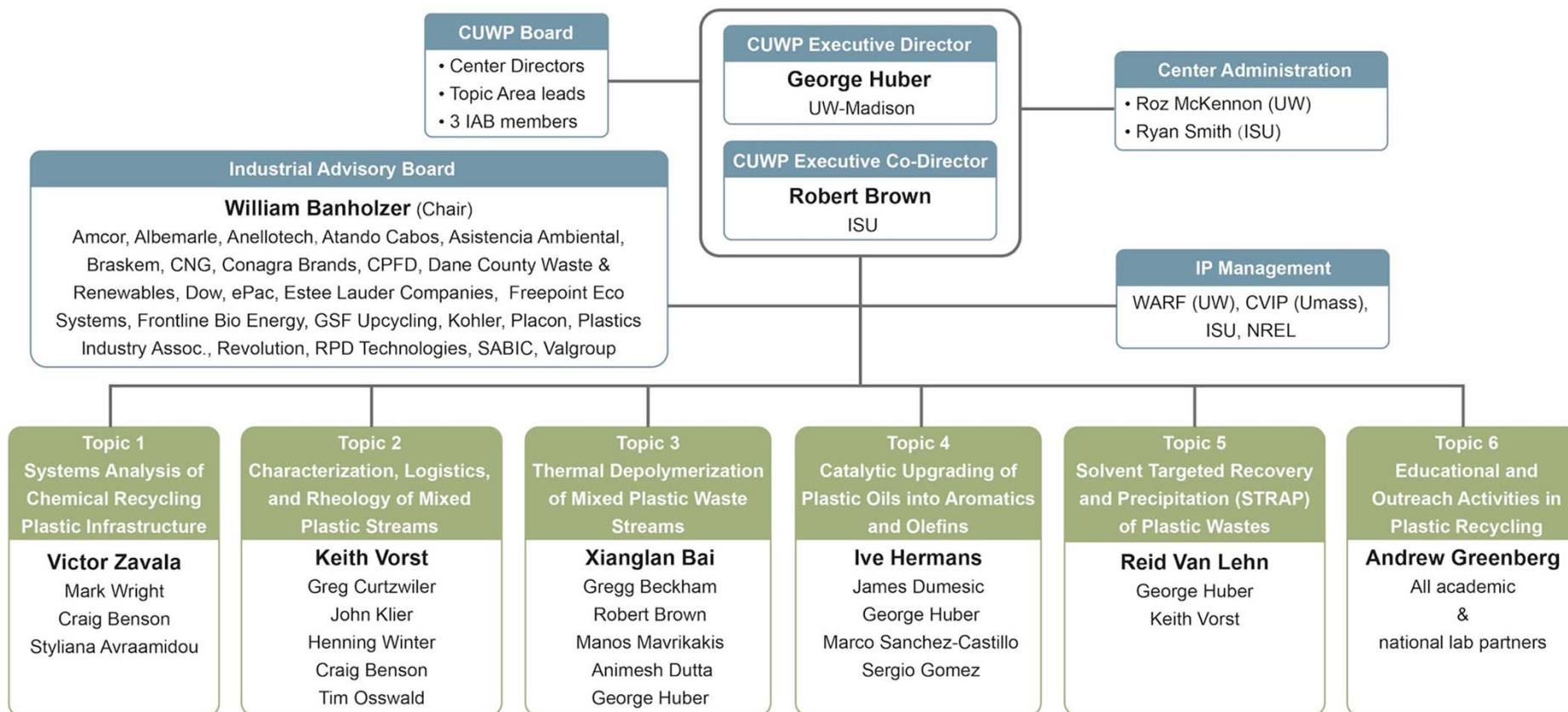
- 18** Principal Investigators
- 29** Industrial Advisory Board Members
- 5** – Post-Doctoral Researchers
- 18** – Graduate Students
- 7+** - Undergraduate Students

CUWP started in 2021, recently funded through 2026

**Led by:
University of Wisconsin-Madison
and Iowa State University**

2024 FlexPack PLACE Conference

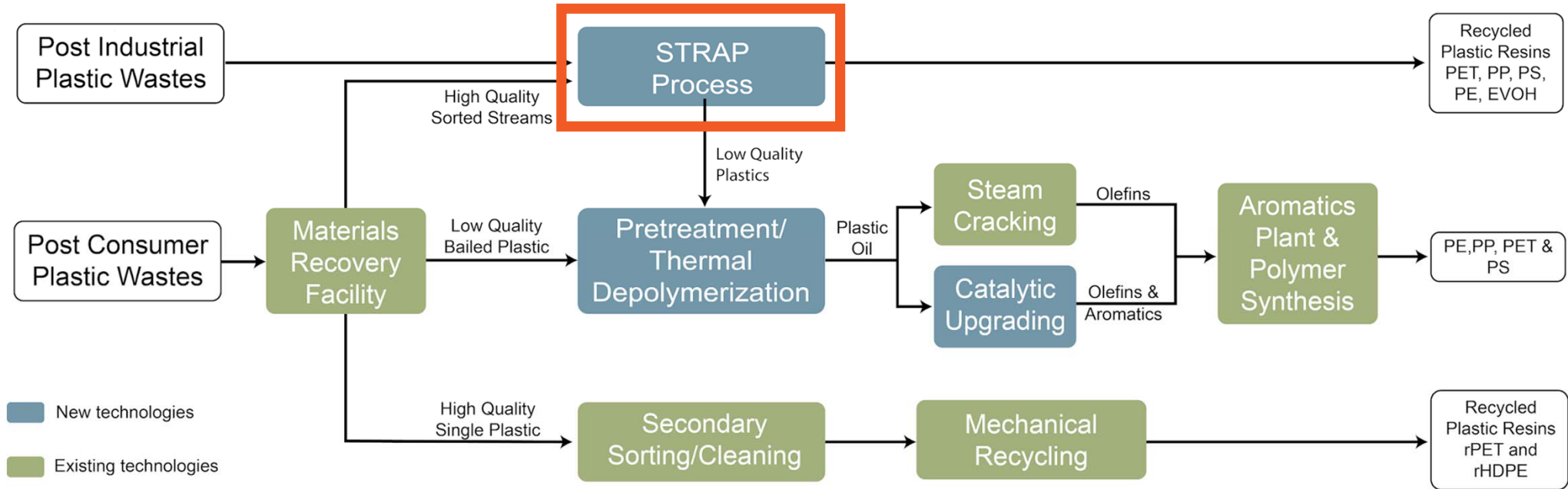
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CUWP supports 23+ graduate students and post-doctoral researchers.



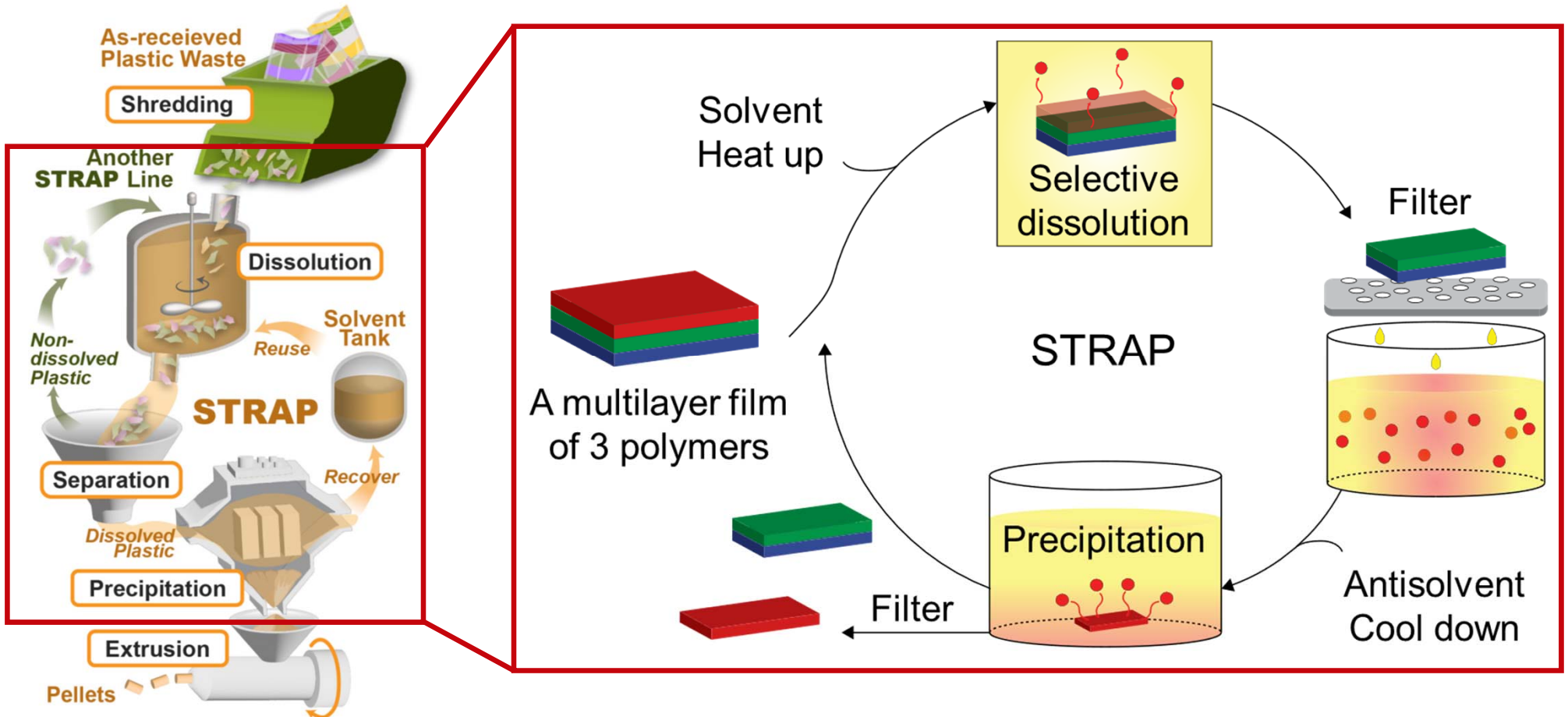
Chemical Recycling in Circular Economy



The objective of CUWP is to develop scientific and engineering principles that enable the recycling of plastic wastes into virgin plastic resins using chemical technology.

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Overview of STRAP:

- STRAP (Solvent-Targeted Recovery and Precipitation) is a physical dissolution-based process that separates polymers from a multicomponent plastic product (e.g., a film)
- Goal is to produce a high-quality food grade resin from multilayer packaging, flexible films and plastic mixtures in as few a steps as possible
- Process is not solvolysis (minimal breakage of bonds).

Challenges with STRAP and other dissolution-based processes:

- Plastic films are complex mixtures that include polymer materials, inks/dyes, additives, etc.
- Solvents must be chosen to selectively dissolve a target component safely.
- The dissolved polymer has to be precipitated without retaining significant solvent.
- Contaminants and color have to be removed.
- Need 99%+ recovery of the solvent
- Need to scale from lab to pilot plant to commercial system and address related challenges (e.g., EHS)



Our Ironton facility has reached another milestone!

Earlier this week we received certification of successful pellet production from our independent construction monitor. ✓



11:16 AM · Jun 29, 2023 · 2,811 Views

Several Dissolution-Based Plastics Recycling Technologies are being Commercialized

- PureCycle (Ohio): Supercritical Butane solvent for PP purification (150 bar of pressure)
- CreaCycle (Germany): High boiling point solvents (flash point above 100 C), using CreaSolve® process.

STRAP uses solvents that operate at ~1 bar pressure and have reasonable boiling points to separate different polymers



We Have Processed a Large Variety of Plastics with STRAP

Focus of this talk:

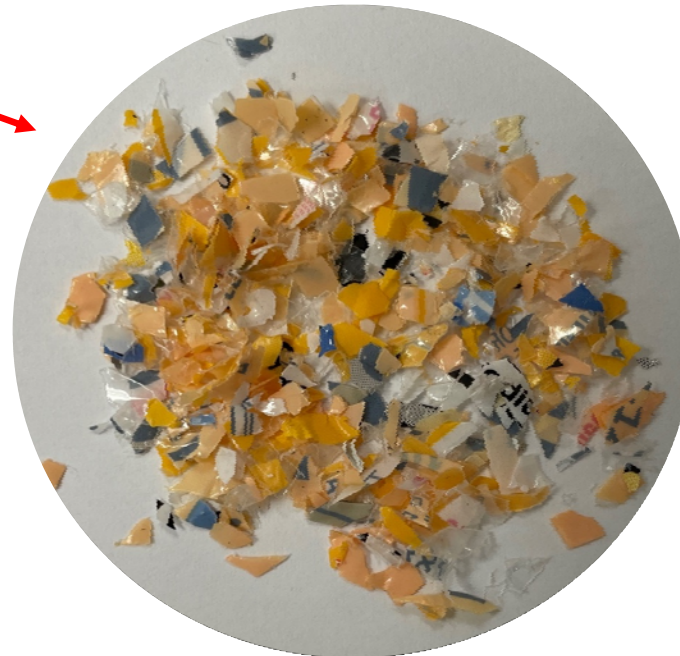
- Printed multilayer flexible films

Multiple multilayer packaging films

- Clear rigid multilayer film
- Mixed multilayer plastic waste
- Printed multilayer nylon flexible films
- PVDC films (flexible and rigid)

Various other plastic feedstocks

- Face masks
- Marine plastics
- Polycarbonate (from eye glass waste)
- Municipal Solid Waste (MSW)





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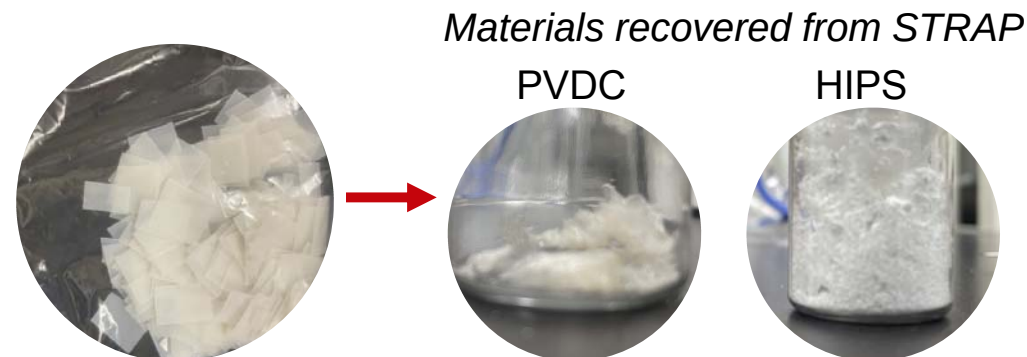
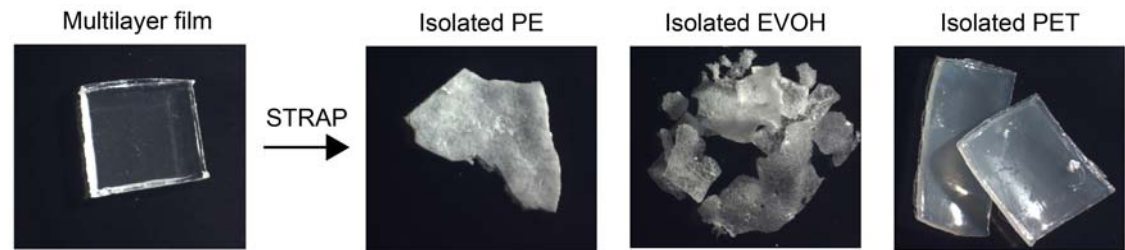
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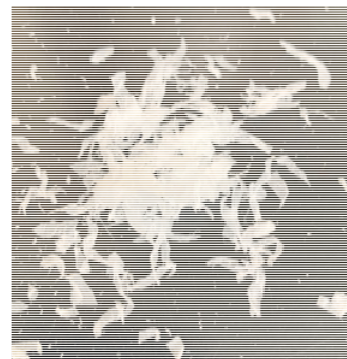
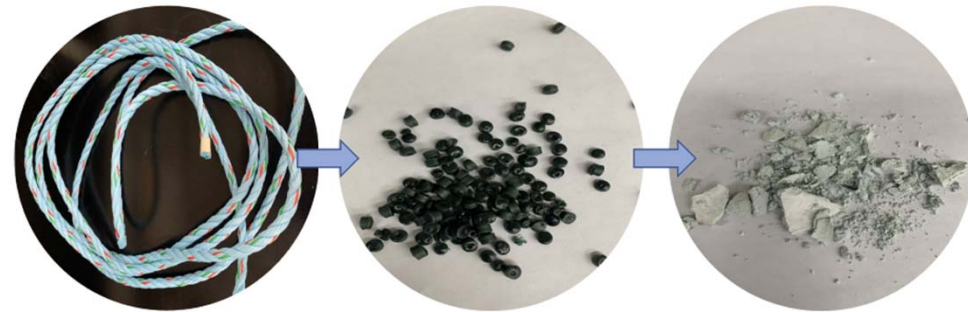
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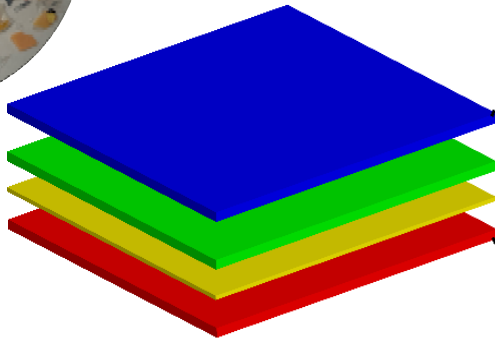
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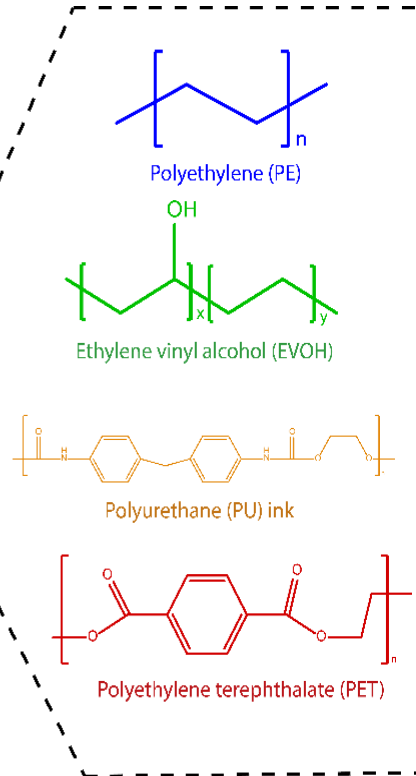




Design Considerations: STRAP Process for a Flexible Printed Film



Multilayer film with polyethylene (PE), ethylene vinyl alcohol (EVOH), polyethylene terephthalate (PET), polyurethane (PU)-based inks.



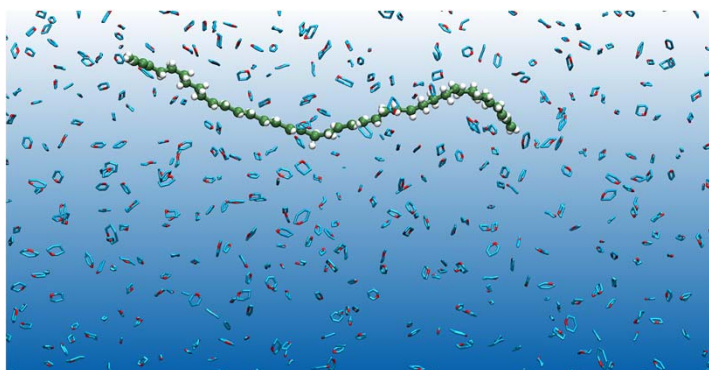
Questions to consider:

- What solvents to use to recover each component?
- Do recovered resins have suitable properties for reuse?
- Is the process economically competitive?
- Is the process sustainable?
- Can the process be scaled up?

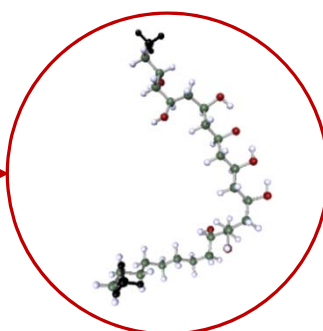


Computational Modeling Guides Solvent Selection

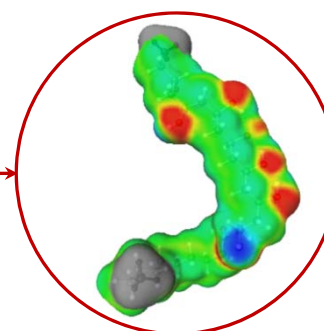
Molecular dynamics simulation



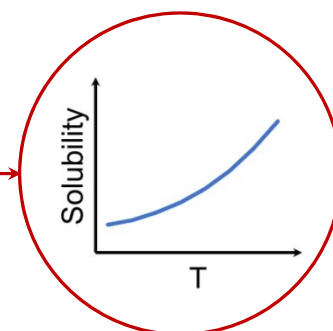
Polymer
conformations



COSMO-RS
calculation



Predicted
solubilities

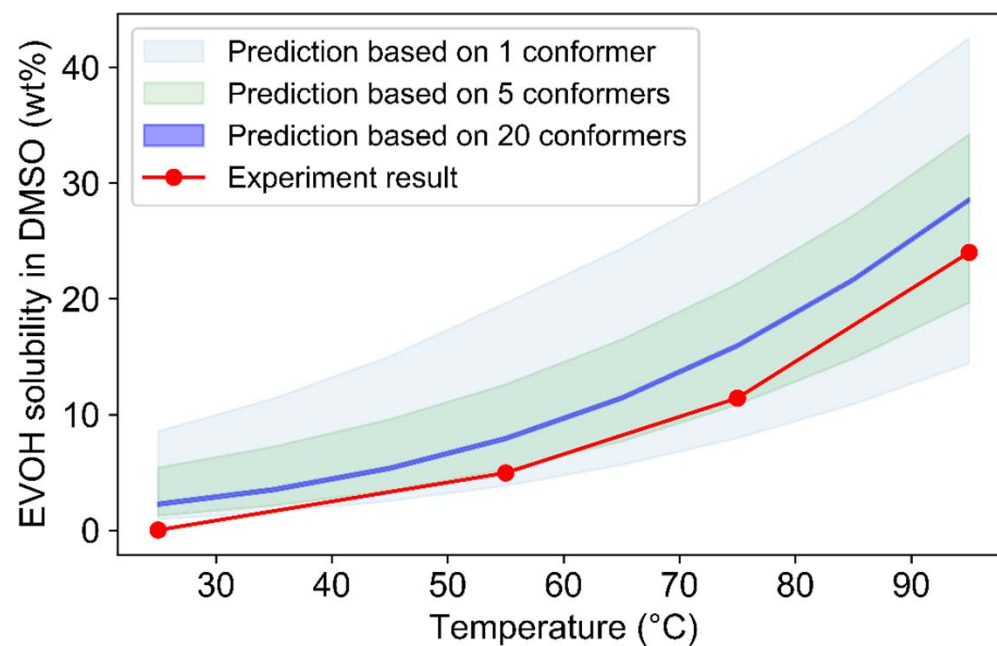
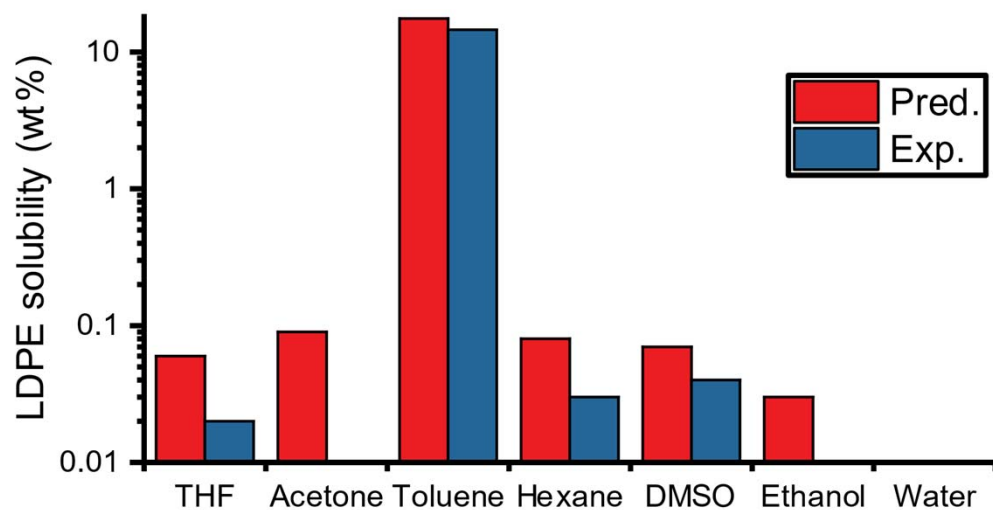


We developed a computational approach for polymer solubility prediction that provides:

- Quantitative results: numerical value of predicted solubility
- Temperature-dependent solubilities: from room temperature to each solvent's boiling point
- Composition-dependent solubilities: including pure solvents/multicomponent mixtures



Model Results Agree Well with Experimental Data



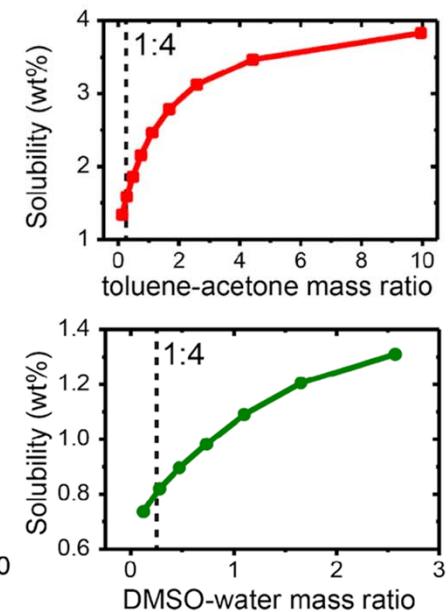
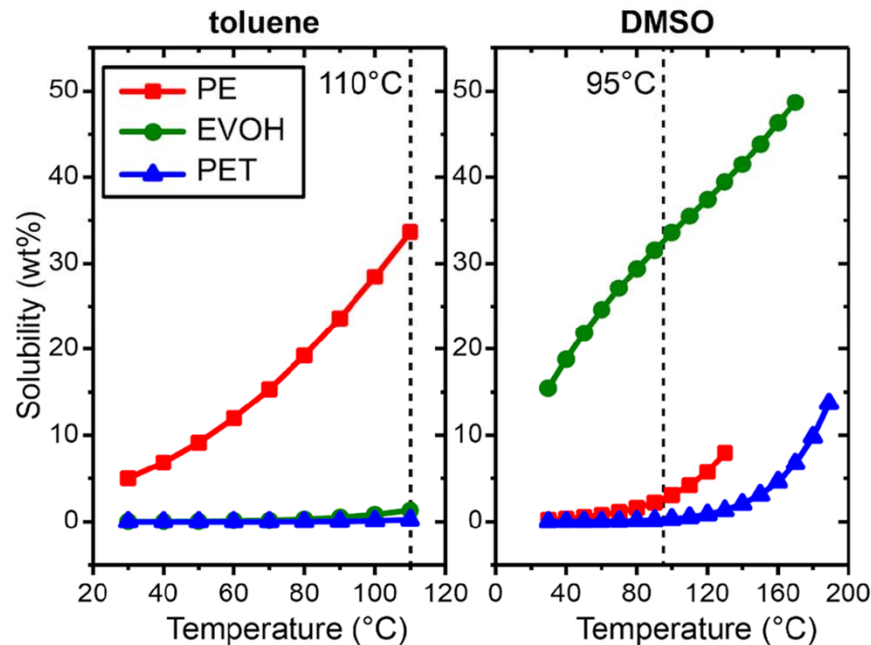
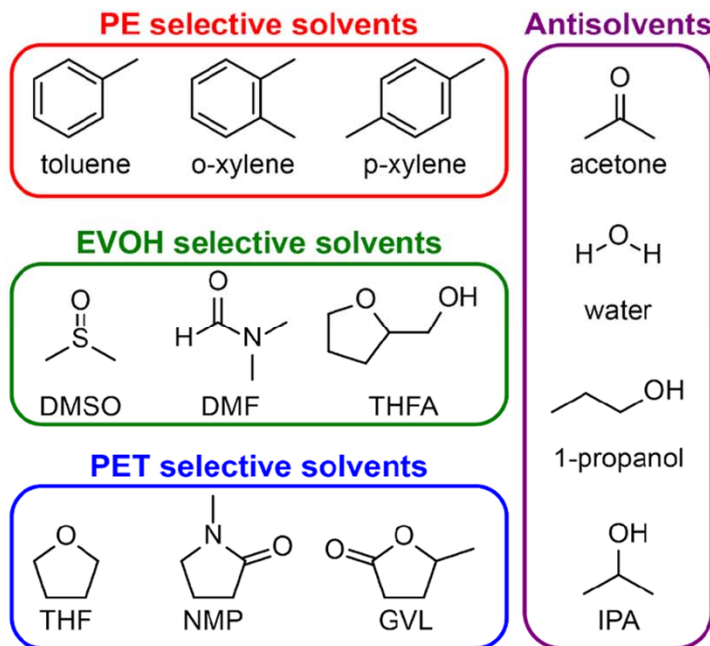


Generated Solubility Database: 11+ Polymers, 1000+ Solvents

abbr	lab name	Solvent name in cosmobase	CAS numbe	BP (°C)	Th (°C)	EVOH		PE		PET		PP		PS		PVC		Nylon 6		Nylon 66	
						RT	Th	RT	Th	RT	Th	RT	Th	RT	Th	RT	Th	RT	Th	RT	Th
	methanol	methanol	67-56-1	64.6	63.6	0.0	0.8	0.0	0.1	0.0	0.0	0.0	0.1	0.0	0.0	0.1	0.8	0.0	0.3	0.0	0.1
DCM	dichloromethane	ch2cl2	75-09-2	40	39.0	0.0	0.0	0.0	0.1	0.3	0.8	0.2	0.5	4.6	8.5	2.7	4.6	0.9	1.7	0.2	0.5
	ethylene glycol	glycol	107-21-1	197.3	120.0	0.0	10.6	0.0	0.9	0.0	0.0	0.0	0.1	0.0	0.0	0.0	1.6	0.0	0.4	0.0	0.2
	Acetone	propanone	67-64-1	56	55.0	0.0	0.2	0.0	0.3	0.1	0.7	0.3	1.4	9.2	21.3	10.9	19.8	0.0	0.2	0.0	0.1
	Isopropanol	2-propanol	67-63-0	82.3	81.3	0.0	1.4	0.0	1.6	0.0	0.0	0.1	2.3	0.0	1.2	0.2	2.9	0.0	1.0	0.0	0.4
	1-propanol	propanol	71-23-8	97.2	96.2	0.0	4.1	0.0	4.2	0.0	0.1	0.1	4.1	0.0	2.8	0.1	5.4	0.0	2.6	0.0	1.1
	toluene	toluene	108-88-3	110.6	109.6	0.0	0.3	0.1	22.6	0.0	2.5	1.1	30.9	3.6	41.0	0.7	14.8	0.0	1.3	0.0	0.4
	chloroform	chcl3	67-66-3	61.1	60.1	0.0	0.0	0.0	0.6	0.2	1.0	0.5	3.1	2.3	9.8	1.1	4.2	4.4	6.2	1.9	2.9
THF	tetrahydrofuran	thf	109-99-9	65	64.0	0.1	0.9	0.1	1.7	0.0	0.8	2.0	10.1	14.0	31.3	8.9	19.1	0.0	0.4	0.0	0.2
THP	tetrahydropyran	thp	142-68-7	88	87.0	0.0	1.1	0.1	7.3	0.0	0.8	2.0	20.9	7.2	33.7	3.9	17.9	0.0	0.7	0.0	0.3
	cyclohexane	cyclohexane	110-82-7	80.7	79.7	0.0	0.0	0.1	6.9	0.0	0.0	4.0	24.0	0.2	4.6	0.1	1.2	0.0	0.0	0.0	0.0
	heptane	n-heptane	142-82-5	98.5	97.5	0.0	0.0	0.1	15.3	0.0	0.0	2.9	29.3	0.1	5.2	0.0	1.7	0.0	0.0	0.0	0.0
	triethylamine	triethylamine	121-44-8	89	88.0	nan	7.7	0.1	8.7	0.0	0.0	2.8	23.2	0.8	12.9	0.5	4.7	0.0	0.2	0.0	0.1
	1,2-propanediol	propyleneglycol	57-55-6	187.6	120.0	0.0	12.4	0.0	3.2	0.0	0.0	0.0	0.6	0.0	0.3	0.0	3.8	0.0	1.7	0.0	0.7
DMSO	dimethyl sulfoxide	dimethylsulfoxide	67-68-5	189	120.0	1.3	35.3	0.0	5.3	0.0	8.3	0.0	1.7	1.5	18.2	8.4	33.2	0.0	3.0	0.0	1.6
	hexane	hexane	110-54-3	68.7	67.7	0.0	0.0	0.1	3.1	0.0	0.0	3.6	16.2	0.1	1.9	0.1	0.6	0.0	0.0	0.0	0.0
	acetylacetone	acetylacetone	123-54-6	138	120.0	0.0	6.6	0.0	8.2	0.0	2.0	0.0	3.0	0.5	23.0	2.1	23.7	0.0	1.7	0.0	0.7
	tert-butanol	tert-butanol	75-65-0	82.4	81.4	0.0	0.9	0.0	2.1	0.0	0.0	0.3	3.8	0.0	2.0	0.2	3.3	0.0	0.7	0.0	0.3

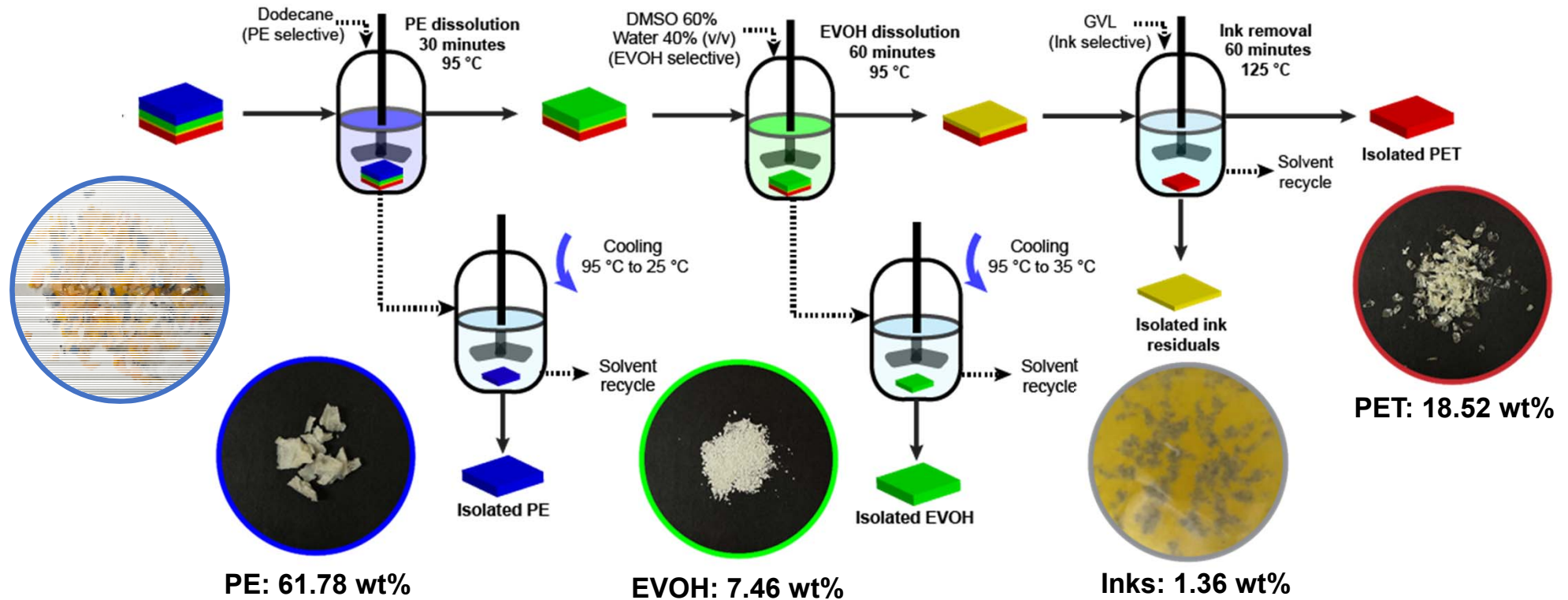


Models Identify Selective Solvents, Antisolvents, and Temperatures





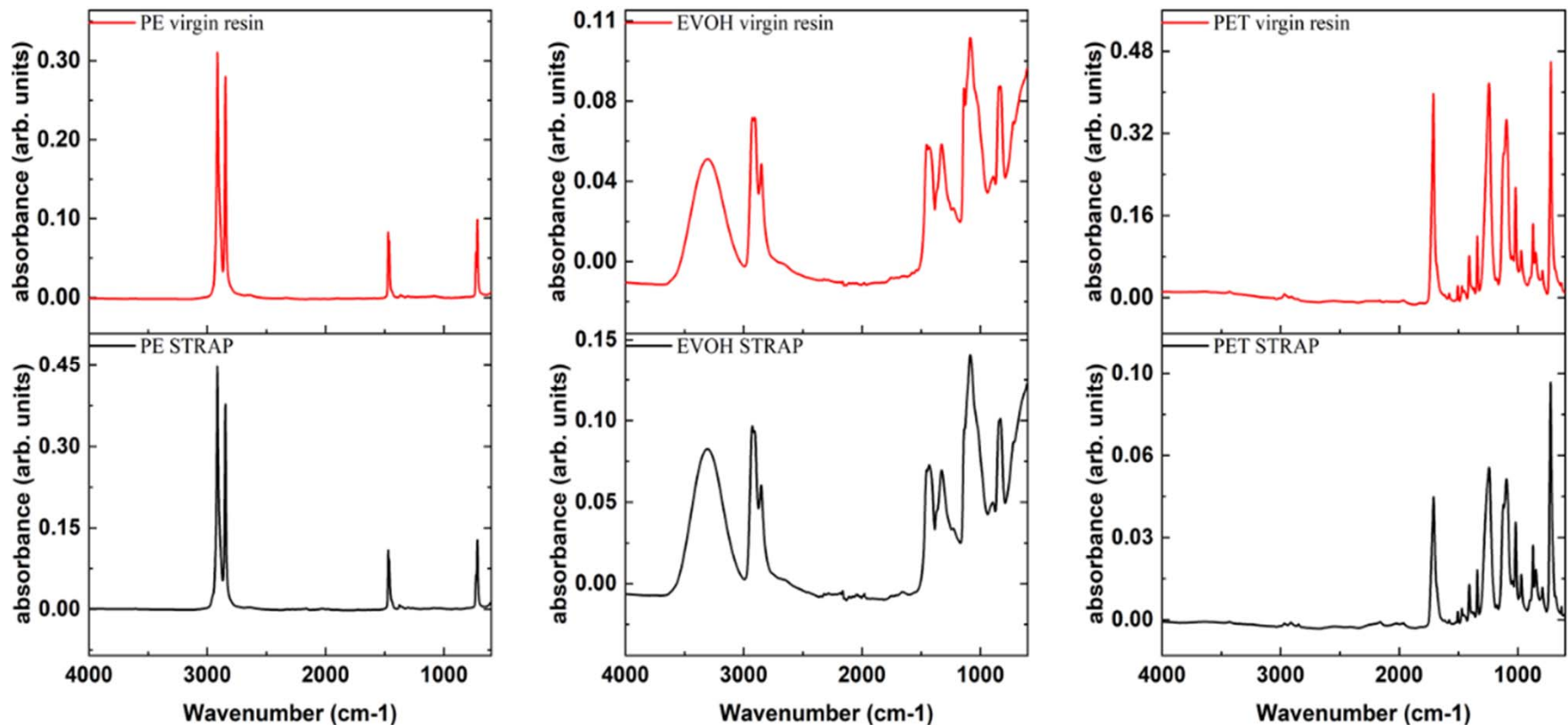
STRAP Process Flow Diagram for Printed Multilayer Film



Overall mass balance: 88.66%, ~96% including material left in equipment



Recovered Resin Properties are Similar to Virgin Resins





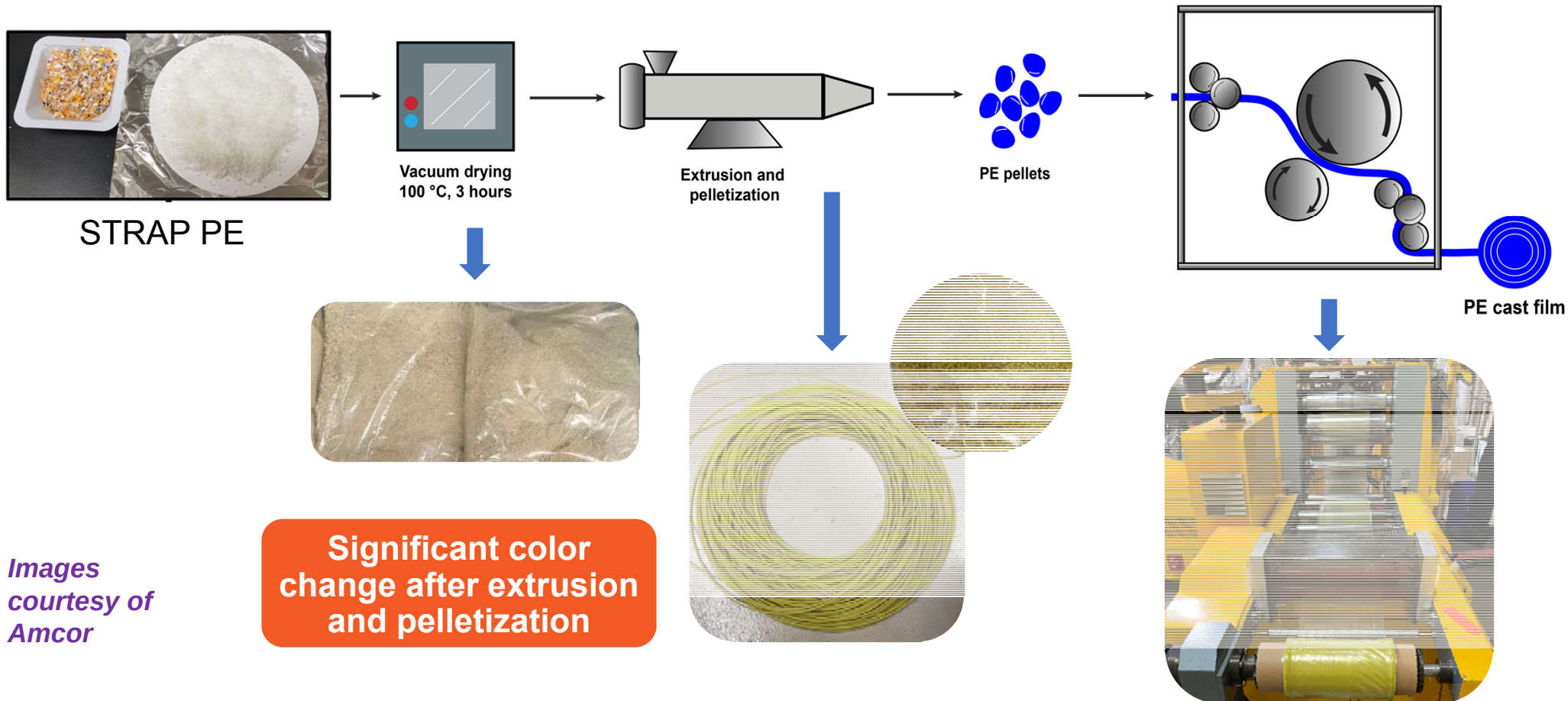
Recovered Resin Properties are Similar to Virgin Resins

Resin	T _c (°C)	T _{m,2} (°C)	ΔH _c (J/g)	ΔH _{m,2} (J/g)	Crystallinity %
PE STRAP	105.0	119.7	76.0	82.3	28.38%
LDPE Virgin	98.3	112.0	84.8	86.1	29.69%
LLDPE Virgin 45G	106.1	122.4	83.3	85.5	29.48%
LLDPE Virgin 47N	107.0	122.2	70.2	73.3	25.28%
EVOH STRAP	150.4	175.7	41.8	37.4	17.17%
EVOH Virgin	147.8	176.4	54.2	54.3	24.93%
PET STRAP	209.6	246.0	41.7	22.7	16.21%
PET Virgin	169.2	244.6	30.0	38.5	27.50%

- Melt temperature (T_{m,2}) of recovered resins (printed film) were comparable to original
- Differences were some samples of PET & EVOH are due to residuals
- Similarly found comparable melt flow index, molecular weight values



Recovered Sufficient PE to Test Cast Film Properties

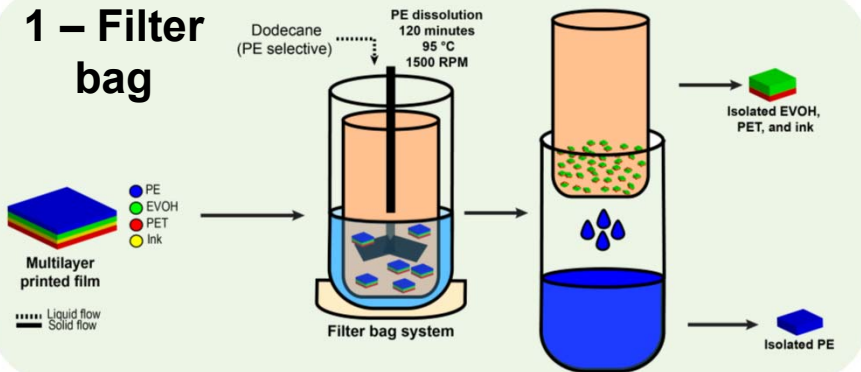


Images
courtesy of
Amcor

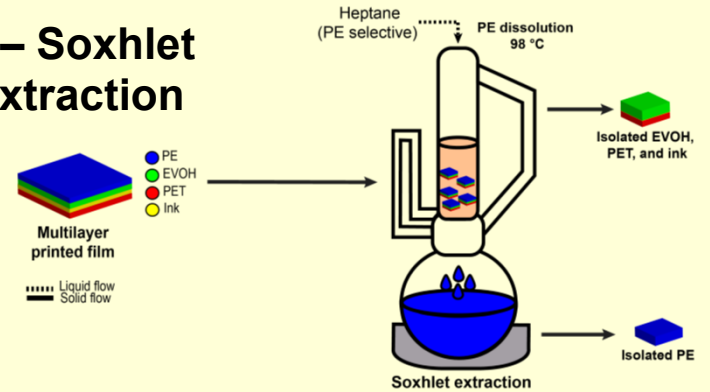


Evaluated Methods to Create High-Quality Films

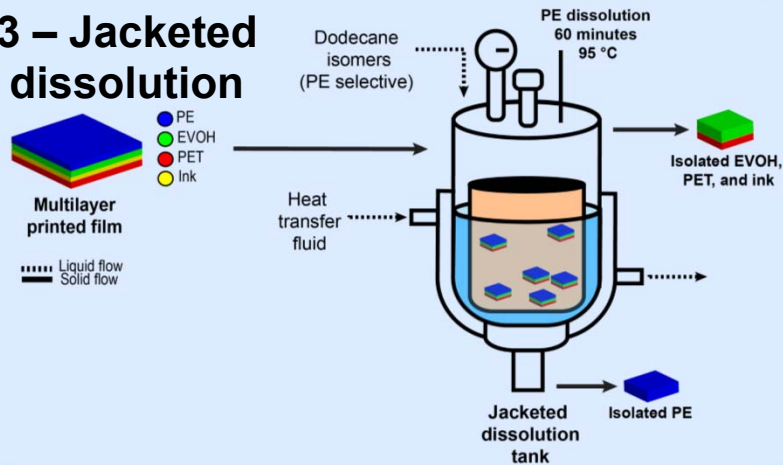
1 – Filter bag



2 – Soxhlet extraction



3 – Jacketed dissolution



Produced >1 kg of STRAP PE with each approach, then cast films

Films produced





Quantified Film Impurities Compared to Control Films

Film sample	Average number of impurities and defects per 60x60 mm ² of film
C1 ^a	457 ± 163
C2 ^b	591 ± 266
STRAP PE - 1	2475 ± 378
STRAP PE - 2	798 ± 237
STRAP PE - 3	1273 ± 256

^aC1 film has LDPE, LLDPE, and tie layers

^bC2 film has VLDPE, LLDPE, and EVA

Testing data courtesy of collaboration with Amcor

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Tested Film Tensile Properties to Compare to Control Films

Film sample	Film thickness (μm)	Young's modulus (MPa)	Stress at break (MPa)	Force at break (N)	Elongation at break (%)
Machine direction					
C1 ^a	79 $\pm$ 15.08	124 $\pm$ 4.49	32.2 $\pm$ 1.03	64.6 $\pm$ 6.85	719 $\pm$ 38.38 %
C2 ^b	82 $\pm$ 14.36	112 $\pm$ 1.12	43.0 $\pm$ 0.64	90.3 $\pm$ 11.85	745 $\pm$ 42.43 %
STRAP PE – 1	124 $\pm$ 10.40	158 $\pm$ 4.35	14.5 $\pm$ 3.05	57.2 $\pm$ 11.53	494 $\pm$ 109.42 %
STRAP PE – 2	87 $\pm$ 5.76	108 $\pm$ 6.00	13.1 $\pm$ 0.74	27.6 $\pm$ 5.54	698 $\pm$ 29.53 %
STRAP PE – 3	84 $\pm$ 12.60	120 $\pm$ 5.73	21.4 $\pm$ 1.09	45.7 $\pm$ 4.62	592 $\pm$ 18.52 %
Transverse direction					
C1 ^a	82 $\pm$ 1.98	122 $\pm$ 4.85	24.6 $\pm$ 0.26	55.7 $\pm$ 1.69	854 $\pm$ 7.59 %
C2 ^b	74 $\pm$ 3.00	119 $\pm$ 5.37	34.2 $\pm$ 2.02	71.0 $\pm$ 4.53	803 $\pm$ 16.87 %
STRAP PE – 1	127 $\pm$ 12.95	167 $\pm$ 16.10	12.1 $\pm$ 2.63	47.5 $\pm$ 5.83	568 $\pm$ 86.70 %
STRAP PE – 2	84 $\pm$ 4.93	103 $\pm$ 7.95	9.1 $\pm$ 0.15	22.0 $\pm$ 1.04	622 $\pm$ 26.95 %
STRAP PE – 3	81 $\pm$ 4.36	134 $\pm$ 7.10	18.8 $\pm$ 1.04	40.6 $\pm$ 3.40	685 $\pm$ 24.54 %

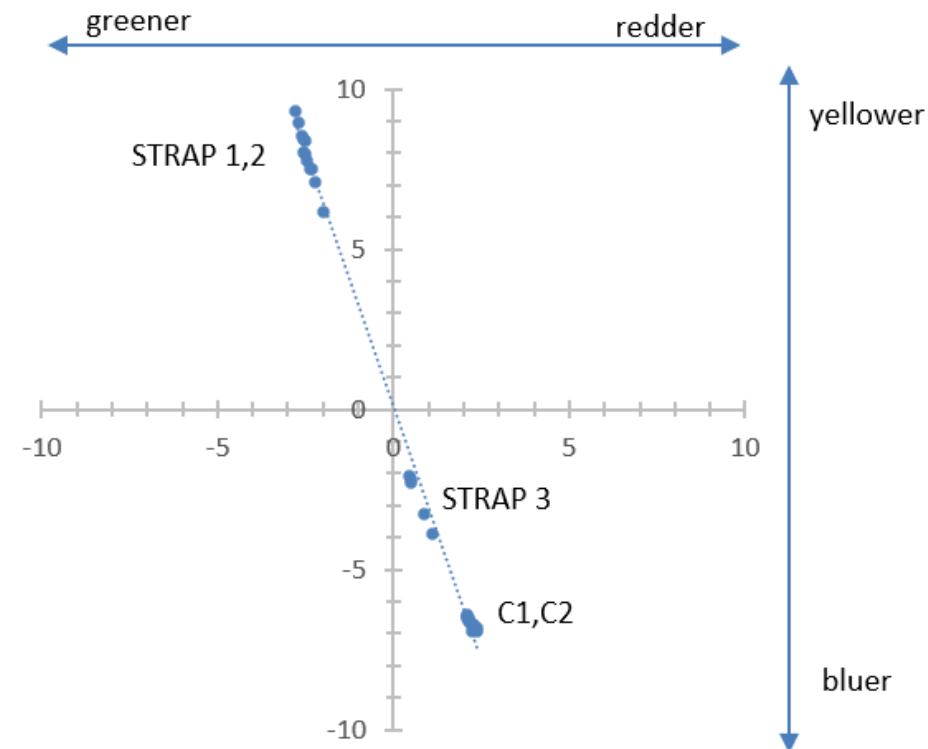


Tested Film Optical Properties to Compare to Control Films

Film	Clarity	Haze %
C1 ^a	87.8	7.9
C2 ^b	94.4	4.7
STRAP PE - 1	59.0	30.9
STRAP PE - 2	83.4	26.7
STRAP PE - 3	86.9	8.1

^aC1 film has LDPE, LLDPE, and tie layers

^bC2 film has VLDPE, LLDPE, and EVA



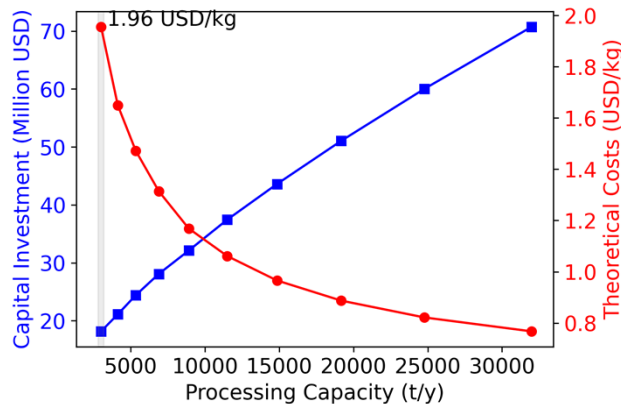
Testing data courtesy of collaboration with Amcor



Estimated Costs from Process Modeling

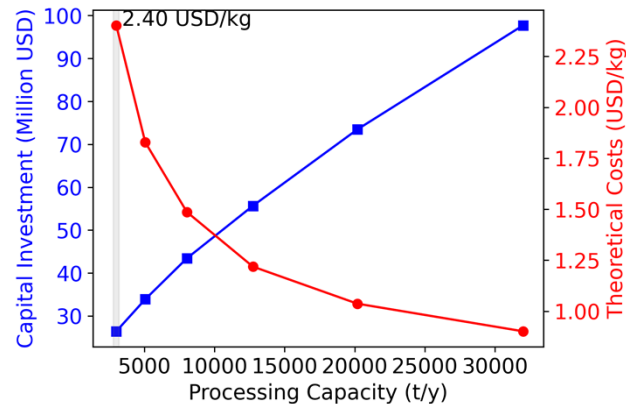
Theoretical costs for resin recovery via STRAP were computed based on process models (estimating solvent prices, operating costs, capital costs, etc.) to gauge economies of scale for different scenarios; numbers are for illustration only.

PE only



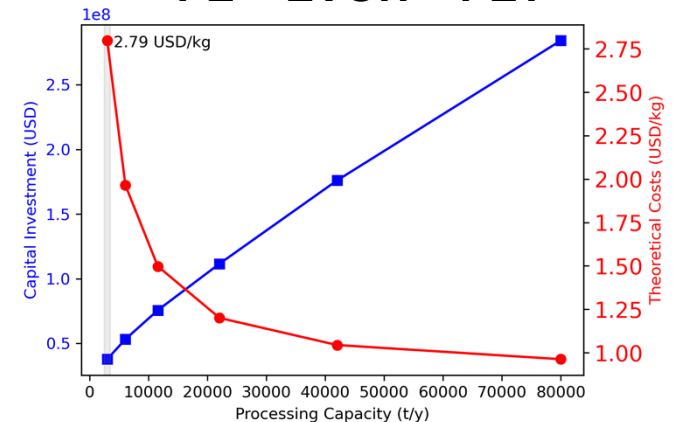
Cost (3,000 tons/yr): 1.96 \$/kg

PE + EVOH



Cost (3,000 tons/yr): 2.40 \$/kg

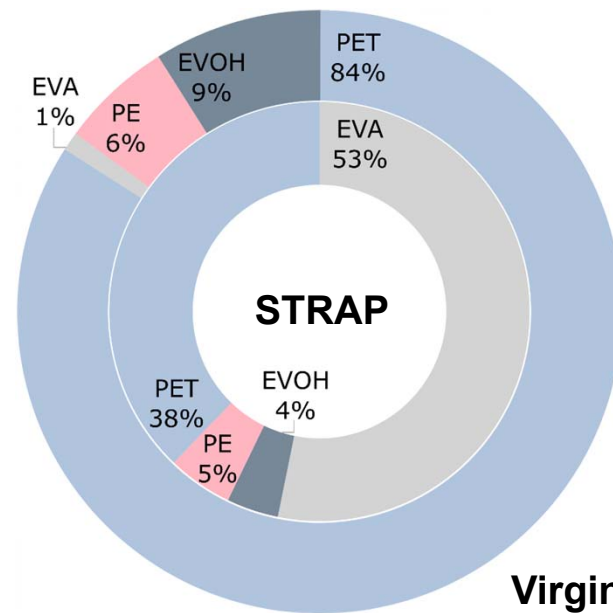
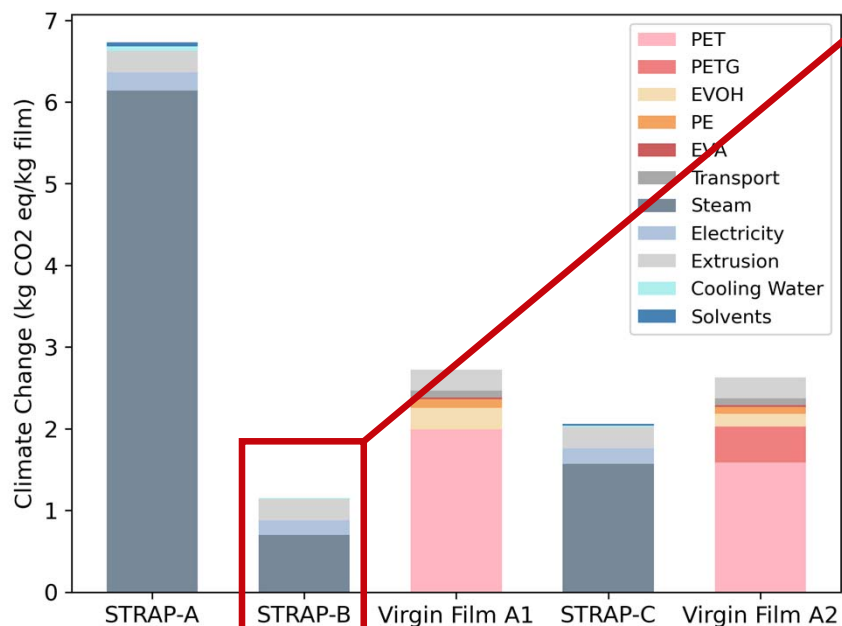
PE + EVOH + PET



Cost (3,000 tons/yr): 2.79 \$/kg



STRAP is Economically, Environmentally Beneficial



STRAP:
18 MJ/kg film

Virgin process:
68 MJ/kg film

STRAP produces film components with ~70% lower energy, CO₂ emissions than virgin processes



Derisking STRAP: Building Pilot Plant to Produce STRAP resins

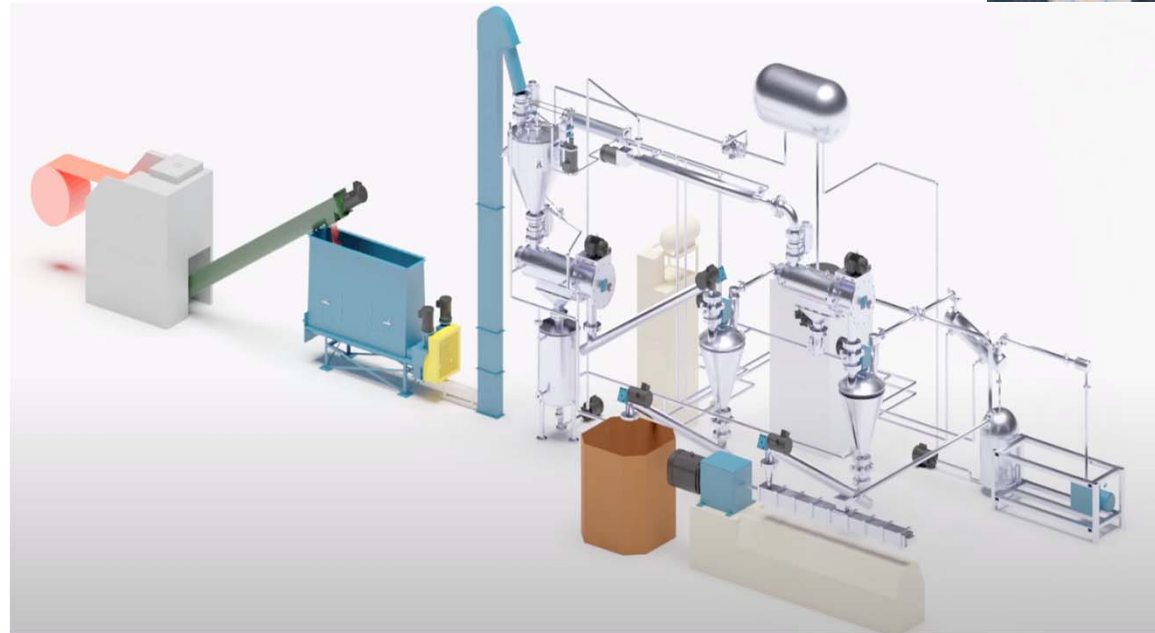
Challenges for Scale-Up

- Pre-processing to shred feedstock
- Feeding and conveying
- Dissolution of polymer in minimum time
- Separation of solution/non-dissolved flakes at high efficiency
- Filtration of fine particles from solution
- Precipitation of dissolved polymer without surface sticking
- Recovering at least 99.9% of solvent
- Safely operating with solvents

Aim to address these challenges by building pilot plant at 25 kg/hr scale

Designing, building pilot plant in collaboration with Michigan Technical University

Prof. Ezra Bar Ziv





Summary: STRAP is Moving Towards Commercialization

- STRAP can recover polymers from multilayer plastic films and other feedstocks (e.g., municipal solid waste)
- Films made from recovered resins demonstrate properties similar to films made from virgin resins
- STRAP is economically competitive and reduces emissions compared to virgin resin production
- We are currently building a 25 kg/hr pilot plant
- Looking for partners who want to help us commercialize or implement STRAP technology

Papers, STRAP Fact Sheet: <https://cuwp.org/>

Acknowledgements:



George Huber



Charles



Aurora



Kevin



Pan

Faculty: Prof. Ezra Bar-Ziv, Prof. Greg Curtzwiler, Prof. George Huber, Prof. Keith Vorst, Prof. Victor M Zavala

Students and postdocs: Victor Cecon, John Estella, Charles Granger, Min Soo Kim, Aurora Munguía-López, Euncheol Ra, Kevin L Sánchez-Rivera, Theodore Walker, Zhuo Xu, Tianwei Yan, Jiuling Yu, Panzheng Zhou

Industry collaborators: Steve Grey, Daniel Miller, Kevin Nelson (Amcor)