



GREENER CIRCUIT BOARDS

Alternative Substrates for
Sustainable Electronics

Our Team



Ryan Carpio-Brown

*M.Eng. in
Materials Science
and Engineering*



John (JD) Davis

*PhD Candidate in
Physical
Chemistry*



**Marie-Batisse
Heite**

*Master's in
Bioprocess
Engineering*



Ashley Kochans

*MPH in
Environmental
Health Sciences*



Finn Moran

*MS in
Materials
Science and
Engineering*



Yitong Tian

*MPH in
Environmental
Health Sciences*

Outline

DEFINING THE PROBLEM

Background 01

Incumbent Materials & Processes 02

Approach 03

OUR STRATEGIES

1: Isosorbide Thermosets 04

2: Vitrimer Alternatives 05

3: Thermoplastic Composites 06

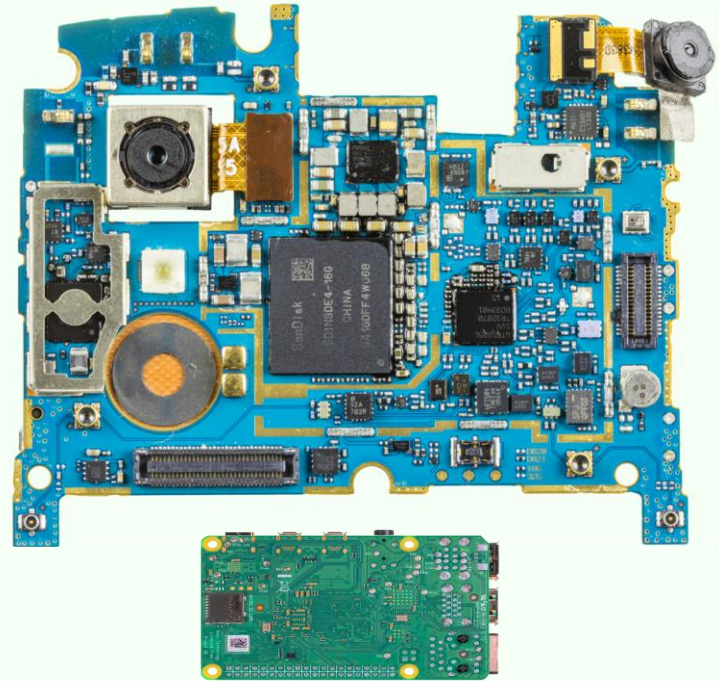
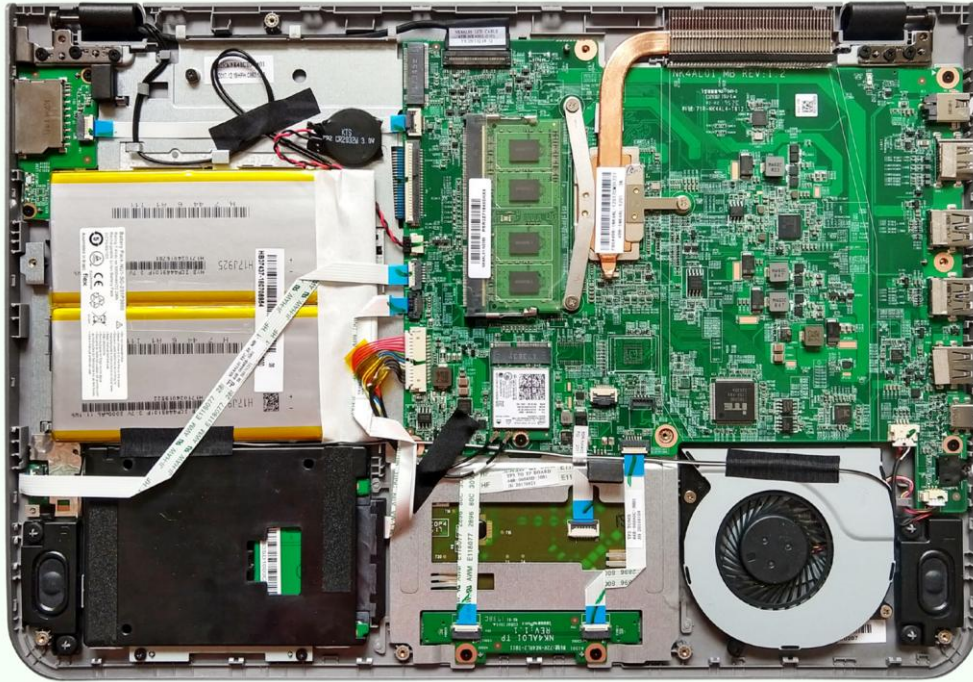
Discussion + Next Steps 07





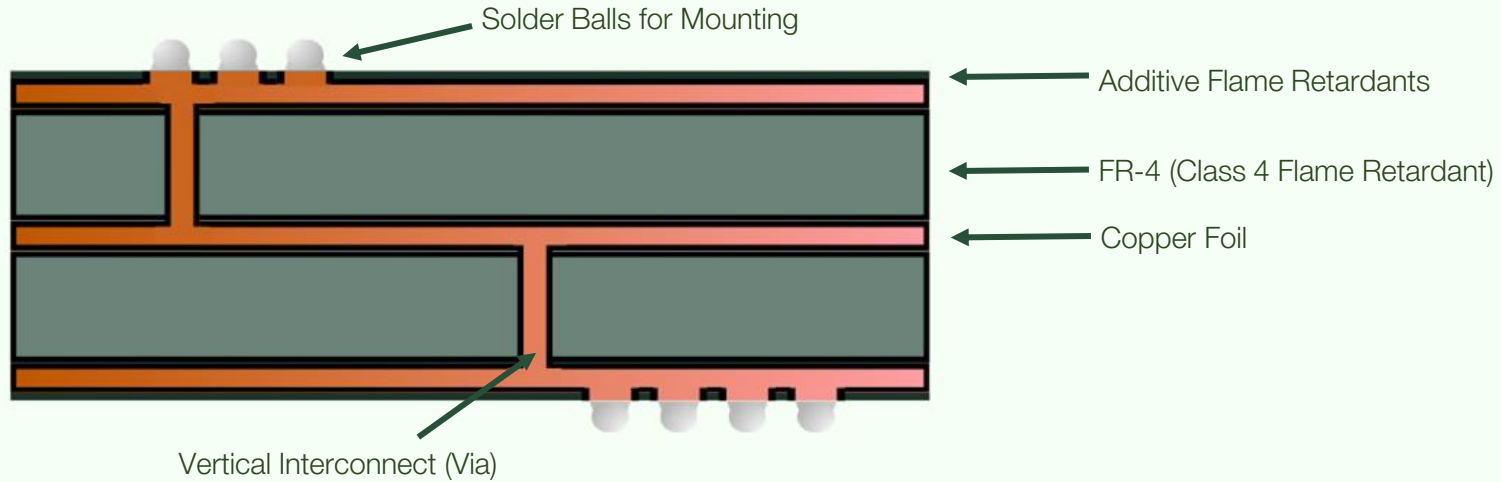
BACKGROUND

PCBs are Ubiquitous and Hard to Replace



Provides secure & reliable mounting for electronic components

Rigid PCBs Rely on FR-4 Composites



- Allows PCBs to **maintain rigidity** and **conduct electricity**
- **Protects against fires** from overheating
- **Adheres layers** together and **insulates** against electromagnetic interference (EMI)

FR-4 Contains Epoxy Resin and Additives



Epichlorohydrin (**ECH**)
Bisphenol A diglycidyl ether (**BADGE**)
Bisphenol A (**BPA**)



Phosphate-based flame retardants
(historically halogenated)



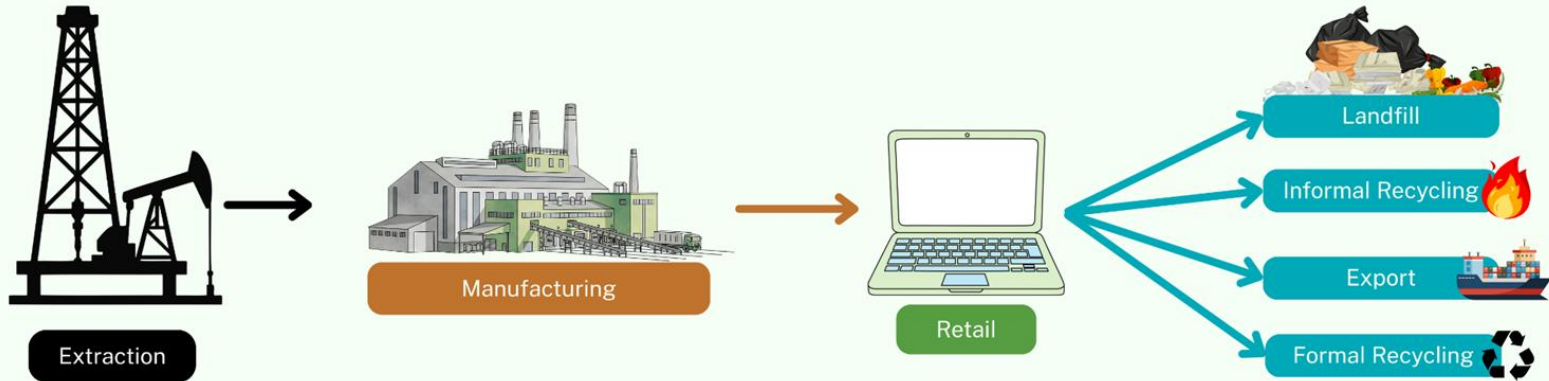
Phenol Novolac

3-Glycidyloxypropyl Trimethoxysilane
(**GPTMS**)



Triphenyl Phosphate (**TPhP**)

Exposure Varies at the 4 Stages of Life Cycle



Primarily concerned with the **manufacturing** and **disposal** stages because:

- Chemical & mechanical processing in manufacture **release chemicals more readily**
- More than **75% of e-waste** is landfilled, burned, or recycled in unregulated settings (*Unitar, The Global E-Waste Monitor, 2024*)



INCUMBENT

Relevance	Name	Group I Human Endpoints			Group II Endpoints				Ecotoxicity	Fate	Physical Hazard	Relevant Life Cycle Stage
		Carcinogenicity	Developmental & Reproductive	Endocrine	Systemic Toxicity	Neuro-toxicity	Skin, Eye, Respiratory Irritation	Skin, Eye, Respiratory Sensitization	Aquatic Toxicity	Persistence & Bioaccumulation	Reactivity	
		Mutagenicity							<i>Acute & Chronic</i>		Other	
Precursor	BPA	M	H	H	M	M	vH	L	vH	L	L	Sourcing, Manufacture & End-of-Life
Cross-Linker	ECH	vH	H	M	H	M	vH	H	M	vH	vH	
Monomer	BADGE	M	L	H	H	L	H	M	vH	L	M	
Fire Retardant	RBD	M	L	M	M	M	L	L	vH	M	L	Manufacture & End-of-Life
Coupling Agent	GPTMS	M	M	L	M	M	M	L	L	L	H	Sourcing & Manufacture
Curing Agent	Phenol novolac	L	L	L	L	L	M	M	L	vH	L	
Accelerators	TPhP	L	L	H	H	vH	L	M	vH	H	M	

Relevance	Name	Group I Human Endpoints			Group II Endpoints			Ecotoxicity	Fate	Physical Hazard	Relevant Life Cycle Stage	
		Carcinogenicity	Developmental & Reproductive	Endocrine	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation	Skin, Eye, Respiratory Sensitization	Aquatic Toxicity	Persistence & Bioaccumulation		Reactivity
		Mutagenicity							<i>Acute & Chronic</i>			Other
Precursor	BPA	M	H	H	M	M	vH	L	vH	L	Sourcing, Manufacture & End-of-Life	
Cross-Linker	ECH	For each chemical , we conducted some literature reviews										vH
Monomer	BADGE	M	L	H	H	L	H	M	vH	L	M	
Fire Retardant	RBD	M	L	M	M	M	L	L	vH	M	L	Manufacture & End-of-Life
Coupling Agent	GPTMS	M	M	L	M	M	M	L	L	L	H	Sourcing & Manufacture
Curing Agent	Phenol novolac	L	L	L	L	L	M	M	L	vH	L	
Accelerators	TPhP	L	L	H	H	vH	L	M	vH	H	M	

Relevance	Name	Group I Human Endpoints			Group II Endpoints				Ecotoxicity	Fate	Physical Hazard	Relevant Life Cycle Stage
		Carcinogenicity	Developmental & Reproductive	Endocrine	Systemic Toxicity	Neuro-toxicity	Skin, Eye, Respiratory Irritation	Skin, Eye, Respiratory Sensitization	Aquatic Toxicity	Persistence & Bioaccumulation	Reactivity	
		Mutagenicity							<i>Acute & Chronic</i>		Other	

Precursor	BPA	M	M	M	M	M	M	M	M	L	L	Sourcing, Manufacture & End-of-Life
Cross-Linker	ECH	vH	vH	vH	vH	vH	vH	vH	M	vH	vH	
Monomer	BADGE	M	L	H	H	L	H	M	vH	L	M	
Fire Retardant	RBD	M	L	M	M	M	L	L	vH	M	L	Manufacture & End-of-Life
Coupling Agent	GPTMS	M	M	L	M	M	M	L	L	L	H	Sourcing & Manufacture
Curing Agent	Phenol novolac	L	L	L	L	L	M	M	L	vH	L	
Accelerators	TPhP	L	L	H	H	vH	L	M	vH	H	M	

We ranked hazard for each **toxicological endpoint**

- Using Globally Harmonised System (**GHS**) method

Relevance	Name	Group I Human Endpoints			Group II Endpoints				Ecotoxicity	Fate	Physical Hazard	Relevant Life Cycle Stage	
		Carcinogenicity	Developmental & Reproductive	Endocrine	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation	Skin, Eye, Respiratory Sensitization	Aquatic Toxicity	Persistence & Bioaccumulation	Reactivity		
		Mutagenicity							<i>Acute & Chronic</i>		Other		
Precursor	BPA	M	H	H	M	M	vH	L	vH	L	L	Sourcing, Manufacture & End-of-Life	
Cross-Linker	ECH	We evaluated how chemicals were likely to be released									vH		vH
Monomer	BADGE	M	L	H	H	L	H	M	vH	L	M	Manufacture & End-of-Life	
Fire Retardant	RBD	We recorded the relevant life cycle stage of the potential exposure											
		M	L	M	M	M	L	L	vH	M	L		
Coupling Agent	GPTMS	M	M	L	M	M	M	L	L	L	L	H	Sourcing & Manufacture
Curing Agent	Phenol novolac	L	L	L	L	L	M	M	L	vH	L		
Accelerators	TPhP	L	L	H	H	vH	L	M	vH	H	M		

Relevance	Name	Group I Human Endpoints			Group II Endpoints				Ecotoxicity	Fate	Physical Hazard	Relevant Life Cycle Stage		
		Carcinogenicity	Developmental & Reproductive	Endocrine	Systemic Toxicity	Neuro-toxicity	Skin, Eye, Respiratory Irritation	Skin, Eye, Respiratory Sensitization	Aquatic Toxicity	Persistence & Bioaccumulation	Reactivity			
		Mutagenicity							<i>Acute & Chronic</i>		Other			
Precursor	BPA	Divided the health categories into 3 groups for analysis									L	L	Sourcing, Manufacture & End-of-Life	
Cross-Linker	ECH	M	H	M	M	vH	H	M	vH	vH				
Monomer	BADGE	M	○ High-priority hazards that can lead to fatal effects									L	M	
Fire Retardant	RBD	M	○ Important but more mitigatable hazards, including single and repeated exposures											Manufacture & End-of-Life
Coupling Agent	GPTMS	M	M	L	M	M	M	L	L	L	H	Sourcing & Manufacture		
Curing Agent	Phenol novolac	L	L	L	L	L	M	M	L	vH	L			
Accelerators	TPhP	L	L	H	H	vH	L	M	vH	H	M			

Relevance	Name	Group I Human Endpoints			Group II Endpoints				Ecotoxicity	Fate	Physical Hazard	Relevant Life Cycle Stage
		Carcinogenicity	Developmental & Reproductive	Endocrine	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation	Skin, Eye, Respiratory Sensitization	Aquatic Toxicity	Persistence & Bioaccumulation	Reactivity	
		Mutagenicity							<i>Acute & Chronic</i>		Other	
Precursor	BPA	M	H	H	M	M	vH	L	vH	L	L	Sourcing, Manufacture & End-of-Life
Cross-Linker	ECH	vH	H	M	H	M	vH	H	M	vH	vH	
Monomer	BADGE	M	L	H	H	L	H	M	vH	L	M	
Fire Retardant	RBD	The components of the epoxy resin are by far the most hazardous										Manufacture & End-of-Life
Coupling Agent	GPTMS	M	M	L	M	M	M	L	L	L	H	Sourcing & Manufacture
Curing Agent	Phenol novolac	L	L	L	L	L	M	M	L	vH	L	
Accelerators	TPhP	L	L	H	H	vH	L	M	vH	H	M	

Relevance	Name	Group I Human Endpoints			Group II Endpoints				Ecotoxicity	Fate	Physical Hazard	Relevant Life Cycle Stage
		Carcinogenicity	Developmental & Reproductive	Endocrine	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation	Skin, Eye, Respiratory Sensitization	Aquatic Toxicity	Persistence & Bioaccumulation	Reactivity	
		Mutagenicity							<i>Acute & Chronic</i>		Other	
Precursor	BPA	M	H	H	M	M	vH	L	vH	L	L	Sourcing, Manufacture & End-of-Life
Cross-Linker	ECH	vH	H	M	H	M	vH	H	M	vH	vH	
Monomer	BADGE	Epichlorohydrin (ECH) stands out as at least moderately hazardous across every end point we evaluated										
Fire Retardant	RBD	M	L	M	M	M	L	L	vH	M	L	Manufacture & End-of-Life
Coupling Agent	GPTMS	M	M	L	M	M	M	L	L	L	H	Sourcing & Manufacture
Curing Agent	Phenol novolac	L	L	L	L	L	M	M	L	vH	L	
Accelerators	TPhP	L	L	H	H	vH	L	M	vH	H	M	

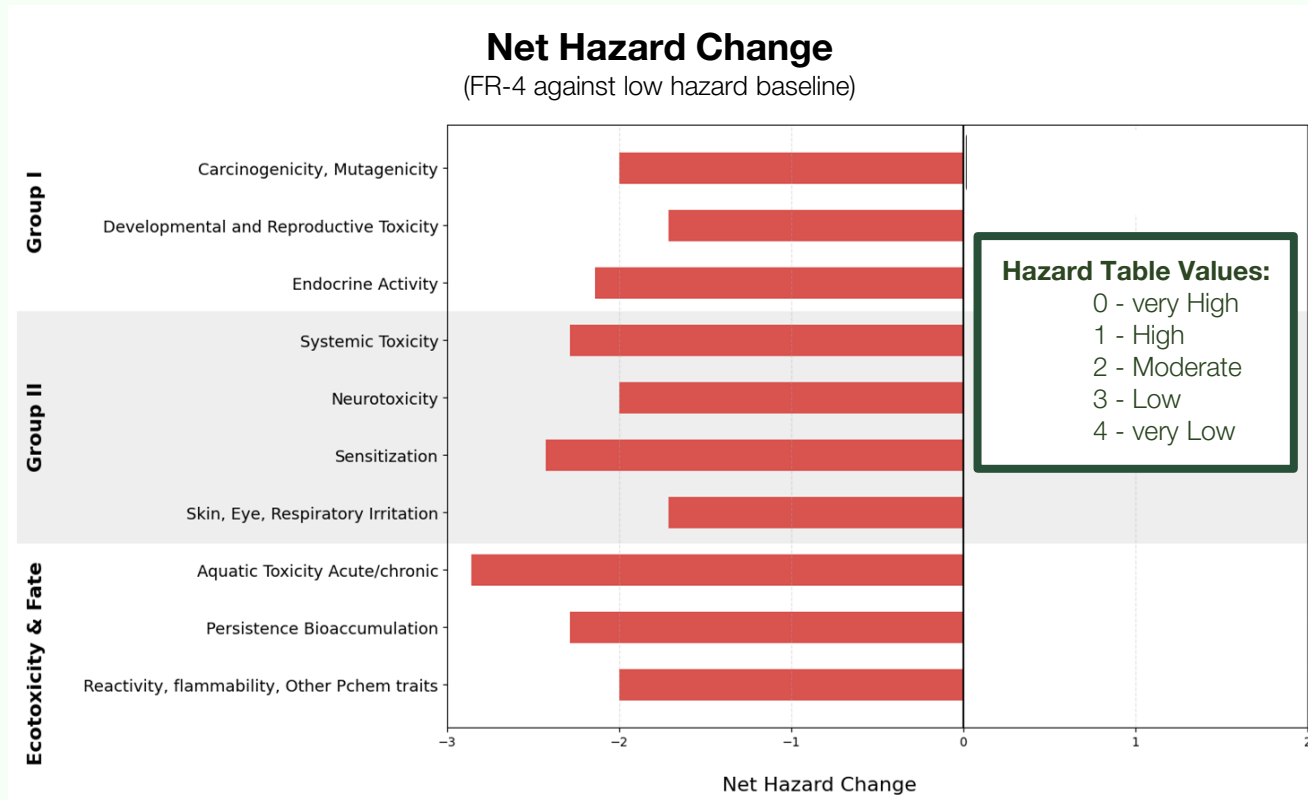
Relevance	Name	Group I Human Endpoints			Group II Endpoints				Ecotoxicity	Fate	Physical Hazard	Relevant Life Cycle Stage
		Carcinogenicity	Developmental & Reproductive	Endocrine	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation	Skin, Eye, Respiratory Sensitization	Aquatic Toxicity	Persistence & Bioaccumulation	Reactivity	
		Mutagenicity							<i>Acute & Chronic</i>		Other	
Precursor	BPA	M	H	H	M	M	L	L	L	L	Sourcing, Manufacture & End-of-Life	
Cross-Linker	ECH	vH	Although they make up a small percentage by weight, the additives pose a fair amount of hazard.							vH		
Monomer	BADGE	M	L	H	H	L	H	M	L	M		
Fire Retardant	RBD	M	L	M	M	M	L	L	vH	M	L	Manufacture & End-of-Life
Coupling Agent	GPTMS	M	M	L	M	M	M	L	L	L	H	Sourcing & Manufacture
Curing Agent	Phenol novolac	L	L	L	L	L	M	M	L	vH	L	
Accelerators	TPhP	L	L	H	H	vH	L	M	vH	H	M	

Relevance	Name	Group I Human Endpoints			Group II Endpoints				Ecotoxicity	Fate	Physical Hazard	Relevant Life Cycle Stage
		Carcinogenicity	Developmental & Reproductive	Endocrine	Systemic Toxicity	Neurotoxicity	Skin, Eye, Respiratory Irritation	Skin, Eye, Respiratory Sensitization	Aquatic Toxicity	Persistence & Bioaccumulation	Reactivity	
		Mutagenicity							Acute & Chronic		Other	
Precursor	BPA	M	H	H	M	M	vH	L	L		Sourcing, Manufacture & End-of-Life	
Epoxy Resin	ECH	Hazards in the ecotoxicity & environmental fate group were very high for most chemicals							M	vH		vH
Monomer	BADGE	M	L	H	H	L	H	M	vH	L		M
Fire Retardant	RBD	Because environmental exposure is most likely to occur at disposal , this is particularly concerning							vH	M	L	Manufacture & End-of-Life
Coupling Agent	GPTMS	M	M	L	M	M	M	L	L	L	H	Sourcing & Manufacture
Curing Agent	Phenol novolac	L	L	L	L	L	M	M	L	vH	L	
Accelerators	TPhP	L	L	H	H	vH	L	M	vH	H	M	

Relevance	Name	Group I Human Endpoints			Group II Endpoints				Ecotoxicity	Fate	Physical Hazard	Relevant Life Cycle Stage
		Carcinogenicity	Developmental & Reproductive	Endocrine	Systemic Toxicity	Neuro-toxicity	Skin, Eye, Respiratory Irritation	Skin, Eye, Respiratory Sensitization	Aquatic Toxicity	Persistence & Bioaccumulation	Reactivity	
		Mutagenicity							<i>Acute & Chronic</i>		Other	
Precursor	BPA	M	H	H	M	M	vH	L	vH	L	L	Sourcing, Manufacture & End-of-Life
Cross-Linker	ECH	vH	H	M	H	M	vH	H	M	vH	vH	
Monomer	BADGE	M	L	H	H	L	H	M	vH	L	M	
Fire Retardant	RBD	M	L	M	M	M	L	L	vH	M	L	Manufacture & End-of-Life
Coupling Agent	GPTMS	M	M	L	M	M	M	L	L	L	H	Sourcing & Manufacture
Curing Agent	Phenol novolac	L	L	L	L	L	M	M	L	vH	L	
Accelerators	TPhP	L	L	H	H	vH	L	M	vH	H	M	

Condensed Hazard Table for Comparison

1. Convert cell values to numbers
1. Compute chemicals averages per endpoint
1. Compare the average for each endpoint between F-4 and alternative solutions



The Goal:

Find Safer Alternatives for FR-4

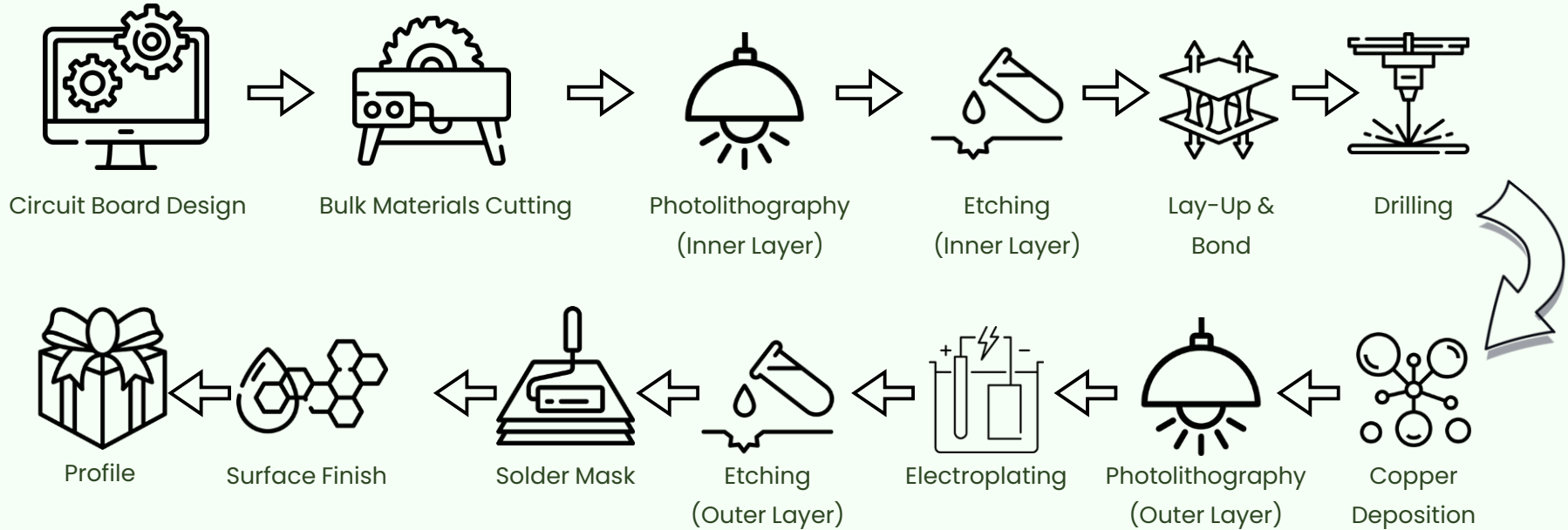


- **Reduce health hazard** of handling of FR-4 at the **manufacturing** stage
- **Mitigate the ecotoxicity** that make **e-waste disposal** even more dangerous, including FR-4's tendency to persist in environments and bioaccumulate in food webs

The image features a dark green background with stylized circuit board traces in a lighter shade of green. Several vertical lines represent traces, with a small orange pill-shaped component on one of them. A dark grey rectangular box with rounded corners is centered horizontally, containing the word "APPROACH" in a bold, white, sans-serif font. The box is surrounded by several light grey, pill-shaped components that look like pins or connectors. There are also four orange circular elements scattered around the scene: one on the left, one at the top right, and two at the bottom left.

APPROACH

Tough Compounds Withstand Harsh Conditions

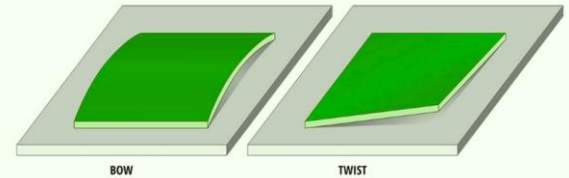


Thermomechanical Performance Criteria

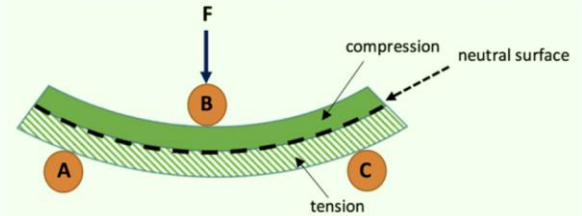
CTE - X, Y (ppm/°C)	CTE - Z (ppm/°C)	Tensile Strength (MPa)	Spec	Point Value
>90	>115	<180	Below	0
85-95	90-115	180-200	Nearly Meets	1
65-85	80-90	200-300	Meets	2
55-65	70-80	300-375	Exceeds	3
<55	<70	>375	Far Exceeds	4

We identified failure mechanisms in manufacturing and assigned their causes to specific material properties.

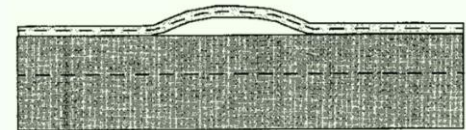
- Relative specs were dictated based on literature and existing FR-4 datasheets.



PCB Warping as a consequence of thermal expansion



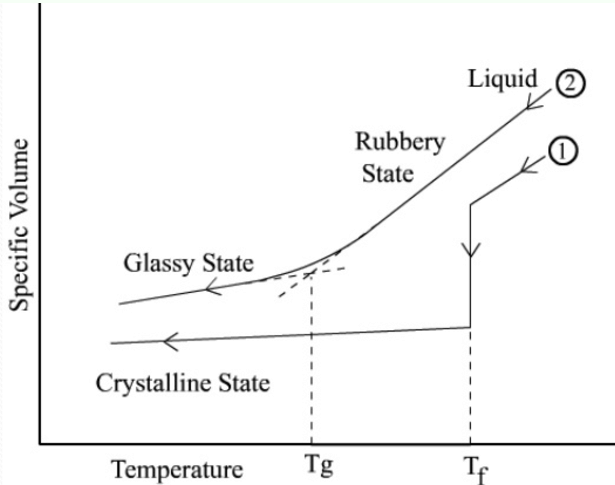
3-Point Bend Test places top surface in compression, while the bottom is in tension



Composite layer delamination

Thermomechanical Performance Criteria

Glass Transition Temperature
(T_g)

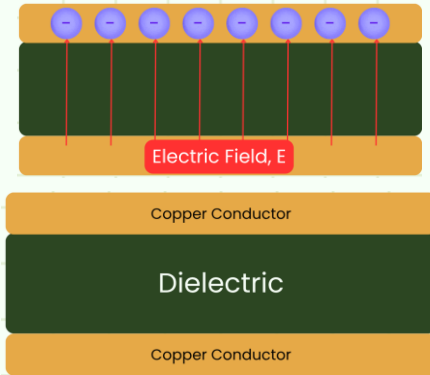


T_g (°C)	T_{max} (°C)	Point Value	Spec
<100	<125	0	Below
100-125	125-140	1	Nearly Meets
125-140	140	2	Meets
140-160	140-160	3	Exceeds
>160	>160	4	Far Exceeds

→ Current manufacturing processing necessitates high glass transition temperature

Dielectric Performance Criteria

Dielectric constant



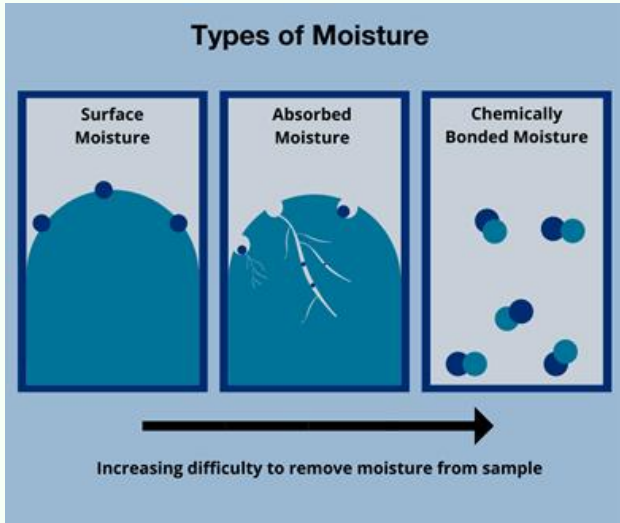
Dk	Df		
>6	<0.002	0	Below
5-6	0.002-0.005	1	Nearly Meets
3-5	0.005 - 0.006	2	Meets
2-3	0.006-0.007	3	Exceeds
<2	0.007-0.01	4	Far Exceeds

Reinforcement materials identified based on electrical performance needs.

How stable are the insulation characteristics?

Chemical Performance Criteria

Moisture content %

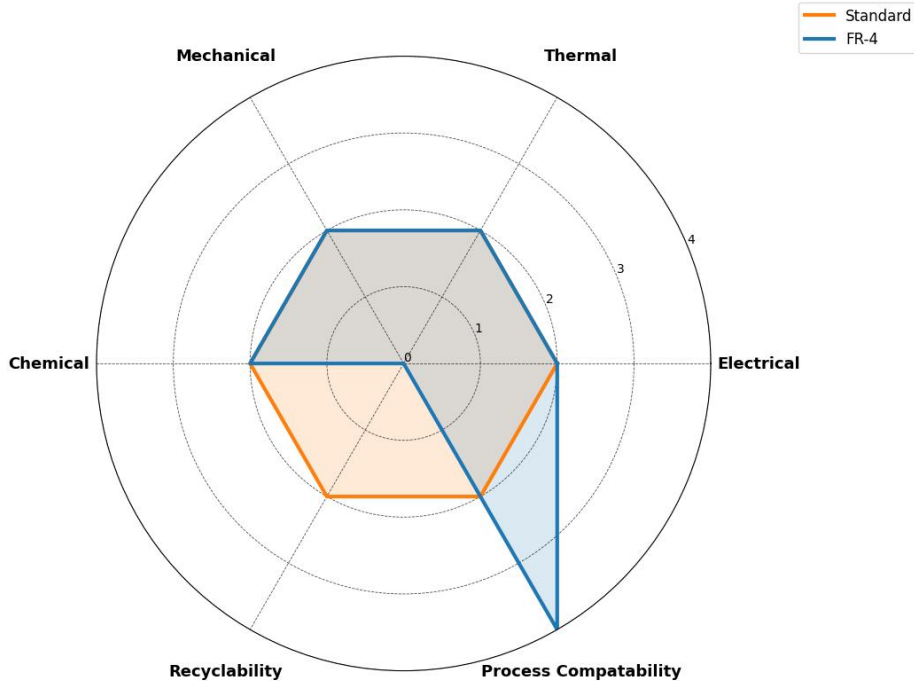


pH Stability	Moisture Content (%)		
4-11	>15	0	Below
2-12 (Bias)	10-15	1	Nearly Meets
2-12	5-10	2	Meets
1-13	3-5	3	Exceeds
0-14	<3	4	Far Exceeds

Image from Precisa moisture technology

Benchmarking Technical Performance

FR-4 Material Performance



→ We identified 2 qualitative metrics

Recyclability	Process Compatibility		
Not Possible	Completely New Pipeline	0	Below
Some Recovery (Chemical Recycling)	Mostly New Equipment	1	Nearly Meets
High Recovery (Chemical Recycling)	Some New Equipment	2	Meets
Some Recovery (Mechanical Recycling)	New Processes	3	Exceeds
High Recovery (Mechanical Recycling)	No Changes	4	Far Exceeds

Challenges with Finding Alternative Substrates

High glass transition temperature and mechanical strength



Strong bonding → reactive/ hazardous chemistries

Low dielectric constant



Limited to mainly organic compounds

Mechanical Recyclability



Implies breakable or manipulative bonding networks

Three Potential Alternatives:

From Most Manufacturing Compatibility to Least

Bio-based Epoxy Thermosets

Example

Isosorbide, crosslinked with ECH

Main Advantage

Improves sourcing while maintaining the incumbent thermoset chemistry

Alternative Thermosets

Example

Vitrimers, a reprocessable thermoset

Main Advantage

Offers improved recyclability without departing too much from traditional thermosets

Thermoplastics

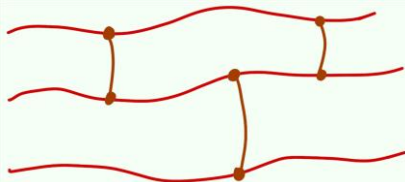
Example

PICT (*isosorbide-CHDM-terephthalate*)

Main Advantage

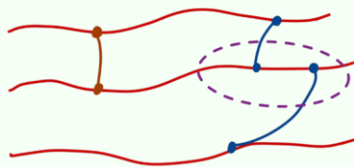
Drastically reduces hazard, but requires alternative processing methods

Strategy 1: Thermosets



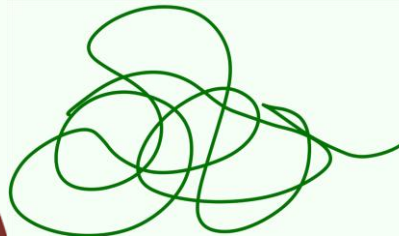
Covalently cross-linked
polymer chains
High Rigidity
Chemical resistance
Non-recyclable

Strategy 2: Vitrimers



Covalently adapted
exchange networks
Malleable when heated
Self-Healing

Strategy 3: Thermoplastics



Reprocessable
Recyclable
Poor chemical resistance
No chemical cross-links
Flows when heated



**OUR
STRATEGIES**

STRATEGY ONE:

Bio-based epoxy thermosets

Strategy	Time Table	Compatibility	Hazard Reduction	Performance	Renewable Sourcing	Processability
1. Bio-Based Epoxy Thermoset	Near-term	✓✓	✗	✓✓	✓	✗

Pro:

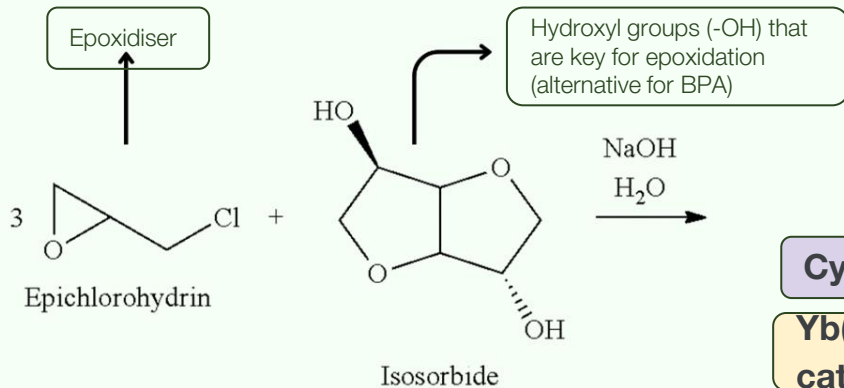
- Drop-in solution that uses the same chemistry as the incumbent

Con:

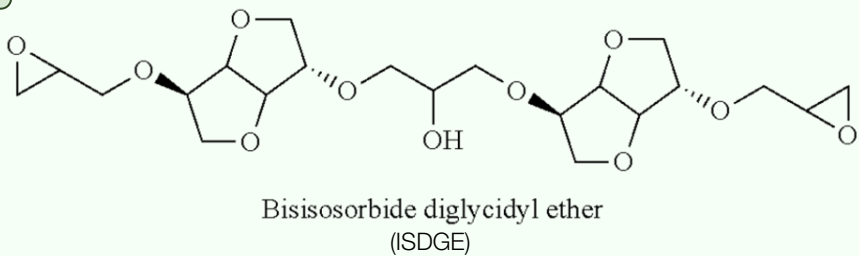
- Does not replace toxic ECH at the manufacturing stage

Synthesizing Isosorbide Resin

1



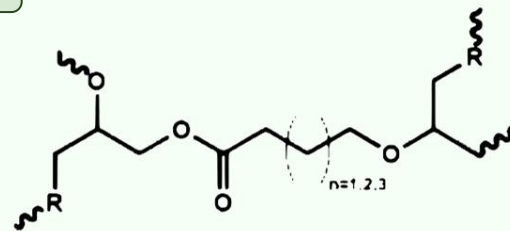
2



Cyclic lactones

Yb(OTf)₃
catalyst

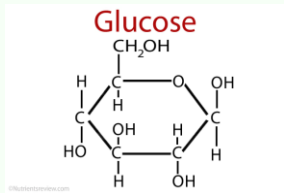
3



Lim et al. (2025). Sustainable, degradable and malleable low-dielectric-constant thermosets derived from biomass for recyclable green electronics.

Isosorbide is Synthesized from Plant Starches

Isosorbide → a biogenic diol
(a molecule with two hydroxyl groups, $-OH$)
obtained from sorbitol, which comes from the fermentation of glucose

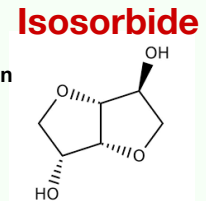


Engineered yeast*
(*Saccharomyces cerevisiae*)

Fermentation



Chemical dehydration



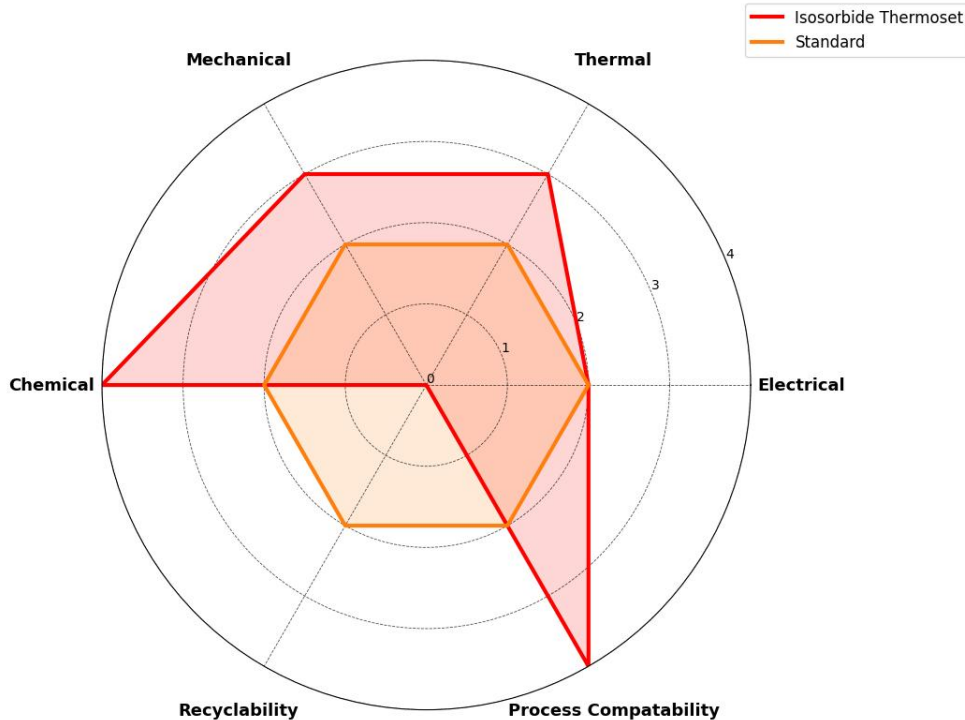
*Natural conversion of glucose to sorbitol in bacteria; *Zymomonas mobilis*, *Candida boidinii* and *Gluconobacter oxydans*

Brandi, F., & Al-Naji, M. (2022). Sustainable Sorbitol Dehydration to Isosorbide using Solid Acid Catalysts: Transition from Batch Reactor to Continuous-Flow System.

Bottega Pergher et al. (2024). The search for rigid, tough polyesters with high Tg - renewable aromatic polyesters with high isosorbide content.

Isosorbide Technical Performance

Isosorbide Thermoset Material Performance

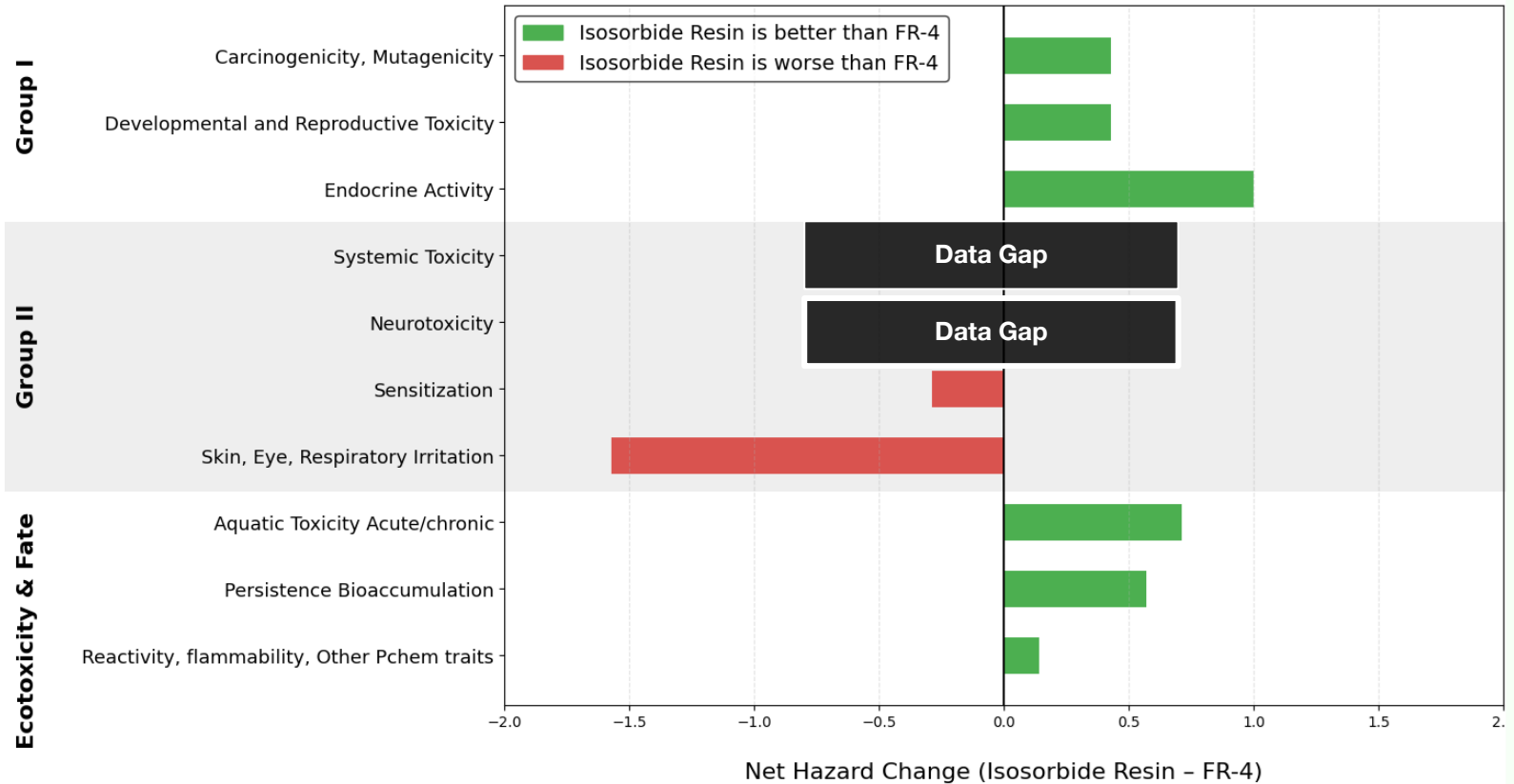


Main takeaway:

Drop-in hazard reduction, but stuck with thermoset limitations.

Same as current FR-4 recycling today = metal recovery, not PCB recovery.

Hazard Comparison: Isosorbide Resin vs FR-4



STRATEGY TWO:

Alternative thermosets

Strategy	Time Table	Compatibility	Hazard Reduction	Performance	Renewable Sourcing	Processability
2. Vitrimer	Mid-term	✓	✗	✓✓	✓	✓

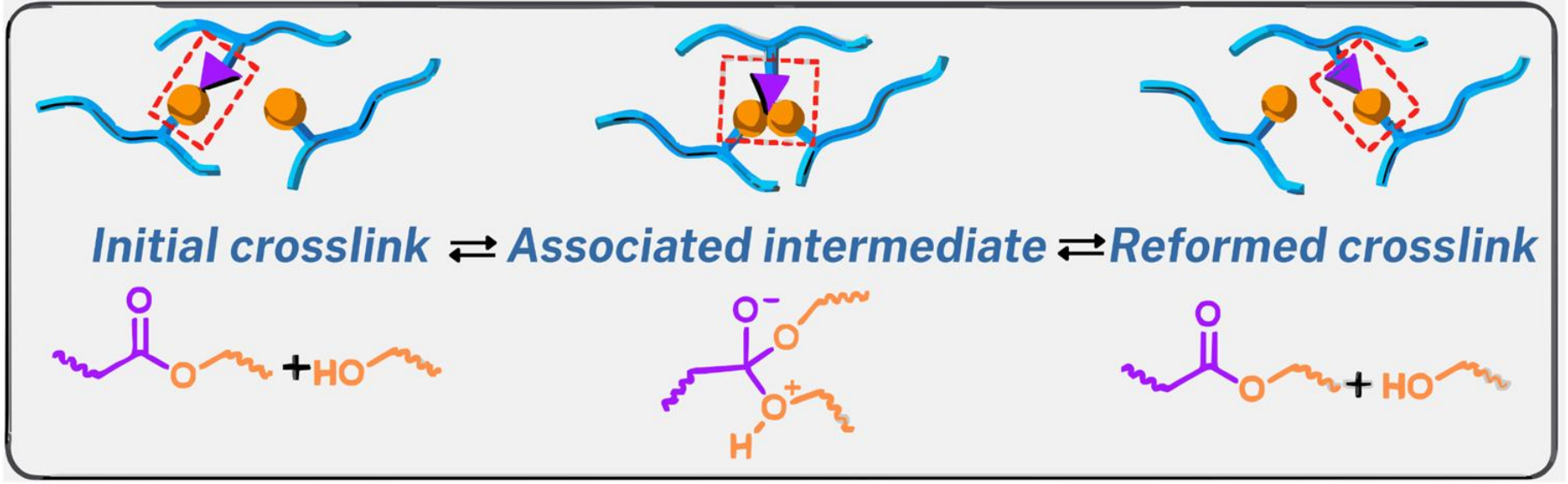
Pros:

- Meet all the performance criteria
- Can be chemically recovered at end of life

Cons:

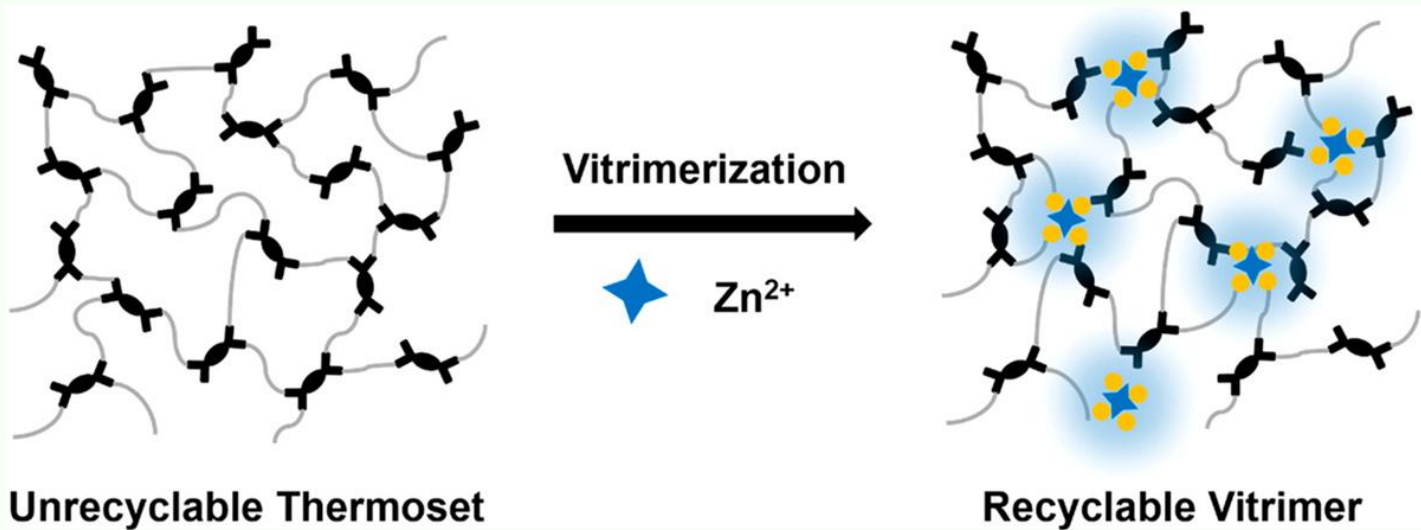
- Doesn't replace toxic BADGE
- Introduces new hazards at recycling

Inspiration



Chen et al. (2021). "Reprocessable Thermosets": Synthesis and Characterization of Vitrimer in the Undergraduate Lab Course.

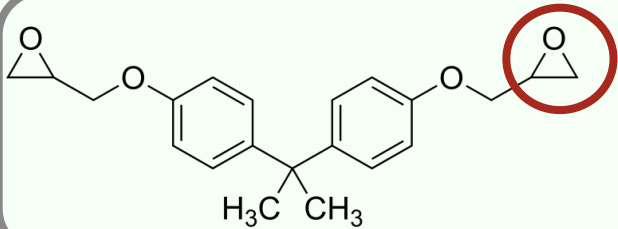
Inspiration



Yue et al. (2022). *Vitrimerization: Converting Thermoset Polymers into Vitrimers.*

Synthesizing Epoxy Vitrimers

1 Curing

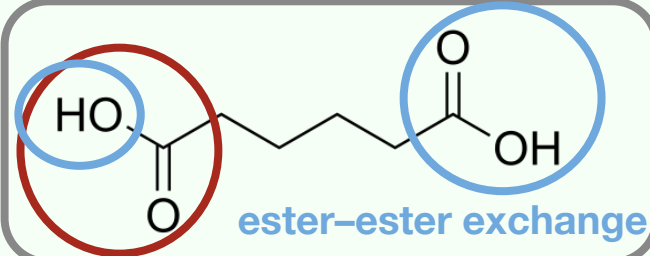


BADGE

bisphenol A diglycidyl ether

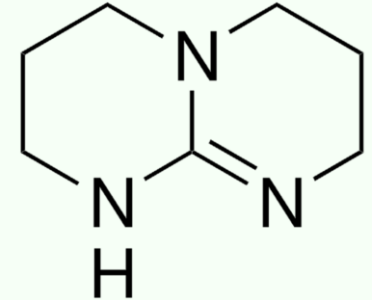
bifunctional epoxy monomer
(primary vitrimer monomer / resin)

β -hydroxy ester



Adipic acid

co-monomer forms ester
linkages



TBD

1,5,7-Triazabicyclo[4.4.0] dec-5-ene

transesterification
catalyst

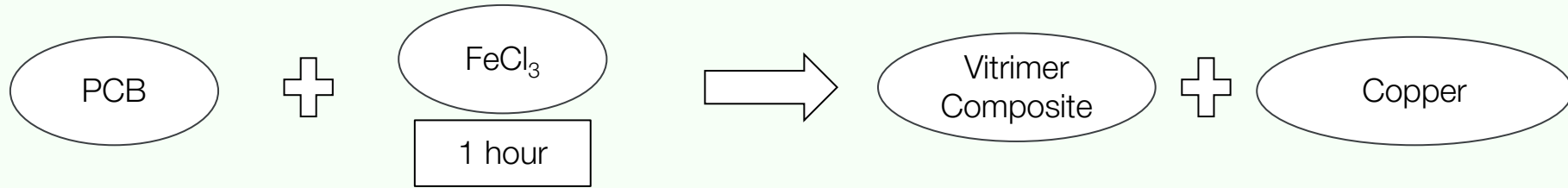
2

Vitrimer exchange (transesterification)

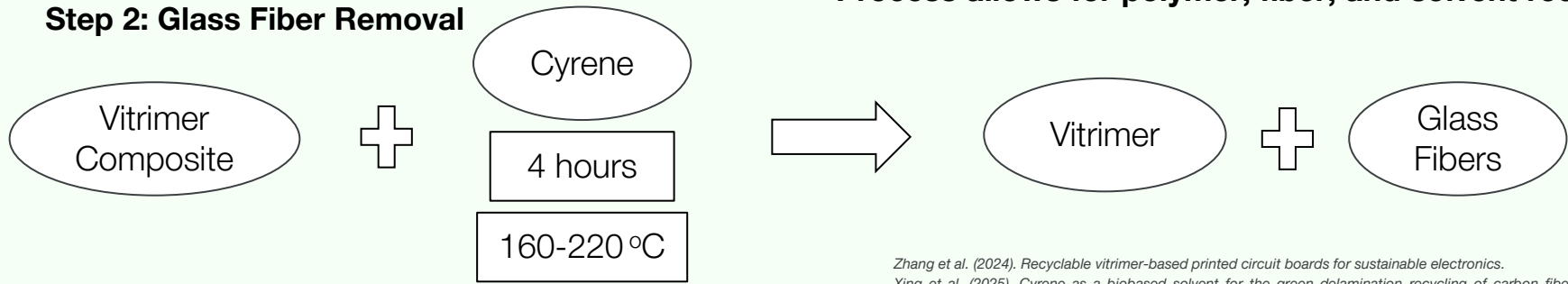
Zhang et al. (2024). Recyclable vitrimer-based printed circuit boards for sustainable electronics

Vitrimer Recycling: Recovery of Materials

Step 1: Copper Removal



Step 2: Glass Fiber Removal



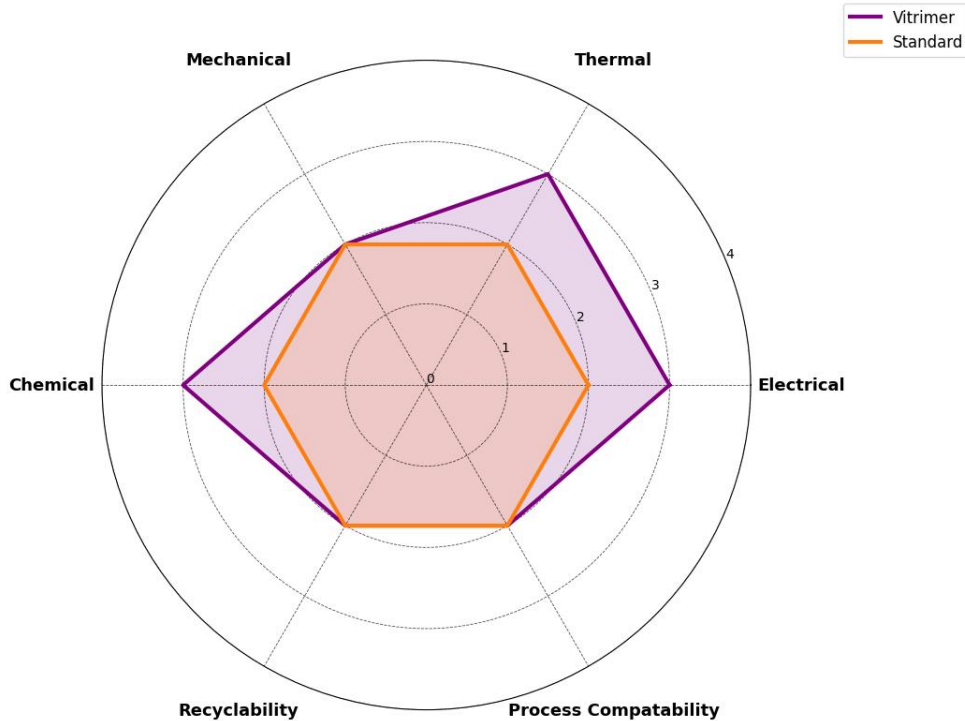
Process allows for polymer, fiber, and solvent recovery

Zhang et al. (2024). Recyclable vitrimer-based printed circuit boards for sustainable electronics.

Xing et al. (2025). Cyrene as a biobased solvent for the green delamination recycling of carbon fiber-reinforced polymer laminates.

Vitrimer Technical Performance

Vitrimer Material Performance

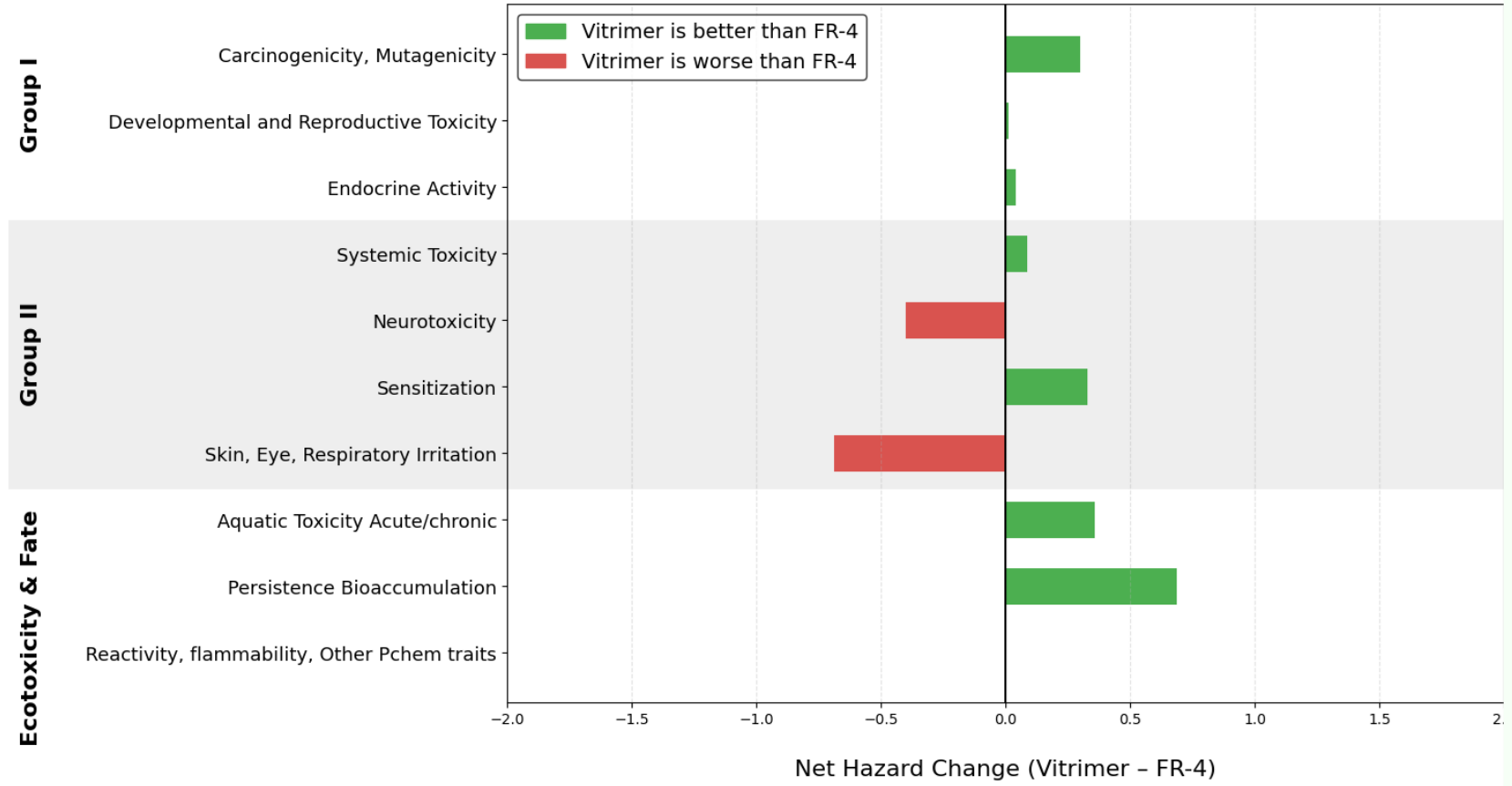


Main takeaway:

“Recyclable” thermoset that meets technical standard.

Not a drop-in solution.

Hazard Comparison: Vitrimer vs FR-4



Vitrimer Health Comparison Data

Relevance	Common name or trade name	Group I Human Endpoints			Group II and Group II* Endpoints				Ecotoxicity	Fate	Physical Hazard
		Carcinogenicity	Developmental and Reproductive Toxicity	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Sensitization	Skin, Eye, Respiratory Irritation	Aquatic Toxicity Acute/chronic	Persistence Bioaccumulation	Reactivity, flammability
		Mutagenicity									Other Pchem traits
Epoxy Resin	BPA	M	H	H	M	M	vH	L	vH	L	L
Epoxy Resin	Epichlorohydrin	vH	H	M	H	M	vH	H	M	vH	vH
Epoxy Resin	BADGE	M	L	H	H	L	H	M	vH	L	M
Phosphorus-based Flame Retardant	Resorcinol bis(diphenyl)	M	L	M	M	M	L	L	vH	M	L
Co-monomer	Adipic acid	L	L	DG	M	M	M	H	L	L	L
Catalyst	TBD	L	L	L	H	DG	L	H	H	H	L
Chemical recycling	Ferric chloride	L	DG	L	L	DG	L	vH	L	L	DG
	Isopropyl alcohol	L	L	L	M	M	L	H	L	L	H
Chemical recycling	Cyrene	L	L	L	L	DG	L	M	L	L	L

STRATEGY THREE:

Thermoplastics

Strategy	Time Table	Compatibility	Hazard Reduction	Performance	Renewable Sourcing	Processability
3. Thermoplastics (PICT)	Long-term	✗	✓✓	✓	✓	✓✓

Pros:

- Drastically reduced hazards for individual chemicals

Cons:

- Requires some boosting to be compliant

Inspiration for Thermoplastics

**Partly biobased,
like our
isosorbide
thermoset**

**Less aggressive
processing (lower
temperatures,
fewer irreversible
reactions) & better
recyclability**

**(thermoplastic vs.
thermoset)**

**Bold step into a
new material
class
–
risky, but
potentially
transformative**

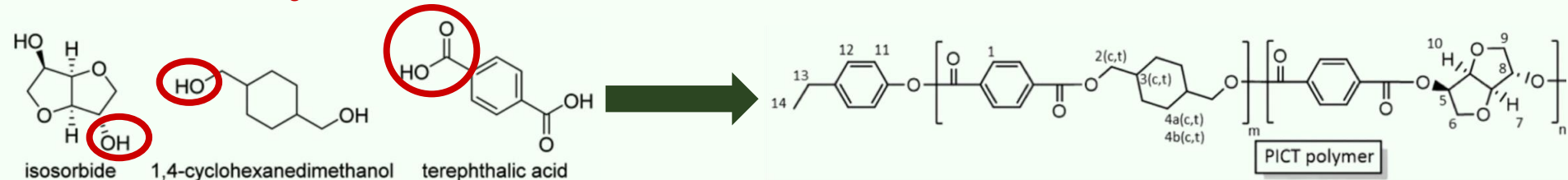
Chemical Synthesis Aromatic Polyester

Aromatic

PICT (isosorbide-CHDM-terephthalate)

- Isosorbide raises T_g
- CHDM adds rigidity

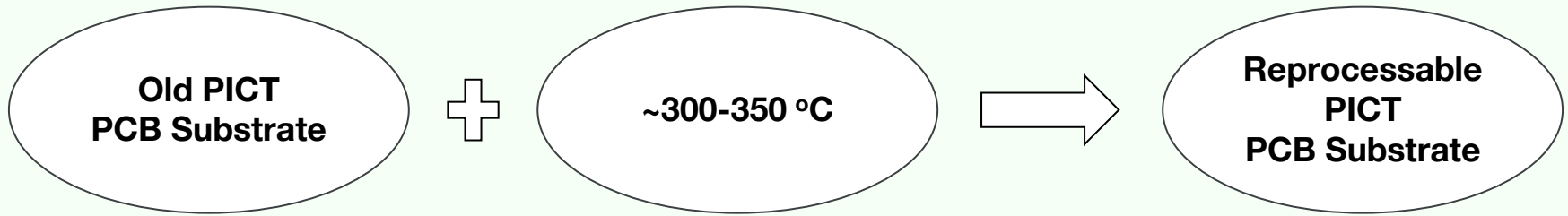
Ester-linkages



Bottega Pergher et al. (2024). The search for rigid, tough polyesters with high T_g - renewable aromatic polyesters with high isosorbide content.

- Amorphous, high-T_g (≈140–150 °C) thermoplastic
- Renewable & melt-processable → suitable for PCB substrate development

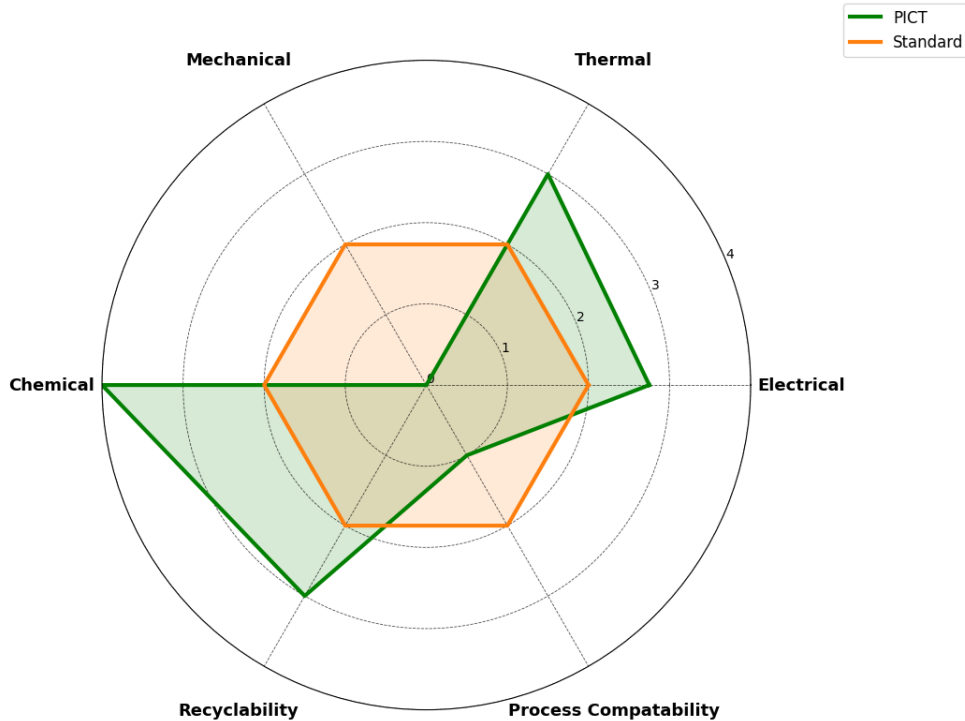
PICT Recycling



- PICT can be thermally recycled, offering a far cleaner end-of-life path than FR-4.

PICT Technical Performance

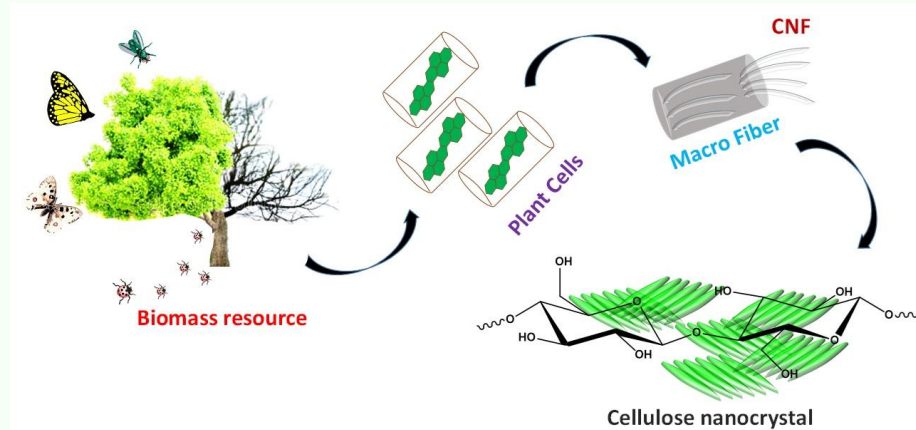
PICT Material Performance



Main takeaway:

Lacking mechanical performance. Needs reinforcement.

Cellulose Nanocrystals Improve Mechanical Rigidity

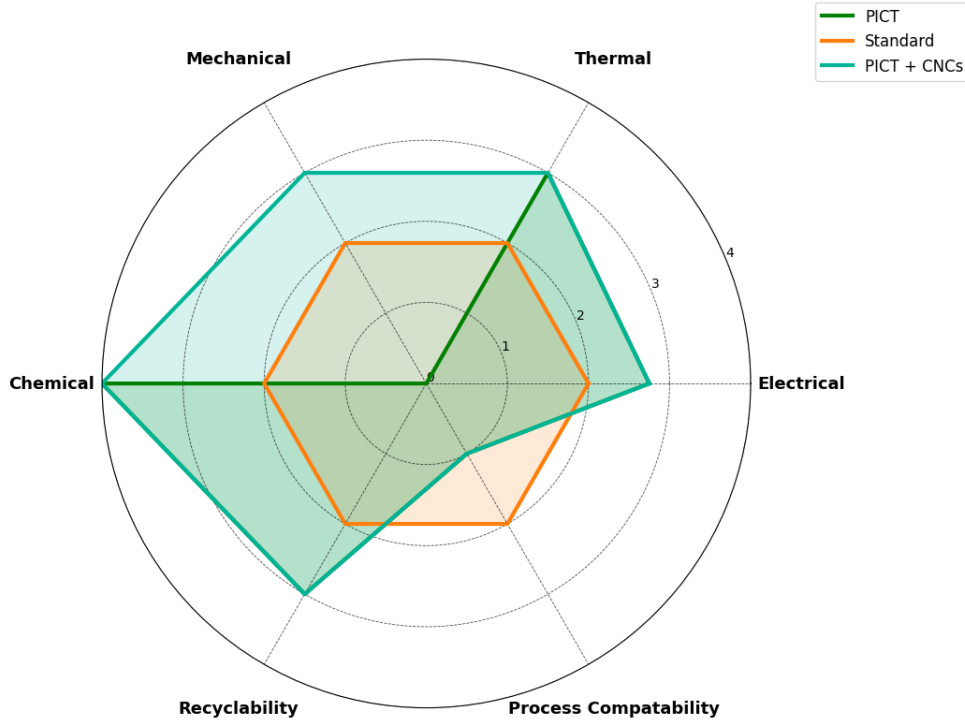


Durairaj, A et al. (2022) Cellulose Nanocrystals (CNC)-Based Functional Materials for Supercapacitor Applications.

- Strong, light-weight, biodegradable, and renewable
- Can be used in combination with PICT to increase the tensile strength/flexural modulus

PICT Theoretical Performance (+ Cellulose Nanocrystals)

PICT + CNCs Material Performance



Main takeaway:

More circular, bio-based thermoplastic.
Needs reinforcement.

Hazard Comparison: PICT vs FR-4





DISCUSSION

PCB Substrate Comparison

Bio-based thermosets and vitrimers offer incremental improvements, but PICT unlocks real change.

Thermoplastics (like PICT) provide the strongest route to safer chemistry and true recyclability.

Strategy	Time Table	Compatibility	Hazard Reduction	Performance	Renewable Sourcing	Processability
1. Bio-Based Epoxy Thermoset	Near-term	✓✓	✗	✓✓	✓	✗
2. Vitrimer	Mid-term	✓	✗	✓✓	✓	✓
3. Thermoplastics (PICT)	Long-term	✗	✓✓	✓	✓	✓✓



THANK YOU!

Questions?

We Condensed Health Data

		M	H	H	M	M	vH	L	vH	L	L
		vH	H	M	H	M	vH	H	M	vH	vH
		M	L	H	H	L	H	M	vH	L	M
		M	L	M	M	M	L	L	vH	M	L
		M	M	L	M	M	M	L	L	L	H
		L	L	L	L	L	M	M	L	vH	L
		L	L	H	H	vH	L	M	vH	H	M

		2	1	1	2	2	0	3	0	3	3	
		0	1	2	1	2	0	1	2	0	0	
		2	3	1	1	3	1	2	0	3	2	
		2	3	2	2	2	3	3	0	2	3	
		2	2	3	2	2	2	3	3	3	1	
		3	3	3	3	3	2	2	3	0	3	
		3	3	1	1	0	3	2	0	1	2	
		AVG	2	2.28	1.85	1.71	2	1.57	2.28	1.14	1.71	2

We Condensed Health Data

1. Convert Cell Values



		M	H	H	M	M	vH	L	vH	L	L
		vH	H	M	H	M	vH	H	M	vH	vH
		M	L	H	H	L	H	M	vH	L	M
		M	L	M	M	M	L	L	vH	M	L
		M	M	L	M	M	M	L	L	L	H
		L	L	L	L	L	M	M	L	vH	L
		L	L	H	H	vH	L	M	vH	H	M

		2	1	1	2	2	0	3	0	3	3
		0	1	2	1	2	0	1	2	0	0
		2	3	1	1	3	1	2	0	3	2
		2	3	2	2	2	3	3	0	2	3
		2	2	3	2	2	2	3	3	3	1
		3	3	3	3	3	2	2	3	0	3

AVG	2	2.28	1.85	1.71	2	1.57	2.28	1.14	1.71	2
-----	---	------	------	------	---	------	------	------	------	---

We Condensed Health Data

1. Convert Cell Values

2. Compute Averages per Endpoint



		M	H	H	M	M	vH	L	vH	L	L
		vH	H	M	H	M	vH	H	M	vH	vH
		M	L	H	H	L	H	M	vH	L	M
		M	L	M	M	M	L	L	vH	M	L
		M	M	L	M	M	M	L	L	L	H
		L	L	L	L	L	M	M	L	vH	L
		L	L	H	H	vH	L	M	vH	H	M

		2	1	1	2	2	0	3	0	3	3	
		0	1	2	1	2	0	1	2	0	0	
		2	3	1	1	3	1	2	0	3	2	
		2	3	2	2	2	3	3	0	2	3	
		2	2	3	2	2	2	3	3	3	1	
		3	3	3	3	3	2	2	3	0	3	
		3	3	1	1	0	3	2	0	1	2	
		AVG	2	2.28	1.85	1.71	2	1.57	2.28	1.14	1.71	2

Tornado Plot Methods

Tornado Plots:

I wrote a script that converts all of the letters from our hazard tables into numbers. So, there is an exact copy of our table with the following substitutions

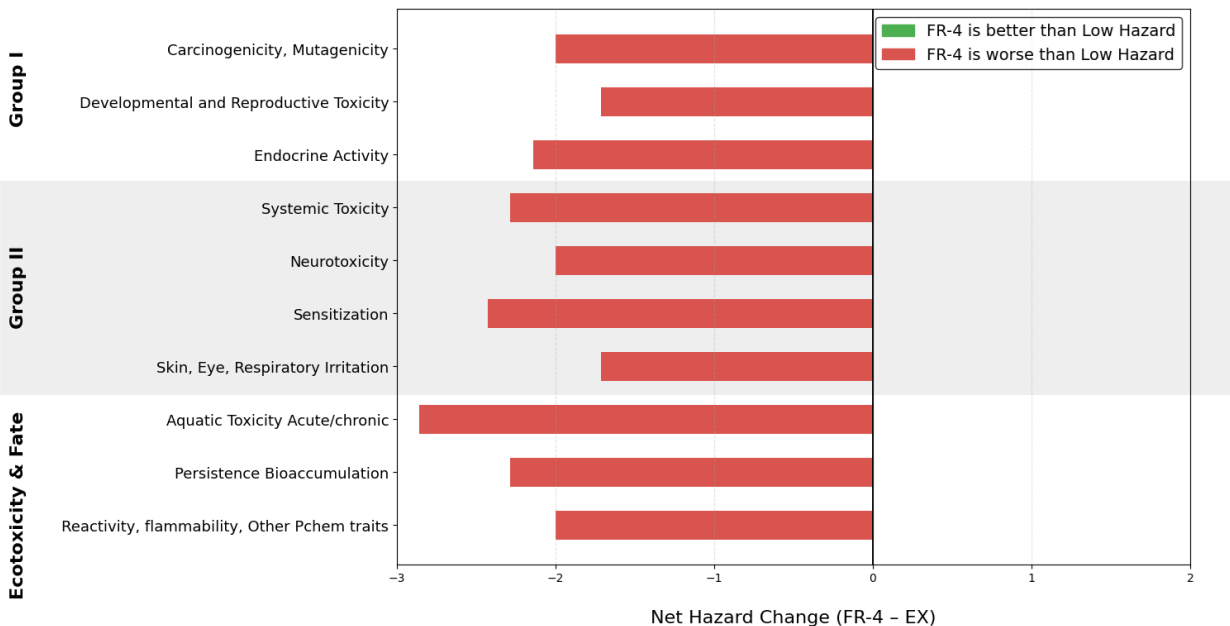
In that same table layout, the columns are averaged for each strategy .

For example, 10 chemicals have data for Carcinogenicity within PICT. All of their values are averaged. This continues for all remaining endpoints. The same is done for FR-4. Those two averages are subtracted and the plot shows the net change in those average values.

For this plot, FR-4 is in place of the strategy and an artificial stand-in containing only very low values (vL) is the baseline. All of the chemicals used in FR-4 average a system toxicity around 1.7 -> $1.7 - 4 = -2.3$

All solutions are computed as
 $\text{TARGET} - \text{BASELINE} = \text{NET CHANGE}$

Hazard Comparison: FR-4 vs EX



Isosorbide Health Comparison Data

Chemical	Group1	Group2	Eco
ISDGE	3.7	2	3
Isosorbide	4	3.8	4
ECH	2	2	3.5
γ -lactone	4	2	3.5
δ -lactone	4	2	3.5
ϵ -lactone	4	2.5	4.5

Relevance	Common name or trade name	Group I Human Endpoints			Group II and Group II* Endpoints				Ecotoxicity	Fate	Physical Hazard
		Carcinogenicity	Developmental and Reproductive Toxicity	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Sensitization	Skin, Eye, Respiratory Irritation	Aquatic Toxicity Acute/chronic	Persistence Bioaccumulation	Reactivity, flammability
		Mutagenicity									Other Pchem traits
Isosorbide	Isosorbide diglycidyl ether (ISDGE)	M	L	L	DG	DG	H	H	H	L	L

PICT Health Comparison Data

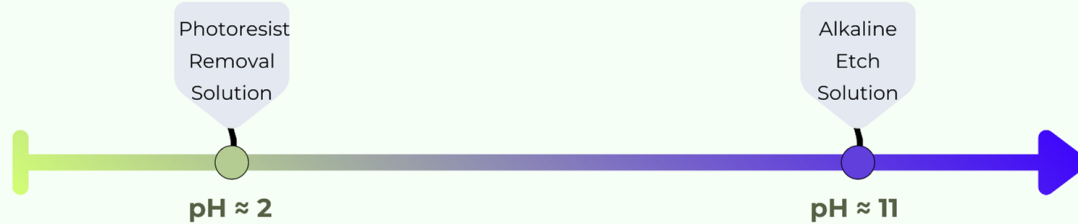
Chemical	Group1	Group2	Eco
TPA	3.3	3.8	4
Isosorbide	4.0	3.8	4
CHDHM	4.0	3.5	4
4-eth	3.7	3.3	3.5
4-meth	3.7	3.0	4

Chemical	Group1	Group2	Eco
Butyltin	3.7	3.3	3
CNCs	3.7	4.0	4
Dihydrate	4.0	2.0	4
Ammonium	3.7	3.3	4
Ammonia	4.0	3.0	4

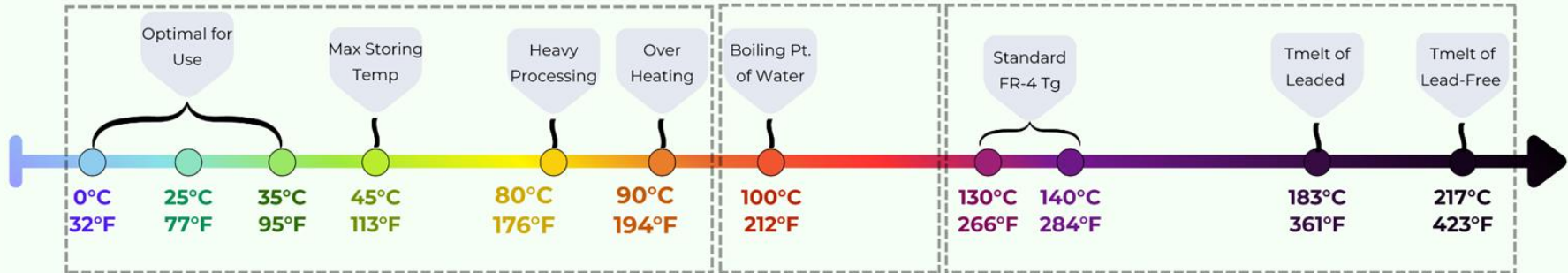
	Relevance	Common name or trade name	Group I Human Endpoints			Group II and Group II* Endpoints				Ecotoxicity	Fate	Physical Hazard
			Carcinogenicity	Developmental and Reproductive Toxicity	Endocrine Activity	Systemic Toxicity	Neurotoxicity	Sensitization	Skin, Eye, Respiratory Irritation	Aquatic Toxicity Acute/chronic	Persistence Bioaccumulation	Reactivity, flammability
			Mutagenicity									Other Pchem traits
PICT	Chemical recycling	Dihydrate	L	DG	DG	H	DG	H	H	H	L	DG
PICT	Chemical recycling	Ammonium chloride	L	L	DG	M	DG	L	M	L	L	L
PICT	Chemical recycling	Ammonium hydroxide (Ammonia)	L	DG	DG	M	DG	L	H	M	L	L

Tough Compounds Withstand Harsh Conditions

CHEMICAL STABILITY in PCB Manufacturing



TEMP RANGE Normal Use



Grading Material Performance

Performance Criteria Bins						
Thermal	Tg (°C)	Tmax (°C)	CTE - X, Y (ppm/°C)	CTE - Z (ppm/°C)	Point Value	Spec
	<100	<125	>90	>115	0	Below
	100-125	125-140	85-95	90-115	1	Nearly Meets
	125-140	140	65-85	80-90	2	Meets
	140-160	140-160	55-65	70-80	3	Exceeds
	>160	>160	<55	<70	4	Far Exceeds
Electrical	Dk	Df				
	>6	<0.002			0	Below
	5-6	0.002-0.005			1	Nearly Meets
	3-5	0.005 - 0.006			2	Meets
	2-3	0.006-0.007			3	Exceeds
	<2	0.007-0.01			4	Far Exceeds
Mechanical	Tensile Strength (MPa)	Flexural Modulus (GPa)				
	<180	<13.5			0	Below
	180-200	13.5-15			1	Nearly Meets
	200-300	15-16.5			2	Meets
	300-375	16.5-18.5			3	Exceeds
	>375	18.75			4	Far Exceeds
Chemical	pH Stability	Moisture Content (%)	Viscosity (cP)			
	4-11	>15	>3000		0	Below
	2-12 (Bias)	10-15	3000-2000		1	Nearly Meets
	2-12	5-10	1000-2000		2	Meets
	1-13	3-5	500-1000		3	Exceeds
	0-14	<3	<500		4	Far Exceeds

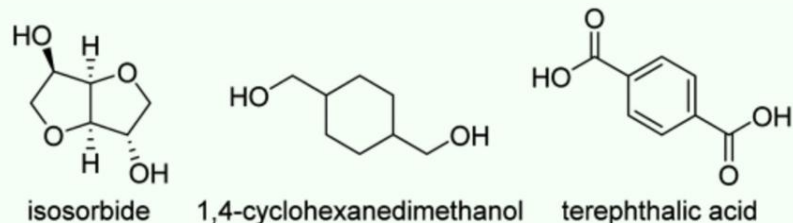
Chemical Synthesis Aromatic Polyester

Aromatic

PICT (isosorbide-CHDM-terephthalate)

→ Isosorbide raises T_g

→ CHDM adds rigidity



Step 1: Esterification

- React terephthalic acid, isosorbide & CHDM
- Add reactive phenolic solvent (e.g., p-cresol)
- Catalyst: Butyltin hydroxide or Ti(OBu)₄

Step 2: Polycondensation

- High vacuum (0.5 mbar)
- High temperature (260 - 300 °C)
- Phenolic solvent aids isosorbide reactivity

- Amorphous, high-T_g (≈140–150 °C) thermoplastic
- Renewable & melt-processable → suitable for PCB substrate development