

PFAS and Molded fiber: Challenges and Opportunities

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Roadmap



Per- and Polyfluoroalkyl substances in Food Packaging



Our Scope: Molded Fiber



Alternatives to PFAS outside the Paper System



Alternatives to PFAS within the Paper System



Technical & Hazard Assessments



Recommendations and Next Steps

Roadmap



Per- and Polyfluoroalkyl Substances in Food Packaging



Our Scope: Molded Fiber



Alternatives to PFAS outside the Paper System



Alternatives to PFAS within the Paper System



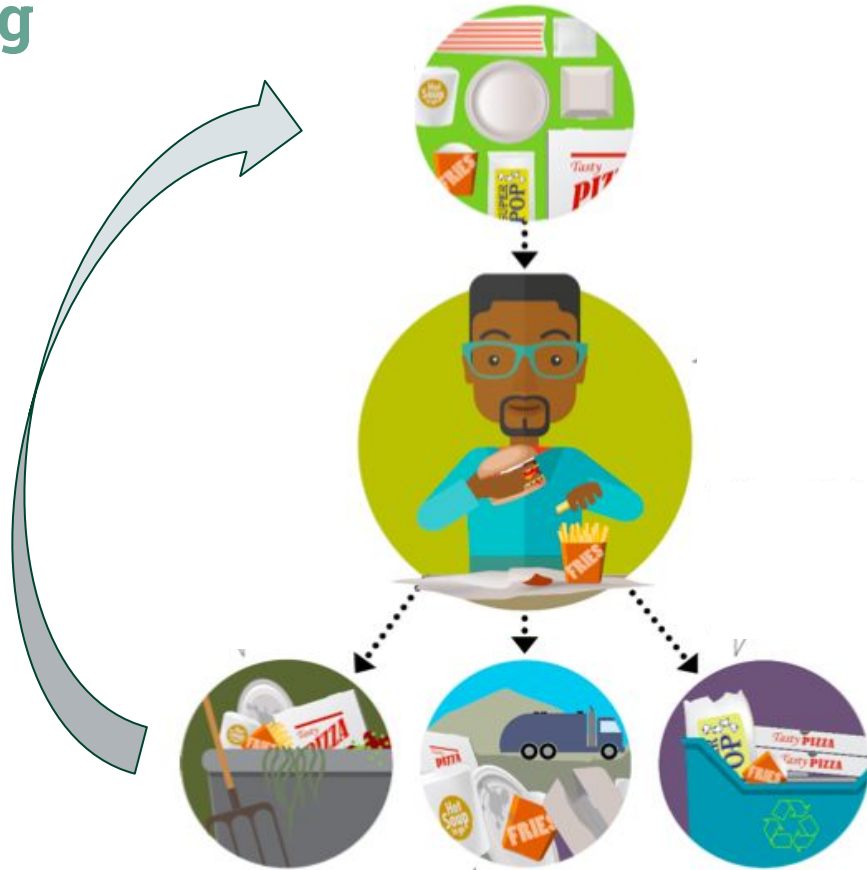
Technical & Hazard Assessments



Recommendations and Next Steps

PFAS in Food Packaging

PFAS is Persistent and Difficult to Remove Once it is in the System



Roadmap



Per- and polyfluoroalkyl substances in food packaging



Our Scope: Molded Fiber



Alternatives to PFAS outside the Paper System



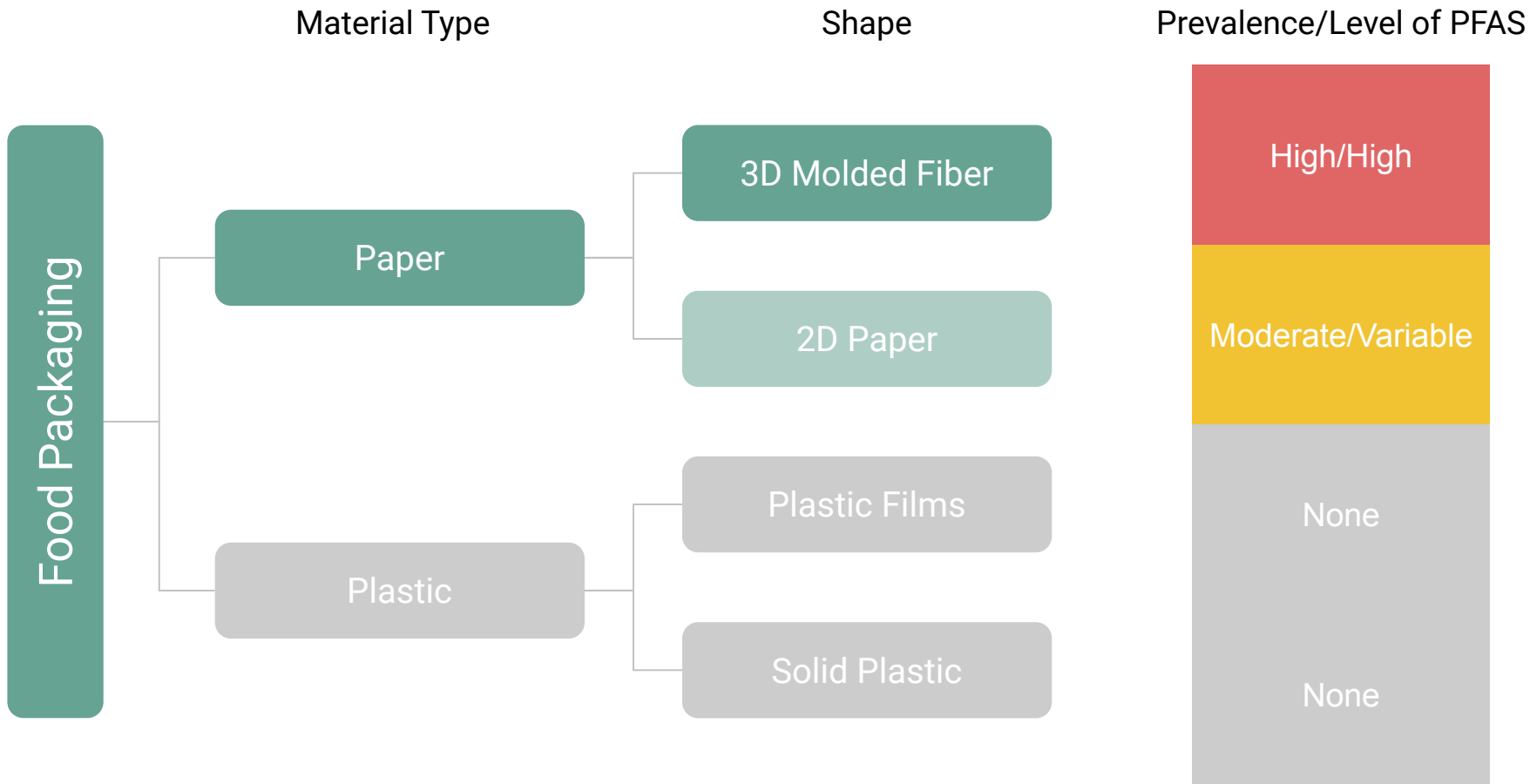
Alternatives to PFAS within the Paper System



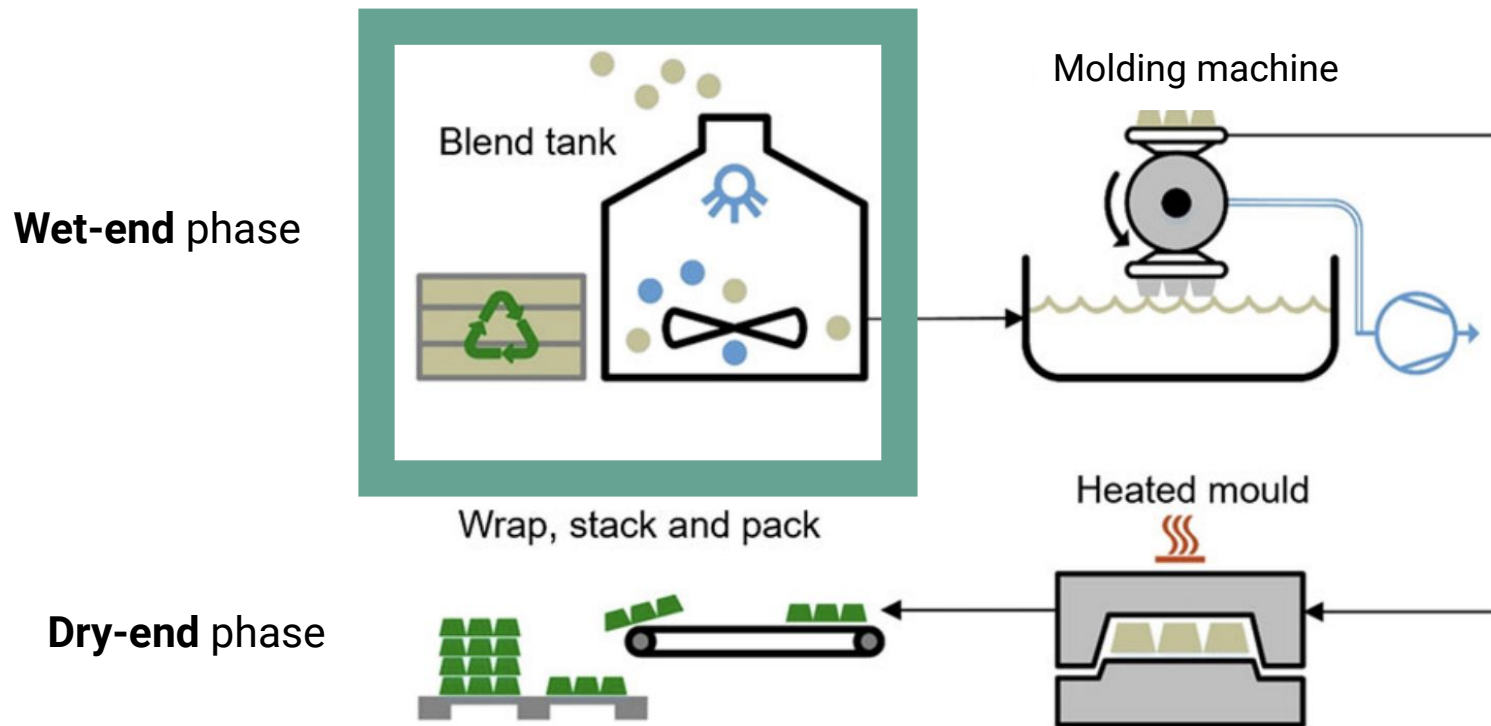
Technical & Hazard Assessments

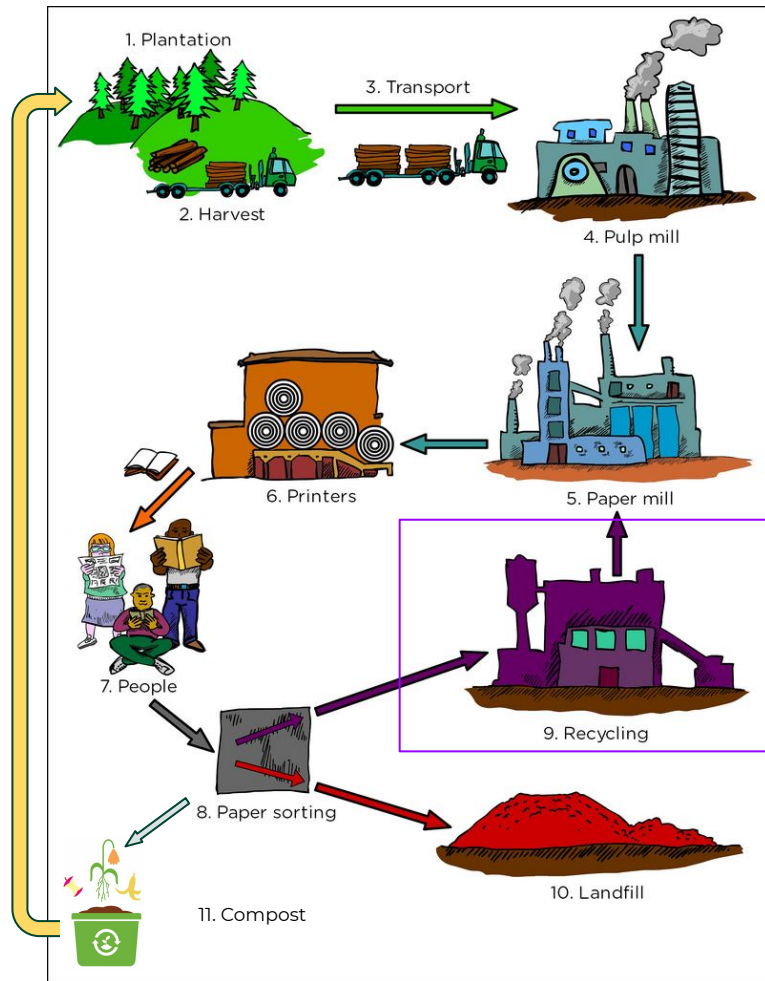


Recommendations and Next Steps



PFAS dominates Wet End Processing








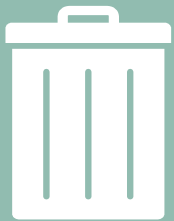
Molded Fiber could close the loop

- Marketed as a plastic replacement
- But not truly compostable due to PFAS
- The industry needs solutions that eliminate PFAS while moving toward greater degradability

Food Served in Molded Fiber

Food Type			
Temperature	Room Temp	Hot	Hot
Water Content	Medium	Low	Medium
Oil Content	Low	High	Medium

A replacement for PFAS among molded fiber...



Is compostable
Plant or biologically
sourced



**Provides a barrier
property**
Either water or oil



**Is less hazardous
than PFAS**

Roadmap



Per- and polyfluoroalkyl substances in food packaging



Our Scope: Molded Fiber



Alternatives to PFAS Added to the Paper System



Alternatives to PFAS within the Paper System

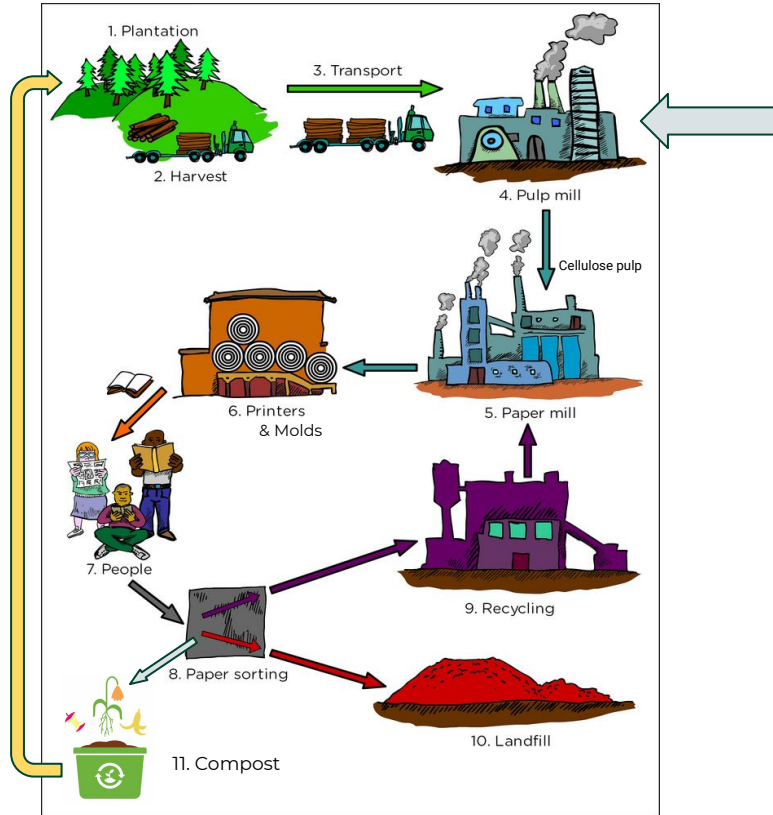


Technical & Hazard Assessments

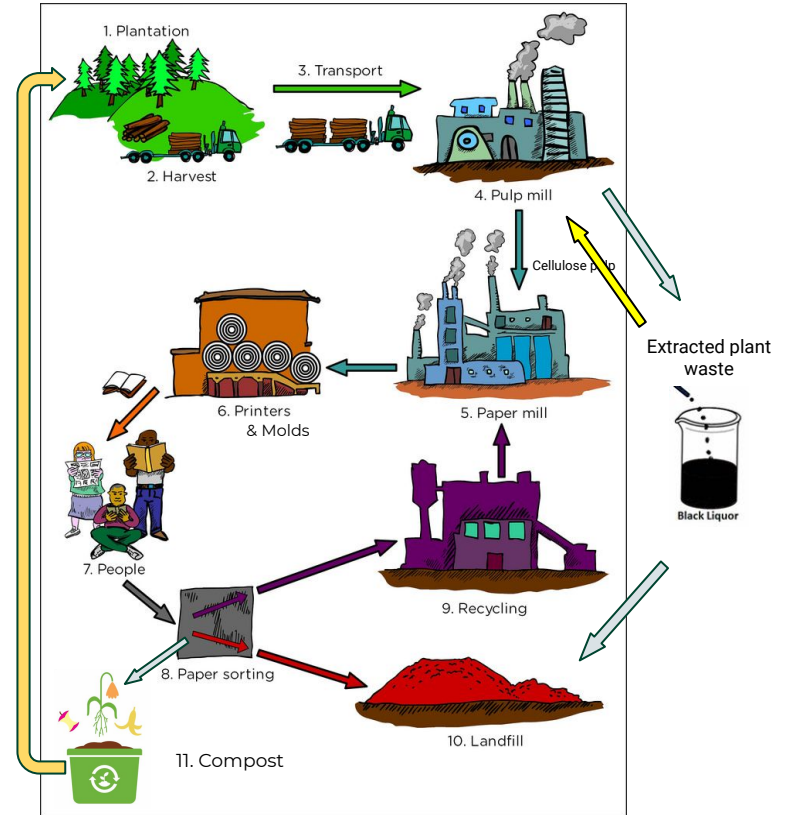


Recommendations and Next Steps

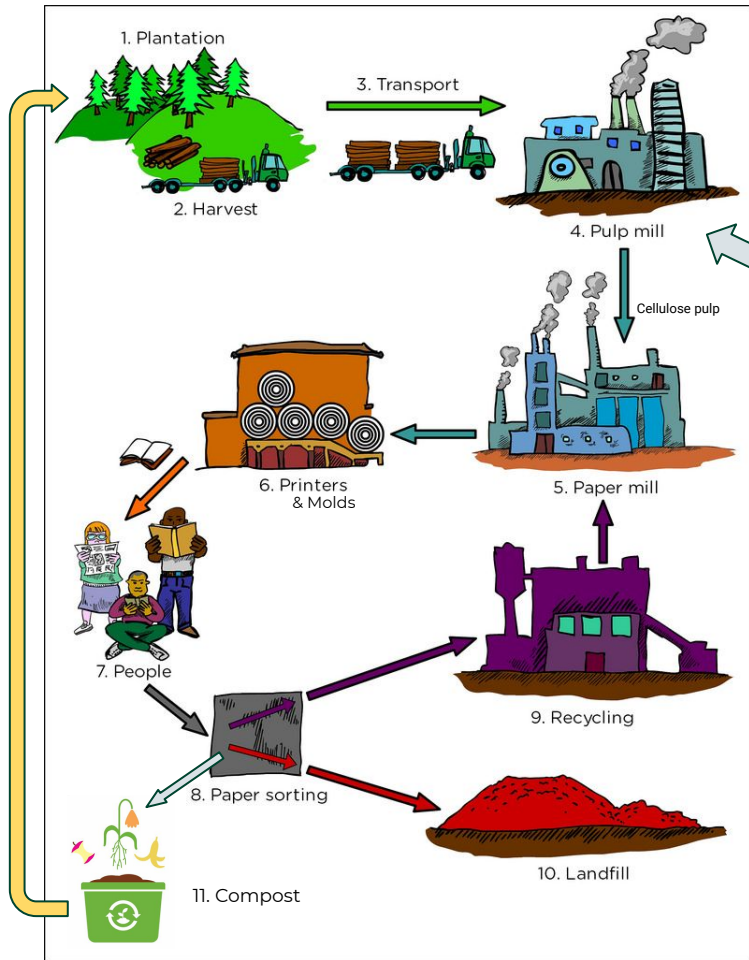
Category 1: Alternatives *Added* to the Paper System



Category 2: Alternatives *Within* the Paper System



Alternatives Added to the Paper System



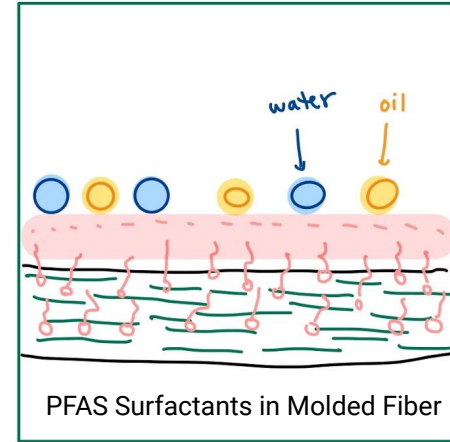
Small molecules added to bind to cellulose pulp

Solutions:

- Rhamnolipids
- Pectin

Derived from plants or microbes

RHAMNOLIPIDS



Source / Manufacture	Key chemical characteristics	Expected mechanism of action at wet-end	Biodegradable?
microbes, typically <i>Pseudomonas</i>	hydrophilic head and hydrophobic tails	Head groups bind to hydroxyl groups of cellulose, with hydrophobic tails extending out	Yes

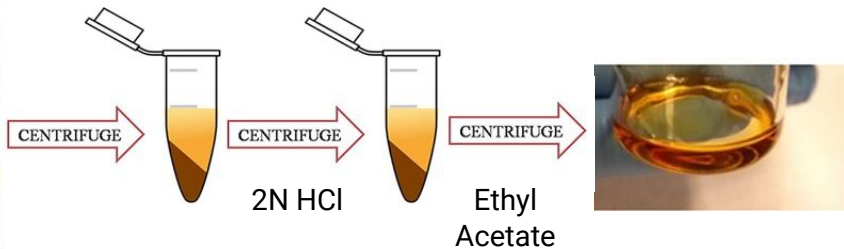
Rhamnolipids

Incorporation Mechanism

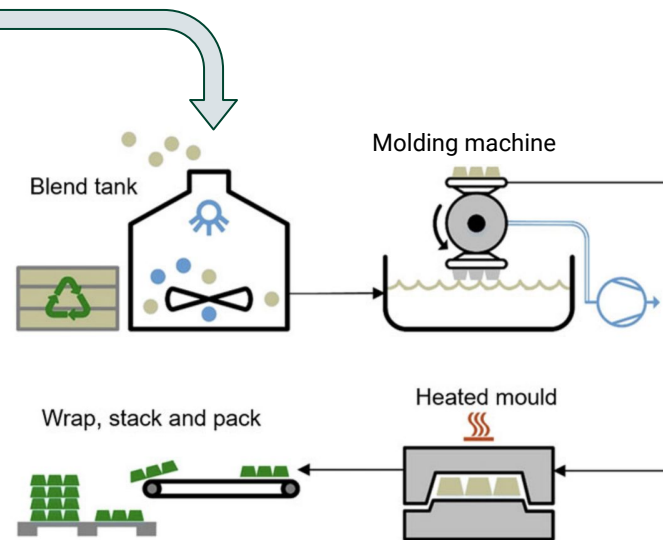


PRODUCTION

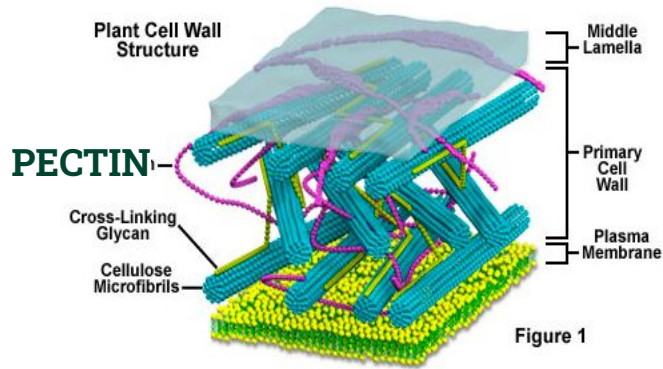
Extraction from
Pseudomonas Bacteria



Enters Molded Fiber Production
from Wet End

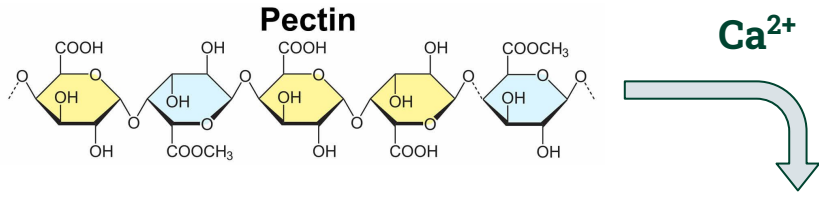


PECTIN



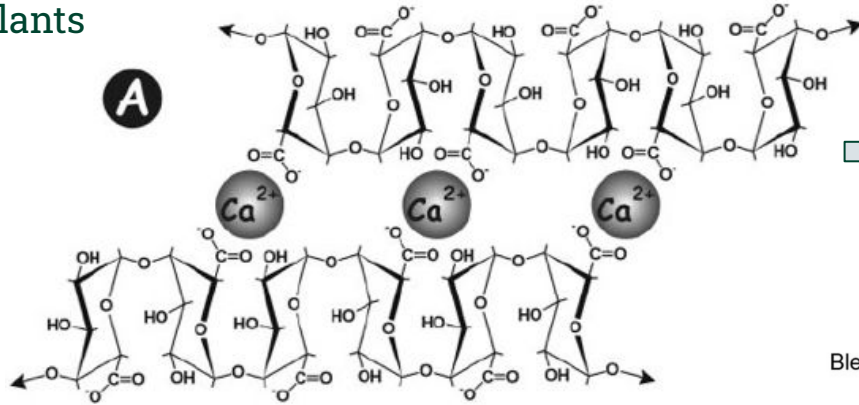
Plums contain pectin

Source / Manufacture	Key chemical characteristics	Expected mechanism of action at wet-end	Biodegradable?
Biopolymer found in ripening fruits	Reduces fiber porosity, and increase barrier properties.	Cross-linking to reduce cell porosity	Yes



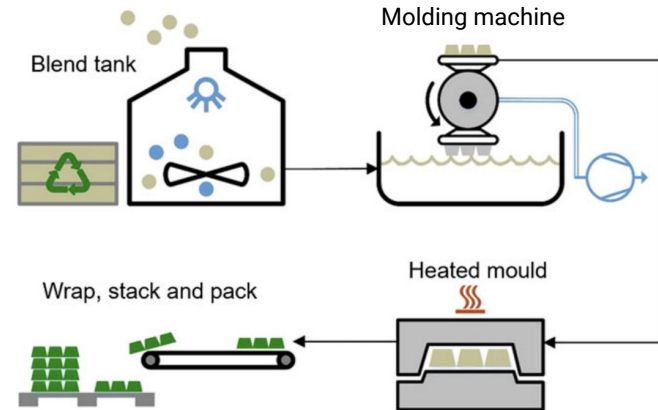
Pectin Incorporation Mechanism

Extraction from
cell wall of plants



Cross-linkage with Ca^{2+}
cations forming hard gels

Enters Moulded Fiber Product
from Wet End



Roadmap



Per- and polyfluoroalkyl substances in food packaging



Our Scope: Molded Fiber



Alternatives to PFAS Added to the Paper System



Alternatives to PFAS within the Paper System

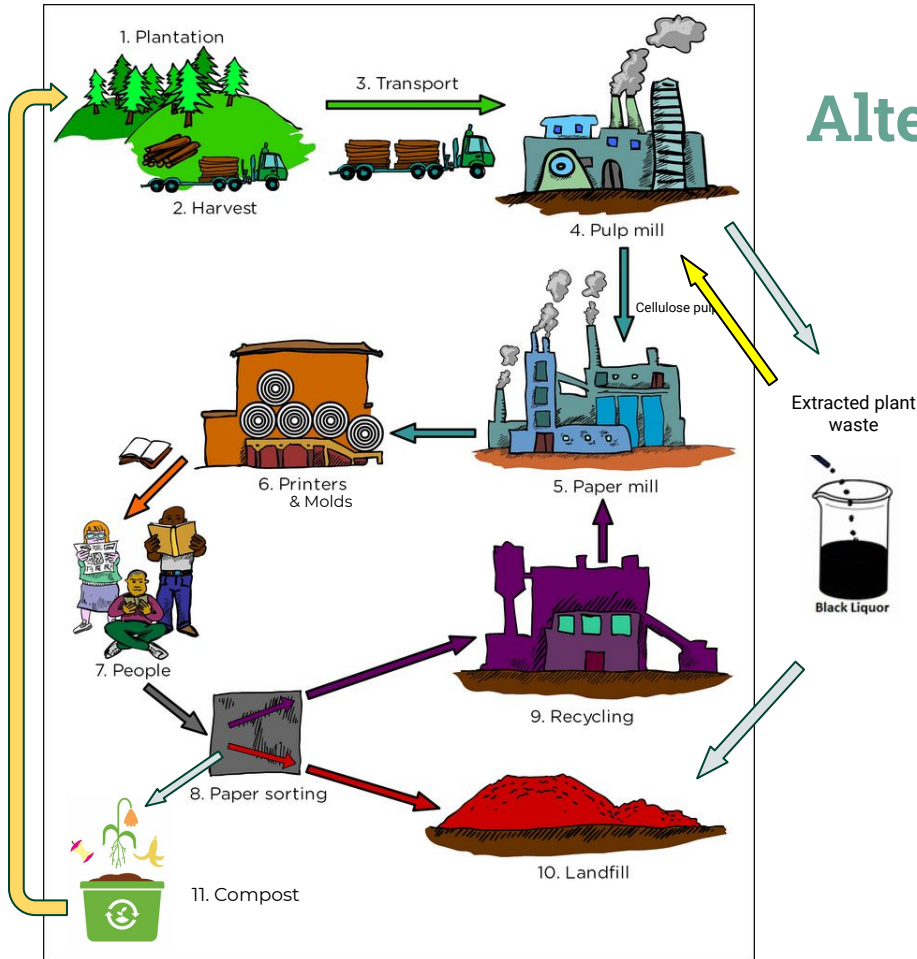


Technical & Hazard Assessments



Recommendations and Next Steps

Alternatives *Within* the Paper System



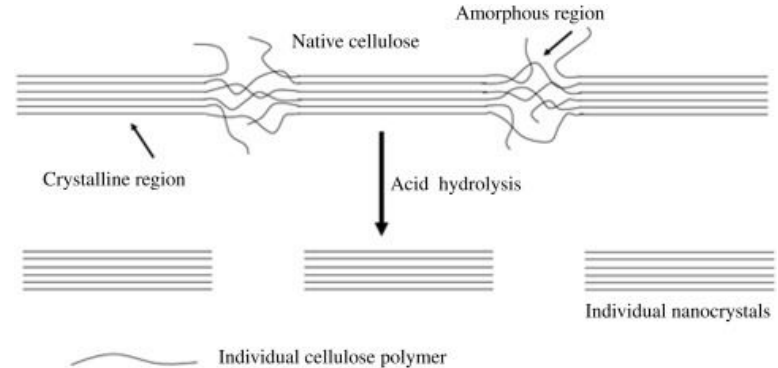
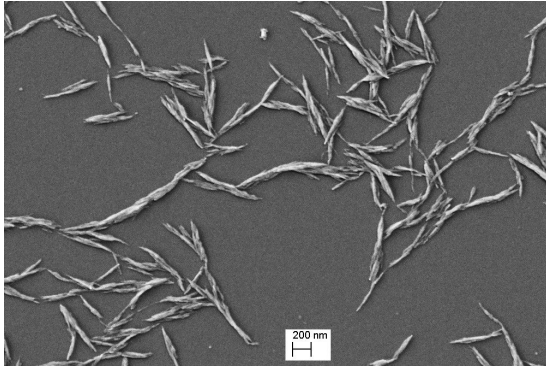
Solutions:

- Nanocellulose
- Lignin

Materials normally wasted
could be reutilized

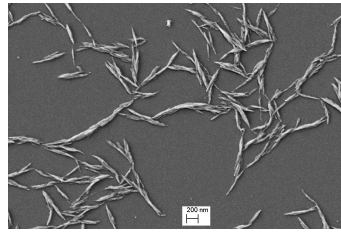
Potential for reduced cost

CRYSTALLINE NANOCELLULOSE



Source / Manufacture	Key chemical characteristics	Expected mechanism of action at wet-end	Biodegradable?
Recycled or newly manufactured cellulose	Improves rigidity and reduces water uptake of cellulose	Cross-linking to reduce cell porosity	yes

Crystalline Nanocellulose Incorporation Mechanism



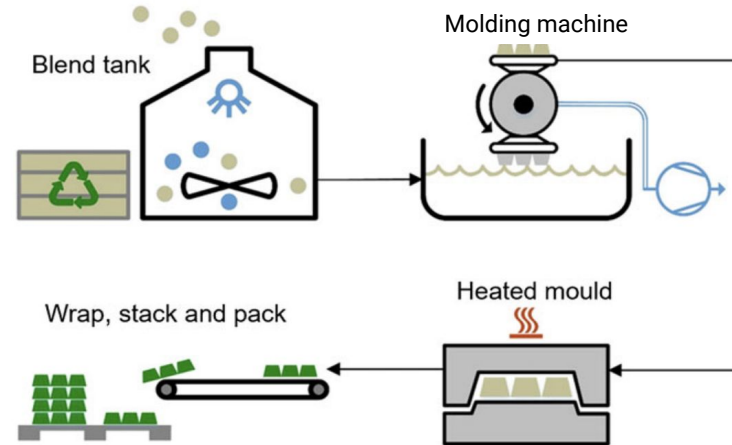
Bulk pulp

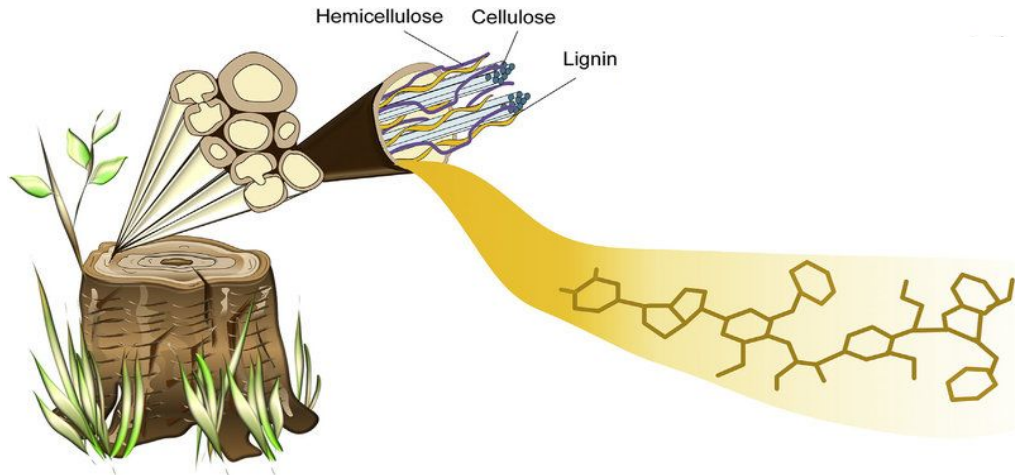
Nano-crystals

Acid treatment

Low dose dispersing agent

Enters Molded Fiber
Production from Wet End





LIGNIN



dried lignin

Source / Manufacture	Key chemical characteristics	Expected mechanism of action at wet-end	Biodegradable?
Waste from Paper Industry (and ethanol production)	Organic polymer that improves rigidity, thermal stability	Once evenly dispersed, binds with and cross-links cellulose fibers	Yes

Lignin

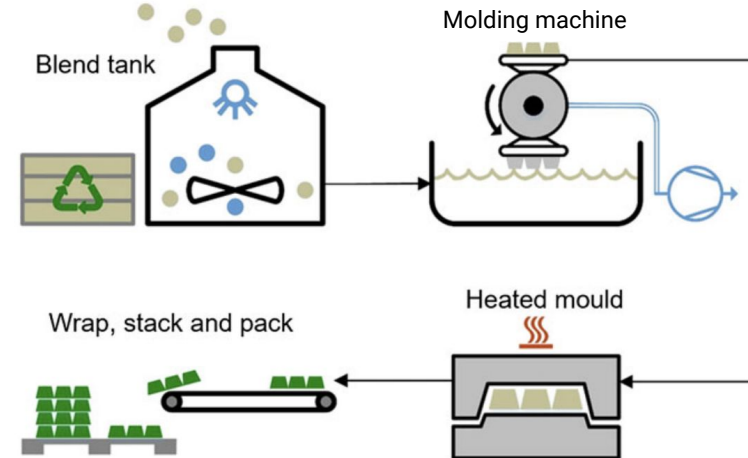
Incorporation Mechanism

Extraction from Waste



+ Ionic Liquid, Xylan & other cellulose derivatives

Enters Molding Fiber Production from Wet End



Roadmap



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Our Scope: Molded Fiber



Alternatives to PFAS Added to the Paper System



Alternatives to PFAS within the Paper System



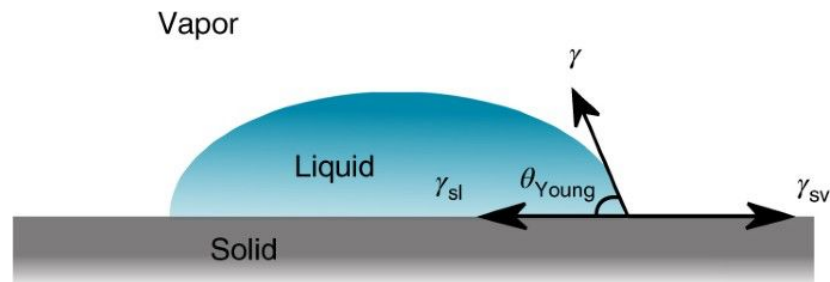
Technical & Hazard Assessments



Recommendations and Next Steps

What properties of performance do we desire?

- Barrier properties
- Surface properties
- Thermal properties
- Chemical Properties
- Mechanical Properties
- End-of-life properties



Our Baseline: PLA

	Relevant property	Units	PLA	Rhamnolipid (Proxy: Palmitic Acid w/ minerals)	Pectin	Lignin-modified cellulose	Crystalline Nanocellulose
Application of Data Source							
Barrier properties							
Surface properties							
Thermal properties							
Chemical properties							
End-of-Life properties							
Mechanical Properties							

*values collected from a variety of applications of alternatives

Rankings are relative to each other:

Ideal

Moderate

Non-ideal

DG = data gap

Rhamnolipid Data Partially Sourced from Proxy

	Relevant property	Units	PLA	Rhamnolipid (Proxy: Palmitic Acid w/ minerals)	Pectin	Lignin-modified cellulose	Crystalline Nanocellulose
Application of Data Source							
Barrier properties							
Surface properties							
Thermal properties							
Chemical properties							
End-of-Life properties							
Mechanical Properties							

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Data Source Varies

	Relevant property	Units	PLA	Rhamnolipid (Proxy: Palmitic Acid w/ minerals)	Pectin	Lignin-modified cellulose	Crystalline Nanocellulose
Application of Data Source							
Barrier properties							
Surface properties							
Thermal properties							
Chemical properties							
End-of-Life properties							
Mechanical Properties							

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Ranking is Relative

	Relevant property	Units	PLA	Rhamnolipid (Proxy: Palmitic Acid w/ minerals)	Pectin	Lignin-modified cellulose	Crystalline Nanocellulose
Application of Data Source							
Barrier properties							
Surface properties							
Thermal properties							
Chemical properties							
End-of-Life properties							
Mechanical Properties							

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Application of Data Source

	Relevant property	Units	PLA	Rhamnolipid (Proxy: Palmitic Acid w/ minerals)	Pectin	Lignin-modified cellulose	Crystalline Nanocellulose
Application of Data Source	coating/film or within molded fiber matrix	--	Films	Fiber Matrix	Films	Fiber Matrix	Films
Barrier properties							
Surface properties							
Thermal properties							
Chemical properties							
End-of-Life properties							
Mechanical Properties							

*values collected from a variety of applications of alternatives

Rankings are relative to each other:

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Barrier Properties

	Relevant property	Units	PLA	Rhamnolipid (Proxy: Palmitic Acid w/ minerals) Fiber Matrix	Pectin	Lignin-modified cellulose	Crystalline Nanocellulose
Application of Data Source	coating/film or within molded fiber matrix	--	Films	Fiber Matrix	Films	Fiber Matrix	Films
Barrier properties	grease resistance	kit value	12+	DG	DG	12	11
	water contact angle	degrees	75 - 85	120-140	47-87	89	65
	water vapor permeability (WVP)	g.mm/m ² .kPa.day	0.161-0.237	DG	2.26 - 2.83	5.3 ± 0.1	9
Surface properties							
Thermal properties							
Chemical properties							
End-of-Life properties							
Mechanical Properties							

PFOA water contact angle: ~160°

*values collected from a variety of applications of alternatives

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Surface Properties

	Relevant property	Units	PLA	Rhamnolipid (Proxy: Palmitic Acid w/ minerals)	Pectin	Lignin-modified cellulose	Crystalline Nanocellulose
Application of Data Source	coating/film or within molded fiber matrix	--	Films	Fiber Matrix	Films	Fiber Matrix	Films
Barrier properties	grease resistance	kit value	12+	DG	DG	12	11
	water contact angle	degrees	75 - 85	120-140	47-87	89	65
	water vapor permeability (WVP)	g.mm/m ² .kPa.day	0.161-0.237	DG	2.26 - 2.83	5.3 ± 0.1	9
Surface properties	porosity (oxygen resistance)	cm ³ /m ² /24hr	38-42	DG	DG	26± 0.5	DG
Thermal properties							
Chemical properties							
End-of-Life properties							
Mechanical Properties							

*values collected from a variety of applications of alternatives

Rankings are relative to each other:

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Moderate

Non-ideal

DG = data gap

Thermal Properties

	Relevant property	Units	PLA	Rhamnolipid (Proxy: Palmitic Acid w/ minerals)	Pectin	Lignin-modified cellulose	Crystalline Nanocellulose
Application of Data Source	coating/film or within molded fiber matrix	--	Films	Fiber Matrix	Films	Fiber Matrix	Films
Barrier properties	grease resistance	kit value	12+	DG	DG	12	11
	water contact angle	degrees	75 - 85	120-140	47-87	89	65
	water vapor permeability (WVP)	g.mm/m ² .kPa.day	0.161-0.237	DG	2.26 - 2.83	5.3 ± 0.1	9
Surface properties	porosity (oxygen resistance)	cm ³ /m ² /24hr	38-42	DG	DG	26± 0.5	DG
Thermal properties	thermal resistance	temperature at major % weight loss	335°C	240°C	174-180 °C (2-8 °C storage)	260-290°C	250°C
	temperature dependence (during manufacture avg temp is 100°C)	°C	52.5-150°C	90-120°C	5 - 35°C	85 - 100°C	30-60°C
Chemical properties							
End-of-Life properties							
Mechanical Properties							

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Non-ideal

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Chemical Properties

	Relevant property	Units	PLA	Rhamnolipid (Proxy: Palmitic Acid w/ minerals)	Pectin	Lignin-modified cellulose	Crystalline Nanocellulose
Application of Data Source	coating/film or within molded fiber matrix	--	Films	Fiber Matrix	Films	Fiber Matrix	Films
Barrier properties	grease resistance	kit value	12+	DG	DG	12	11
	water contact angle	degrees	75 - 85	120-140	47-87	89	65
	water vapor permeability (WVP)	g.mm/m2.kPa.day	0.161-0.237	DG	2.26 - 2.83	5.3 ± 0.1	9
Surface properties	porosity (oxygen resistance)	cm3/m2/24hr	38-42	DG	DG	26± 0.5	DG
Thermal properties	thermal resistance	temperature at major % weight loss	335°C	240°C	174-180 °C (2-8 °C storage)	260-290°C	250°C
	temperature dependence (during manufacture avg temp is 100°C)	°C	52.5-150°C	90-120°C	5 - 35°C	85 - 100°C	30-60°C
Chemical properties	dispersability	--	DG	Yes	Yes	Yes, with agent	Yes, with agent
End-of-Life properties							
Mechanical Properties							

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Rankings are relative to each other:

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Non-ideal

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End-of-Life Properties

	Relevant property	Units	PLA	Rhamnolipid (Proxy: Palmitic Acid w/ minerals)	Pectin	Lignin-modified cellulose	Crystalline Nanocellulose
Application of Data Source	coating/film or within molded fiber matrix	--	Films	Fiber Matrix	Films	Fiber Matrix	Films
Barrier properties	grease resistance	kit value	12+	DG	DG	12	11
	water contact angle	degrees	75 - 85	120-140	47-87	89	65
	water vapor permeability (WVP)	g.mm/m ² .kPa.day	0.161-0.237	DG	2.26 - 2.83	5.3 ± 0.1	9
Surface properties	porosity (oxygen resistance)	cm ³ /m ² /24hr	38-42	DG	DG	26± 0.5	DG
Thermal properties	thermal resistance	temperature at major % weight loss	335°C	240°C	174-180 °C (2-8 °C storage)	260-290°C	250°C
	temperature dependence (during manufacture avg temp is 100°C)	°C	52.5-150°C	90-120°C	5 - 35°C	85 - 100°C	30-60°C
Chemical properties	dispersability	--	DG	Yes	Yes	Yes, with agent	Yes, with agent
End-of-Life properties	degradability (at least 70% in soil)	days	> 150	8-12	4	23	2
Mechanical Properties							

*values collected from a variety of applications of alternatives

Rankings are relative to each other:

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Moderate

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Mechanical Properties

	Relevant property	Units	PLA	Rhamnolipid (Proxy: Palmitic Acid w/ minerals)	Pectin	Lignin-modified cellulose	Crystalline Nanocellulose
Application of Data Source	coating/film or within molded fiber matrix	--	Films	Fiber Matrix	Films	Fiber Matrix	Films
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Surface properties	porosity (oxygen resistance)	cm ³ /m ² /24hr	38-42	DG	DG	26± 0.5	DG
Thermal properties	thermal resistance	temperature at major % weight loss	335°C	240°C	174-180 °C (2-8 °C storage)	260-290°C	250°C
	temperature dependence (during manufacture avg temp is 100°C)	°C	52.5-150°C	90-120°C	5 - 35°C	85 - 100°C	30-60°C
Chemical properties	dispersability	--	DG	Yes	Yes	Yes, with agent	Yes, with agent
End-of-Life properties	degradability (at least 70% in soil)	days	> 150	8-12	4	23	2
Mechanical Properties	tensile strength	MPa	27-35	DG	7.10 ± 0.22	20.3	15.6

*values collected from a variety of applications of alternatives

Rankings are relative to each other:

Ideal

Moderate

Non-ideal

DG = data gap

Hazard screening approach: modified GreenScreen

Group I					Group II and II*							Ecotox	Fate	
C	M	R	D	E	AT	ST	N	SnS*	SnR*	IrS	IrE	AA/CA	P	B

Group I endpoints:

Carcinogenicity
 Mutagenicity
 Reproductive Toxicity
 Developmental Toxicity

Group II and II* endpoints:

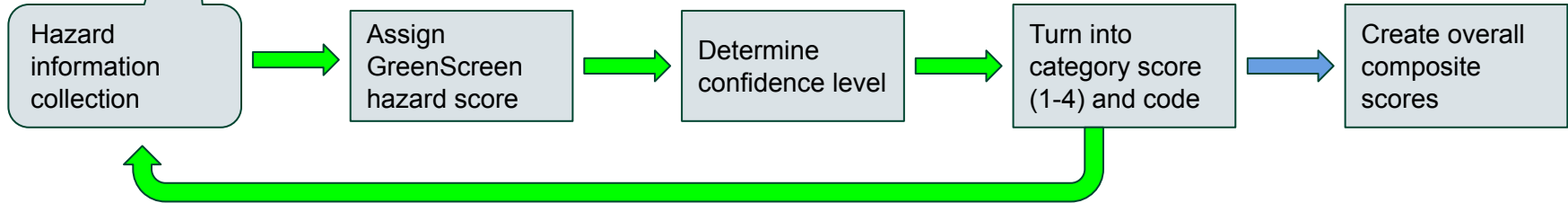
Acute mammalian toxicity (all routes)
 Systemic/organ toxicity
 Neurotoxicity
 Skin sensitization
 Respiratory sensitization
 Skin irritation
 Eye irritation
 * - indicates repeated exposure

Ecotoxicity and environmental fate

Acute and chronic aquatic (and terrestrial) toxicity
 Persistence
 Bioaccumulation

Evaluating toxicities, step-wise:

Group I					Group II and II*							Ecotox	Fate	
C	M	R	D	E	AT	ST	N	SnS*	SnR*	IrS	IrE	AA/CA	P	B



Faludi, et al. (2016) for scoring methods and composite scores

Selecting baseline compounds that represent existing hazards

	Group I					Group II and II*							Ecotox	Fate	
	C	M	R	D	E	AT	ST	N	SnS*	SnR*	IrS	IrE	AA/CA	P	B
6:2 FT MAC															
6:2 FTOH															
DEAE MAC															

Selecting baseline compounds that represent existing hazards

	Group I					Group II and II*								Ecotox	Fate	
	C	M	R	D	E	AT	ST	N	SnS*	SnR*	IrS	IrE	AA/CA	P	B	
6:2 FT MAC	2	3	2	2	1	2	2	UNK	3	3	1	1	3	1	1	
6:2 FTOH	2	3	3	2	1	3	2	UNK	3	3	2	2	1	1	1	
DEAE MAC	3	3	3	3	UNK	1	3	UNK	1	UNK	1	1	1	4	4	

Very High Hazard	High Hazard	Moderate Hazard	Low Hazard	Data Gap
1	2	3	4	UNK

Italic = Low confidence

Bold = High confidence

Pectin and rhamnolipids are safer alternatives for Group I, II, and environmental endpoints.


	Group I					Group II and II*								Ecotox	Fate	
	C	M	R	D	E	AT	ST	N	SnS*	SnR*	IrS	IrE	AA/CA	P	B	
6:2 FT MAC	2	3	2	2	1	2	2	UNK	3	3	1	1	3	1	1	
6:2 FTOH	2	3	3	2	1	3	2	UNK	3	3	2	2	1	1	1	
DEAE MAC	3	3	3	3	UNK	1	3	UNK	1	UNK	1	1	1	4	4	
Pectin	4	4	UNK	UNK	UNK	4	4	UNK	3	2	2	2	4	4	4	
Rhamnolipid	3	3	UNK	UNK	UNK	4	UNK	UNK	3	UNK	4	1	3	4	4	



Italic = Low confidence

Bold = High confidence

Lignin is a benign compound.

	Group I					Group II and II*								Ecotox	Fate	
	C	M	R	D	E	AT	ST	N	SnS*	SnR*	IrS	IrE	AA/CA	P	B	
6:2 FT MAC	2	3	2	2	1	2	2	UNK	3	3	1	1	3	1	1	
6:2 FTOH	2	3	3	2	1	3	2	UNK	3	3	2	2	1	1	1	
DEAE MAC	3	3	3	3	UNK	1	3	UNK	1	UNK	1	1	1	4	4	
Pectin	4	4	UNK	UNK	UNK	4	4	UNK	3	2	2	2	4	4	4	
Rhamnolipid	3	3	UNK	UNK	UNK	4	UNK	UNK	3	UNK	4	1	3	4	4	
Lignin 																
Crystalline Nanocellulose	3	3	3	3	UNK	4	3	UNK	3	2	4	3	3	4	4	

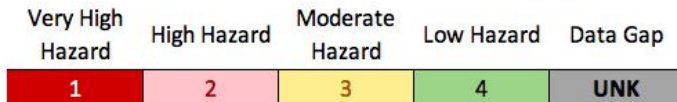


Italic = Low confidence

Bold = High confidence

Crystalline nanocellulose require further health evaluation, but preliminary assessment indicates significant reductions in hazards

	Group I					Group II and II*							Ecotox	Fate	
	C	M	R	D	E	AT	ST	N	SnS*	SnR*	IrS	IrE	AA/CA	P	B
6:2 FT MAC	2	3	2	2	1	2	2	UNK	3	3	1	1	3	1	1
6:2 FTOH	2	3	3	2	1	3	2	UNK	3	3	2	2	1	1	1
DEAE MAC	3	3	3	3	UNK	1	3	UNK	1	UNK	1	1	1	4	4
Pectin	4	4	UNK	UNK	UNK	4	4	UNK	3	2	2	2	4	4	4
Rhamnolipid	3	3	UNK	UNK	UNK	4	UNK	UNK	3	UNK	4	1	3	4	4
Lignin															
Crystalline Nanocellulose	3	3	3	3	UNK	4	3	UNK	3	2	4	3	3	4	4



Italic = Low confidence

Bold = High confidence

Safer, but not perfect, alternatives



In terms of safety, proposed solutions are much safer than fluoropolymer mixtures, with some/minimal tradeoffs



Improvements in environmental safety and performance for many safer alternatives



Data gaps and low confidence scores indicate opportunities for research, specifically on endpoints related to oral ingestion if solution(s) were adopted as food packaging additives.

Roadmap



Per- and polyfluoroalkyl substances in food packaging



Our Scope: Molded Fiber



Alternatives to PFAS Added to the Paper System



Alternatives to PFAS within the Paper System

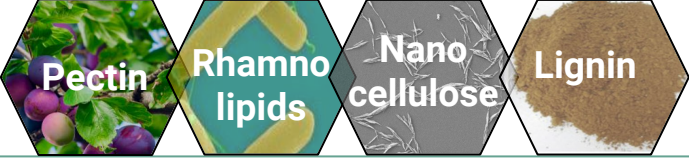
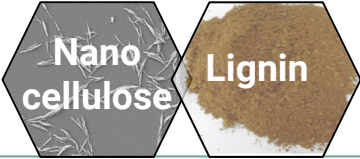
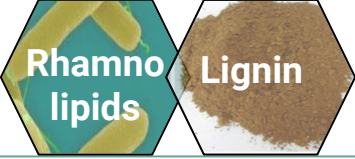





Technical & Hazard Assessments



Recommendations and Next Steps

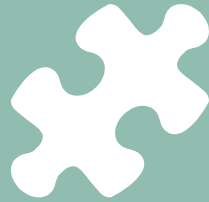
Possible Usage of Alternatives

<p>Possible Alternatives</p>			
<p>Food Type</p>			
<p>Temperature</p>	<p>Room Temp</p>	<p>Hot</p>	<p>Hot</p>
<p>Water Content</p>	<p>Medium</p>	<p>Low</p>	<p>Medium</p>
<p>Oil Content</p>	<p>Low</p>	<p>High</p>	<p>Medium</p>

Improving the search for greener solutions in molded fiber technology



Product testing and toxicity research on promising wet-end PFAS alternatives



A common language facilitates the search for greener solutions



Identify greener functional additives for traditional processes

Thank you!

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Greener Solutions Teams

