SAVING COHO SALMON:

alternatives for 6PPD in tire manufacturing

Illustration and copyright: Paul Vecsei/DFO

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December 7th, 2021

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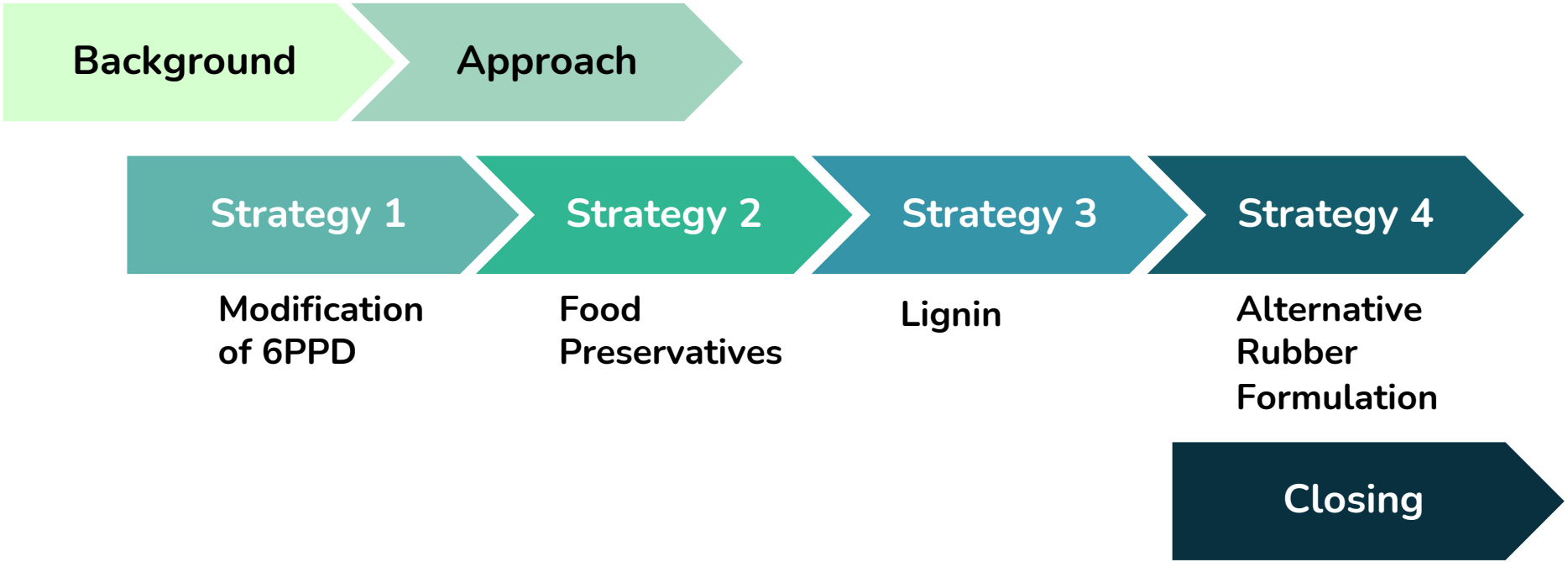
Presentation Outline



BACKGROUND

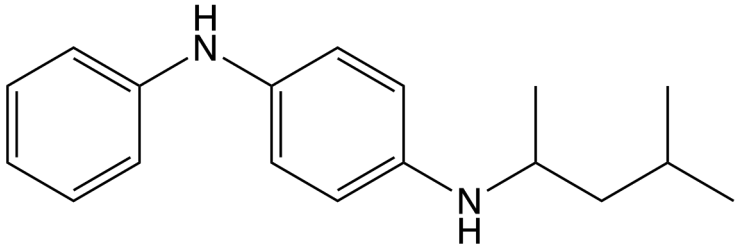
The mysterious recurring die-off of coho salmon

yuroktribe.org

- Salmon are a keystone species
  - High ecological importance in both terrestrial and aquatic environments
- Cultural and financial dependency for the Yurok Tribe and further tribes along the Pacific Northwest.
- High rates of pre-spawning mortality of adult coho salmon in urban watersheds has been documented since the late 1990s
- Previously associated with stormwater runoff, but exact agent was not known until 2020

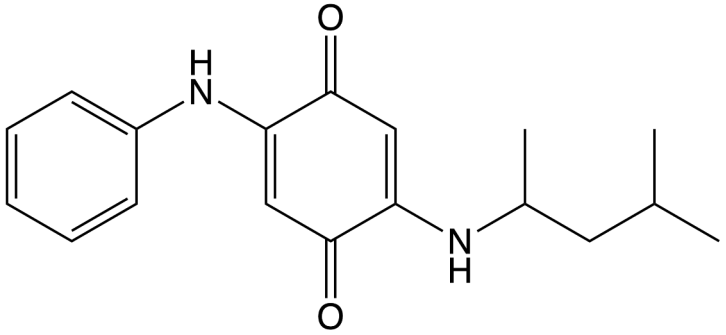
Image: adult female coho carcass with characteristically high egg retention.
Photo by Tiffany Linbo, NOAA Fisheries.

The problem



O_3

In tires



N-(1,3-dimethylbutyl)-*N'*-phenyl-p-phenylenediamine

6PPD

functional compound

highly lethal to coho salmon

(LC_{50} = 0.79 ± 0.16 ug/L)

2-anilino-5-[(4-methylpentan-2-yl)amino]cyclohexa-2,5-diene-1,4-dione

6PPD quinone

toxicant of primary concern

Tian, *et al., Science* **371**, 185-189 (2021).

Hiki, *et al.*, *Environ. Sci. Technol. Lett.* **8**, 779-784 (2021).

6PPD

N-(1,3-Dimethylbutyl)-*N*′-phenyl-*p*-phenylenediamine

Antidegradants are added to tires in order to slow the degradation of tires by oxygen and ozone.
Used in some tires in the 1970s and then adopted by all other tire manufacturers in the early 2000s

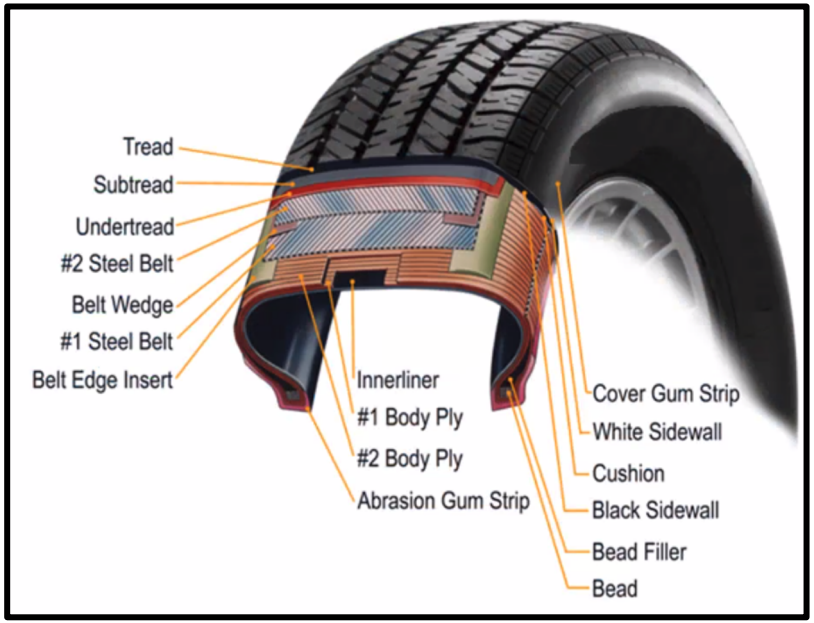
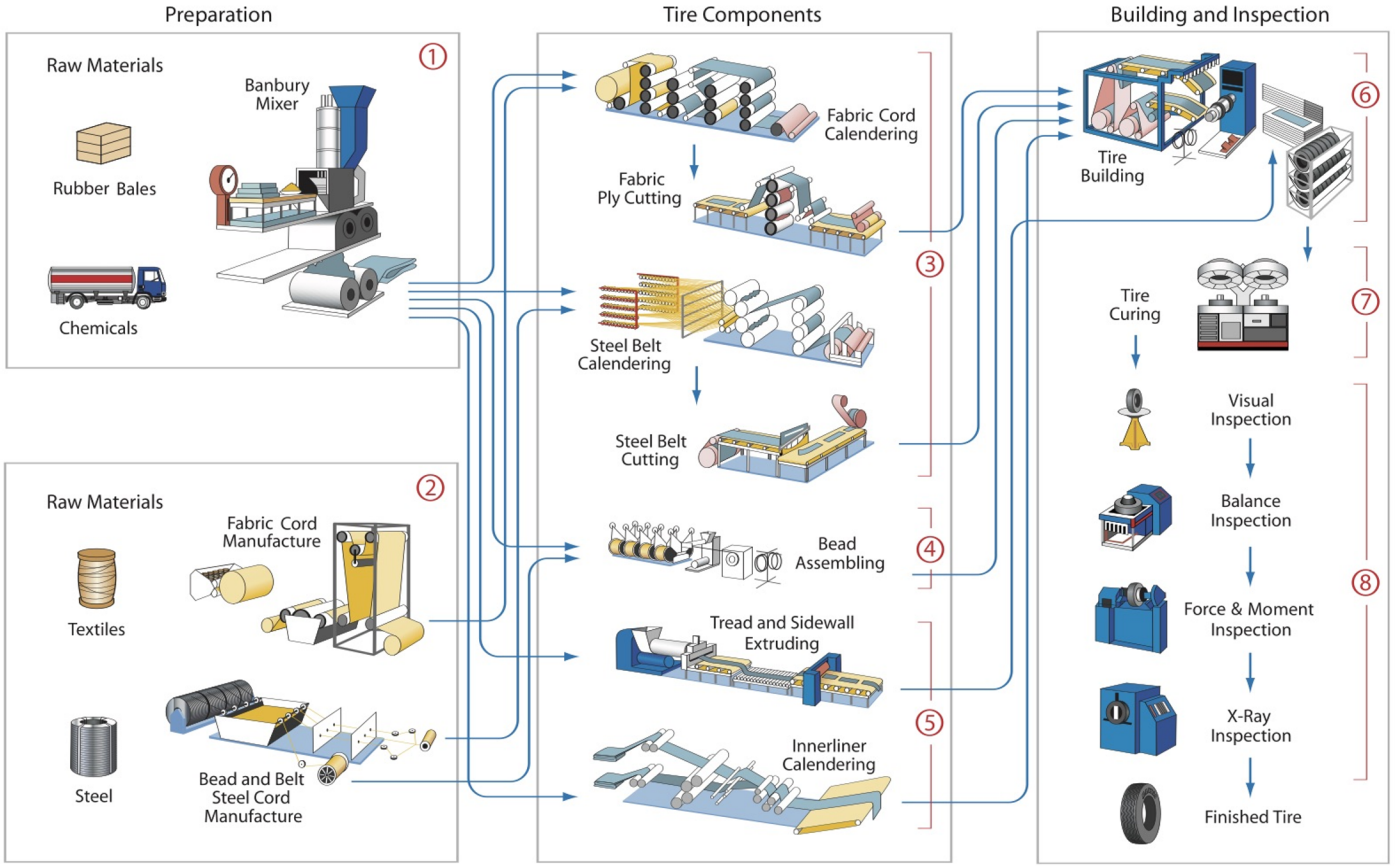


Image courtesy of the U.S. Tire Manufacturers Association



Source: maxxis tires

Tire variety

Passenger vehicle tires

Source: Asad Zahid Parkwheels.com

Tire variety

Passenger vehicle
Commercial vehicle

Source: Asad Zahid Parkwheels.com

Source: HunterTires

Tire variety

Passenger vehicle
Commercial vehicle
Aircraft

Source: Asad Zahid Parkwheels.com

Source: HunterTires

Steve Drummond, Airspace

Tire variety

Passenger vehicle
Commercial vehicle
Aircraft
Bicycle

Source: Asad Zahid Parkwheels.com

Source: HunterTires

Steve Drummond, Airspace

Source: Lumin.com

Tire variety

Passenger vehicle
Commercial vehicle
Aircraft
Bicycle
Lawn and garden

Source: Asad Zahid Parkwheels.com

Source: HunterTires

Steve Drummond, Airspace

Source: Lumin.com

Millersburg Tires

Tire variety

Passenger vehicle
Commercial vehicle
Aircraft
Bicycle
Lawn and garden
Recreation
Construction
Etc.


Asad Zahid / Parkwheels.com


Source: HunterTires


OneWheel


Steve Drummond, Airspace


Lumin.com


Carly Earl / The Guardian


World of Mining professionals


Millersburg Tires


Dirt Wheels Mag.


Getty Images

Rubber performance is highly sensitive to formulations and manufacturing processes

Tires must…

…support the weight of a vehicle

…provide everyday and emergency steering

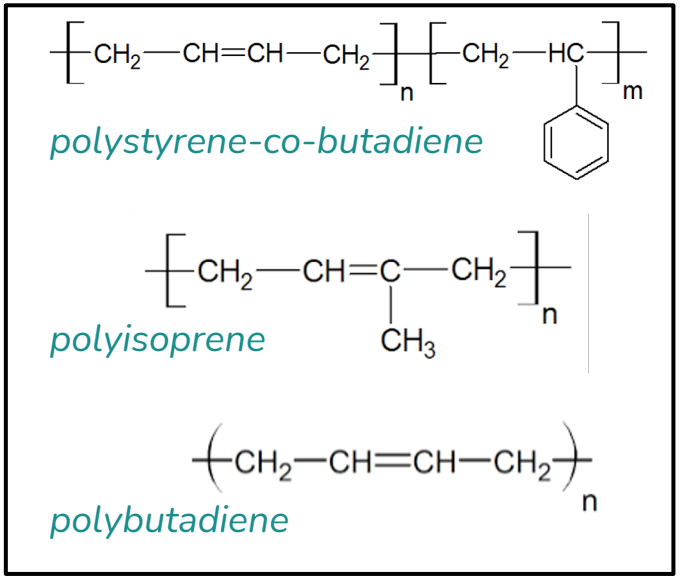
…grip the road

…perform in a variety of environments

…absorb vibrations and impacts

Untreated rubber is susceptible to various forms of severe degradation

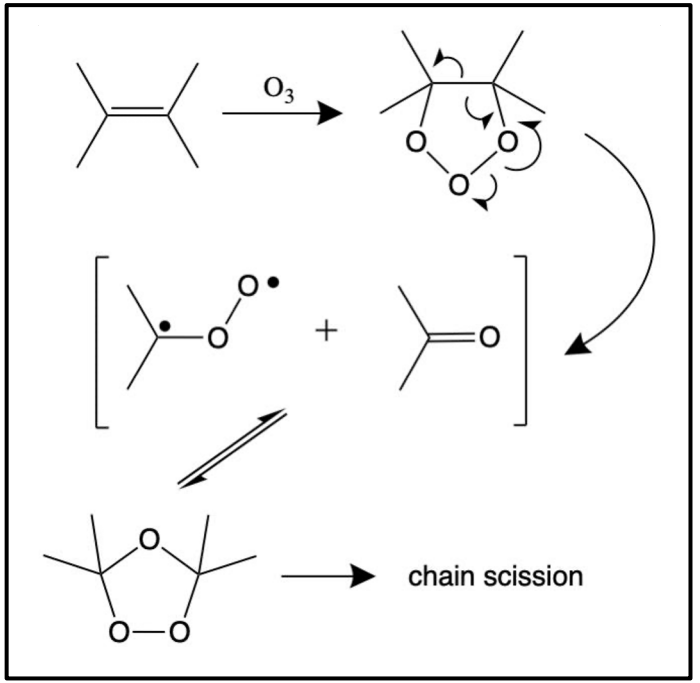
Rubber is comprised of unsaturated, cross-linked polymers



Structures courtesy of polymerdatabase.com

Untreated rubber is susceptible to various forms of severe degradation

Rubber is comprised of unsaturated, cross-linked polymers
Three key breakdown mechanisms:
- ***Ozonation*** (surface phenomenon)



N. M. Huntink, ``Durability of rubber products: Development of new antidegradants for long-term protection'' (2003).

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Three key breakdown mechanisms:

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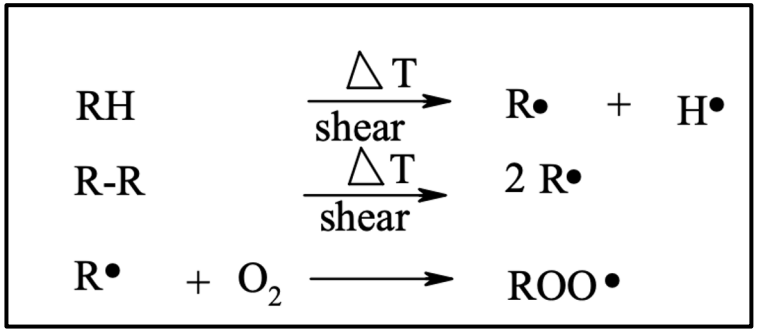
- ***oxidation***



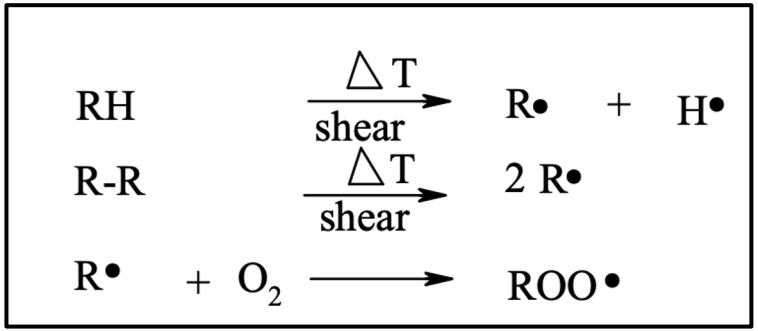
N. M. Huntink, ``Durability of rubber products: Development of new antidegradants for long-term protection'' (2003).

Untreated rubber is susceptible to various forms of severe degradation

Rubber is comprised of unsaturated, cross-linked polymers

Three key breakdown mechanisms:

- ozonation
- oxidation
- ***flex cracking***



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6PPD protects tires from all three mechanisms of tire breakdown

Scavenges surface O_3

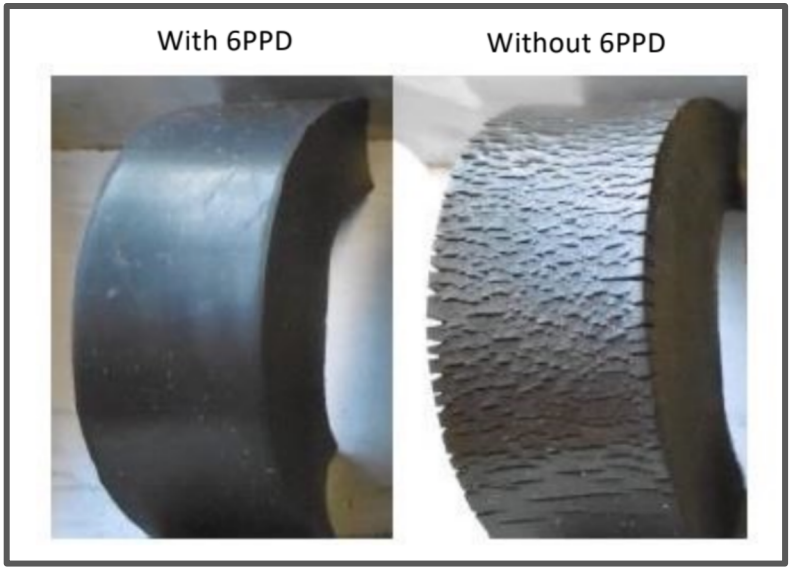

Image courtesy of the U.S. Tire Manufacturers Association

N. M. Huntink, ``Durability of rubber products: Development of new antidegradants for long-term protection'' (2003).

6PPD protects tires from all three mechanisms of tire breakdown

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Forms ***protective barrier***

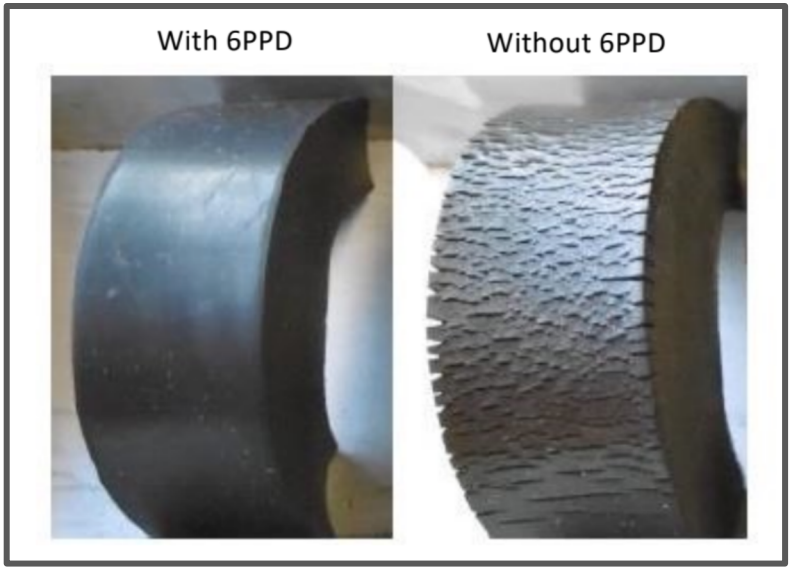

Image courtesy of the U.S. Tire Manufacturers Association

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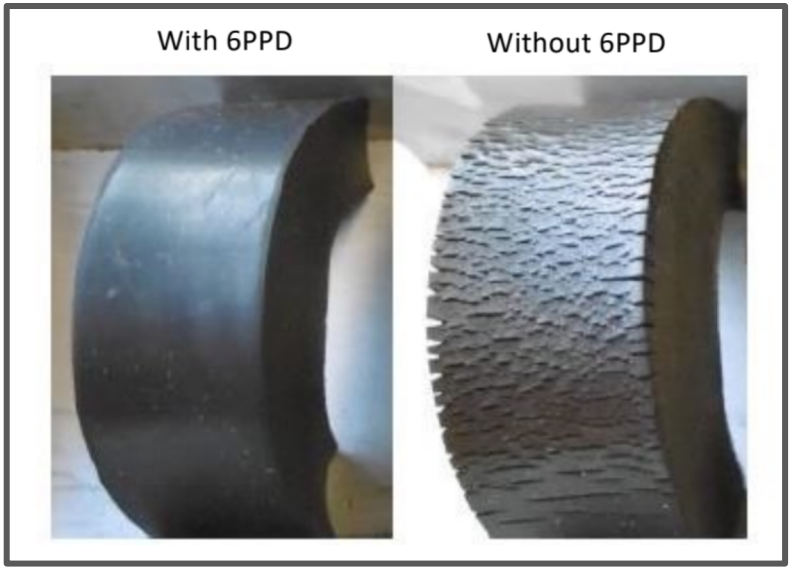
6PPD protects tires from all three mechanisms of tire breakdown

Scavenges surface O_3

Forms protective barrier

Consumes ***oxygen and carbon radicals*** within the tire to terminate chain reactions



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N. M. Huntink, ``Durability of rubber products: Development of new antidegradants for long-term protection'' (2003).

APPROACH

Criteria for alternatives

Rubber chemistry

Continuously present at the tire surface
Reactive with ozone, but not too reactive
Antioxidant properties
No adverse effects on the rubber processing
Available in rubber compound over its entire life cycle to ensure protection of rubber

Criteria for alternatives

Rubber chemistry
Tire needs to meet national ***tire regulation standards***

Criteria for alternatives

Rubber chemistry
Tire needs to meet national tire regulation standards
Environmental and human health criteria

Necessary (but not sufficient) physical criteria:

Reactivity

- Redox potential (E_h): measure of the tendency of a substance to give or gain electrons to or from an electrode
- Rate of reaction with ozone

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Reactivity

- Redox potential (E_h): measure of the tendency of a substance to give or gain electrons to or from an electrode
- Rate of reaction with ozone

Diffusivity

- Molecular weight
- Octanol-water partition coefficient (K_{ow}): a measure of the hydrophilicity of a substance

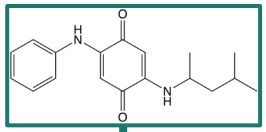
Framing the hazard assessment

Authoritative listings
Broad, cursory literature searches
Computational/predictive toxicological methods

Globally Harmonised System (GHS) Categories
GreenScreen
Cradle2Cradle Material Health Assessment Methodology
Hodge-Sterner Scale

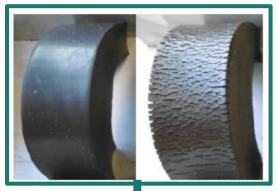
Source: https://www.greenscreenchemicals.org/

This is the beginning of the process



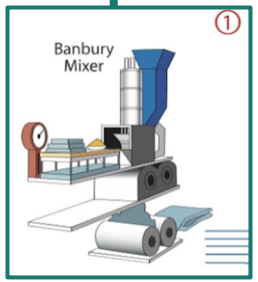
Tian, et al. (2021)

Identifying candidates



Performance & toxicity testing

Rubber compounding tests

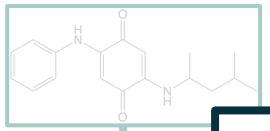


FLEXSYS

Identifying suppliers

Wheel tests, road tests

This is the beginning of the process



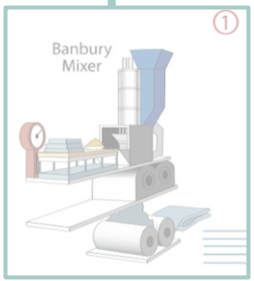
Tian, et al. (2021)

Identifying candidates

WE ARE HERE

Performance & toxicity testing

Rubber compounding tests



FLEXSYS

Identifying suppliers

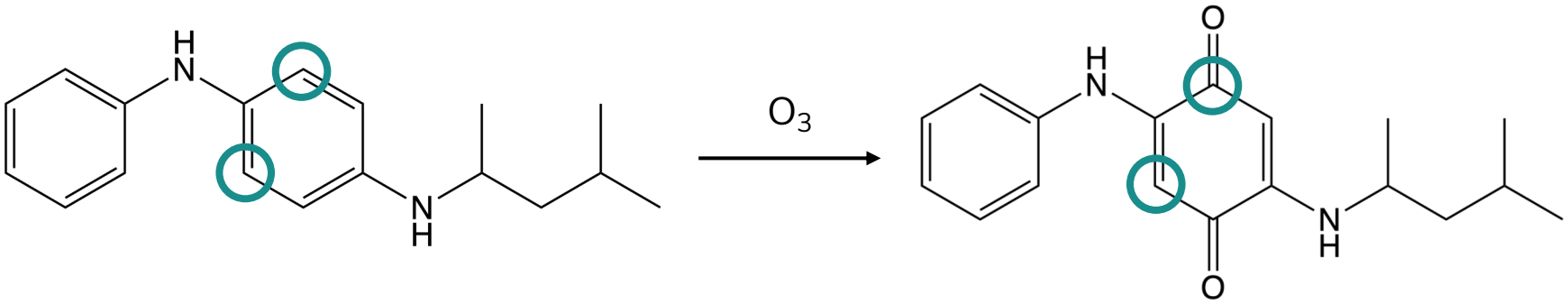
Wheel tests, road tests

Strategy 1:

MODIFICATION OF 6PPD

Structure modification

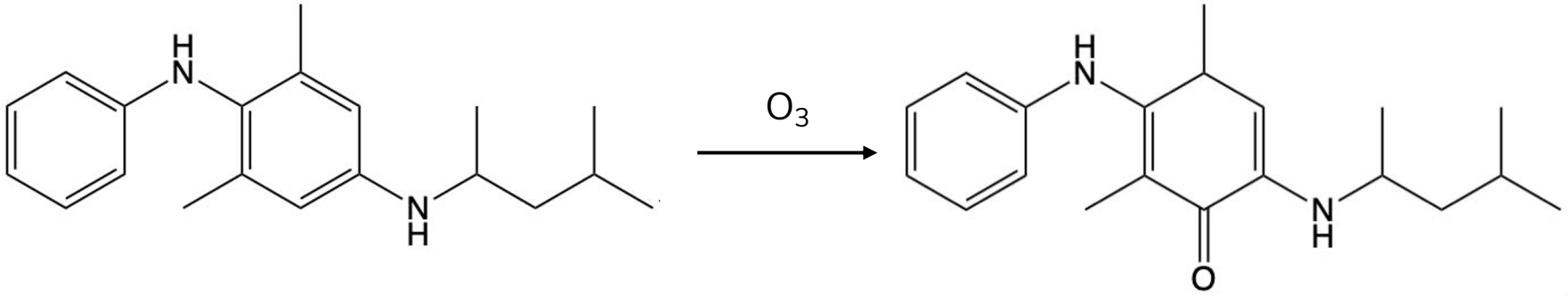
- Modification of 6PPD to ***prevent quinone formation***



6PPD **6PPD quinone**

Structure modification

- Modification of 6PPD to ***prevent quinone formation***

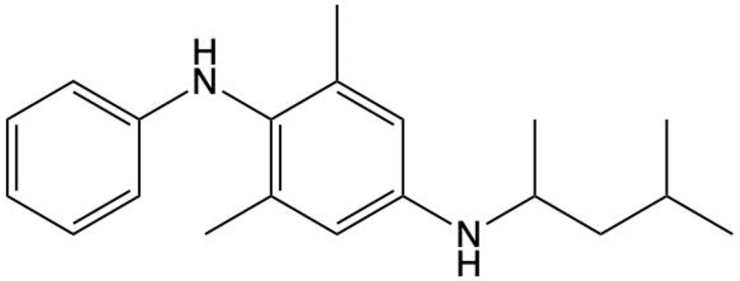


modified 6PPD

modified ozonation product

Modeling of physicochemical properties

- ***Density functional theory (DFT) modeling*** can predict reactivity towards oxygen and carbon radicals

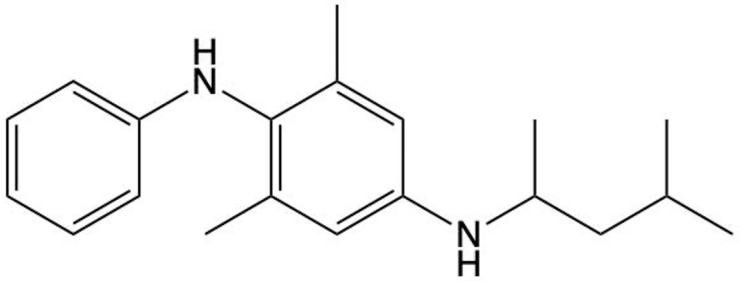


modified 6PPD

N. Mardirossian and M. Head-Gordon, *Mol. Phys.* **115**, 2315-2372 (2017).

Modeling of physicochemical properties

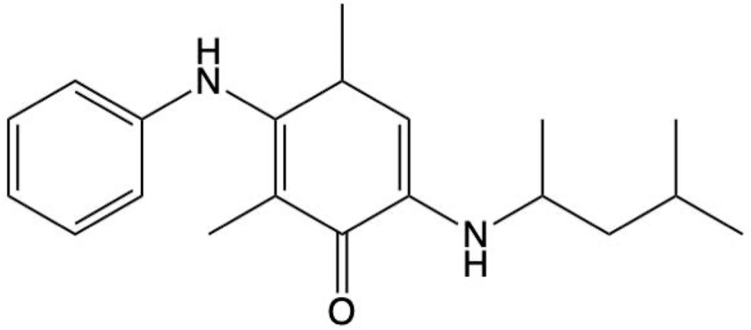
- Density functional theory (DFT) modeling can predict reactivity towards oxygen and carbon radicals
- ***Film formation*** may be more difficult to predict



modified 6PPD

Environmental concerns are difficult to predict

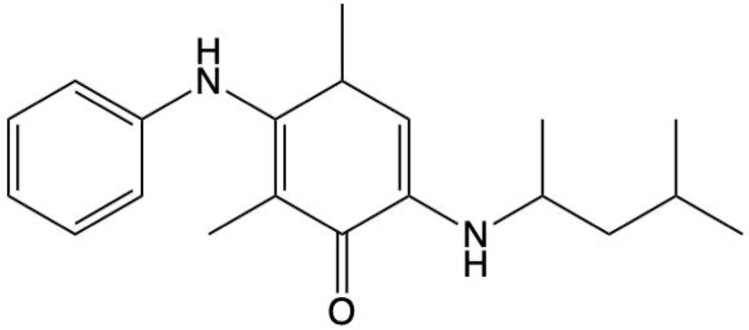
- Exact ***mechanism*** of toxicity to coho salmon is ***unknown***



modified ozonation product

Environmental concerns are difficult to predict

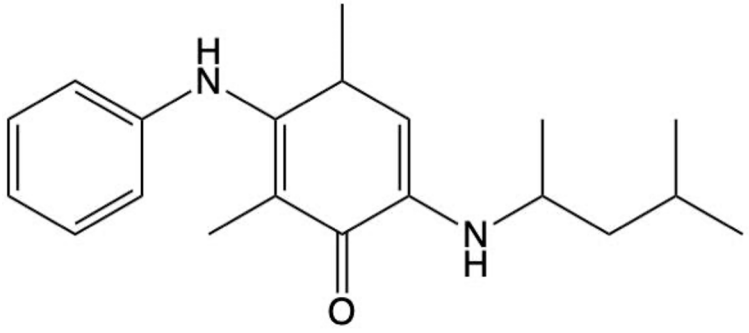
- Exact mechanism of toxicity to coho salmon is unknown
- Computational toxicology models unlikely to appreciate ***subtle structural differences***



modified ozonation product

Environmental concerns are difficult to predict

- Exact mechanism of toxicity to coho salmon is unknown
- Computational toxicology models unlikely to appreciate subtle structural differences
  - Severe, acute toxicity to coho salmon ***may be reduced***



modified ozonation product

Strategy 2:

FOOD PRESERVATIVES

Food preservatives and additives

Antioxidants added to food to extend shelf-life
Historical overlap between AOs used in rubber and in food
Several types, including **Gallates**

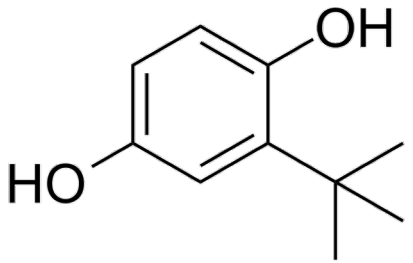
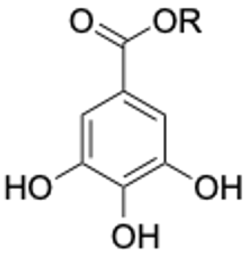


Image: Melro, E., Filipe, A., Sousa, D., Medronho, B., & Romano, A. (2021). Revisiting lignin: A tour through its structural features, characterization methods and applications. *New Journal of Chemistry*, *45*(16), 6986–7013. https://doi.org/10.1039/d0nj06234k

Gallates | antioxidant/antiozonant activity

Substance	Redox Potential ($E_{1/2}$ V vs Fe/Fe^{+})
6PPD	-0.12
Gallates	0.49-0.52



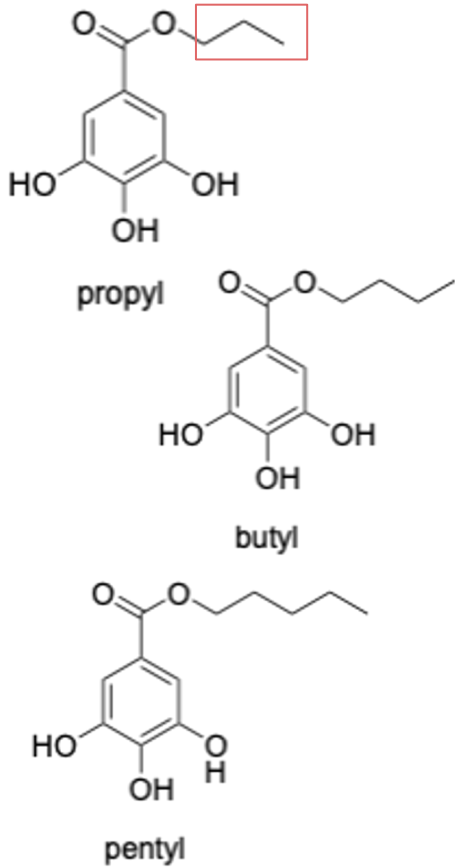
R = H, Pr, iPr, nBu, iBu, nPent, iPent

- Gallates protect organisms from damage that occurs through ozonation
  - Addition of propyl gallate to corn soil protected the corn from ozonation
  - Cellular membranes treated with propyl gallate were less susceptible to ozonation damage than those left untreated

Chem-Biol. Interact., **1998**, *114*, 45-59. *Plant & Cell Physiol.***1982**, *23,* 821-832., *Environ. Exp. Bot.*, **1990**, *30*, 443-449.

Gallates | Diffusion properties

Substance	MW (g/mol)	$LogK_{ow}$
6PPD	268	4.68
n-Propyl Gallate	212	1.80
n-Butyl Gallate	226	2.40 (computed)
n-Pentyl Gallate	240	2.70 (computed)



- Diffusion properties are likely to be similar and are modular

Chem-Biol. Interact., **1998**, *114*, 45-59. *Plant & Cell Physiol.***1982**, *23,* 821-832., *Environ. Exp. Bot.*, **1990**, *30*, 443-449.

Gallates: Hazard assessment

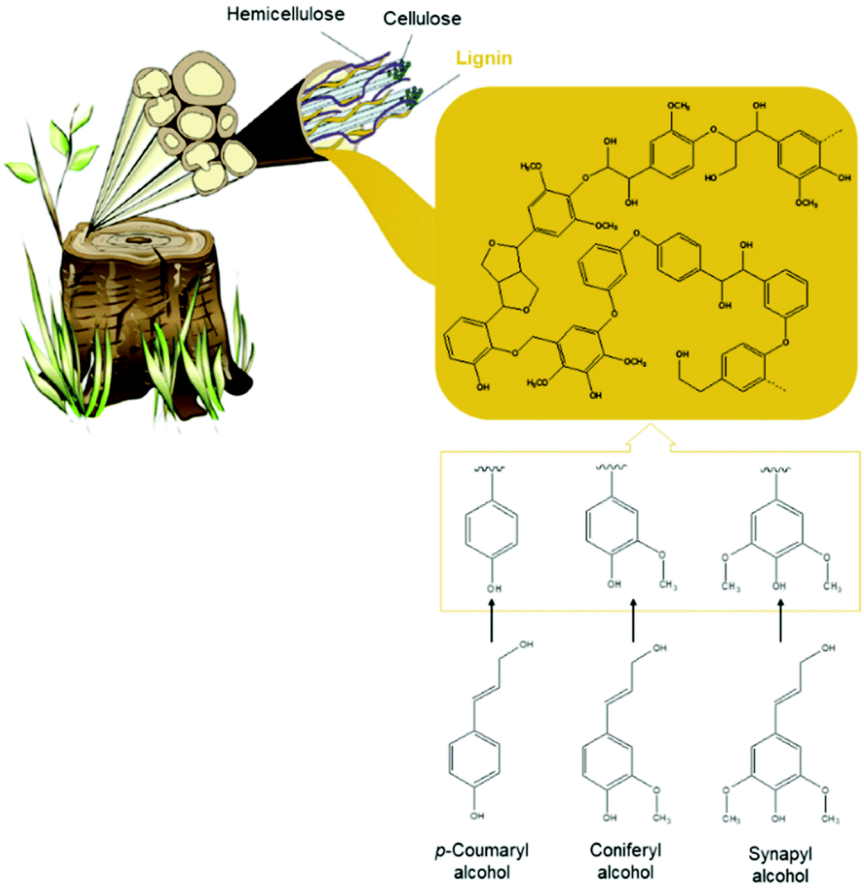
Common Trade Name	Group I Human Endpoints				Group II and Group II* Endpoints				Ecotoxicity	Fate	
	Carcinogenicity/ Mutagenicity	Reproductive Toxicity	Developmental Toxicity	Endocrine Activity	Acute mammalian toxicity	Systemic Toxicity/ Neurotoxicity	Skin sensitization /irritation	Eye irritation	Aquatic Toxicity Acute/chronic	Persistence	Bioaccumulation
Parent Compound											
6PPD	DG	DG	M-L	DG	M	DG	H-M	M	vH	L	vH
6PPD quinone	DG	DG	DG	DG	DG	DG	DG	DG	vH	DG	DG
Strategy: Food additives/preservatives											
Propyl gallate	L	L	L	M	M	DG	H	H	VH	H	vL
Octyl Gallate	L	L	DG	DG	M	DG	H-M	DG	H	DG	L
Epigallocatechin gallate	DG	M	DG	DG	M	DG	H	H	H	DG	DG
Gallic acid	L	L	DG	DG	L	L	M	M	L	L	vL
Lauryl gallate	DG	DG	DG	DG	DG	M	H-M	H	H	H	L

L: Low | M: Moderate | H: High | vH: Very High | DG: Data Gap

Strategy 3:
LIGNIN

Lignin

The second most abundant plant-based organic polymer in the world.
Cost competitive wood-derivative, which possesses antioxidant properties
There are a variety of lignins, which can vary based on their source and manufacturing processes



Lignin | antioxidant/antiozonant activity

Substance	Redox Potential ($E_{1/2}$ V vs Fe/Fe^{+})
6PPD	-0.12
Lignin (Spruce and Birch)	0.31-0.35

- Limited data on antiozonant reactivity shows minimal activity for lignin (0.12-11.0 mol O_3/C_9 unit lignin/min)
- Comparisons of ozonation rates of these materials in tires is necessary

Polym. Degred. Stabil. **2009**, *94*, 1457-1466, *Biotechnol. Biofuels* **2018**, *11*, 296., *Polym. Sci.* **1981**, *19*, 2053-2063., *Wood. Res. Technol.* **2004**, *58*, 263-268

Lignin | Diffusion Properties

Substance	MW (g/mol)	$LogK_{ow}$
6PPD	268	4.68
Indulin AT (Lignin)	5000 (relative average)	-0.57
P1000 (Lignin)	5200 (relative average)	-0.818
S5000 (Lignin)	5600 (relative average)	-1.09

- Diffusion of lignin is likely to be slower than that of 6PPD

J. Pharm. Sci. **2008**, *97*, 584-598., *Green Chem.* **2020**, *22*, 7031-7046.

Kraft Lignin vs. 6PPD

(Nilmini and Surej, 2019)
Aging 70 hours at 70 degrees Celsius

Tensile Strength (MPa)	Aging
Tear Strength (N/mm)	Flex Fatigue (Cycles to crack)
Abrasion Resistance (mm^3 lost)	Concentration (phr)

Lignin/silica and calcium liginate/calcium silicate vs. IPPD & TMQ

(Zaher et al., 2014)
Aging 7 days at 90 degrees Celsius

Tensile Strength (MPa)	Aging
Elongation @ Break (%)	Crosslink density
Thermal Stability	Concentration (phr)

Better Performance	Similar Performance	Slightly worse Performance	Much worse Performance

Lignin: Hazard assessment

Common Trade Name	Group I Human Endpoints				Group II and Group II* Endpoints				Ecotoxicity	Fate	
	Carcinogenicity/ Mutagenicity	Reproductive Toxicity	Developmental Toxicity	Endocrine Activity	Acute mammalian toxicity	Systemic Toxicity/ Neurotoxicity	Skin sensitization /irritation	Eye irritation	Aquatic Toxicity Acute/chronic	Persistence	Bioaccumulation
Parent Compound											
6PPD	DG	DG	M-L	DG	M	DG	H-M	M	vH	L	vH
6PPD quinone	DG	DG	DG	DG	DG	DG	DG	DG	vH	DG	DG
Strategy: Lignin											
p-Coumaryl alcohol	DG	DG	DG	DG	DG	M	H	H	DG	DG	DG
coniferyl alcohol	DG	DG	DG	DG	DG	M	H	H	DG	DG	DG
Sinapyl alcohol	DG	DG	DG	DG	DG	M	H	H	DG	DG	DG
Lignin	L	L	L	L	L	L	L	L	L	L	L

L: Low | M: Moderate | H: High | vH: Very High | DG: Data Gap

1. Biosynth Carbosynth, "p-coumaryl alcohol", FC145653, Safety Data Sheet; Biosynth AG, USA, May 29, 2021.
2. Biosynth Carbosynth, "coniferyl alcohol", FC69901, Safety Data Sheet; Biosynth AG, USA, May 29, 2021.
3. Cayman Chemical, "coniferyl alcohol", 29470, Safety Data Sheet; Cayman Chemical Company, USA, Jan 19, 2020.
4. Pubchem identifier: 528050. URL: https://pubchem.ncbi.nlm.nih.gov/compound/Sinapyl-alcohol
5. DOI: https://doi.org/10.1016/j.indcrop.2007.07.011

Strategy 4:

ALTERNATIVE RUBBER FORMULATIONS

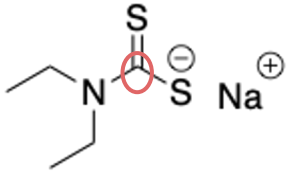
Vulcanization | process modifications

Process	Temp. [°C]	Time [min.]
Mixing	100 – 170	5 – 9
Calendering	80 – 120	2 – 3
Extrusion	100 – 140	1 – 2
Curing	140 – 210	Varies (10+)

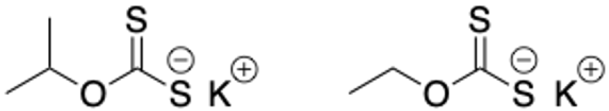
- High temperatures degrade many common AOs
- Alternative formulation schemes may require lower temperatures

Vulcanization | Different Accelerators

- Accelerator: A substance that causes the vulcanization process to occur more rapidly or at lower temperatures
- Dithiocarbamates: well-established accelerator in vulcanization
  - Activated through reaction at carbon



- Xanthogenates: replace N with O to increase reactivity of carbon leading to faster activation of the accelerator



- Able to achieve cure temperatures <120 °C for natural and synthetic rubber cements and adhesives

ACS Catal. **2021**, *11,* 4441−4455, *J. Am. Chem. Soc.* **2010**, *132*, 178-184.

Natural rubber | alternative sources

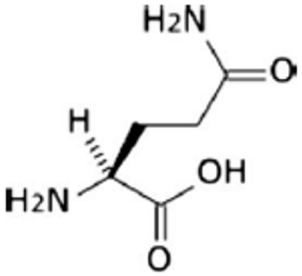
Natural rubber (NR) is essential in tire formulations

Hevea (currently favored)

Guayule

Russian Dandelion (Taraxagum)

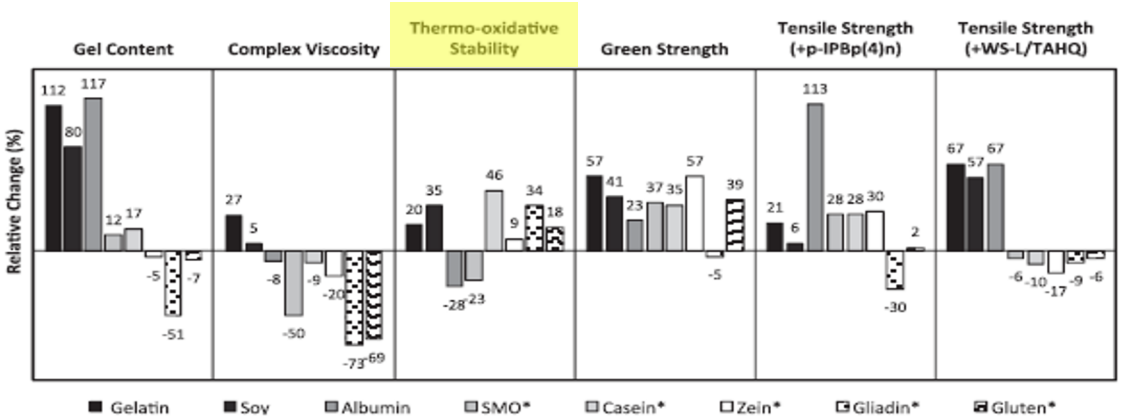
Natural rubber | alternative antioxidants



Amino Acids

L-glutamine: plasticizer, antioxidant, and anti-reversion agent.

Proteins served as AOs, plasticizers, cure accelerators, and anti-reversion agents



Rubber Chemistry and Technology, **2015**, *88*, 310-323.

Rubber Chemistry and Technology, **2017**, 90, 387-404

Alternative natural rubbers | a unique opportunity to reformulate the tire

Other explorations into NR AOs:

Chitosan derivatives - demonstrated aging protection (Khalaf et. al., 2013)

Oil palm leaves - effective for some vulcanization schemes (Komethi et. al., 2011)

Henna - promising alternative to traditional AOs for NR (Öncel et. al., 2019)

Comparison of our strategies

	Modified 6PPD	Food Preservatives	Lignin	Alt. formulations
Advantages	Potential “drop in” solution for industry Manufacturing should be relatively easy	Food-grade safety Already produced in large quantities	Bio-based Well-researched rubber additive	Opportunity to reformulate tire without 6PPD Potential to source rubber sustainably
Challenges	Potential to have similar toxic effects Modified chemicals difficult to assess for hazards	Potentially still has aquatic toxicity Thermal stability during processing may be an issue	Questionable antiozonant abilities Not a “drop in” solution	Extensive research must be conducted Requires complete overhaul of current manufacturing process

THANK YOU!

- Greener Solutions teaching team
- Colleen McMahan (USDA)
- USTMA
- Berkeley Center for Green Chemistry
- Flexsys