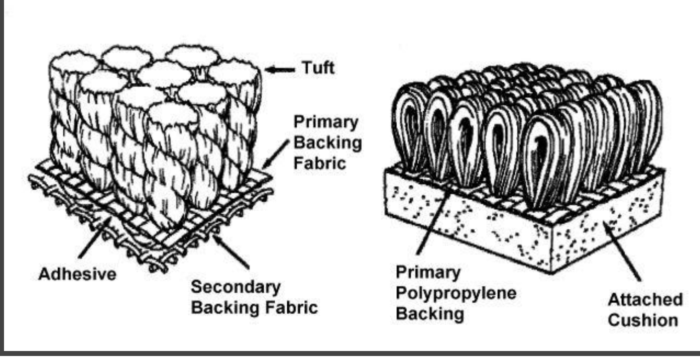

In collaboration with




# Investigating PFAS Removal Strategies During Carpet Recycling: A Greener Solutions Approach

Ned Antell, Andrew Cullen, & Michael Kado

American Chemical Society Conference
June 2021



https://www.recyclingproductnews.com/article/34775/californias-carpet-recycling-rate-soars-according-to-annual-report

Moody, V & Needles, HL. (2004) Tufted Carpet: Textiles, fibers, dyes, finishes, & processes. USA William Andrew Inc.

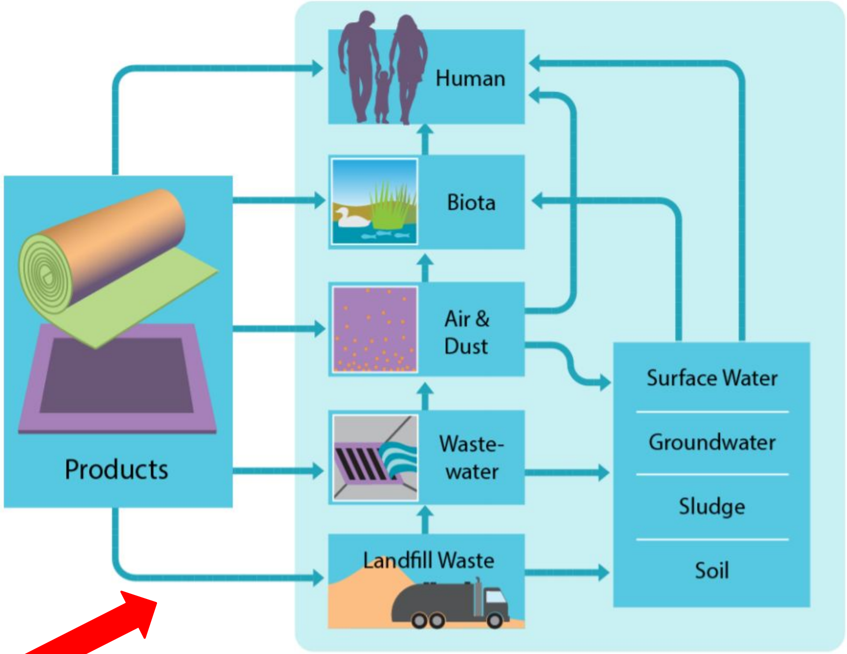
# The Challenge: **Investigate methods of removing PFASs from recycled carpet stock during carpet recycling**

1. Identify carpet recycling processes and intervention points where PFAS removal methods can be implemented
2. Review current PFAS treatment options
3. Conduct a comparative chemical hazard assessment on the treatments proposed
4. Present the hazards, efficacy and feasibility of each approach

<u>Final Product:</u> To create an opportunity map of the available options for PFAS removal during carpet recycling.

# Carpets and rugs are a major waste stream

- Carpets make up over half of the flooring market and 3% of current landfill volume in the U.S.
- PFAS was added to the synthetic facefibers of carpets and rugs for stain, grease, and oil repellency until 2019.
- ~14 year lifetime of carpet leads to potential for PFAS exposure.




***Intervention***

Product – Chemical Profile for Carpets and Rugs Containing Perfluoroalkyl or Polyfluoroalkyl Substances, DTSC, 2019

# Existing approaches to recycle or dispose of carpet do not remove or treat PFASs

**Landfilling**

Contaminates ground/surface waters and wastewater effluents with PFAS

**Incineration**

Releases short-chain PFAS, CFCs, and greenhouse gases

**Recycling**

Reintroduces PFAS into new consumer products that are not controlled

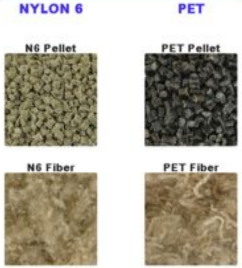
https://citytile.net/going-green-recycling-reusing-rethinking-old-rugs/

https://www.waste360.com/landfill/worlds-trash-increasingly-ending-incinerators

https://www.pca.state.mn.us/waste/construction-and-demolition-landfills-groundwater

# General carpet recycling processes allow for multiple points of intervention

Carpet Removal & collection → Sorting, Baling, and Storing → Separating Carpet Face Fiber → Sorting the Face Fiber → Cleaning &/or Extrusion*


*These represent general processes and vary based upon recycling center and final products.

# Criteria for Success:

## Human Health & Env. Performance

| L: Low | M:Moderate | H: High | VH: Very High | Probable | Data Gap |
|---|---|---|---|---|---|

| Human Endpoints | | | | | | | Environmental | |
|---|---|---|---|---|---|---|---|---|
| Constituent | C/M | D/R | Endocrine | Systematic | Neurotoxicity | Irritation | Aquatic | Bioaccumulative |
| PFOA | M | H | H | H | H | VH | M | H |

C/M= carcinogenic/mutagenic, D/R=developmental/reproductive toxicity

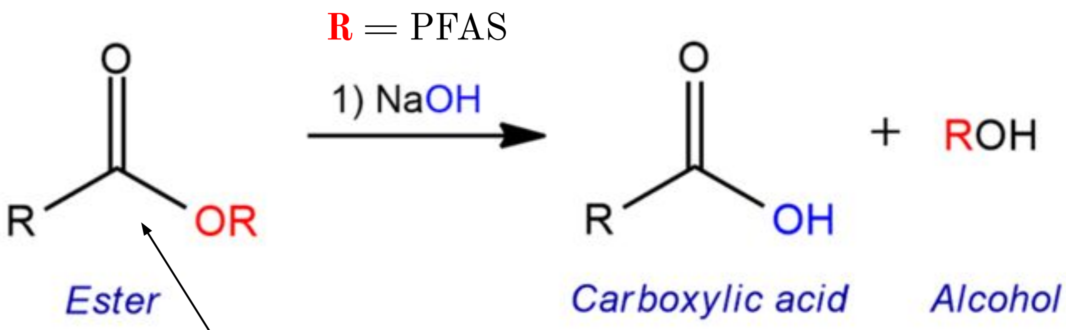
## Technical Performance

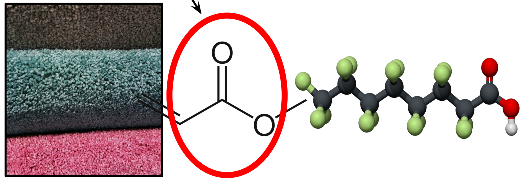
| Good | Moderate | Bad |
|---|---|---|

| Approach | Removal or Destruction | Time to Implement | Reaction speed | Energy Input | Feasibility |
|---|---|---|---|---|---|
| Example Strategy 1 | Removal | Immediately | Months to Years | High | Easy |

# Proposed Solution #1- Base Hydrolysis + Granular Activated Carbon

# Base Hydrolysis + Granular Activated Carbon (GAC)




Methacrylate linkage

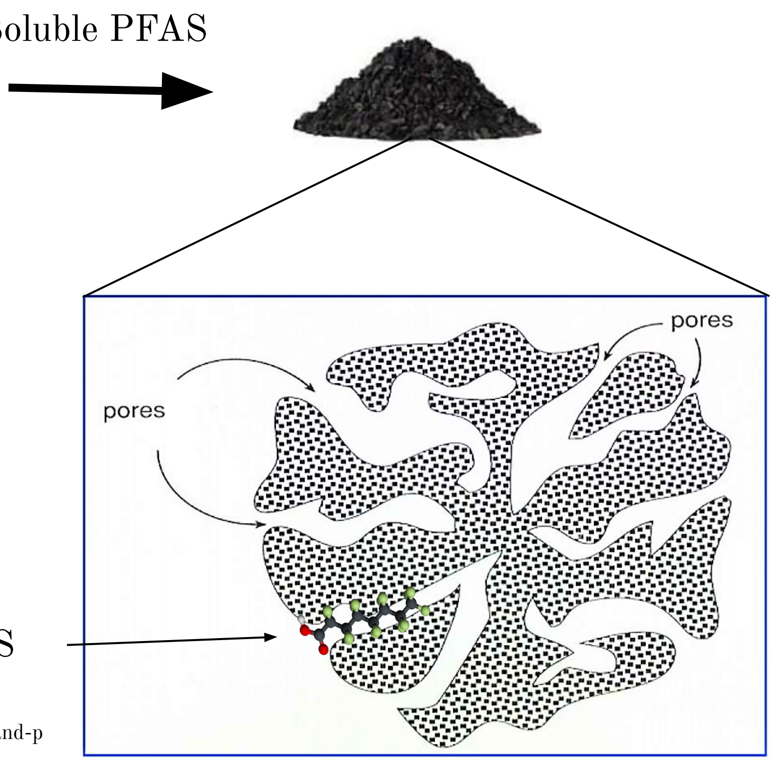



Image source: Chemistyscore.com

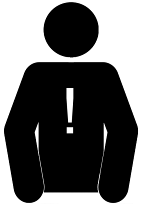
Image Source: https://sswm.info/sswm-university-course/module-6-disaster-situations-planning-and-preparedness/further-resources-0/adsorption-%28activated-carbon%29

# Base hydrolysis doesn't introduce significant health or environmental hazards

| Human Endpoints | | | | | | | Environmental | |
|---|---|---|---|---|---|---|---|---|
| Constituent | C/M | D/R | Endocrine | Systematic | Neurotoxicity | Irritation | Aquatic | Bioaccumulative |
| Sodium Hydroxide | DG | DG | DG | M | DG | VH | DG | DG |
| Hydrochloric Acid | L | L | DG | L | L | VH | L | L |

C/M= carcinogenic/mutagenic, D/R=developmental/reproductive toxicity

| L: Low | M:Moderate | H: High | VH: Very High | Probable | Data Gap |
|---|---|---|---|---|---|




https://sphweb.bumc.bu.edu/otlt/mph-modules/exposureassessment/exposureassessment3.html

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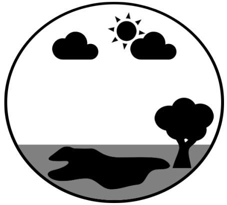
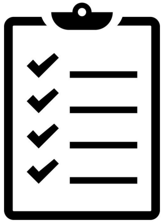


# Technical Performance of Base Hydrolysis + GAC

| | Removal or Destruction | Time to Implement | Reaction speed | Energy Input | Feasibility |
|---|---|---|---|---|---|
| Base Hydrolysis + GAC | Removal | Immediately | Minutes to Hours | Low | Easy |

| Good | Moderate | Bad |
|---|---|---|



# Proposed Solution #2- Base Hydrolysis + Reverse Osmosis + Plasma Treatment

# Base Hydrolysis + Reverse Osmosis (RO) + Plasma treatment

RO concentrate treated by plasma

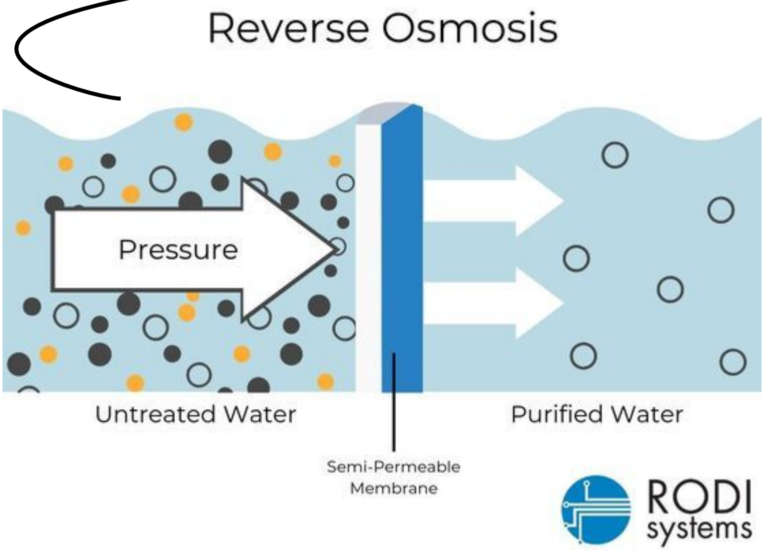



Image Source:
https://www.rodisystems.com/how-does-reverse-osmosis-work.html

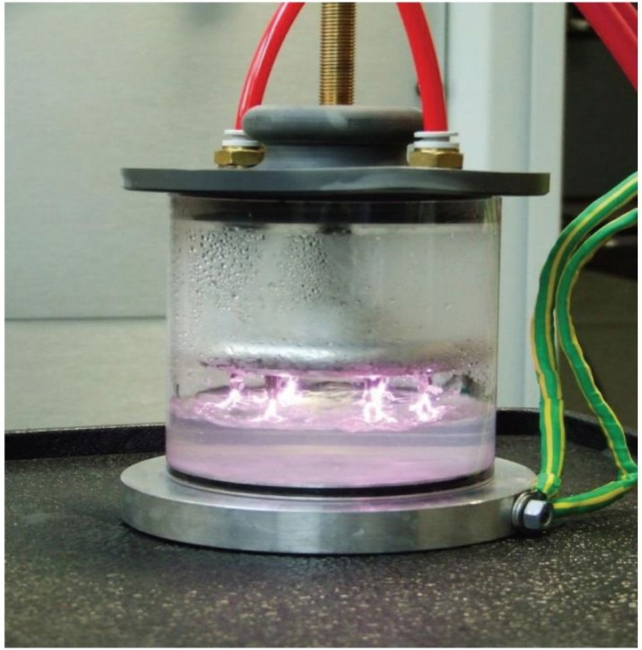
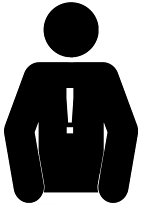


Image source: https://www.hindawi.com/journals/ijmicro/2011/462832/

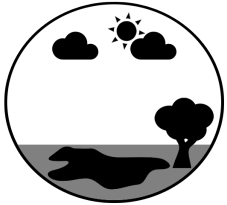
# Any destructive treatment adds the potential for HF generation

| | Human Endpoints | | | | | | Environmental | |
|---|---|---|---|---|---|---|---|---|
| **Constituent** | **C/M** | **D/R** | **Endocrine** | **Systematic** | **Neurotoxicity** | **Irritation** | **Aquatic** | **Bioaccumulative** |
| Sodium Hydroxide | **DG** | **DG** | **DG** | **M** | **DG** | **VH** | **DG** | **DG** |
| Hydrochloric Acid | **L** | **L** | **DG** | **L** | **L** | **VH** | **L** | **L** |
| Hydrofluoric Acid | **L** | **M** | **M** | **H** | **H** | **VH** | **M** | **VH** |

C/M= carcinogenic/mutagenic, D/R=developmental/reproductive toxicity



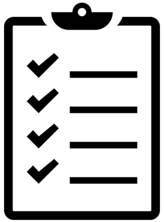

| **L: Low** | **M:Moderate** | **H: High** | **VH: Very High** | **Probable** | **Data Gap** |
|---|---|---|---|---|---|



# Technical Performance of Base Hydrolysis + RO + Plasma treatment

| | Removal or Destruction | Time to Implement | Reaction speed | Energy Input | Feasibility |
|---|---|---|---|---|---|
| Base Hydrolysis + RO + Plasma | Destruction | Months to Years | Minutes to Hours | High | Moderate-Easy |

| Good | Moderate | Bad |
|---|---|---|



# Proposed Solution #3- Esterase

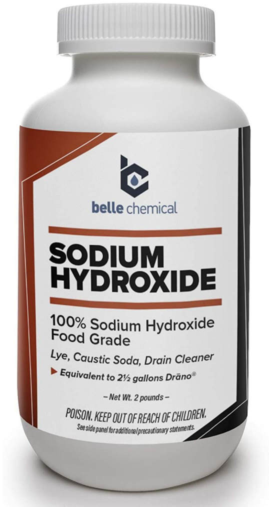



Image Source: https://www.amazon.com/Sodium-Hydroxide-Grade-Caustic-Pound/dp/B07KNR9SVF

Esterase Enzyme

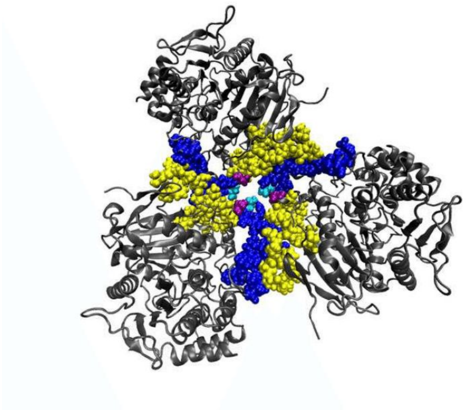


Image Source: https://www.researchgate.net/publication/46404626_Simulation_on_the_structure_of_pig_liver_esterase

# Pig Liver Esterase has no known hazards!

| Human Endpoints | | | | | | | Environmental | |
|---|---|---|---|---|---|---|---|---|
| **Constituent** | **C/M** | **D/R** | **Endocrine** | **Systematic** | **Neurotoxicity** | **Irritation** | **Aquatic** | **Bioaccumulative** |
| Pig Liver Esterase | **DG** | **DG** | **DG** | **DG** | **DG** | **DG** | **DG** | **DG** |

C/M= carcinogenic/mutagenic, D/R=developmental/reproductive toxicity

| L: Low | M:Moderate | H: High | VH: Very High | Probable | Data Gap |
|---|---|---|---|---|---|

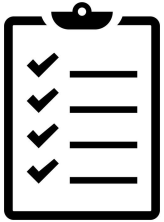
Image Source: https://www.pngegg.com/en/png-ddmjv

Image Source: https://www.dreamstime.com/cute-smart-pig-sitting-floor-anf-reading-book-funny-cartoon-animal-vector-illustration-cute-smart-pig-sitting-floor-image101298624

# Technical Performance of esterase treatments

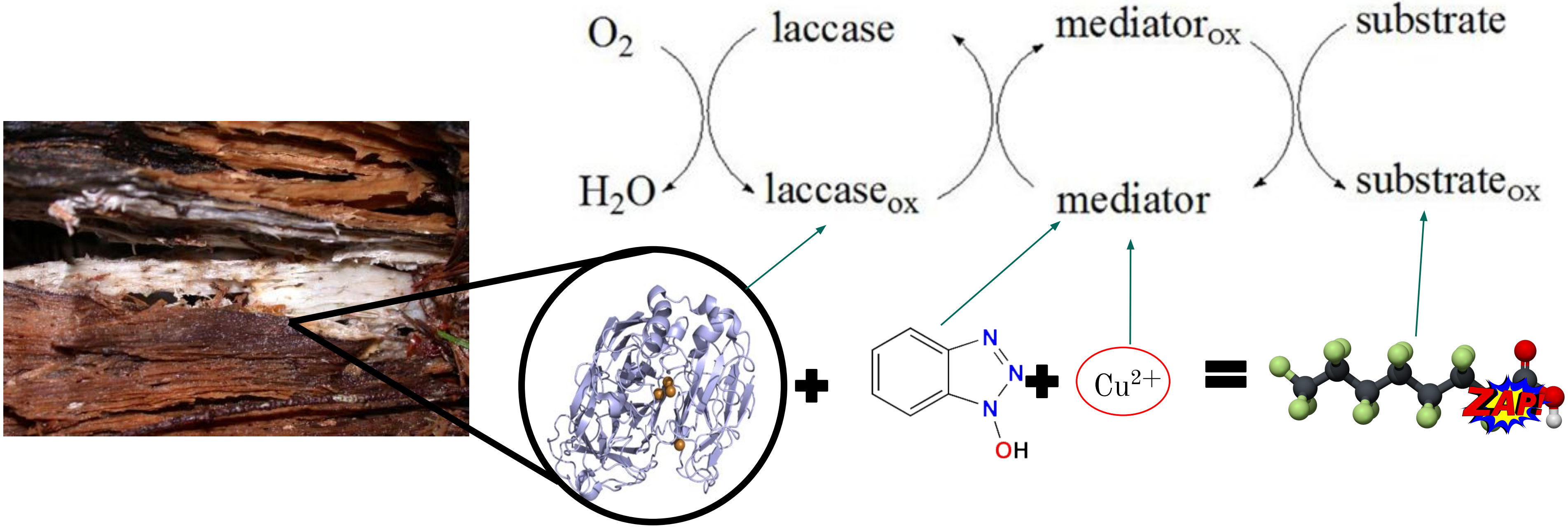
| | Removal or Destruction | Time to Implement | Reaction speed | Energy Input | Feasibility |
|---|---|---|---|---|---|
| Esterase + GAC | Removal | Months to Years | Unknown | Low | Moderate |
| Esterase + RO + Plasma | Destruction | Months to Years | Unknown | Medium | Moderate |

| Good | Moderate | Bad |
|---|---|---|



# Proposed Solution #4- Laccase

# PFAS Removal Strategies- Laccase Mediator




https://www.frontiersin.org/files/Articles/86385/fenrg-02-00012-HTML-r1/image_m/fenrg-02-00012-g004.jpg

https://www.creative-enzymes.com/similar/laccase_388.html

# Hazard Information of Laccase Treatment

| Human Endpoints | | | | | | | Environmental | |
|---|---|---|---|---|---|---|---|---|
| Constituent | C/M | D/R | Endocrine | Systematic | Neurotoxicity | Irritation | Aquatic | Bioaccumulative |
| Copper(II) sulfate | DG | M | M | M | VH | VH | VH | VH |
| 1-hydroxybenzotriazole (HBT) | DG | DG | DG | L | DG | H | M | DG |
| Laccase | DG | DG | DG | DG | DG | H | DG | DG |
| Hydrofluoric Acid | L | M | M | H | H | VH | M | L |

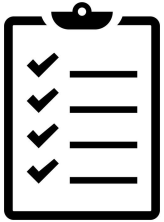
C/M= carcinogenic/mutagenic, D/R=developmental/reproductive toxicity

| L: Low | M:Moderate | H: High | VH: Very High | Probable | Data Gap |
|---|---|---|---|---|---|

# Technical Performance of Laccase Treatment

| | Removal or Destruction | Time to Implement | Reaction speed | Energy Input | Feasibility |
|---|---|---|---|---|---|
| Laccase + (GAC) | Destruction | Long | Unknown | Low | Difficult |

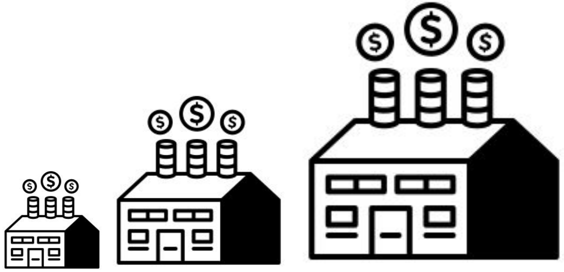
| Good | Moderate | Bad |
|---|---|---|



# Conclusions & Remaining Questions

# Conclusions

- No solution is without hazard
- Doing something is better than doing nothing
- Choosing the best solution will depend on the specific needs of the recycler



# Remaining Questions

### SCALING UP

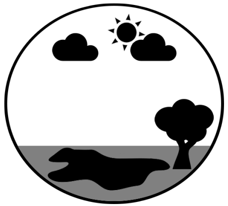
- What are the costs of these operations at a larger scale?
- Who would fund the PFAS removal efforts?

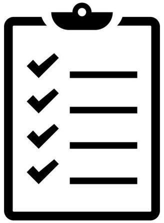
### HEALTH AND ENVIRONMENT

- What are the occupational exposures?
- What is the fate of the adsorbed PFAS?

### TECHNICAL

- Can these enzymes be optimized such that they are competitive with chemical options?
- How much PFAS will the destructive technologies destroy?



# Acknowledgements

Big thank you to-

Our Instruction Team- Dr. Meg Schwarzman, Tom McKeag, Dr. Billy Hart-Cooper, and Kim Hazard.

Dr. Simona Balan- DTSC

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Jackie Killings- K & M Technologies, LLC

Gail Brice and David Ikeda- XT Green

Yunhan Jin

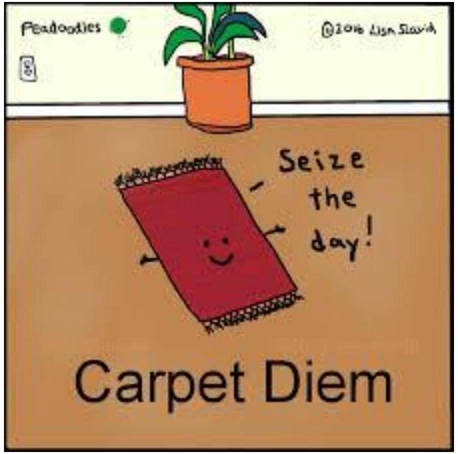
Berkeley

School of Public Health

DTSC
Department of Toxic Substances Control

Berkeley Center for Green Chemistry

# Questions?




http://peadoodles.blogspot.com/2016/02/carpet-diem.html

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# Supplementary Slides

# Nylon face fiber and pH

ELSEVIER

Journal of Molecular Structure (Theochem) 635 (2003) 83–89

THEO CHEM

www.elsevier.com/locate/theochem

## Effect of fluorine substitution on the rate for ester hydrolysis: estimation of the hydrolysis rate of perfluoroalkyl esters

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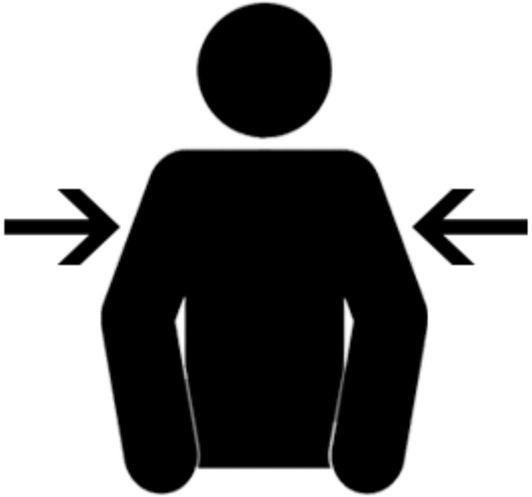
Received 31 January 2002; revised 12 May 2003; accepted 12 May 2003

# Routes of Exposure

**Ingestion**

**Inhalation**



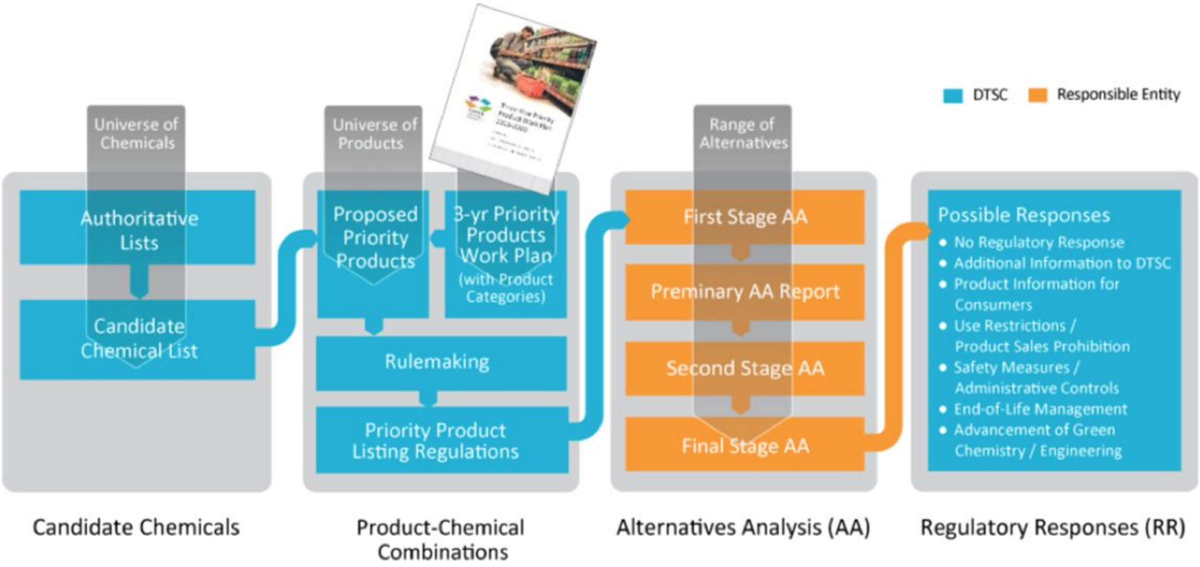
**Dermal**

https://sphweb.bumc.bu.edu/otlt/mph-modules/exposureassessment/exposureassessment3.html

# How to intervene in CA: Safer Consumer Product Regulations

(SB 509 & AB 1879)

- Carpets and rugs were listed by DTSC as a proposed priority product in 2018
  - Potential **exposure** to a Candidate Chemical
  - One or more exposures leads to **significant or widespread adverse impacts**



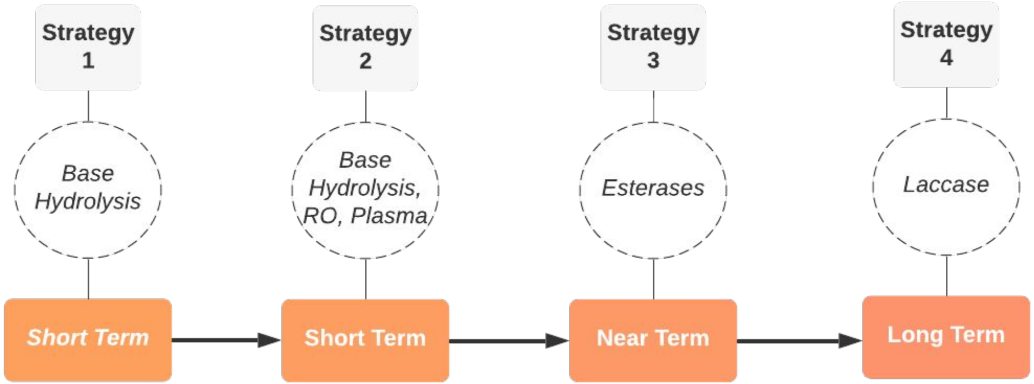

https://dtsc.ca.gov/scp/

# FIN

# OLDER SLIDES

# Overview of Proposed Strategies

1. Base Hydrolysis + Granular Activated Carbon (GAC) Adsorption
2. Base Hydrolysis + Reverse Osmosis (RO) + Plasma Treatment
3. Esterase substitute for Base Hydrolysis
4. Enzymatic Laccase



# Feedback

- Should we include hazards of unkonwn pfas generations?
- Add a slide about mineralization, GAC, other acronyms
- Give time limits for each slide for things
  - Maybe 5 min per approach? = 20 minutes, 5 for intro, 5 for wrapup
- Time at slide 38
- Need to put in CARE as a potential regulatory solution
- Billy:
- Tom:
  - Meth and acrylates for aquatic toxicity
  - How can you mitigate those low scores
- Meg:
  - We must compare to doing nothing, we need to highlight it
  - As few tradeoffs as posible
- 

# Outline

Section 1: Background

Section 2: Approach

Section 3: Strategies

- Strategy 1: Base Hydrolysis + Granular Activated Carbon
- Strategy 2: Base Hydrolysis + Reverse Osmosis + Plasma
- Strategy 3: Esterases
- Strategy 4: Laccases

Section 4: Performance Summaries

Section 5: Recommendations