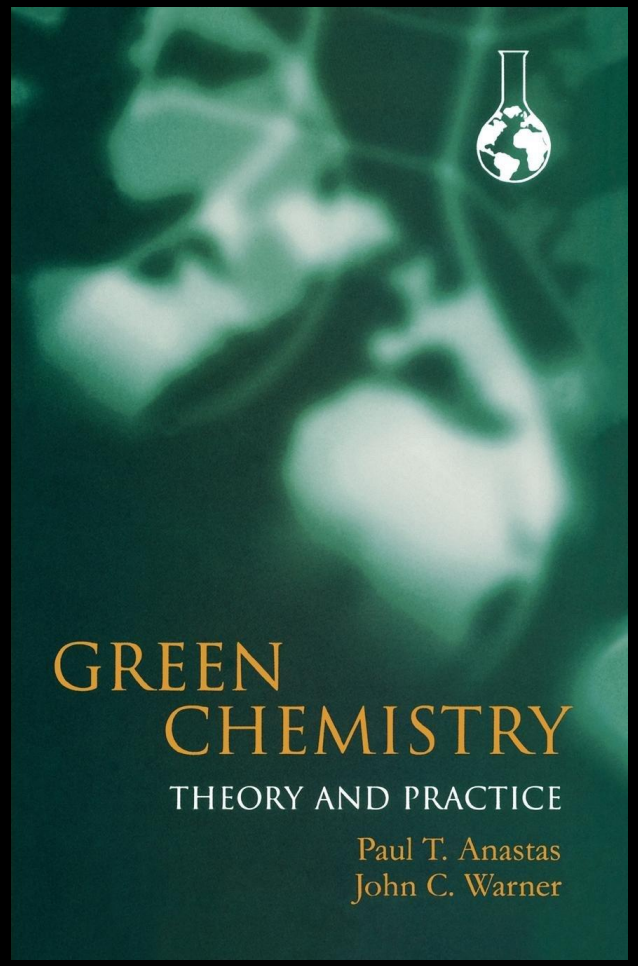
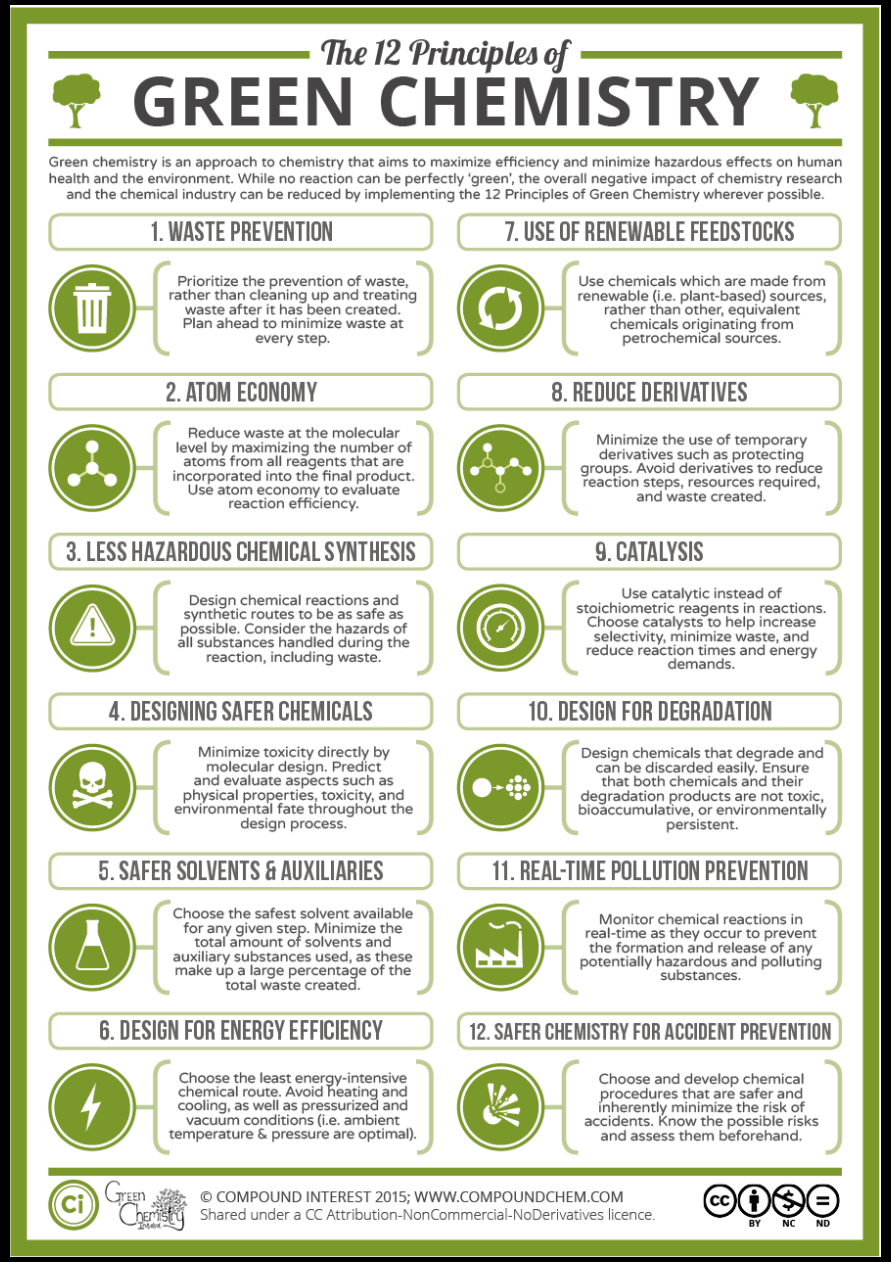
The path to economic and environmental prosperity

25 years of the 12 Principles of Green Chemistry

Green Chemistry: Theory and Practice



(1998)


The 12 Principles of
GREEN CHEMISTRY
Green chemistry is an approach to chemistry that aims to maximize efficiency and minimize hazardous effects on human health and the environment. While no reaction can be perfectly 'green', the overall negative impact of chemistry research and the chemical industry can be reduced by implementing the 12 Principles of Green Chemistry wherever possible.
1. WASTE PREVENTION
Prioritize the prevention of waste, rather than cleaning up and treating waste after it has been created. Plan ahead to minimize waste at every step.
2. ATOM ECONOMY
Reduce waste at the molecular level by maximizing the number of atoms from all reagents that are incorporated into the final product. Use atom economy to evaluate reaction efficiency.
3. LESS HAZARDOUS CHEMICAL SYNTHESIS
Design chemical reactions and synthetic routes to be as safe as possible. Consider the hazards of all substances handled during the reaction, including waste.
4. DESIGNING SAFER CHEMICALS
Minimize toxicity directly by molecular design. Predict and evaluate aspects such as physical properties, toxicity, and environmental fate throughout the design process.
5. SAFER SOLVENTS & AUXILIARIES
Choose the safest solvent available for any given step. Minimize the total amount of solvents and auxiliary substances used, as these make up a large percentage of the total waste created.
6. DESIGN FOR ENERGY EFFICIENCY
Choose the least energy-intensive chemical route. Avoid heating and cooling, as well as pressurized and vacuum conditions (i.e. ambient temperature & pressure are optimal).
7. USE OF RENEWABLE FEEDSTOCKS
Use chemicals which are made from renewable (i.e. plant-based) sources, rather than other, equivalent chemicals originating from petrochemical sources.
8. REDUCE DERIVATIVES
Minimize the use of temporary derivatives such as protecting groups. Avoid derivatives to reduce reaction steps, resources required, and waste created.
9. CATALYSIS
Use catalytic instead of stoichiometric reagents in reactions. Choose catalysts to help increase selectivity, minimize waste, and reduce reaction times and energy demands.
10. DESIGN FOR DEGRADATION
Design chemicals that degrade and can be discarded easily. Ensure that both chemicals and their degradation products are not toxic, bioaccumulative, or environmentally persistent.
11. REAL-TIME POLLUTION PREVENTION
Monitor chemical reactions in real-time as they occur to prevent the formation and release of any potentially hazardous and polluting substances.
12. SAFER CHEMISTRY FOR ACCIDENT PREVENTION
Choose and develop chemical procedures that are safer and inherently minimize the risk of accidents. Know the possible risks and assess them beforehand.
Ci
Green Chemistry
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BY NC ND

The 12 Principles of GREEN CHEMISTRY

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Green Chemistry

Cutting-edge research for a greener sustainable future

rsc.li/greenchem

ISSN 1463-9262

ROYAL SOCIETY OF CHEMISTRY

CRITICAL REVIEW
Paul T. Anastas *et al.*
The Green ChemisTREE: 20 years after taking root with the 12 principles

ISSN 1463-9262

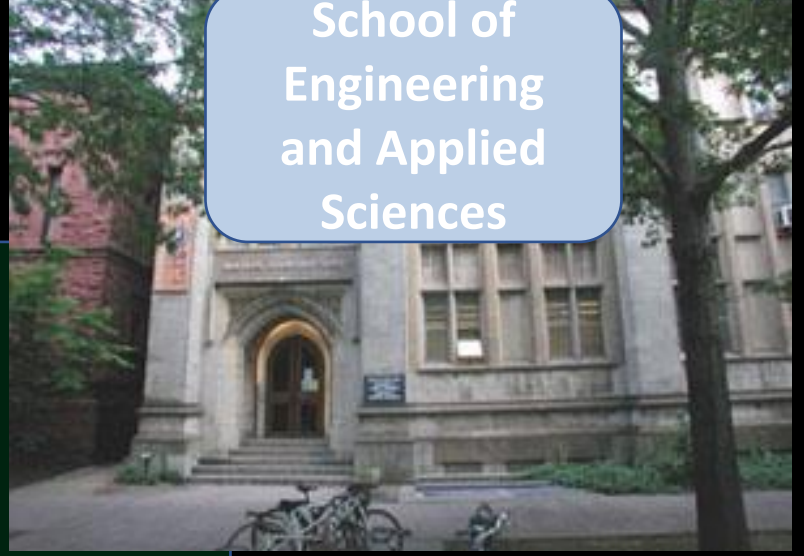
Industry Sectors

Green Chemistry across Industrial Sectors

- Defense and aerospace
  - *Adhesives, coatings, corrosion inhibitors*
- Automotive
  - *Solvents, polymers, fuels*
- Household cleaners
  - *Surfactants, fragrances, dyes*
- Cosmetics
  - *Builders, chelating agents, dyes*
- Agriculture
  - *Pesticides, fungicides, fertilizers*
- Electronics
  - *Solder, housings, displays*
- Pharmaceuticals

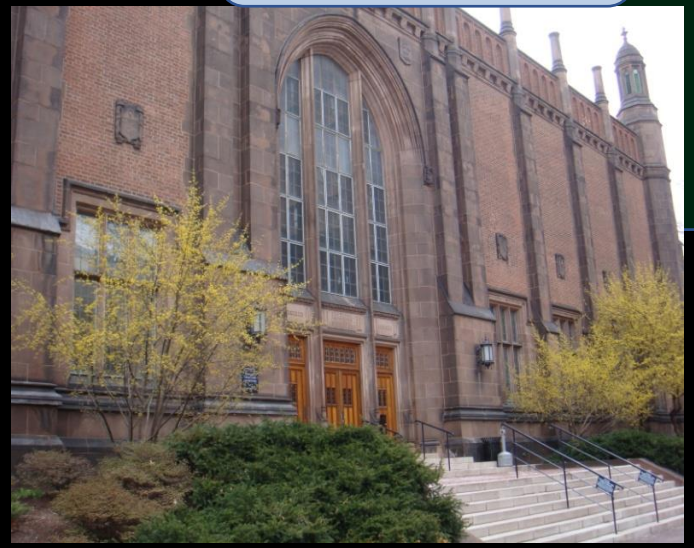
School of the Environment

School of Engineering and Applied Sciences



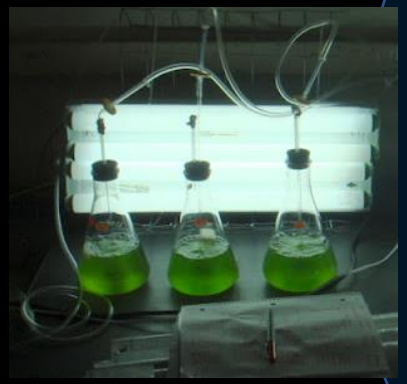
Yale Center For Green Chemistry and Green Engineering

Dept. of Chemistry



School of Public Health

The Center's Work



Advancing the Science

Basic research
Technical workshops
Research tools
Promote research investment
Advance the research agenda

Catalyzing Implementation

Industrial partnerships
Policy advancement
Benchmarking
Roundtables
Assessment protocols

Preparing the Next Generation

Education materials
Yale courses
Training trainers
Graduate workshops
Faculty training

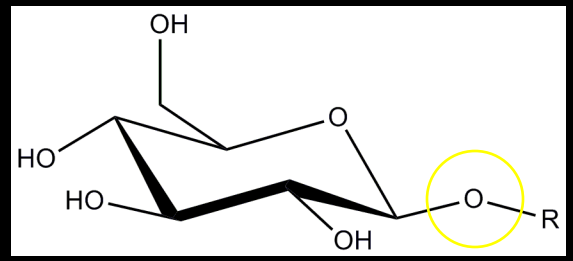
Raising Awareness

Conferences/symposia
Books
Multi-media
Web presence
Public engagement

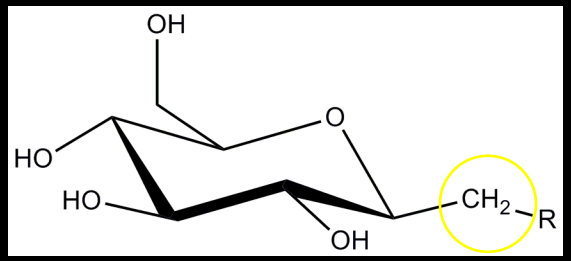
Bio-based surfactants from *C*-glycosides

(P. Foley, Anastas group)

Avoiding petroleum feedstocks, improving performance through a more robust carbohydrate structure:



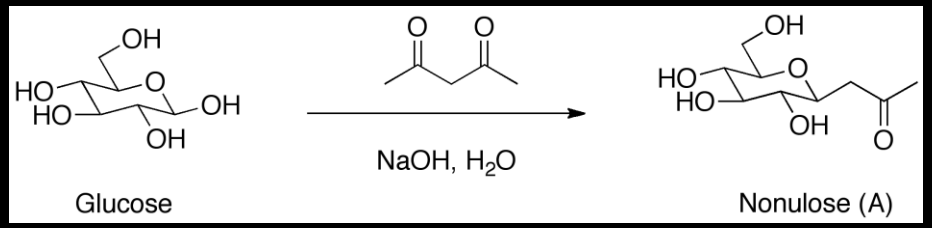
vs.

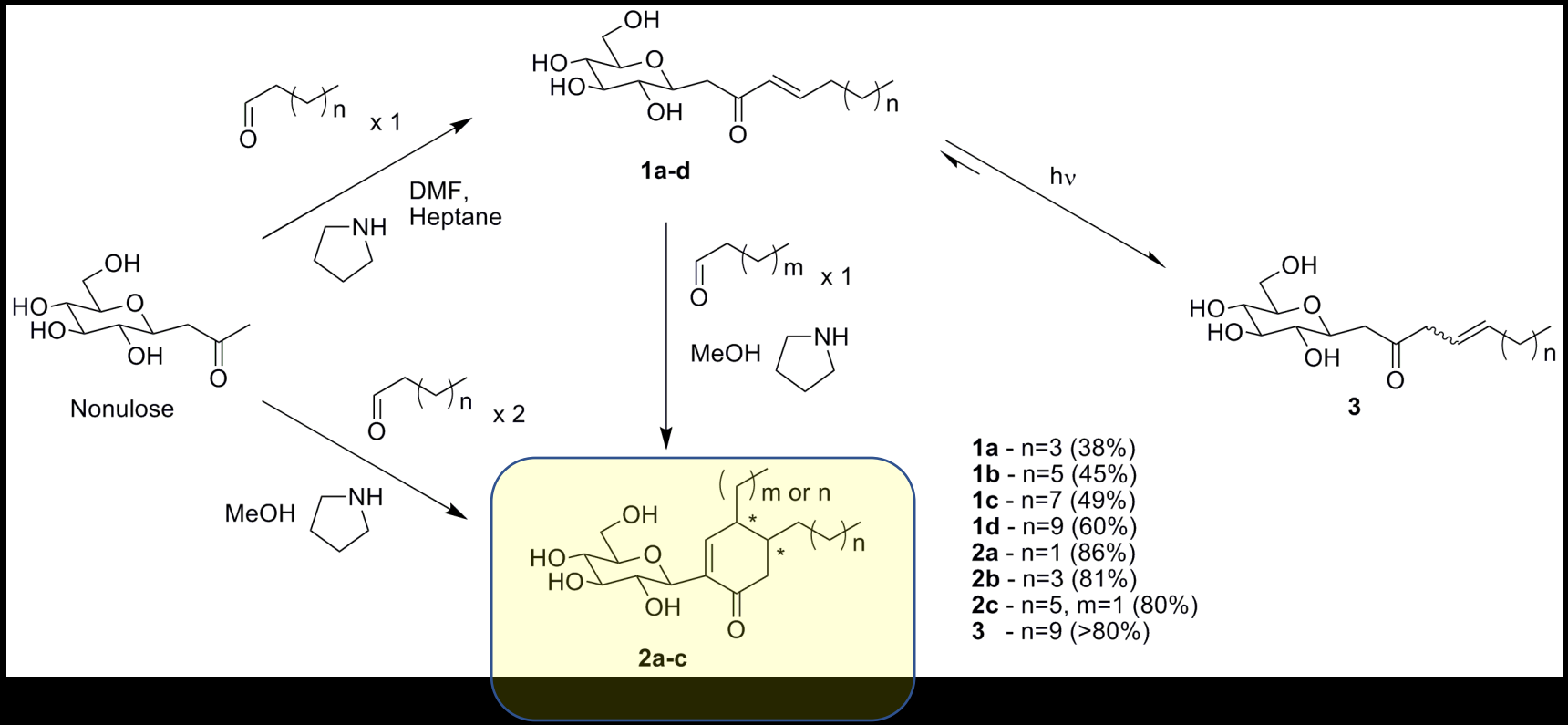


Potential applications in soil remediation, cleaning of metal parts, household uses, cosmetics...

Biodegradable and non-toxic

Synthetic approach





Dr. Patrick Foley

Luxury and elegance from agricultural and timber wastes

P2 Elegant Processes. Sustainable Products.

Flavors & Fragrances (F&F)

Renewable carbonyls from fatty acids and terpenesfor mint, floral, fruity and gourmand accords.

Cosmetics and Personal Care

Liquid polymers, and specialty alcohols as fixatives, silicone replacements, and emollients in skin and hair care.

Specialty Materials

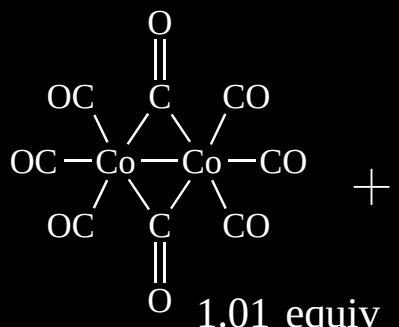
Diacids and esters for renewable polymers. Liquid polymers for coatings, resins, and lubricants.

Bioactives

Specialty acids for skin care and crop care. Terpene and fatty acid oxides for anti-fungals and preservatives.

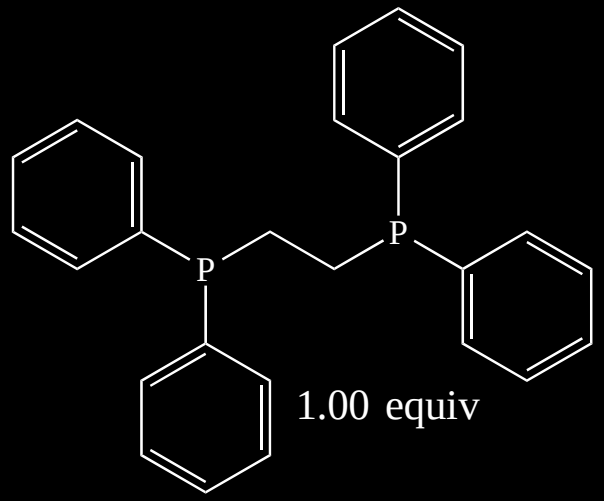
Thermal Synthesis of a Cobalt-Based Water Splitting Catalyst

22 gram yield
in one batch!



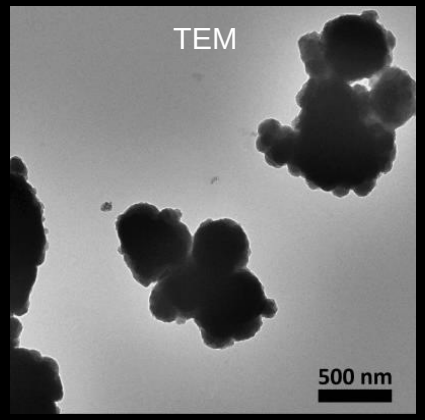
1.01 equiv

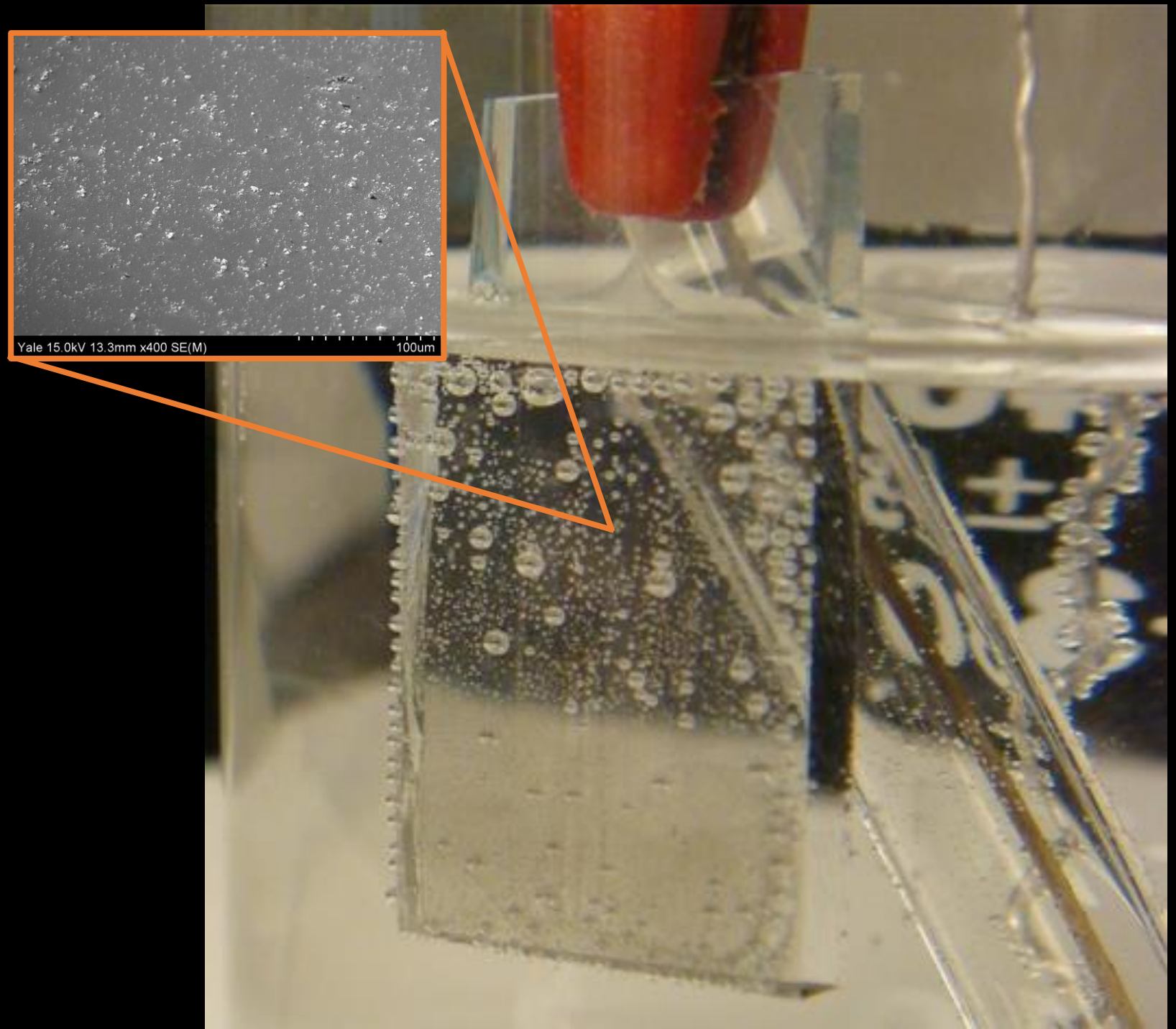
+



1.00 equiv

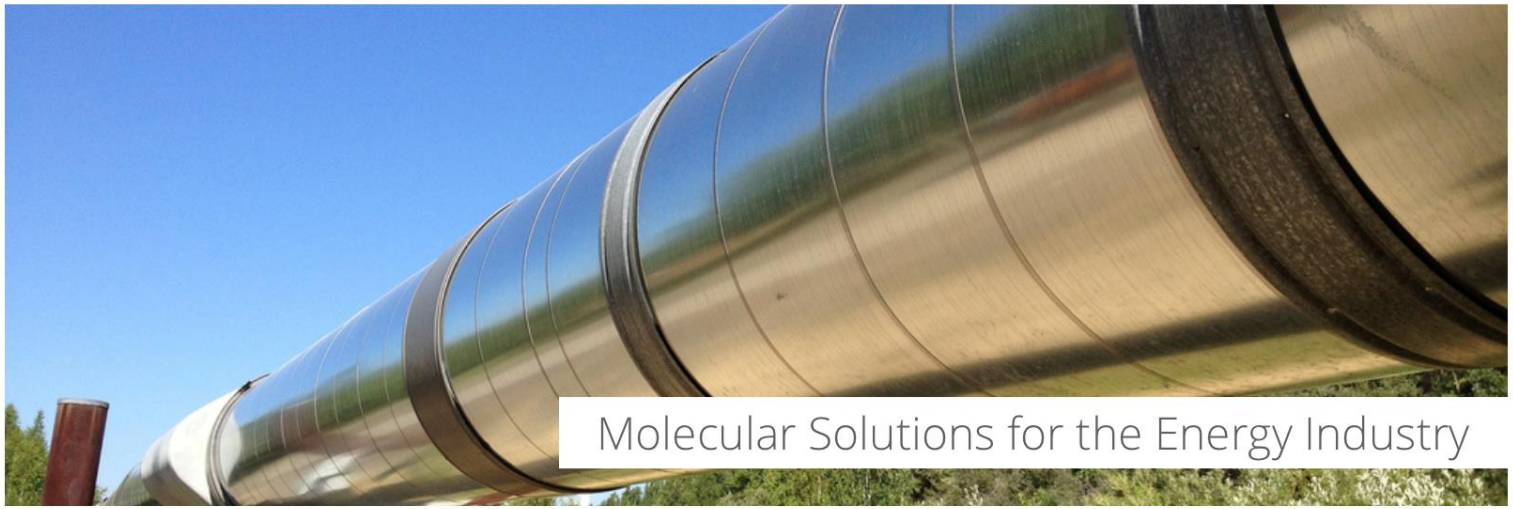
1) Xylenes, 160 °C, 2 h
under N_2
2) 25 °C, 72 h
open to air




Yale 15.0kV 13.3mm x400 SE(M)
100um

CATALYTIC Innovations

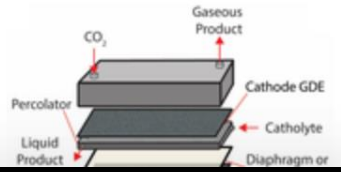
HOME | CARBON DIOXIDE | OXIDATION CATALYSIS | TEAM | CONTACT



ABOUT US

SOLUTIONS

NEWS HIGHLIGHT



RECENT UPDATES

9/13

Publication in *Chem*

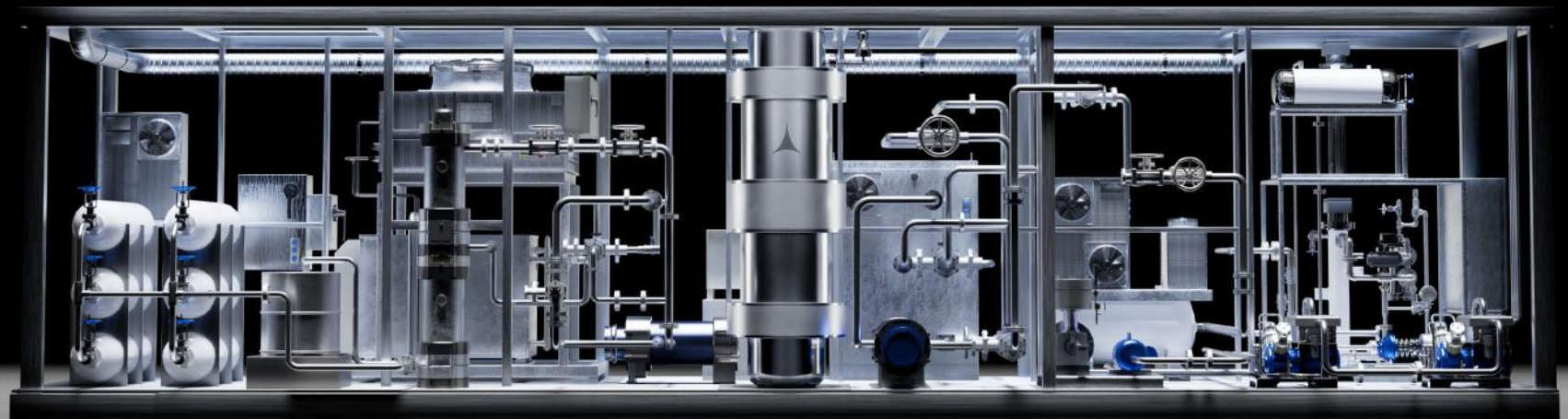
Our technoeconomic analysis and review of upcoming carbon dioxide electrolysis was published.

AIR COMPANY®

AIR COMPANY®


AIR COMPANY.
AIR COMPANY.

AIR COMPANY has developed and successfully deployed a patented Power to Liquids (PtL) Technology that converts captured carbon dioxide (CO_2) into fuels & carbon-negative chemicals.

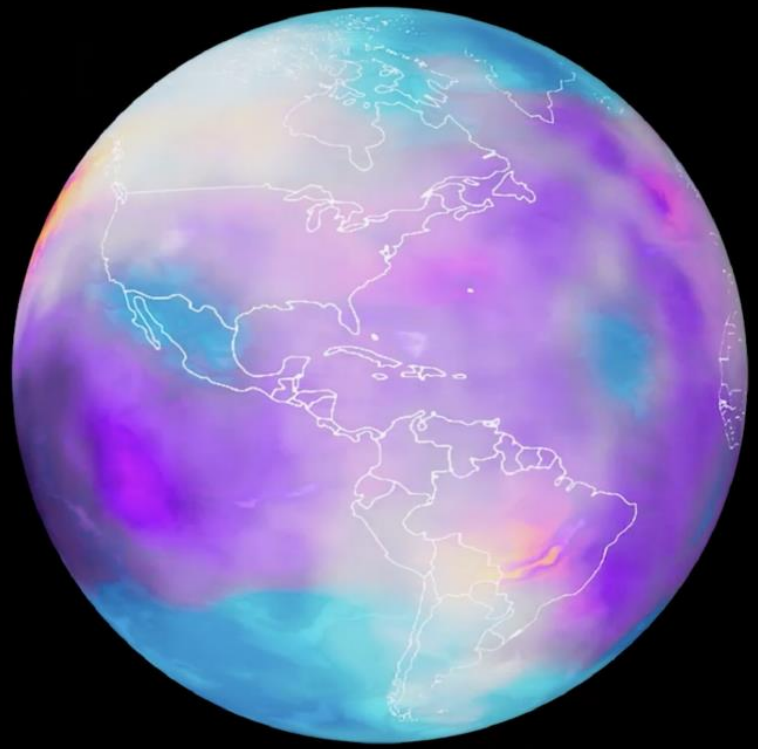


Future of AIR Technology

If the world's industries utilized our technology, we could reduce global emissions by 10.8% annually.

1.3%	3.3%	6.1%
Ethanol	Methanol	Jet Fuel

AIR COMPANY

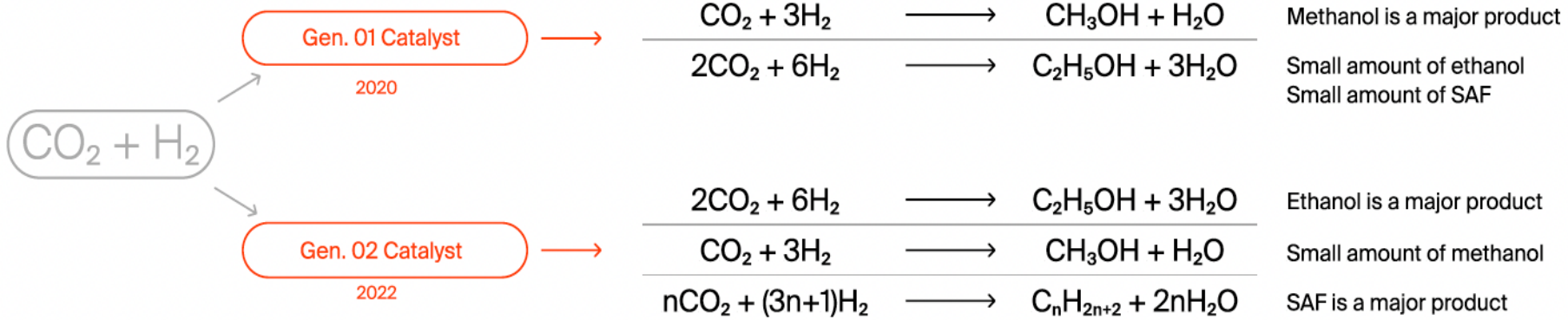


Overview

AIR COMPANY has developed two proprietary process technologies to produce alcohols and fuels

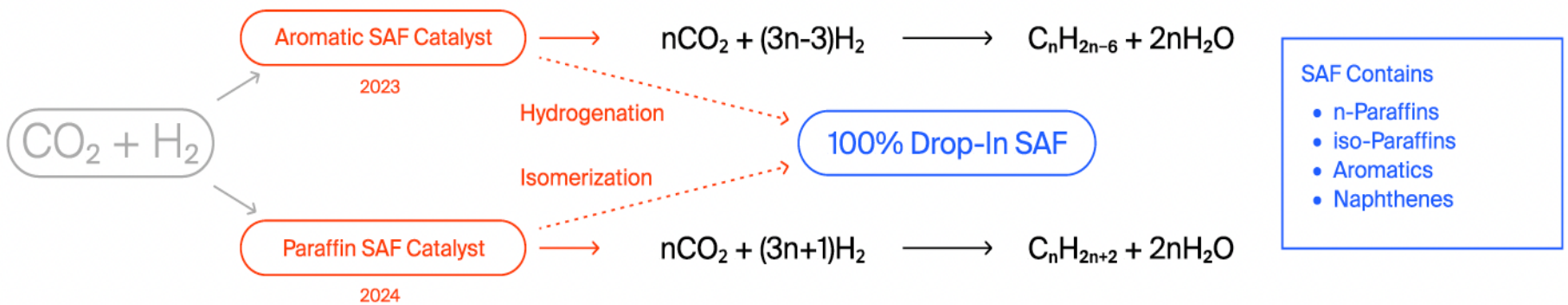
Process 01

CO_2 to Ethanol



Process 02

CO_2 to SAF



AIR TECHNOLOGY APPLICATIONS

Spirits Household Fragrances Ethanol Methanol Jet Fuel

AIR Eau de Parfum

The world's first fragrance made from CO_2

The New York Times

"Offering an intoxicating mix of hope, hype and science."

THE ZOE REPORT

"The tobacco comes through most notably, but not in a smokey bar type of way – it's much more subtle, as if you're leaving a crowded room and walking back into the blazing sunshine."

HYPEBEAST

"A lush, clean fragrance that smells like taking a fresh pair of sneakers on a walk through the park."

Legacy Fragrance CO_2 Emitted per Bottle: 150g

AIR Eau de Parfum CO_2 Utilized per Bottle: 36g

AIR Vodka

The world's first and only vodka made from CO_2

TIME

Time Magazine
Invention of the Year 2020

Forbes

This Startup is Fighting Climate Change by Turning Carbon Dioxide into Vodka

NASA

Winning Team Design Systems to Convert Carbon Dioxide

FORTUNE

The Unconventional Methods Liquor Makers Are Taking to Be More Sustainable

WIRED

This Martini Wants to Kill Climate Change One Sip at a Time

Legacy Vodka
CO_2 Emitted per Bottle

13lbs

AIR Vodka
CO_2 Utilized per Bottle

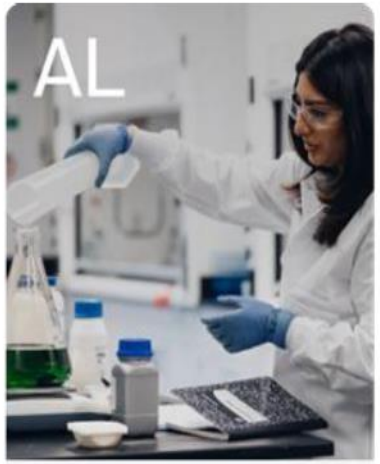
1.0lb

Our Facilities & Locations

Total Employees

80+

We have a growing team of over 80 people across all of our facilities and locations, and we have just received Fast Company's "Best Workplaces for Innovators" award for 2023.



AIR Lab

Catalyst research & development

Location	BROOKLYN, NY
Size	400 SQ FT
Employees	8
Roles	Chemistry

AIR Innovation Center

System 1: Prototype
Catalyst testing and scale-up

Location	BROOKLYN, NY
Size	2,500 SQ FT
Employees	9
Roles	Engineering
	Plant Operations

AIR Factory 01

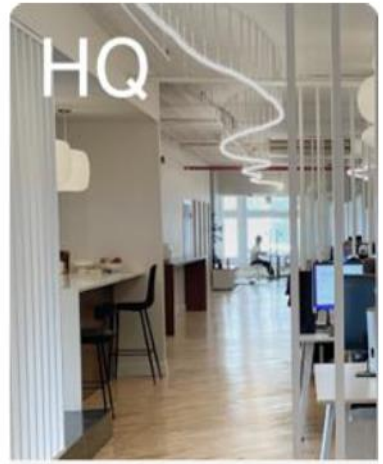
System 2: Pilot Plant
Catalyst testing and scale-up

Location	BROOKLYN, NY
Size	5,000 SQ FT
Employees	10
Roles	Plant Operations

Bogart

Engineering and R&D HQ

Location	BROOKLYN, NY
Size	1,500 SQ FT
Employees	13
Roles	Chemistry
	Engineering



AIR Headquarters

Corporate HQ

Location	NEW YORK, NY
Size	3,000 SQ FT
Employees	29
Roles	Commercial
	Marketing
	Design
	Product
	Finance
	People

ACS NEWS

2023 US EPA Green Chemistry Challenge Awards recipients named

Awardees honored for developing greener products and processes

by **Nina Notman, special to C&EN**

October 27, 2023

Co-Founder/President –P2 Science

Co-founder/CTO Air Company

Senior Scientist Air Company

Co-Founder, CEO – Nth Cycle

Co-Founder/CEO – Metabolic

Co-Founder – Carbon Capture Machine

Co-Founder/CTO – DEMETA

Innovation

“I don’t want to make the best electric car. I want to make the best car - and that will be electric.”

- Elon Musk

Innovation

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- Elon Musk

“We don’t want to make the best green chemistry. We want to make the best chemistry - and that will be green.”

-The global green chemistry community