# How can Fabs Reduce Their Water Footprints:

## From industrial wastewater reuse to atmospheric water harvesting as make-up supplies for ultrapure water


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*Arizona State University (Tempe)*


https://swsie.asu.edu/

Newtcenter.org

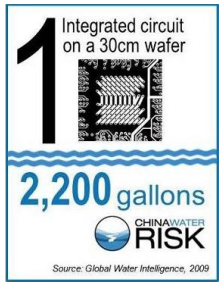
*Intel's corporate sustainability goal for water is to achieve net positive water by 2030*

## Outline

- Water use in Fabs
- Current wastewater reuse in Fabs
- Future wastewater reuse in Fabs
- Atmospheric water harvesting using nanotechnology as a future water source for Fabs
- Summary

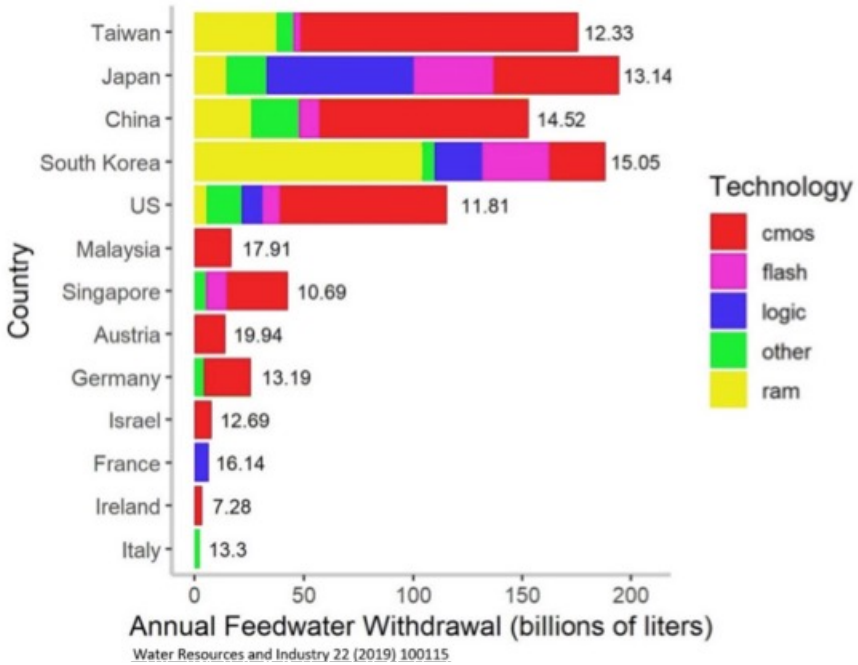
You can't do nanotechnology without water for manufacturing !

# Water Use in Fabs



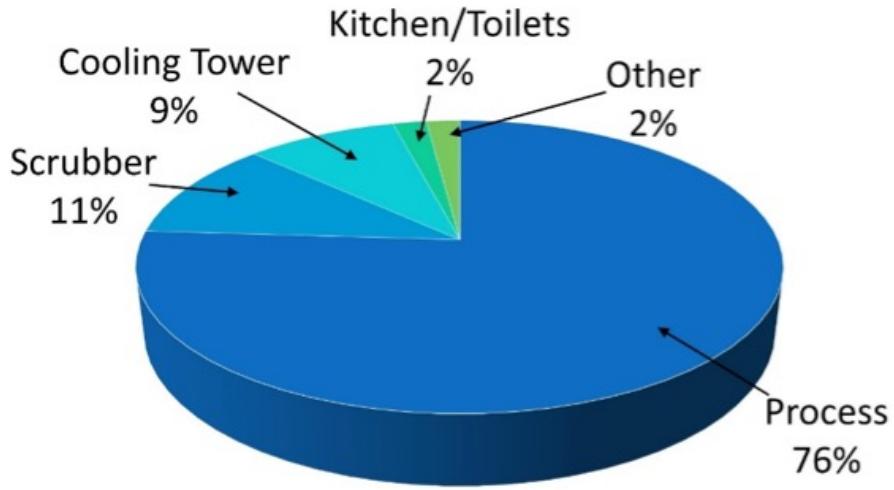

1500 gallon ultrapure water

## Water used by fabs

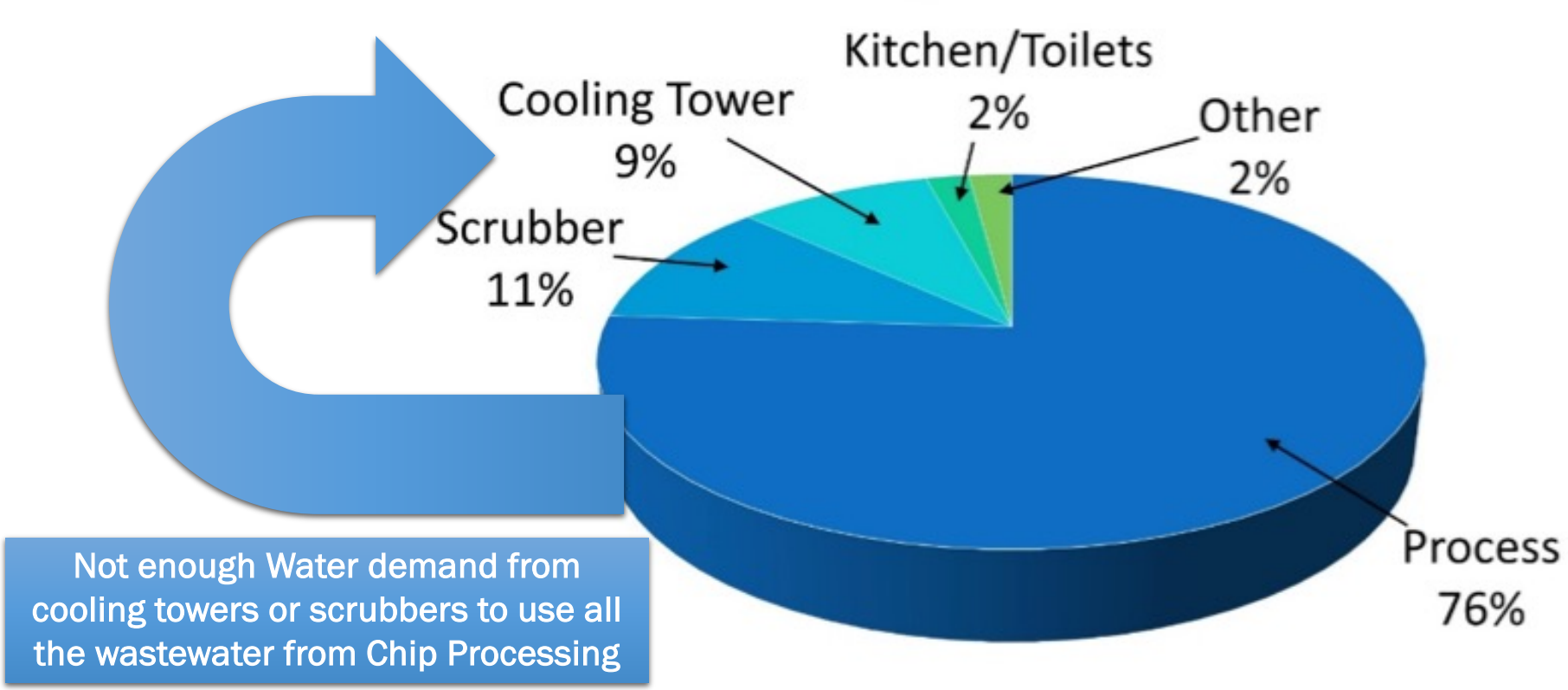



Water Resources and Industry 22 (2019) 100115

## Water usage within a fab



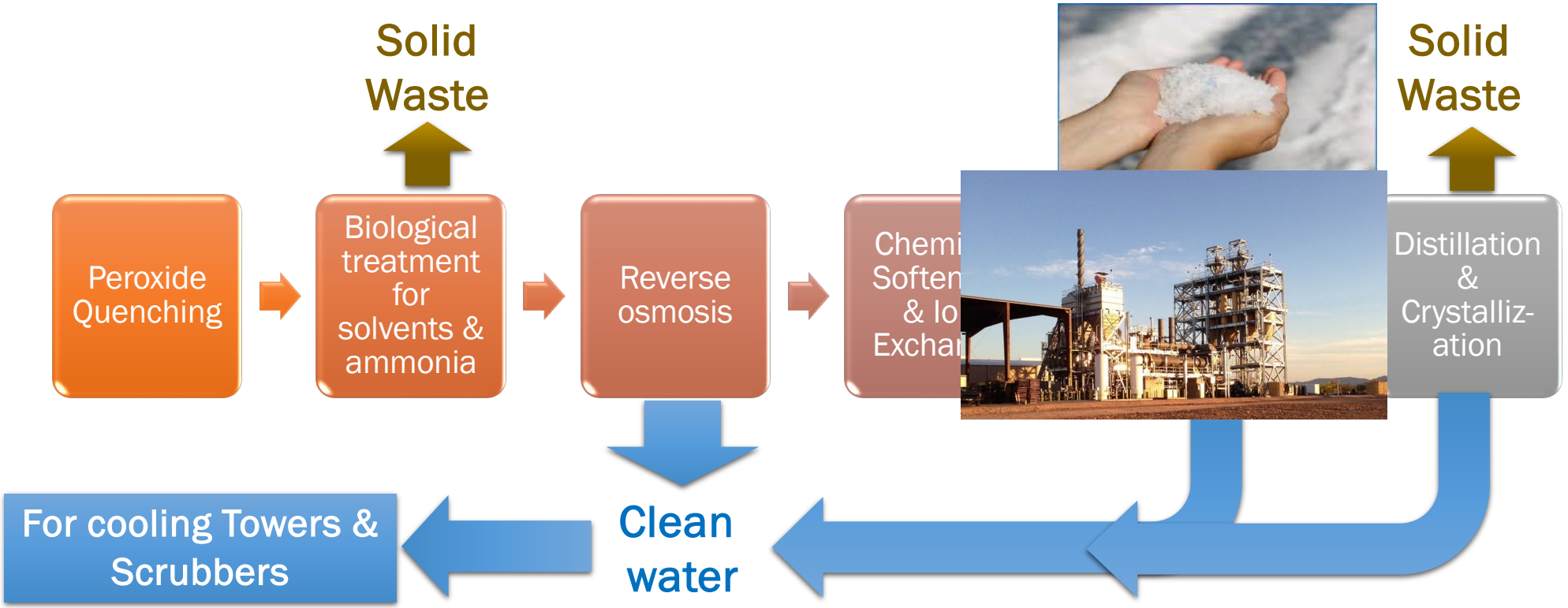
# Water Reuse in Fabs




Not enough Water demand from cooling towers or scrubbers to use all the wastewater from Chip Processing

# Water & Cooling Facilities are LARGE

# Typical Fab Wastewater Treatment Train with Zero Liquid Discharge (ZLD)



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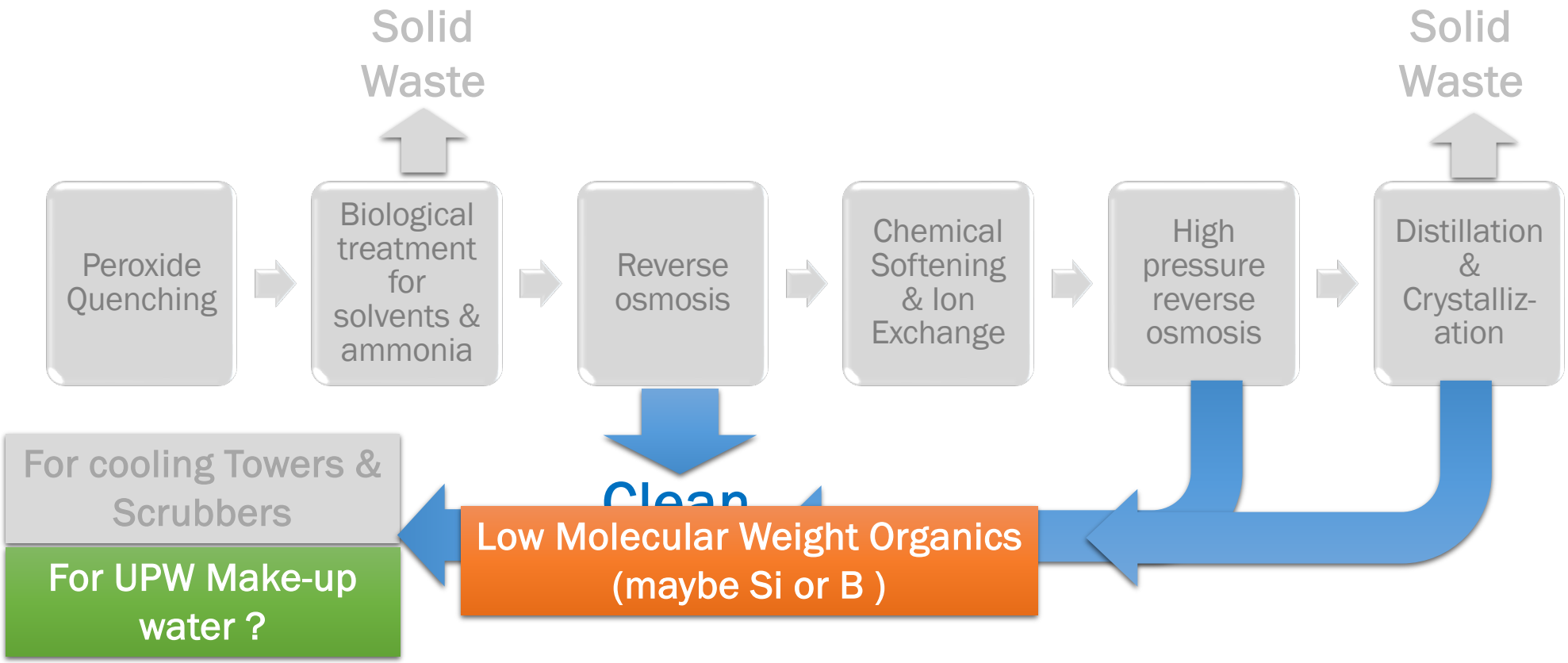
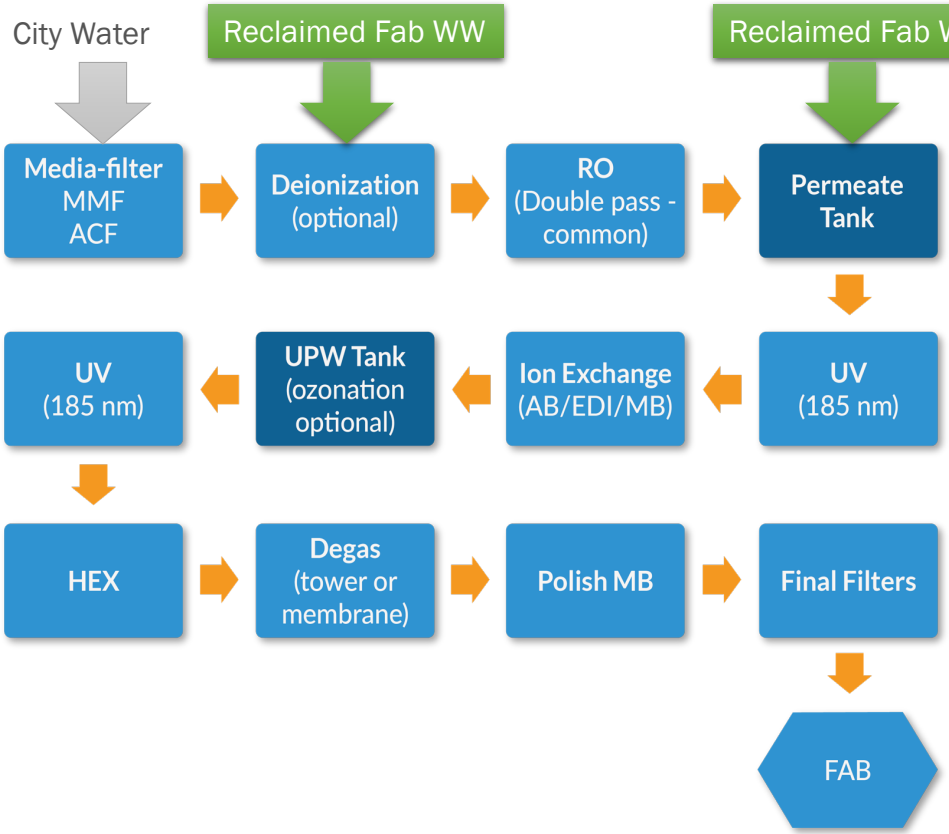
# Typical Fab Wastewater Treatment Train
## *Towards ZLD & Net Zero Manufacturing*

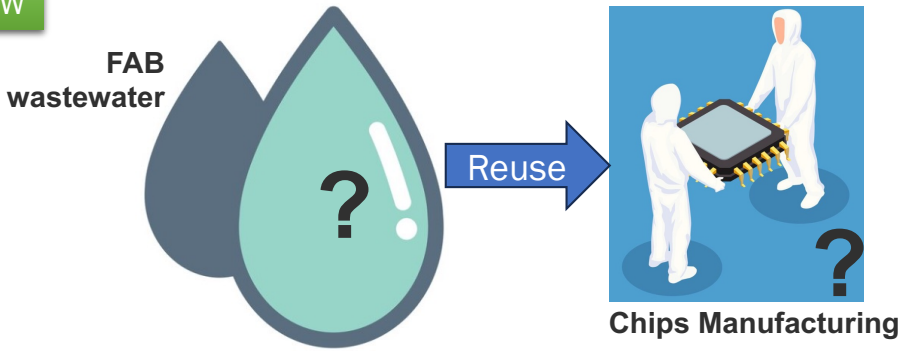


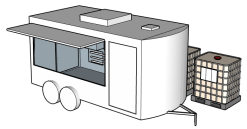
# UPW Systems Convert Tap water to UPW

| Parameter | Municipal Tap Water | Advanced<br><br>Semiconductor UPW | "Clean Water" from RO systems<br><br>in Fab Wastewater |
|---|---|---|---|
| Conductivity | 50 to > 1500 mS/cm | 0.05 mS/cm | 0.04 mS/cm |
| Total organic carbon | 1000 – 5000 µg/L | < 1 µg/L | ~ 300 µg/L |
| Particles | > $10^6$ / mL | < 200 / L;<br><br>Bacteria < 1 CFU/100 mL | **Lower than tap water** |
| Silica | 5 to 50 mg/L | 50 ng/L | |
| Metals | Regulated metals < 1 mg/L | <1 to 10 ng/L | |
| Ions | 1 to > 250 mg/L | 50 ng/L | |
| Microbiological | HPC & E. coli | Bacteria < 1 CFU/100 mL | |

# The NEW Ultrapure Water Approach Towards *Net Zero Manufacturing*



**Demo Facility treated water**

What is most challenging in this scheme ?
Low Molecular Neutral Organic Molecules
*We are examining LMW organics fate in UV185 nm and other oxidation processes*

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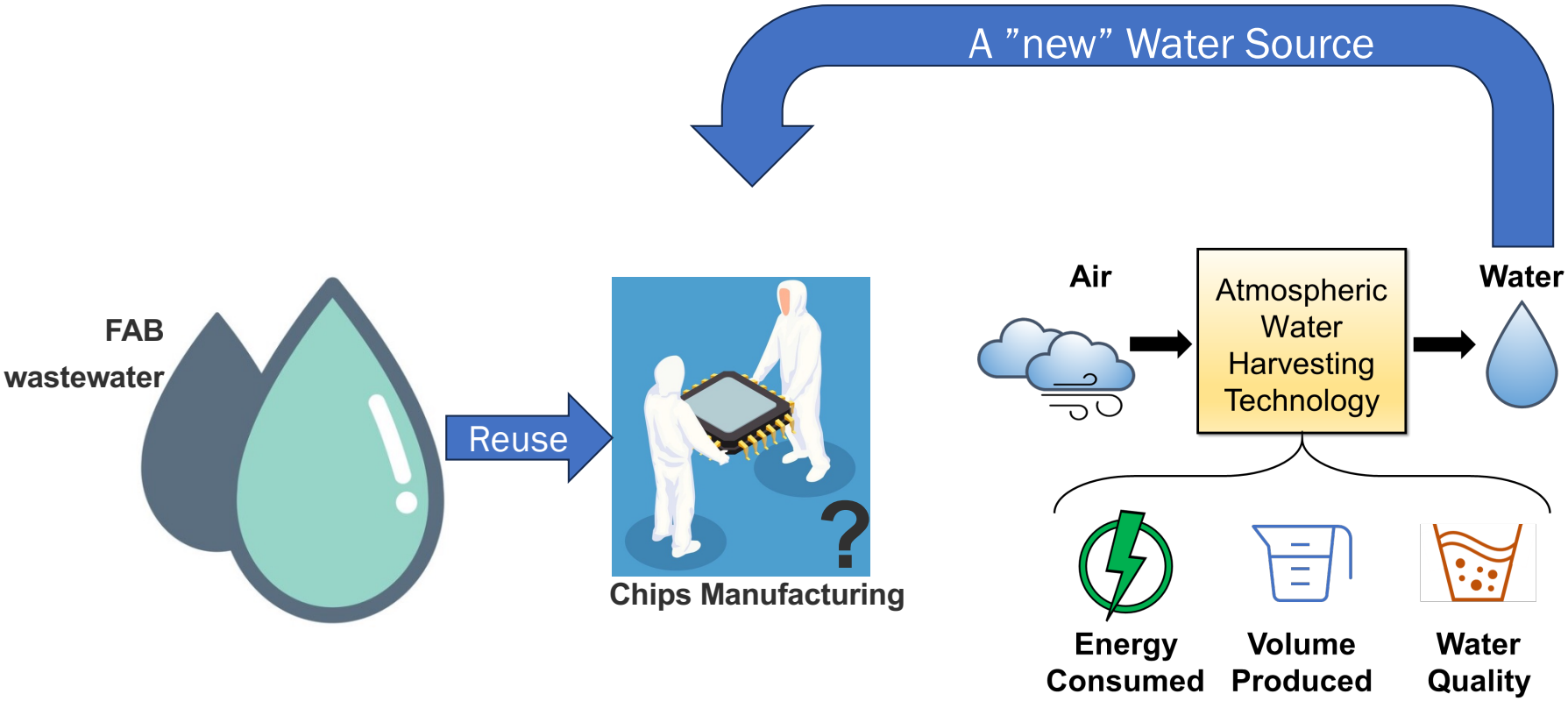
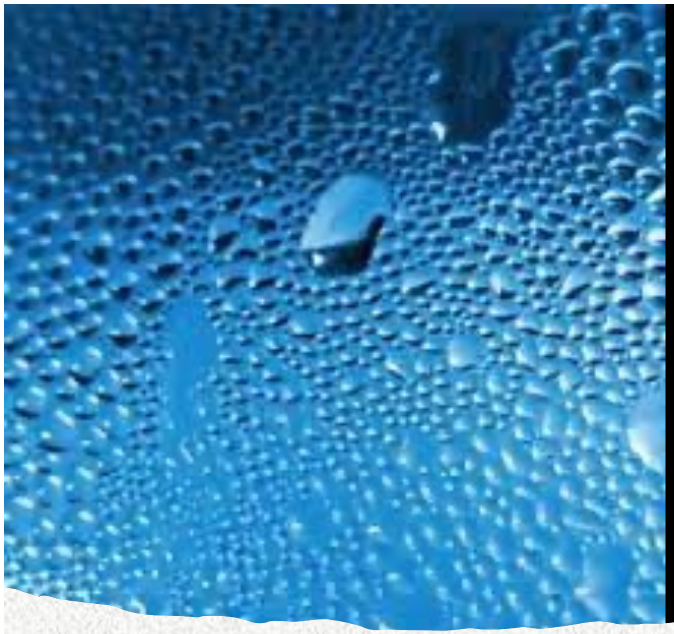

A ”new” Water Source
FAB
wastewater
Reuse
Chips Manufacturing
Air
Atmospheric Water Harvesting Technology
Water
Energy Consumed
Volume Produced
Water Quality




# What is Atmospheric Water Harvesting ?

Three basic types of “dehumidification”

- Condensation on a cold surface – works for RH > 50%
- Adsorption/desorption of water vapor using desiccants – works for any RH – even 10% RH in Arizona
- Dew harvesting – not relevant for Arizona

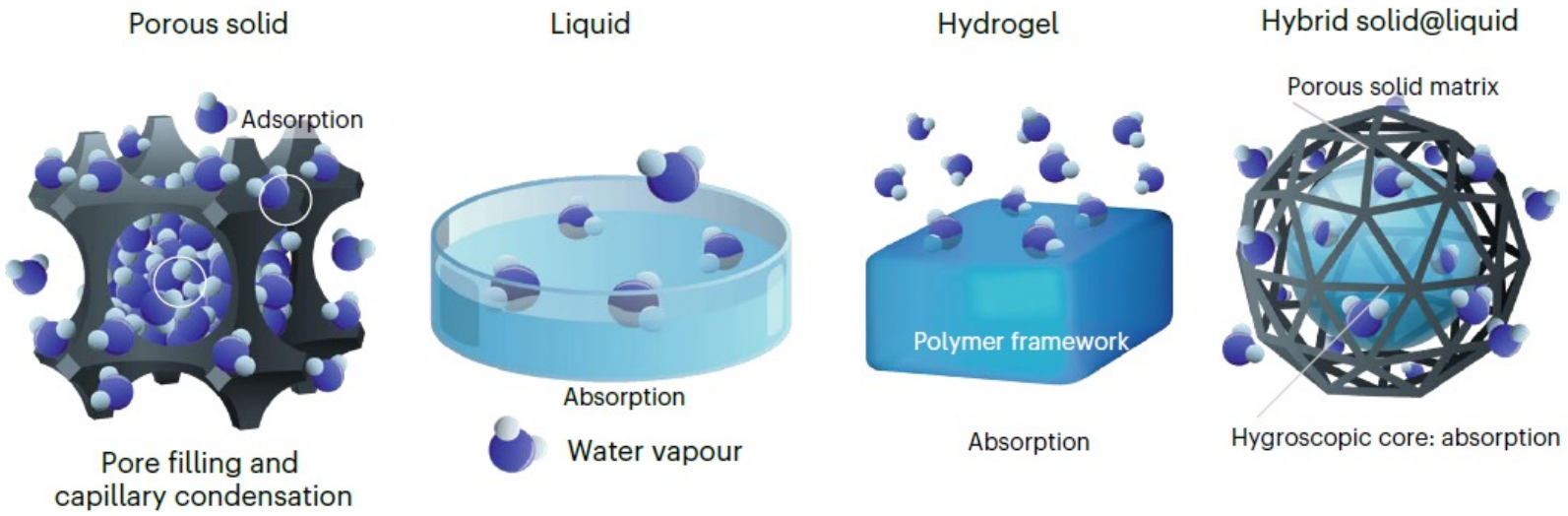
## Dew-point condensation

## Desiccant adsorption-desorption

Technology Exists – At Scale

But hasn't always been used to produce water

# Water Vapor-Phase Desiccant based sorbent types

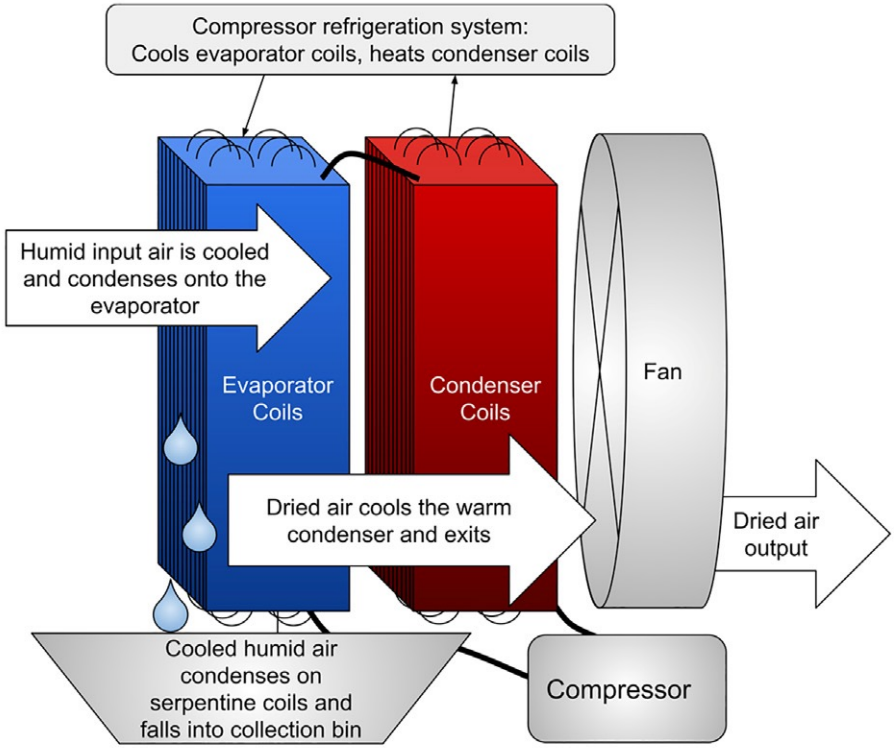



| | Porous solid sorbent | Liquid sorbent | Hydrogel-based sorbent | Hybrid solid@liquid sorbent |
|---|---|---|---|---|
| Examples | COFs, MOFs, silica gels and some zeolites | $CaCl_2$, LiCl, LiBr and ionic liquid | PAETA-Ac,PAM-$CaCl_2$ and SMAGs | LiCl@HCS and LiCl@MOF |
| Water vapor sorption mechanisms | Adsorption, pore filling and capillary condensation | Absorption | Absorption | Adsorption-absorption |

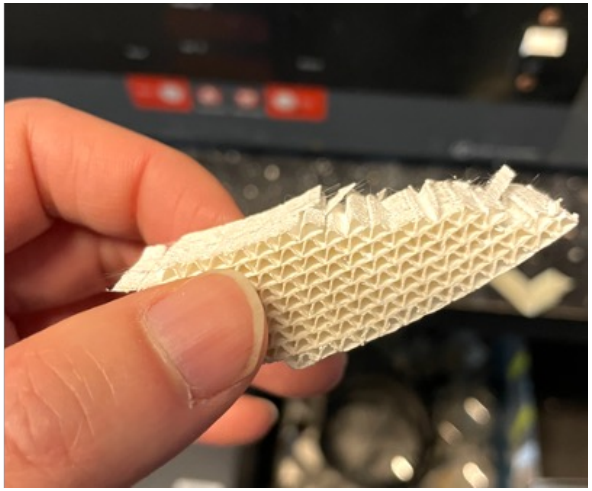
*Source: Peng Wang*

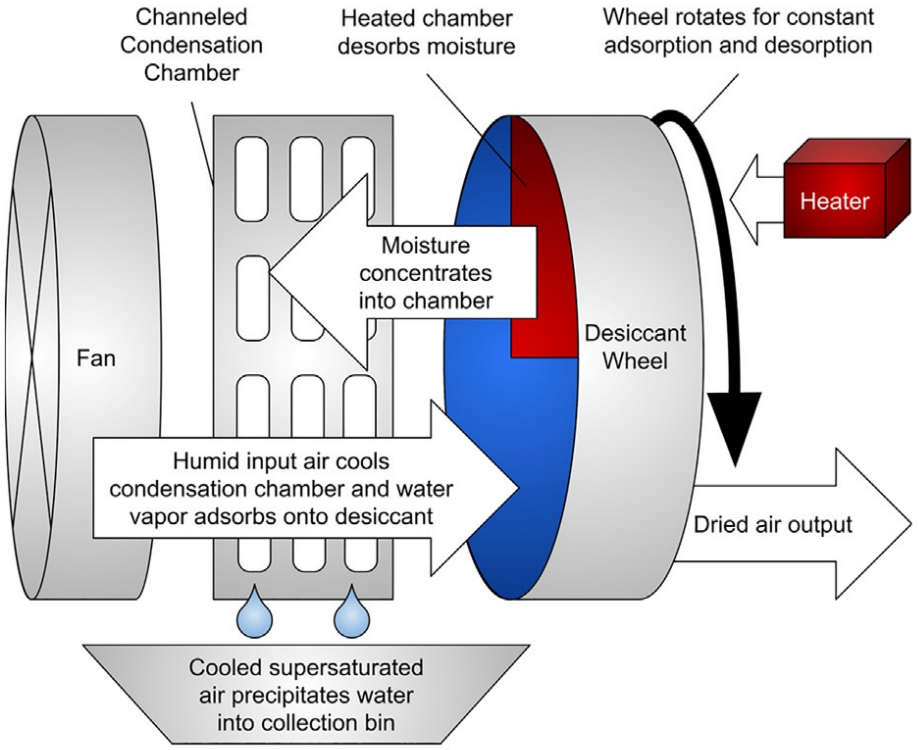
# Does AWH work in Arizona ?

# Dew-point condensation



# Desiccant adsorption-desorption

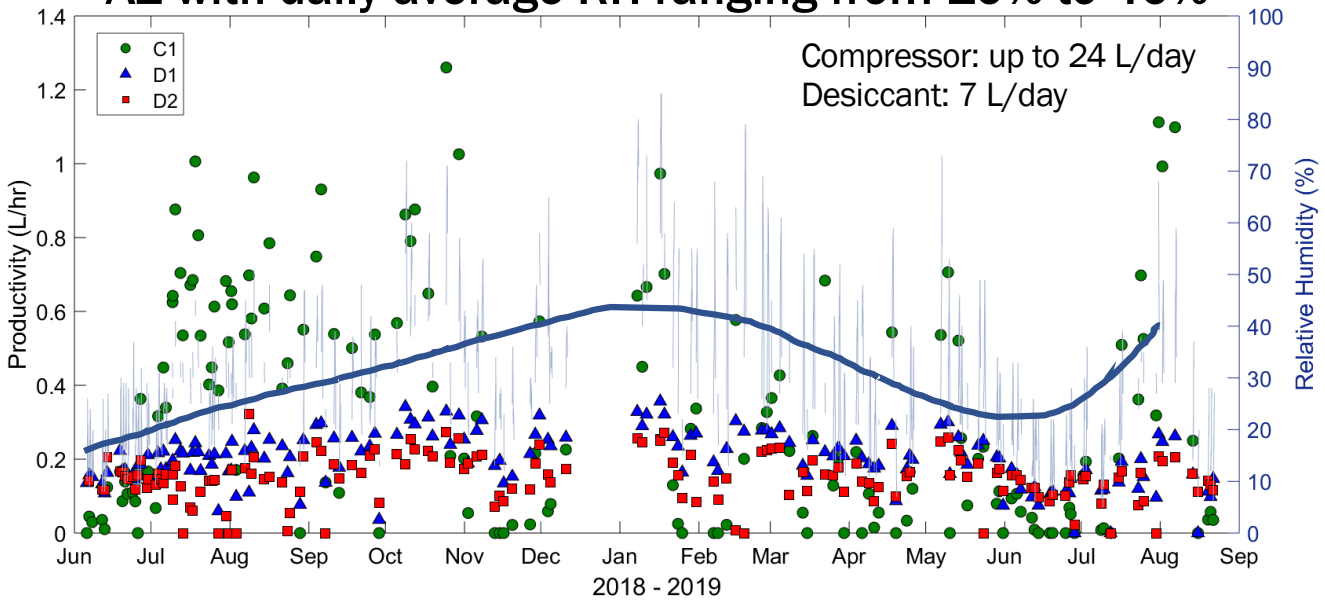




# Mobile Commercial Compressor & Desiccant AWH Systems


# Outdoor AWH System Performance in Phoenix, AZ

**Productivity of Dehumidifiers Over 1 year in Tempe, AZ with daily average RH ranging from 10% to 40%**




**Testbed performance in AZ**: 2-orders of magnitude above **0.042 kWh/L** DARPA target

**Compressor system (C1)**
**RH>30%,** T>30°C, $T_{DP}$>5°C
**1.2 – 4.4 kWh/ L**
Failed to produce meaningful water quantities < 30% RH

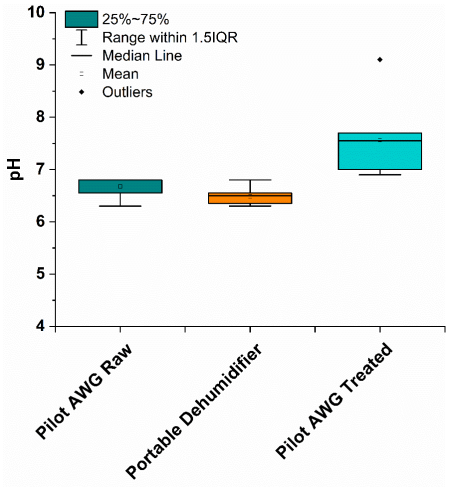
**Desiccant system (D1 & D2)**
**RH<30%,** T<30°C, $T_{DP}$<5°C
**3.2 – 9.7 kWh/ L**
Produced water at all RH%, suggesting inefficient design

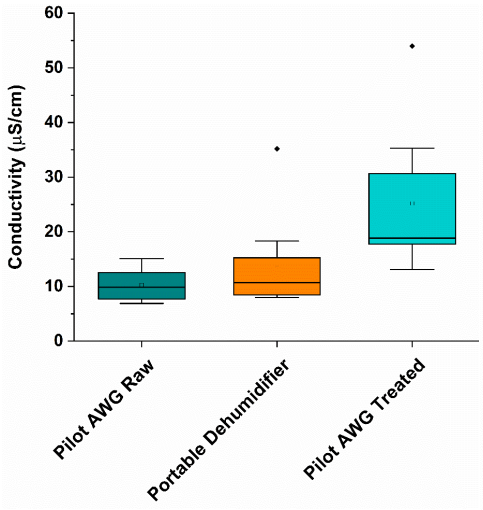
**All systems were >10x less efficient than manufacture claims** (usually reported at RH > 50%)

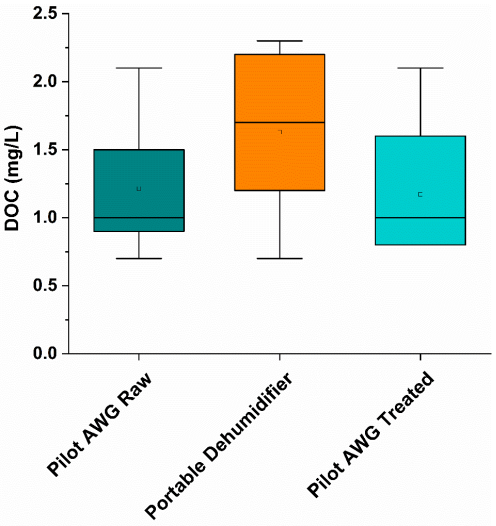
Mulchandani, Edberg, Herckes, Westerhoff, *Science of the Total Environment*, 2022

# Is AWH Water Clean ?

# Mobile Compressor closely models >10x larger system



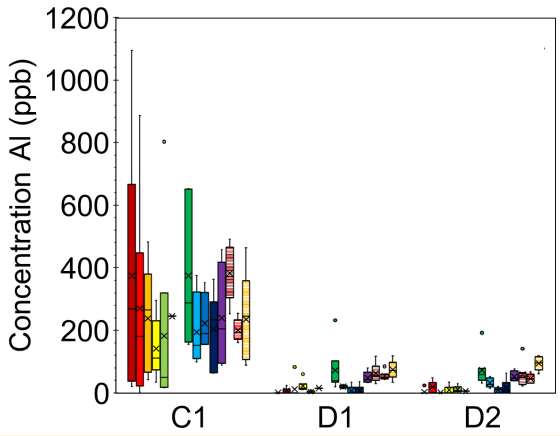



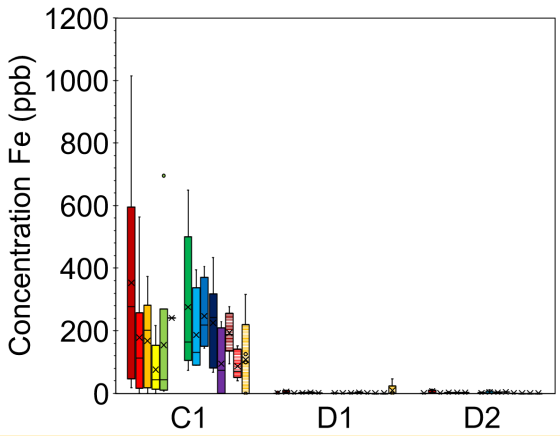

# Metals in water from AWE systems

**Only 3 of 27 analyzed metals** approach non-enforceable EPA Primary and Secondary Drinking Water Standards

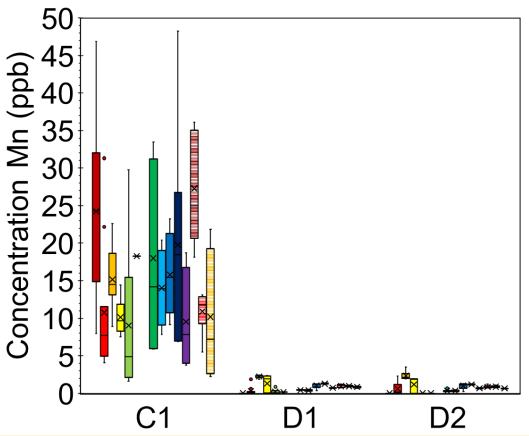
**Aluminum (Secondary MCL 50-200**




**Iron (Secondary MCL 300 ppb)**




**Manganese (Secondary MCL 50 ppb)**





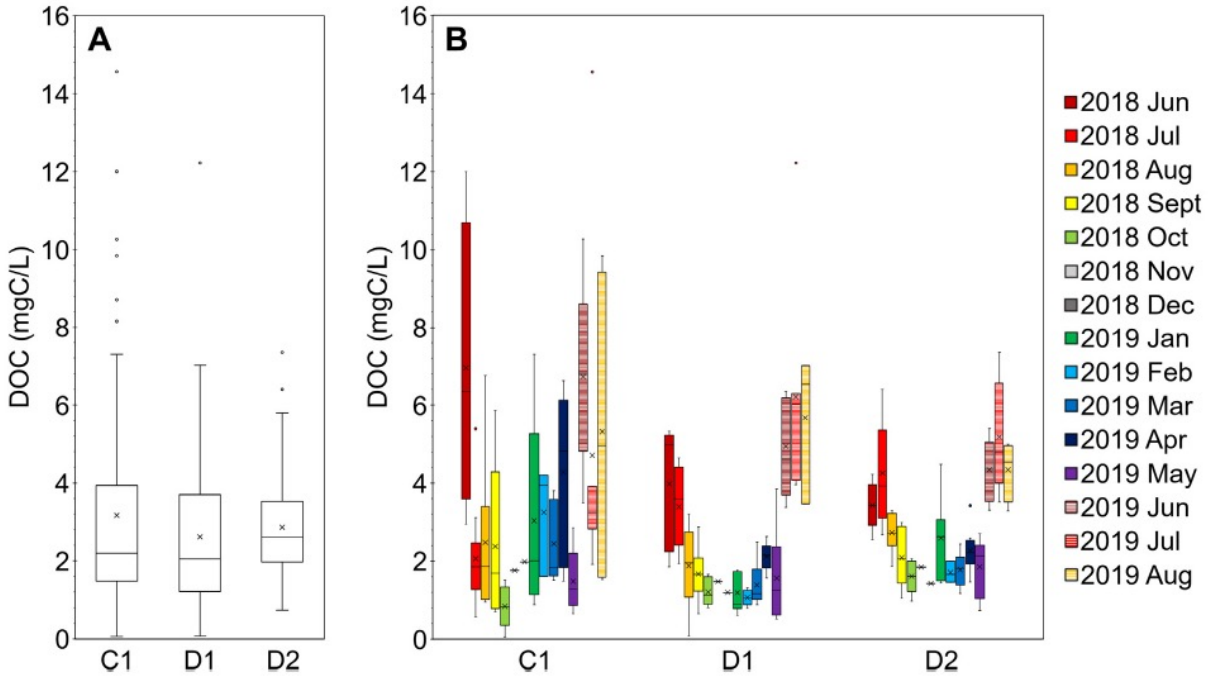
**Desiccant systems have lower metal levels**

**Likely cause:** Airborne particulates attach to water condensate on compression coils

Mulchandani, Edberg, Herckes, Westerhoff, *Science of the Total Environment*, **2022**

# Dissolved Organic Carbon (DOC)

Outdoor Systems show seasonal Impacts



# What makes up the DOC ?

- **Carboxylic acids account for 34% and 46% of total DOC** in the water
- **Aldehydes account for 1% and 13% of total DOC** (formaldehyde dominates in desiccant system)

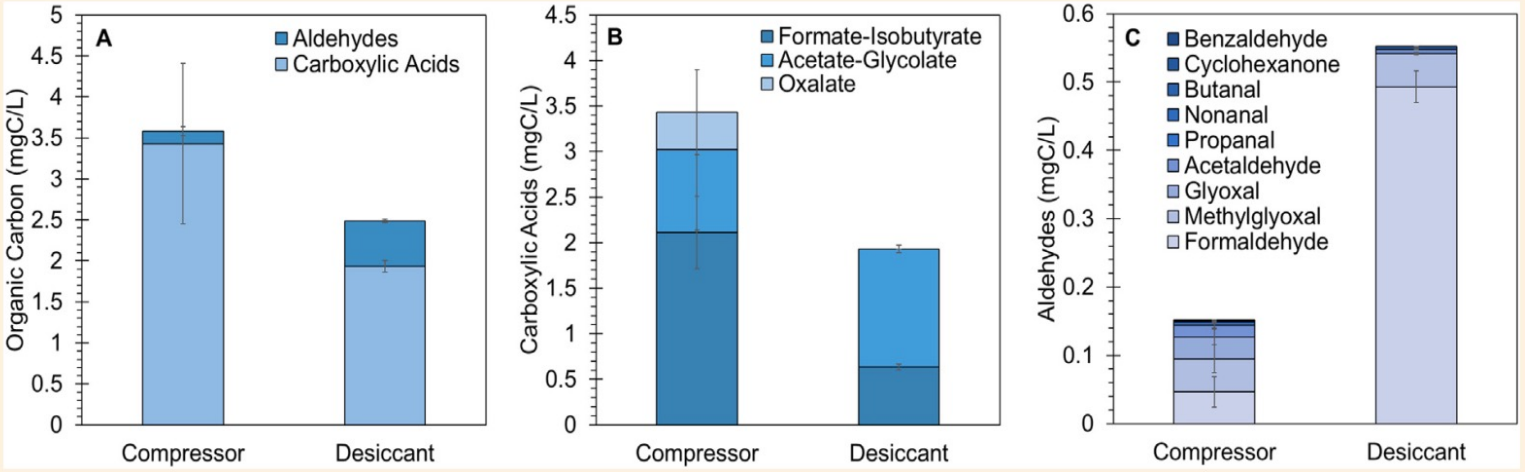



**Fig. 6.** A) Organic carbon, B) carboxylic acids, and C) aldehydes composition of water collected from compressor and desiccant systems. Error bars are one standard deviation above and below the average.

Source: Science of the Total Environment 825 (2022) 153966.

# Summary
# *Towards Net Zero Manufacturing*

## Producing Chips takes a lot of water

## Cutting edge Fabs TODAY do Zero Liquid Discharge

- They produce more clean water than can be used by cooling towers or scrubbers
- Low molecular weight neutral organics that pass through RO will be the challenge to use RO Treated Fab wastewater in UPW systems

## Harvesting water from the air holds promise to disconnect from City water

- Very low salt content lowers UPW treatment costs – but will have to address low molecular weight acids & neutral organics
- Desiccant technology is likely to be most cost-effective from the “air”
- Dew-condensation based systems can be attached too cooling tower exhaust to re-collect very low salt water
- Join our International Atmospheric Water Harvesting Association ( https://www.iawha.org/ )

# Acknowledgements

Contact me: p.Westerhoff@asu.edu

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Newtcenter.org

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