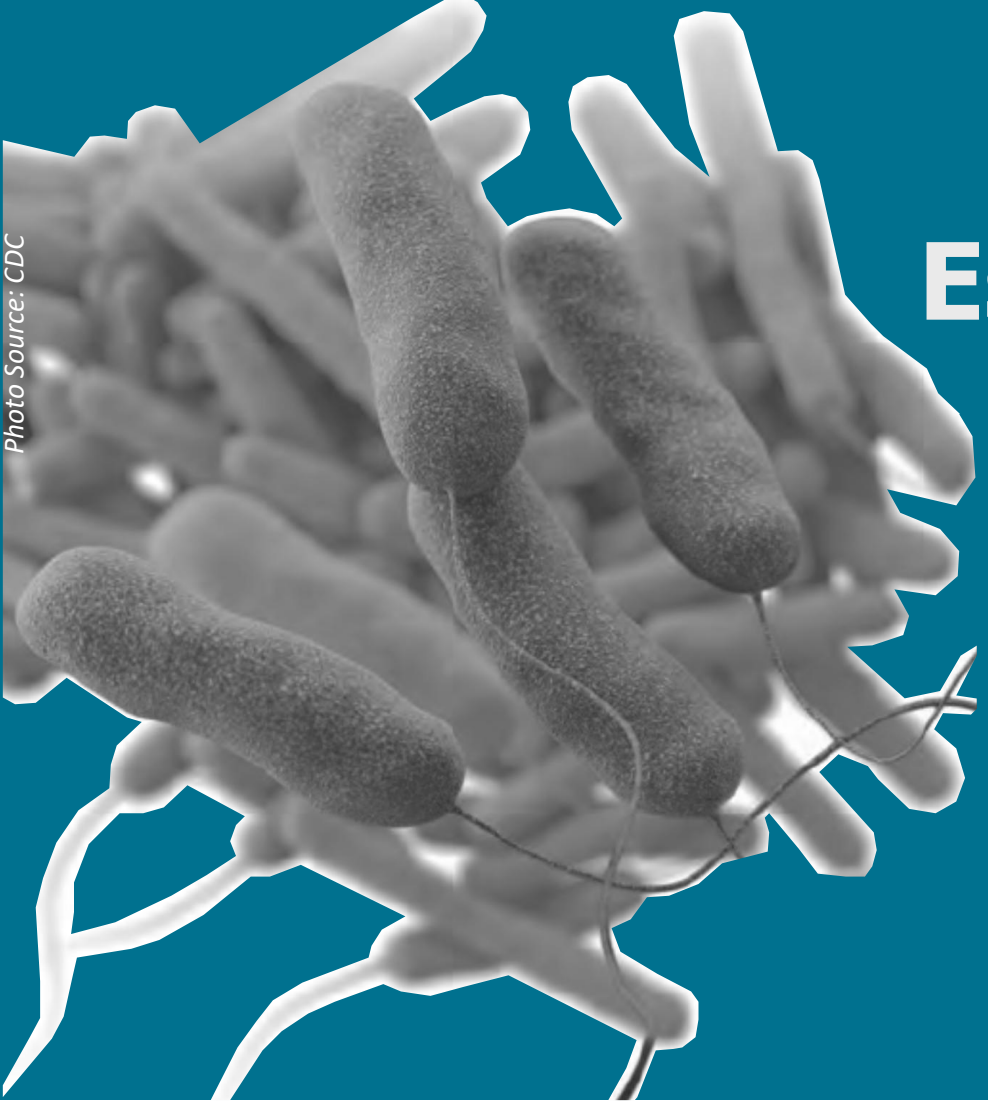


Photo Source: CDC

Establishing Water Treatment Design Criteria for Bacteria Disinfection Credit

PACIFIC NORTHWEST SECTION

American Water Works Association

PNWS Annual Conference

May 6-8, 2026 in Tacoma, Washington

confluence ENGINEERING GROUP LLC

MINNESOTA DEPARTMENT OF HEALTH

Acknowledgements

Project Team

- Technical Team: Confluence (team lead) with CU Boulder
- Funding and Direction: Minnesota Department of Health

Technical Peer Reviewers

- Steve Deem, Washington State Department of Health
- Michael Jahne, United States Environmental Protection Agency
- Tressa Nicholas, Idaho Department of Environmental Quality

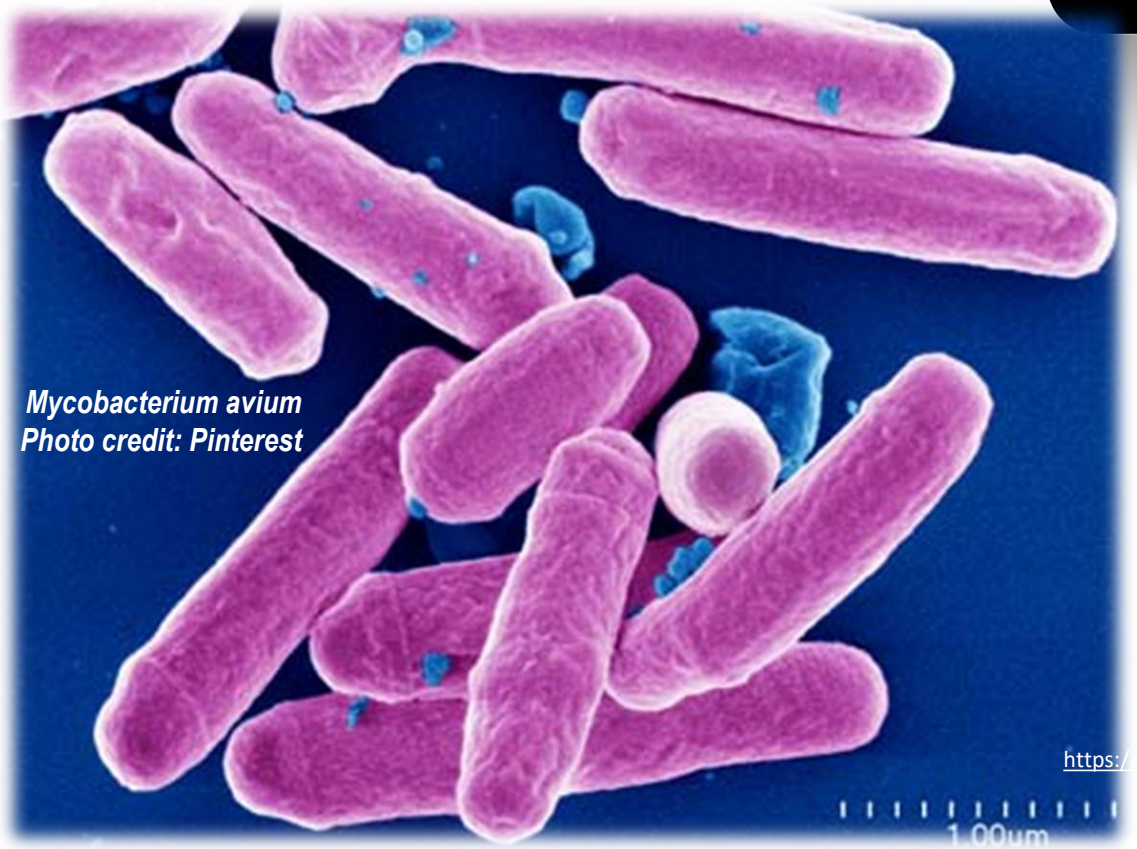
Discussion Items

- Project Drivers
- Literature Search & Quality Review
- Data Mining & Database
- Results & Discussion



Project Drivers





Bacteria Log Reduction Targets (LRTs)

- What LRT is needed to reduce risk?
  - A Quantitative Microbial Risk Assessment (QMRA) estimate
  - LRT_{INF} (10^{-4} infections/person/yr)…… or LRT_{DALY} = 10^{-6} disability-adjusted life years
- Minnesota Plumbing Code (1602.9.6) Needs:
  - On-site non-potable water system (ONWS) treating rainwater needs a minimum of 3.5-log removal credit (LRC) for bacteria
  - *How do you achieve the bacteria LRC, and with what technology?*
- Washington: WAC 246-275-305 for ONWSs is currently in development
  - Code language needs bacteria LRCs for ozone, chlorine, UV light, and others
  - *What chlorine or ozone CxT, or UV dose, is needed for specified bacteria LRCs?*

Data from Jahne et al (2024): QMRA-Based Bacteria LRTs Set for Non-Potable Use

	Campylobacter		Salmonella	
Source of Water	LRT_{INF}	LRT_{DALY}	LRT_{INF}	LRT_{DALY}
Roof runoff[f]	5.0	3.0	3.5	3.5

Jahne, M. A., Schoen, M. E., Garland, J. L., Nappier, S. P., & Soller, J. A. (2024). Microbial treatment targets for potable and non-potable water reuse—A comprehensive update and harmonization. Environmental Science & Technology Letters, 11(11), 1136–1259. https://doi.org/10.1021/acs.estlett.4c00512

Currently Relying Upon Virus Inactivation

- Chlorine *CxT* tables for virus
  - Filtered water applications
  - Water Research Foundation (WRF) Guidance based on post-filtration turbidity requirement (WRF 2020)
  - AUS Reuse Guidance (Watersecure 2017)
- UV dose tables for virus
  - Assumes that virus treatment is conservative approach for bacteria (WRF 2020)

- But….. Is virus *CxT* enough?

Virus C*T for post-filter chlorine (WRF 2020)

pH	Log_{10} inactivation	≤0.2 NTU					≤2 NTU				
		5 °C	10 °C	15 °C	20 °C	25 °C	5 °C	10 °C	15 °C	20 °C	25 °C
≤7	1	4	3	2	2	1	4	3	2	2	1
	2	5	4	3	2	2	5	4	3	2	2
	3	7	5	4	3	2	7	5	4	3	2
	4	8	6	4	3	2	9	6	4	3	2
≤7.5	1	7	5	4	3	2	7	5	4	3	2
	2	10	7	5	4	3	10	7	5	4	3
	3	13	9	7	5	4	13	9	7	5	4
	4	16	11	8	6	4	16	11	8	6	4
≤8	1	9	7	5	3	3	10	7	5	4	3
	2	14	10	7	5	4	15	10	7	5	4
	3	18	13	9	7	5	19	13	10	7	5
	4	23	16	12	8	6	23	16	12	8	6

Virus UV dose requirements (WRF 2020)

Validated Dose[1]	Virus Credit	Protozoa Credit	Bacteria Credit
40	2	3	2
80	3.5	6	3.5
100	4.25	6	4.25
150	6	6	6

1. This dose table is intended to apply for validation protocols using MS2.

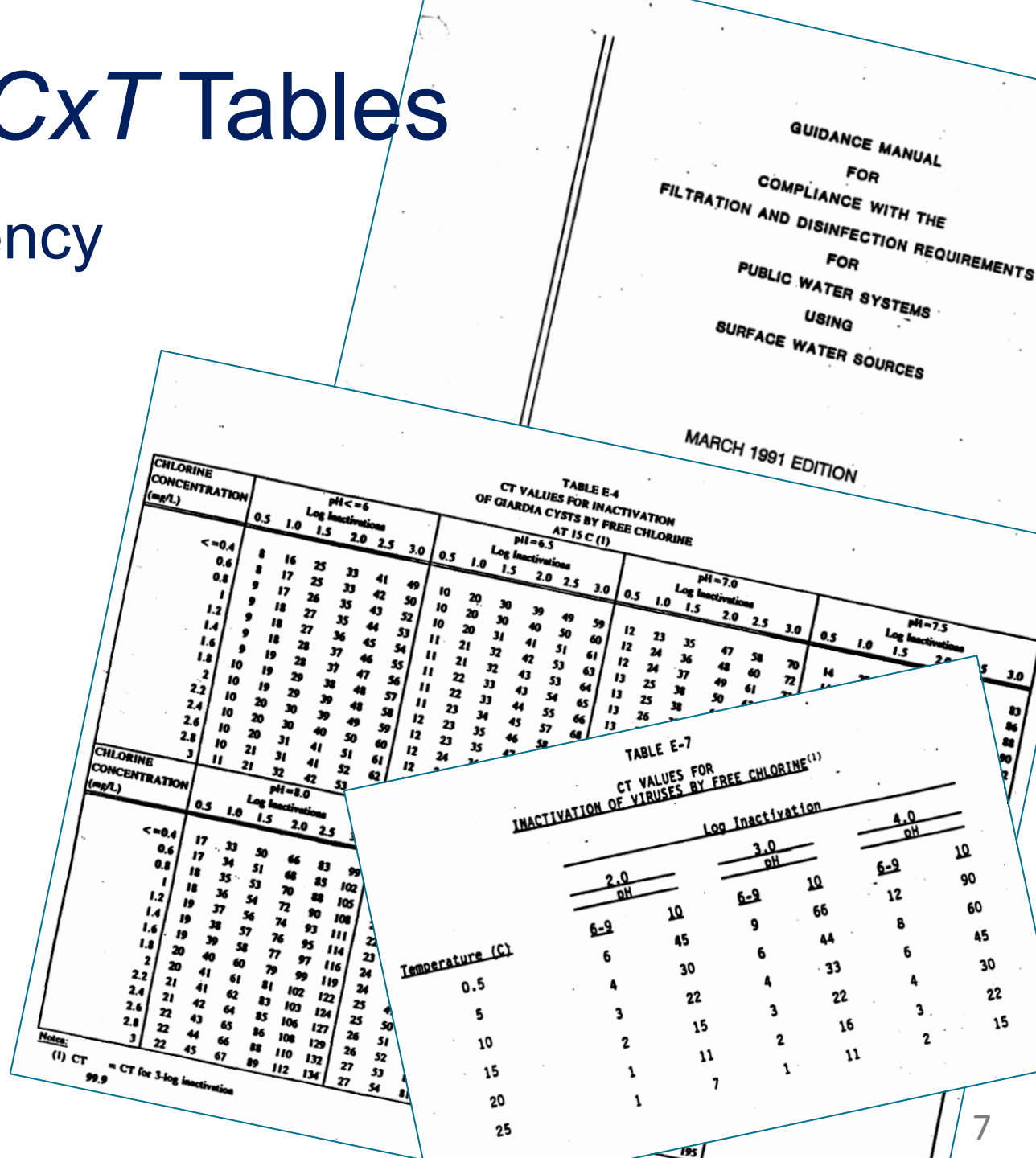
WRF 2020: Onsite Non-Potable Water System Guidance Manual

Watersecure 2017: Chlorine Disinfection, WaterVal Validation Protocol, Australian WaterSecure Innovations. Brisbane, AUS.

Goal: Create Bacteria *CxT* Tables

Bacteria-based disinfection efficiency (*CxT*) tables DO NOT EXIST

- Similar to USEPA's SWTR tables (and UVDGM Dose Tables)
- Bacteria-specific *CxT*
- Disinfectants and membrane filtration
- Guidance for engineers and operators



Literature Search & Quality Review



Finding Published Literature

Followed guidance for systematic reviews (Page et al. 2021)

- Multiple search strings sensitivity tested
- Total manuscripts found:
  - PubMed n = 7,998
  - Web of Science n = 4,509
  - Google Scholar n = 980
  - Personal library n = 14
  - Total n = 13,501
- Preliminary screening left 1,055 remaining
  - 91 not available
  - 1,691 duplicates removed
  - Title/abstract screening removed 10,644

(water OR drinking water OR groundwater OR recycled water) **AND** (chlorine OR chloramines OR chlorine dioxide OR ozone OR ultraviolet light OR UV OR LED OR light emitting diode OR peracetic acid OR membrane technologies OR microfiltration OR ultrafiltration OR nanofiltration OR reverse osmosis OR hypochlorous acid) **AND** (bacteria OR heterotrophic plate count bacteria OR fecal indicator bacteria OR coliform OR Escherichia coli OR E. coli OR Legionella OR pneumophila OR vibrio cholerae OR cholerae OR Bacillus OR Helicobacter OR Campylobacteria OR Mycobacterium OR Salmonella OR Aeromonas OR Aspergillus OR Nitrosomonas OR Clostridium OR Klebsiella OR Shigella OR Pseudomonas OR Microsporidia OR waterborne amoeba OR amoeba OR Acanthamoeba OR Naegleria) **AND** (disinfectant dose levels OR disinfectant demand OR light absorption OR residual levels OR UV transmittance OR UV absorbance OR inactivation OR log kill OR lrv OR removal efficiency OR log reduction value OR percent reduction OR log removal OR percent removal OR treatment effect)

Page et al. 2021: The PRISMA 2020 statement: An updated guideline for reporting systematic reviews. BMJ Research Methods and Reporting (http://dx.doi.org/10.1136/bmj.n71)

QA/QC Review of 1,055 Articles

Article excluded if it:

- Was a literature review
- Didn't include a 'target' technology
- Had insufficient, water quality, controls describing dose-response kinetics
- Didn't describe experiment protocols
- Wasn't water treatment related
- Had unknown "C" or "T" conditions
- Lacked pH or disinfectant residual (*this surprisingly happened a lot*)

Minimum QA/QC Checks for EACH Article

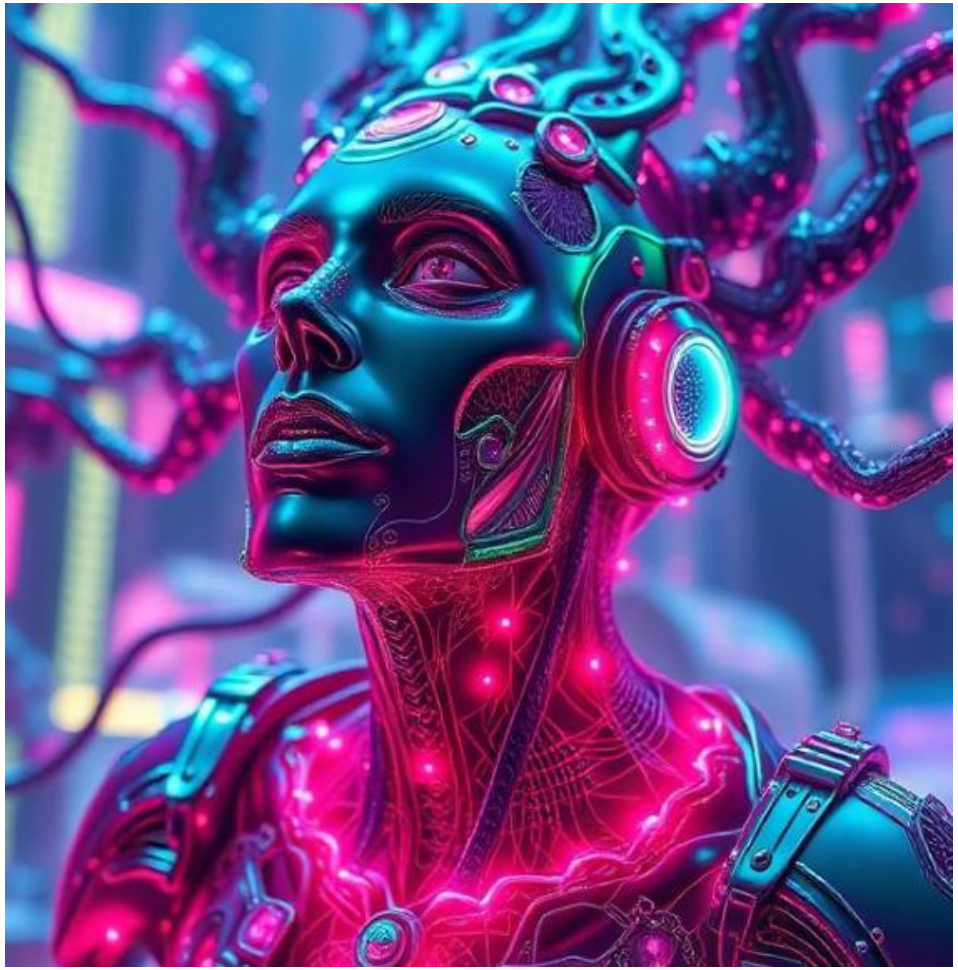
- QA/QC information
- Negative control
- Positive control
- Range of 'log' reduction visibility (identify when "complete inactivation" occurred?)

RESULT = 163 (<1% of start bunch) Peer reviewed articles, reports (WRF, other), university theses, conference proceedings, and presentations (from 1971 to 2022)

Data Mining & Database

All Analysis completed in Tableau Creator (Seattle, WA)

AI for “Data Mining”



https://deepai.org/machine-learning-model/cyberpunk-generator

Image from: https://shutterstock.com/royalty-free/stock-images

Data 

Type of Data

- Processes (Disinfectants & Membranes):
  - Chlorine, chloramine, chlorine dioxide, ozone, peracetic and performic acids, and UV (low, medium, pulsed) technologies
  - Membranes: Micro & ultrafiltration, reverse-osmosis
- "Bacteria": Extracted all datapoints available
  - Positive & negative Gram stain
  - Enteric, environmental, Biofilm-assoc.
  - Non-spore forming
  - Also 'surrogates' like fecal coliforms or HPC bacteria included
- "Secondary" Organisms: **Not all extracted**
  - Spores, amoeba, fungi
  - Radio-tolerant, extremophiles

12
Chemical & Physical Treatment Processes

29
Bacteria species and surrogates (Note: *Legionella pneumophila* is separated from other *Legionella*)

12
"Secondary" organisms; not all of these datapoints were extracted

Image from: https://shutterstock.com/royalty-free/stock-images

Data , Cont'd.

12
Chemical & Physical Treatment Processes

29
Bacteria species and surrogates (Note: *Legionella pneumophila* is separated from other *Legionella*)

12
"Secondary" organisms; not all of these datapoints were extracted ***

Treatment

- Chlorine (free)
- Chloramine
- Chlorine dioxide
- Ozone
- Peracetic acid
- Performic acid

- UV, low pressure
- UV, medium pressure
- UV, pulsed

- Microfiltration membranes
- Ultrafiltration membranes
- RO membranes

Bacteria

- *Acinetobacter* spp.
- *Aeromonas* spp.
- *Brevundimonas* spp.
- *Burkholderia* spp.
- *Campylobacteria* spp.
- *Citrobacter* spp.
- Coliform bacteria, total*
- *Enterobacter* spp.
- *Enterococcus* spp.
- *Escherichia* spp.
- Fecal coliforms, total
- *Helicobacter* spp.
- Heterotrophic bacteria, tot.
- *Klebsiella* spp.
- *Legionella pneumophila*
- *Legionella* spp. (non-*pneumophila*)
- *Listeria* spp.
- *Microbacterium* spp.
- *Microcystis* spp.
- *Mycobacterium* spp.
- *Nitrosomonas* spp.
- *Pseudomonas* spp.
- *Salmonella* spp.
- *Serratia* spp.
- *Shigella* spp.
- *Sphingomonas* spp.
- *Staphylococcus* spp.
- *Streptococcus* spp.
- *Vibrio* spp.

Secondary

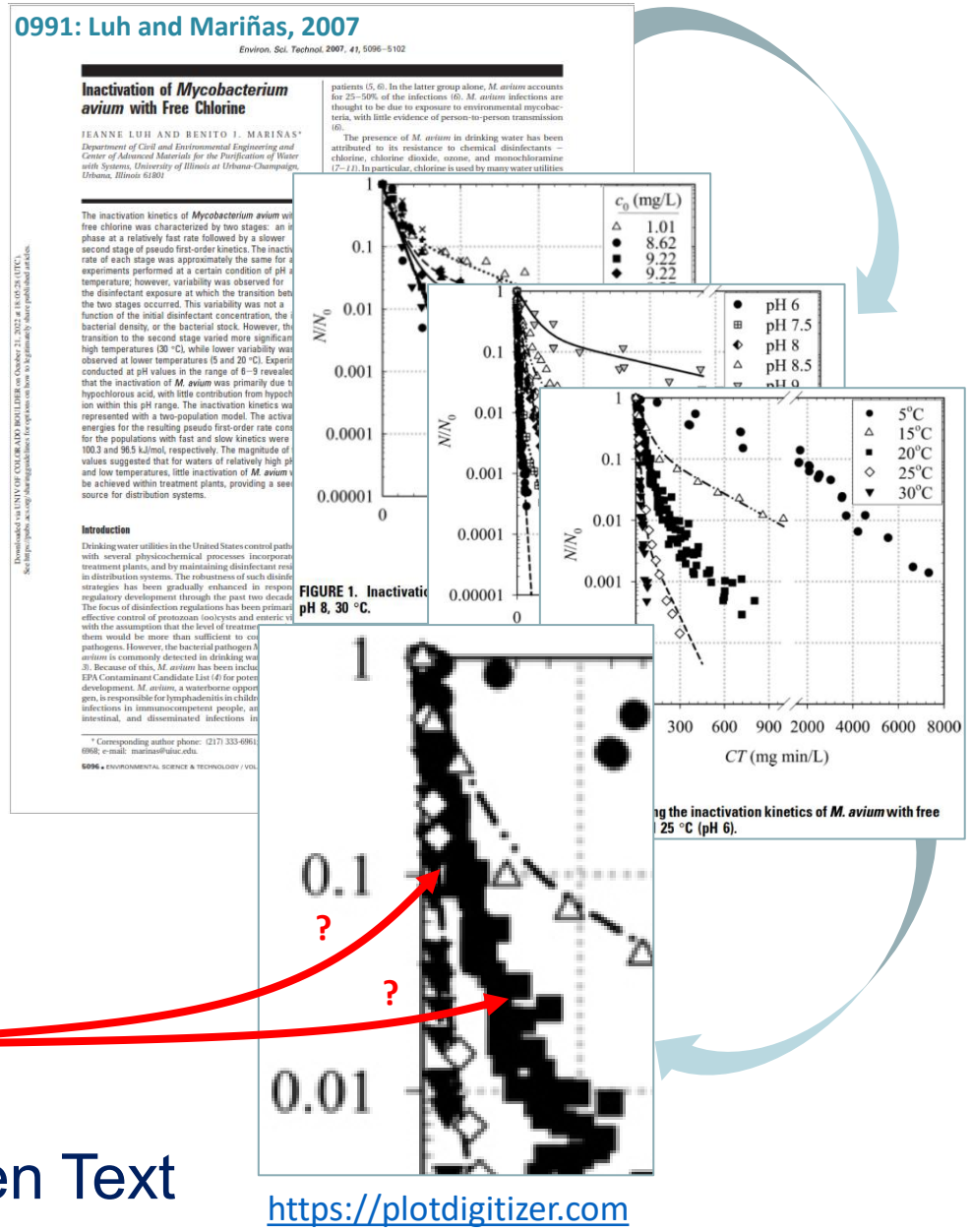
Acanthamoeba spp.	Amoeba
Aerobic spores, total	Spore
Aspergillus spp.	Fungi
Bacillus spp.	Spore
Candida spp.	Fungi
Clostridium spp.	Spore
Deinococcus spp.	Bacteria
Dictyostelium spp.	Amoeba
Encephalitozoon spp.	Fungi
Geobacillus spp.	Spore
Naegleria spp.	Amoeba
Rubrobacter spp.	Rad/Ext

Image from: https://shutterstock.com/royalty-free/stock-images

Data , Cont'd.

Example

- Article: Luh and Mariñas, 2007
  - Article number 991
  - 274 datapoints
  - All chlorine disinfection vs. *Mycobacterium*
- Extraction with Plot Digitizer 3.2.1 Pro, 2023
  - Calibrates/defines X & Y axes to for spatial data grid
  - Allows zoom-in on each datapoint; click select
  - Sometimes, not all data can be selected
- Data From Plots, Bar Charts, Tables, and Written Text



https://plotdigitizer.com

Image from: https://shutterstock.com/royalty-free/stock-images

Data  Result: 8,031 Records

Database abbreviations shown in parentheses

Bacteria Data 4,822 Records

- Chlorine (Cl2): 1,151
- Chloramine (NH2Cl): 919
- Chlorine dioxide (ClO2): 114
- Ozone (O3): 190
- Peracetic acid (APA): 720
- Performic acid (APF): 32
- UV light, low-pressure (UL): 1,206
- UV light, medium-pressure (UM): 86
- UV light, pulsed (UP): 58
- Membranes, microfiltration (MM): 249
- Membranes, ultrafiltration (MU): 83
- Membranes, reverse-osmosis (MR): 14

Secondary Data 3,209 Records

- Chlorine (Cl2): 826
- Chloramine (NH2Cl): 212
- Chlorine dioxide (ClO2): 617
- Ozone (O3): 604
- Peracetic acid (APA): 0
- Performic acid (APF): 0
- UV light, low-pressure (UL): 745
- UV light, medium-pressure (UM): 69
- UV light, pulsed (UP): 43
- Membranes, microfiltration (MM): 5
- Membranes, ultrafiltration (MU): 88
- Membranes, reverse-osmosis (MR): 0

Each Record w/ 67 Data Columns

General information (34)

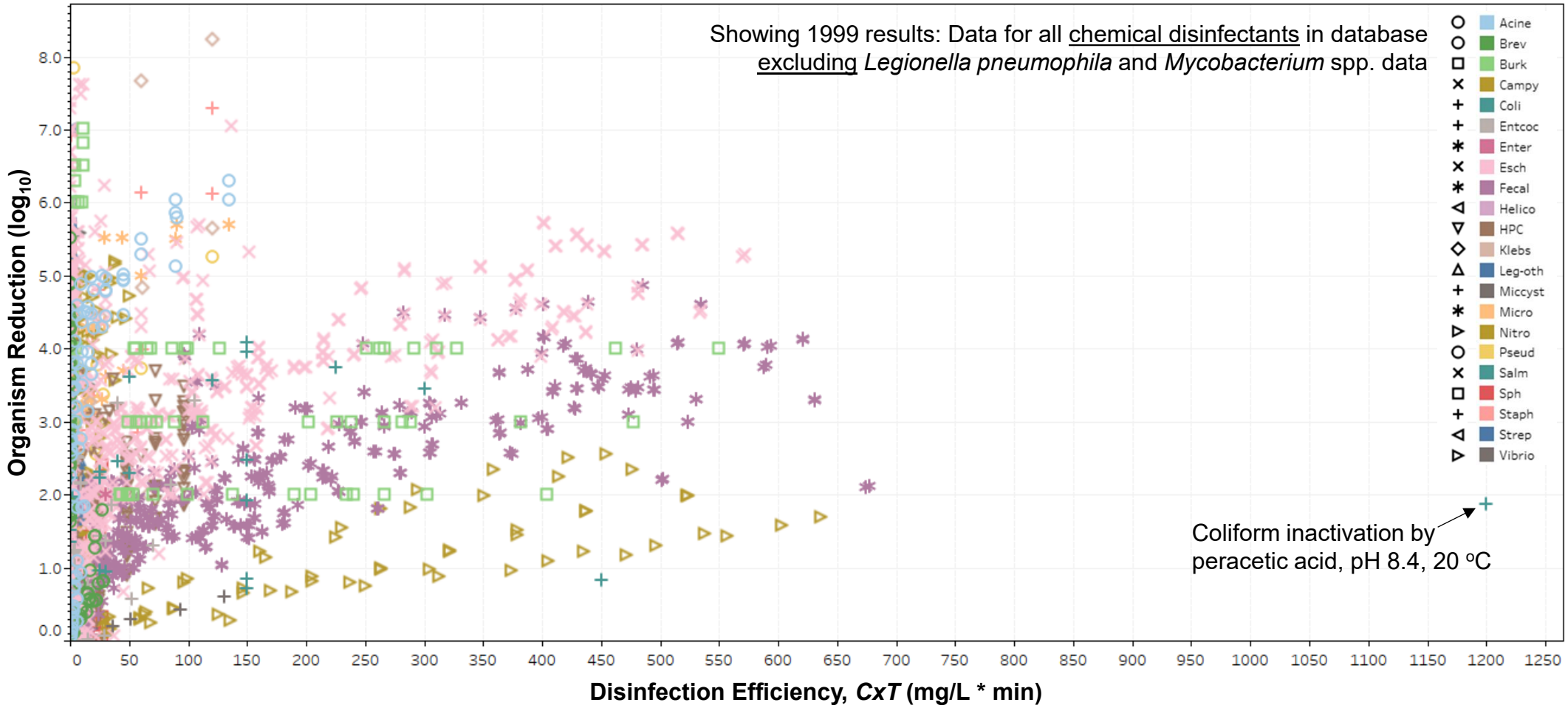
- Article, author, year
- Notes, QA/QC

Treatment/Organism (24)

- Water, test, treatment
- Temp, pH, other
- Chemical dosing

Disinfection (9)

- C*T information
- N/No information
- Log10 reduction info



Article #	Organism(s)
3	HPC
7	Enter Esch Klebs Pseud Salm
20	Salm
30	Esch
63	Esch
69	Esch
71	Helico
74	Esch
89	Klebs
94	Esch Strep
112	Vibrio
136	Leg-oth
145	Staph
184	Esch
193	Coli
209	Acine Micro
210	Esch Staph
221	Esch
224	Esch
231	Nitro
234	Klebs Pseud Staph
298	Coli
300	Leg-oth
314	Esch Pseud
318	Esch
320	Brev Esch Pseud Sph
333	Esch
336	Esch
345	Esch
377	Coli
490	Miccyst
608	Burk
664	Burk
857	Esch Staph
863	Esch Fecal
907	Esch Fecal
952	Esch
956	Entcoc Esch Staph
988	Entcoc Fecal
993	Esch
1064	Esch
1088	Campy
1145	Esch

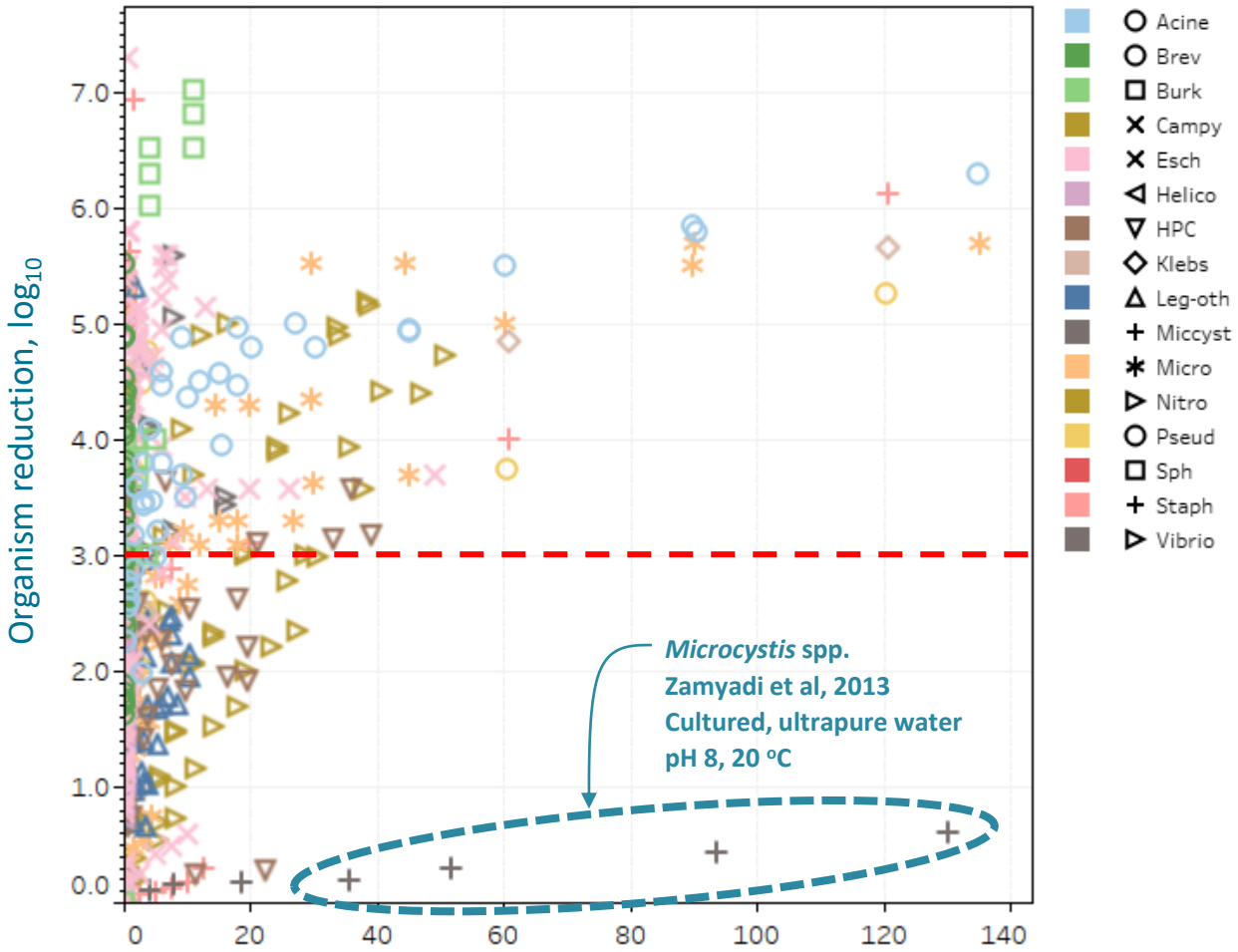
Results & Discussion

Select information for chlorine, chloramine, and UV light only

Chlorine

Atkinson et al., 2022
Blaser et al., 1986
Cervero-Arago et al., 2015
Chen et al., 2012
Cheswick et al., 2020
Clark & Johnson, 1994
Destiani & Templeton, 2019
Goel & Bouwer, 2004
He et al., 2021
Johnson et al., 1997
Lee et al., 2010
O'Connell et al., 2009
Qureshi et al., 2020
Rice et al., 1999
Ridgway & Olson, 1982
Wang et al., 2009
Wang et al., 2022
Ward et al., 1984
Wojcicka et al., 2007
Wolfe et al., 1985
Zamyadi et al., 2013
Zhang et al., 2007
Zhang et al., 2021
Zhao et al., 2001

- All pH and temperature data
- Excluding *L. pneumophila* and *Mycobacterium* spp.
- *Microcystis* spp. are much more resistant
- In General, 40 to 60 mg/L*min can provide at least 3-log_{10} reduction

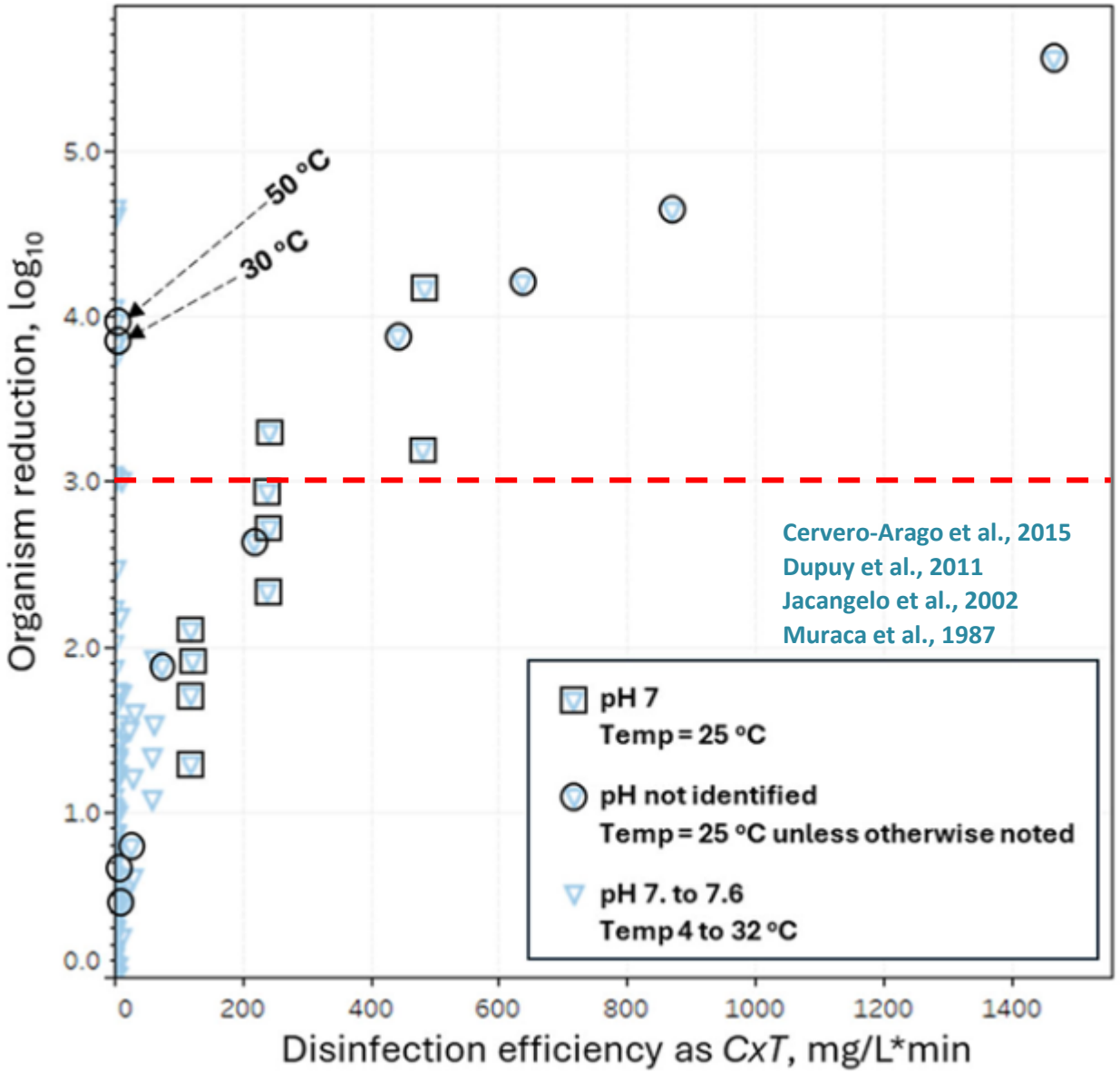


Disinfection efficiency, CxT, for all conditions
Disinfectant residual (C) multiplied by contact time (T)

Chlorine, continued

Legionella pneumophila

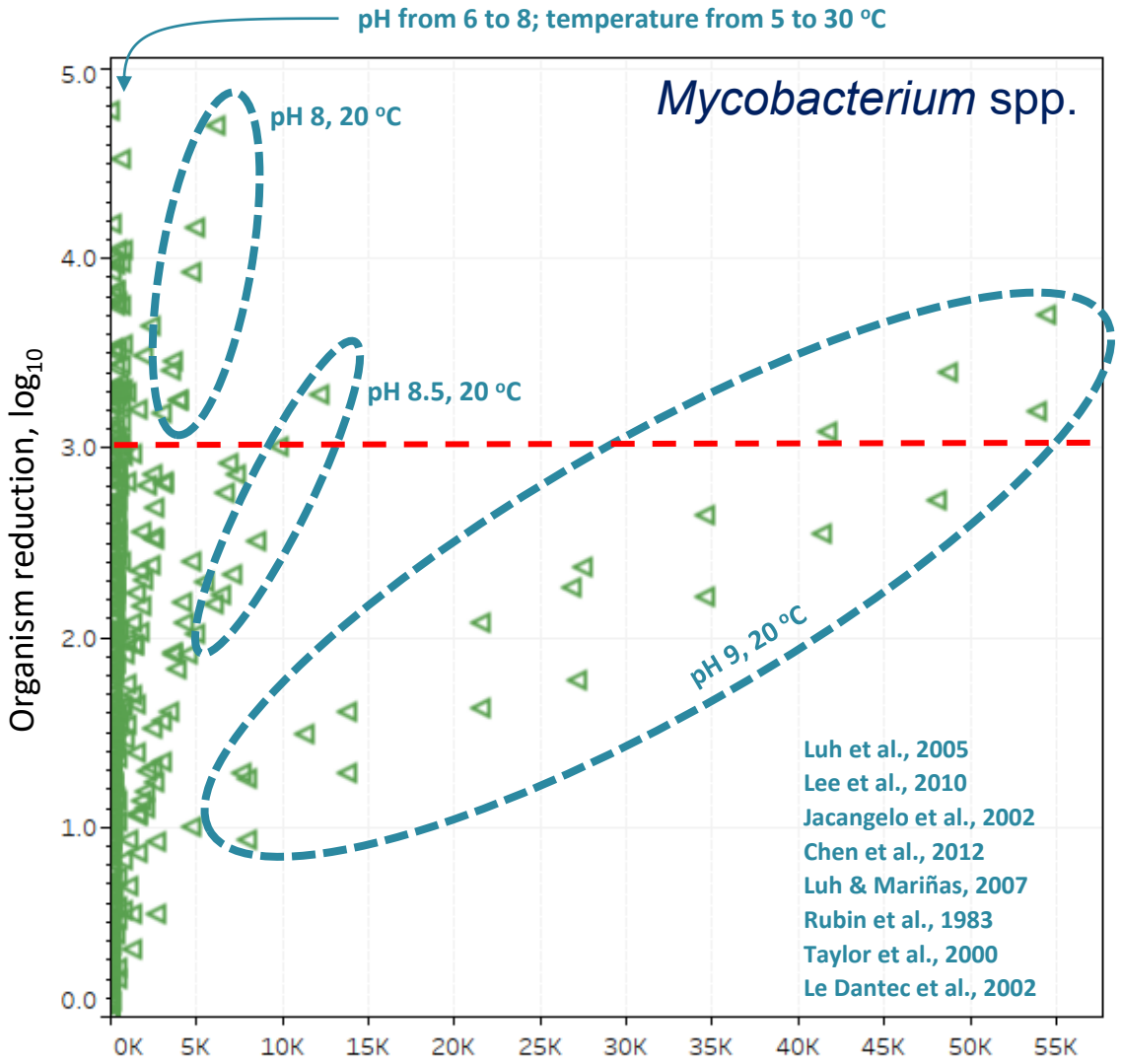
- Temperature from 20 to 25 °C except 2 datapoints marked
- All data in the database at an unknown pH (11 total, circled), or at pH 7 to 7.6
- For at least 3-$\log_{10}$ inactivation, *CxT* exceeds 400 mg/L*min



Chlorine, continued

Mycobacterium spp.

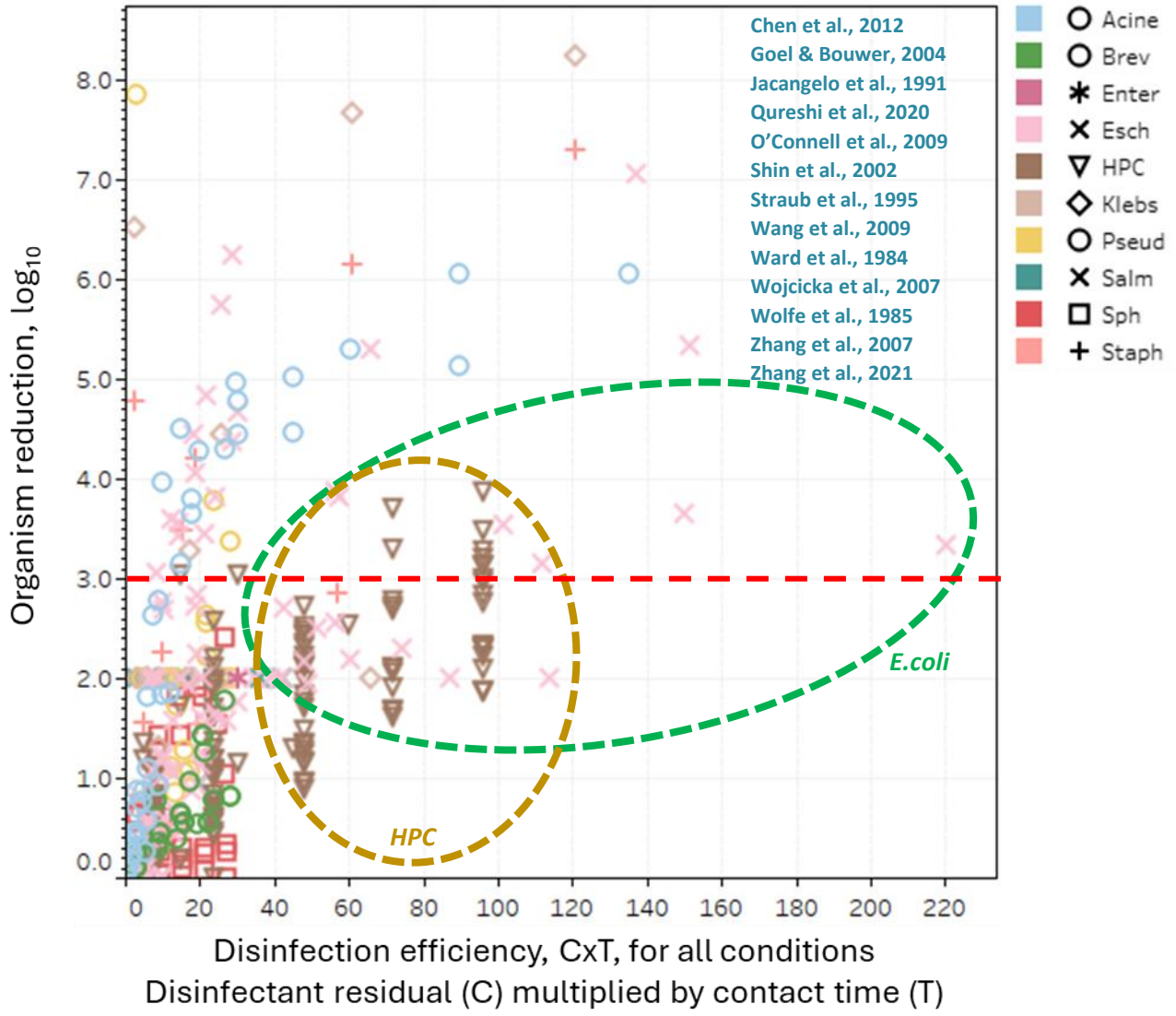
- All data at pH 6 to 9 and 5 to 30°C shown
- To achieve at least 3-log_{10} inactivation, *CxT* can be in the 1,000s or 10,000s



Disinfection efficiency, CxT, for all conditions
Disinfectant residual (C) multiplied by contact time (T)

Chloramine

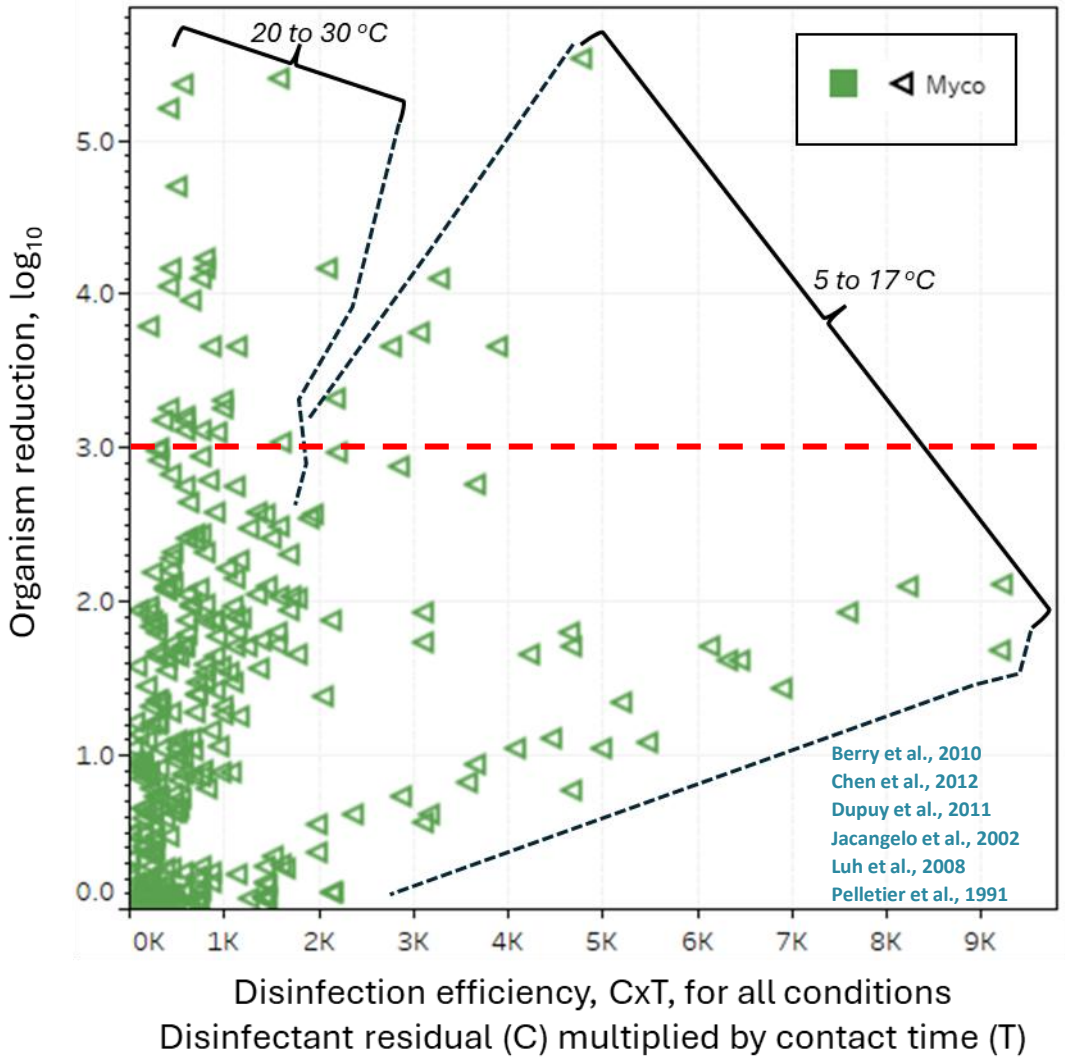
- All pH and temperature data excluding *L. pneumophila* and *Mycobacterium* spp.
- In General, 100-150 mg/L*min may provide 3-log_{10} reduction



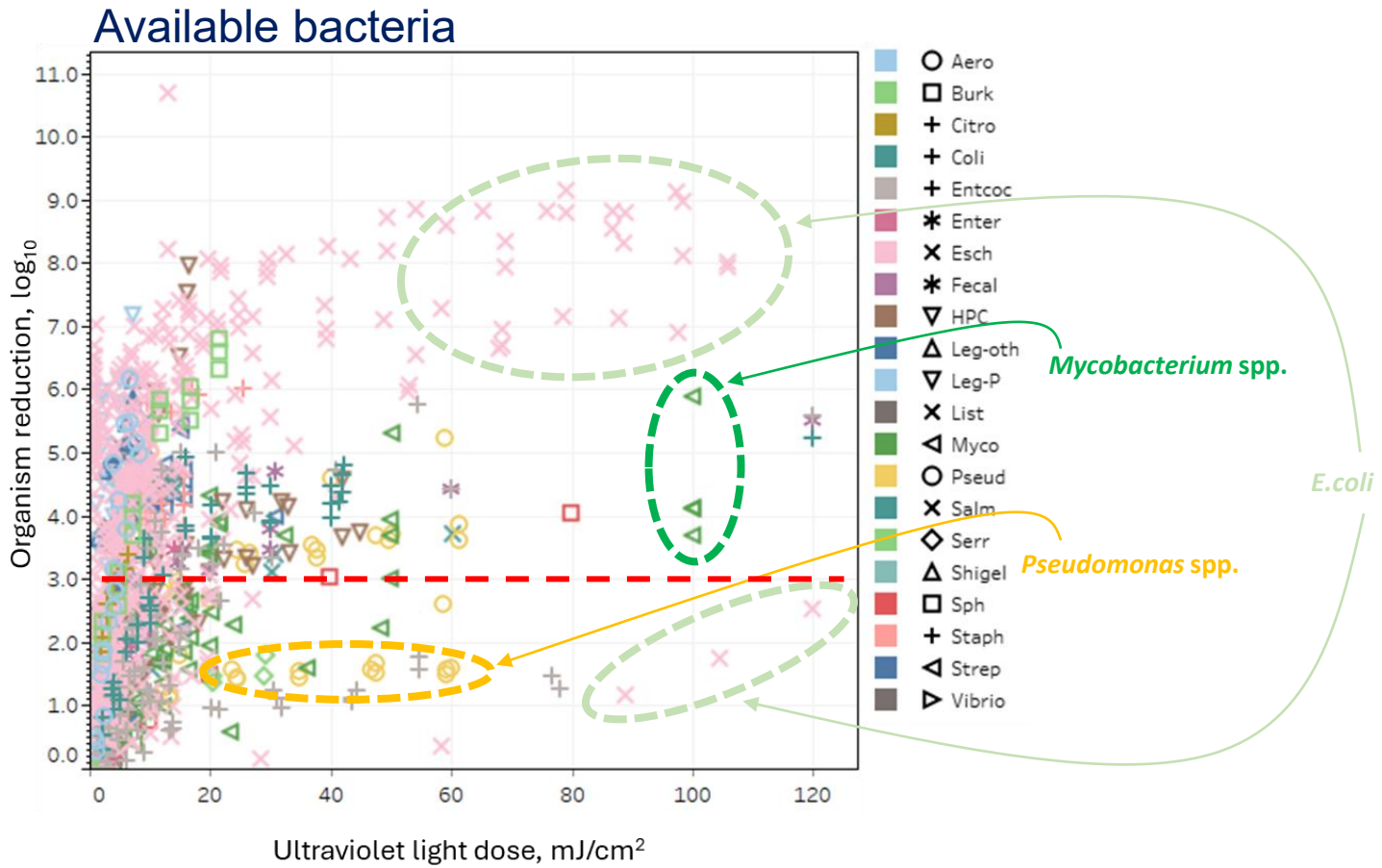
Chloramine, continued

- *Mycobacterium* spp. requires higher *CxT* values (pH 6 to 8 conditions at right)
- *CxT*s for least 3-log_{10} inactivation are in the 1,000s…..

Mycobacterium spp.



Low Pressure UV Light



Beck et al., 2017
Beltran & Jimenez, 2008
Bichai et al., 2009
Blatchley et al., 2001
Blatchley et al., 2012
Bohrerova & Linden, 2006a
Bohrerova & Linden, 2006b
Bohrerova et al., 2008
Buse et al., 2022
California Energy Commission, 1999
Cantwell et al., 2008
Carlson et al., 2017
Cervero-Arago et al., 2014
Chang et al., 1985
Chatterley & Linden, 2010
Chen et al., 2009
Chen et al., 2018
Chen et al., 2022
Collins, 1971
Crook et al., 2015
David et al., 1971
David, 1973
Destiani & Templeton, 2019
Fang et al., 2014
Farrell et al., 2018
Gehr et al., 2003
Harris et al., 1987
Hassen et al., 2000
Hayes et al., 2001
He et al., 2021
Hill et al., 2002
Huffman & Dussert, 2000
Jia et al., 2020
Kashinkunti et al., 2002
Knudson, 1985
Koivunen & Heinonen-Tanski, 2005
Lee et al., 2010
Linden & Mofidi, 2003
Malley et al., 2004
Martino, 2018
Martino et al., 2021
Matsumoto et al., 2022
Maya et al., 2003
McCarthy & Schaefer, 1974
McElmurry & Khalaf, 2016
McKinney & Pruden, 2012
Mofidi et al., 2001
Mofidi & Linden, 2004
Moreno-Andres et al., 2016
Moreno-Andres et al., 2019a
Moreno-Andres et al., 2019b
Moreno-Andres et al., 2020
Nasser et al., 2006
Örmeci & Linden, 2002
Otaki et al., 2003
Rochelle et al., 2010
Shin et al., 2008
Sun et al., 2013
Tree et al., 1997
Tyrrell et al., 1978
Wang et al., 2005
Wang et al., 2012
Xu et al., 2018
Zarif, 2017
Zhang, et al., 2020
Zhang et al., 2022
Zhou et al., 2017

Chlorine, Choramine, and UV light Summary

CxT (mg/L*min) needed to achieve 3-$\log_{10}$ bacteria reduction between 10 to 20 °C

Treatment Process	SWTR Guidance		All Bacteria *CxT* ***EXCLUDING*** *L. pneumophila* and *Mycobacterium* spp.		*CxT* ***FOR ONLY*** *L. Pneumophila*		***FOR ONLY*** *Mycobacterium* spp.	
	Virus *CxT* Range	*Giardia* *CxT* Range	Average	95th Pct.	Average	95th Pct.	Average	95th Pct.
Free Chlorine	2 to 4	36 to 201	8 All pH Values	36	147 pH ≥7 to <8	469	1090 pH <9 49722 pH 9	5417 54373
Chloramine	534 to 1067	1100 to 1850	107 All pH Values	516	120 All pH Values	366	974 pH <9	3398
UV light	143	11	14	47	3	5	30	63

Chlorine SWTR guidance for pH ≤6 to 8 and "C" values from 0.4 to 3 mg/L
Chloramine SWTR guidance for all pH values
All UV data is independent of pH and temperature

Is Virus *CxT* Enough for Bacteria? Answer = No.

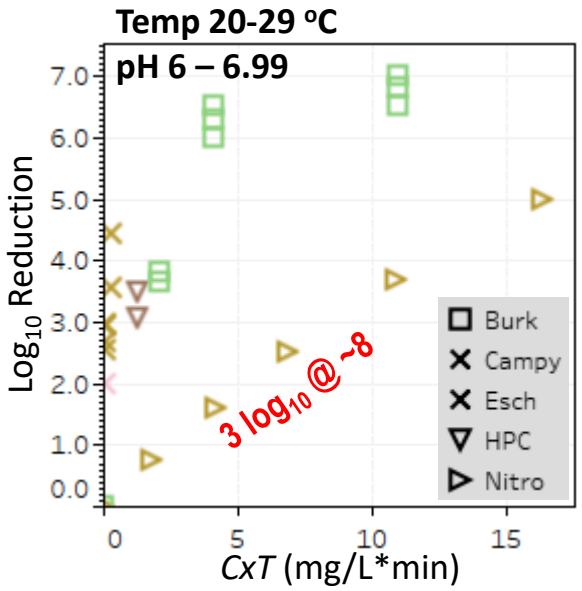
Choose Appropriate Bacteria and Data Statistics Based On Risk

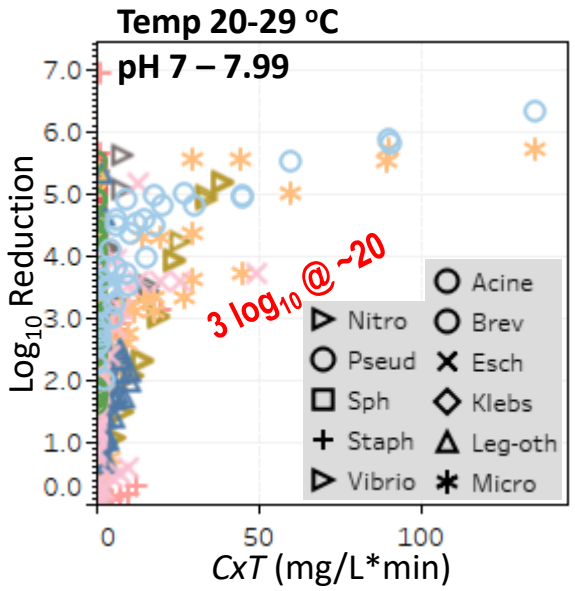
- **Excluding** *Legionella pneumophila* & *Mycobacterium* spp. (at 95th Percentile):
  - Bacteria *CxT* values for disinfectants are similar to *Giardia CxT*, not virus
  - UV light dose is ~1/3 virus dose or ~5x *Giardia* dose for the same LRC
- **Including** *Legionella pneumophila* & *Mycobacterium* spp. (at 95th Percentile): Bacteria *CxT* values for same LRC are higher than SWTR *Giardia CxT*:
  - Chlorine *CxT* for LP/MAC is up to 270-fold higher
  - Ozone *CxT* for LP/MAC is up to 80-fold higher
  - Chlorine dioxide *CxT* for LP/MAC is up to 10-fold higher
  - Chloramine *CxT* for LP/MAC is up to 2-fold higher
  - UV light dose for LP/MAC is up to 6-fold higher

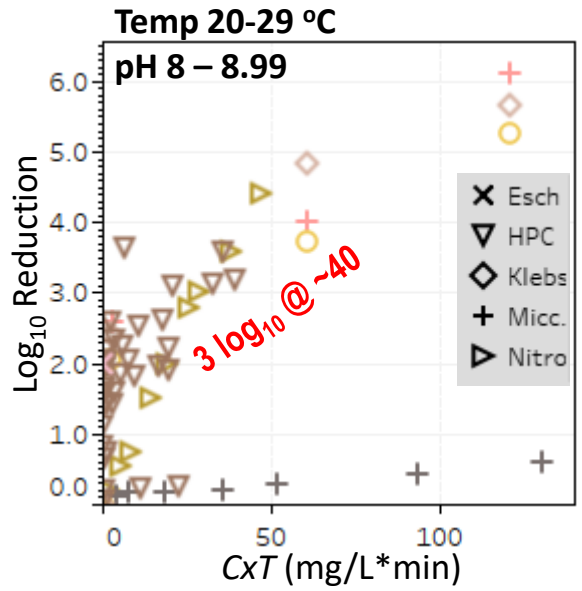
Discussion

- Database publicly available / open source; would benefit from:
  - Further stats analysis & recent data (post-2022 publications)
  - More treatment technologies, disinfectants, AOP technologies?
  - More enteric bacteria data (see below)
- Data for planktonic bacteria with no interferences from organics (biofilm and organics will further increase *CxT* requirements)
- Limitations: Organism, pH, temperature, and bacteria data gaps (**See Next Slides**)

Example: Limited Data (Free Chlorine)



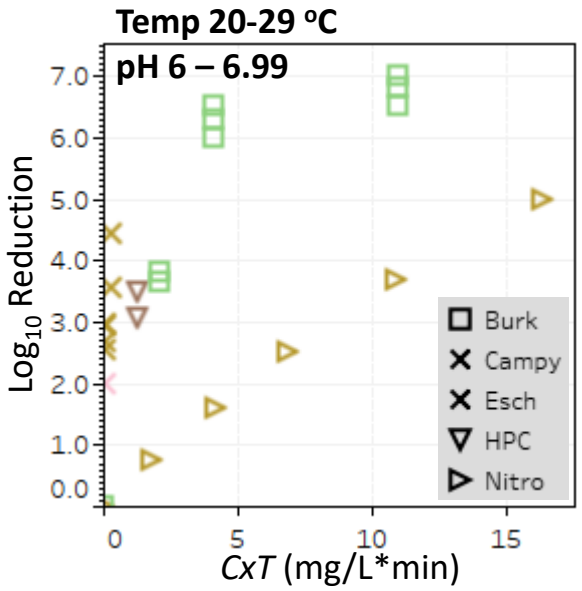


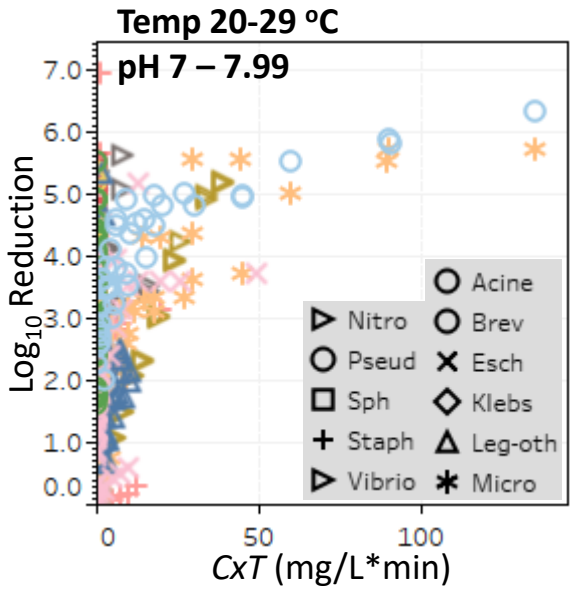


In this temperature range, increasing pH increases *CxT* requirement (but not all the same organisms)

Data shown excludes *Legionella pneumophila* and *Mycobacterium* spp.
CxT values for 3-$\log_{10}$ reduction are estimated & depend on model/estimate method used.

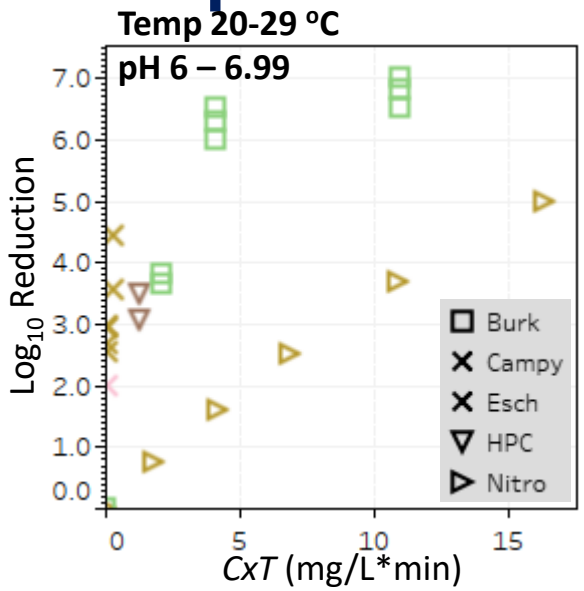
Example: Limited Data (Free Chlorine)





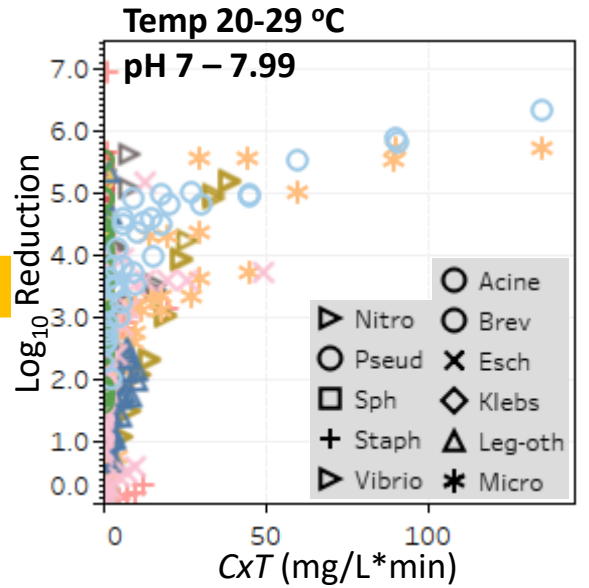
Data shown excludes *Legionella pneumophila* and *Mycobacterium* spp.
CxT values for 3-$\log_{10}$ reduction are estimated & depend on model/estimate method used.

Example: Limited Data (Free Chlorine), Cont'd.



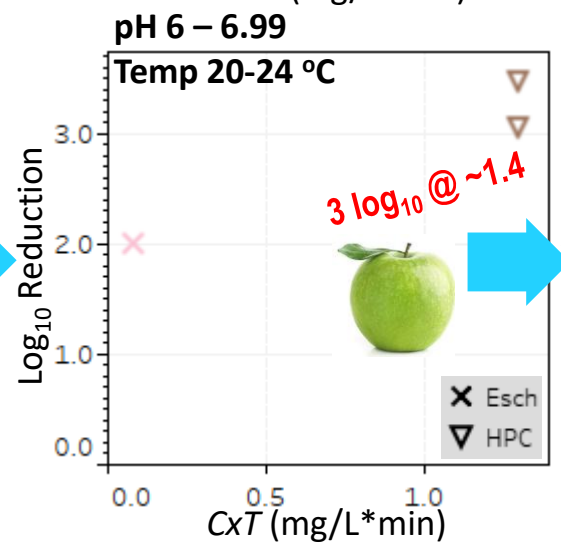
Within pH range, ⇧ temperature <u>does not</u> show a decrease in *CxT* requirement

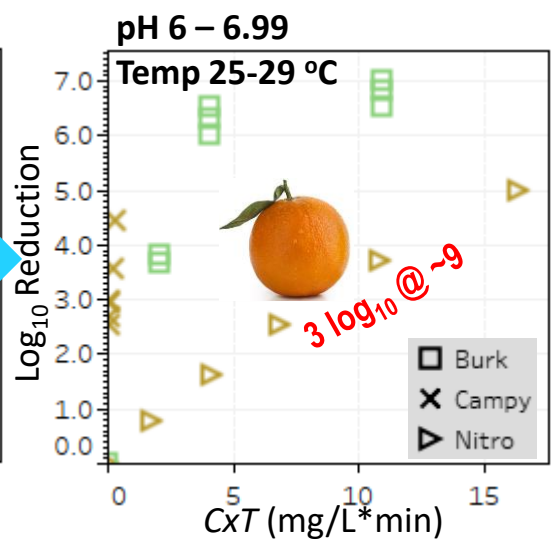
<u>Different organisms</u>

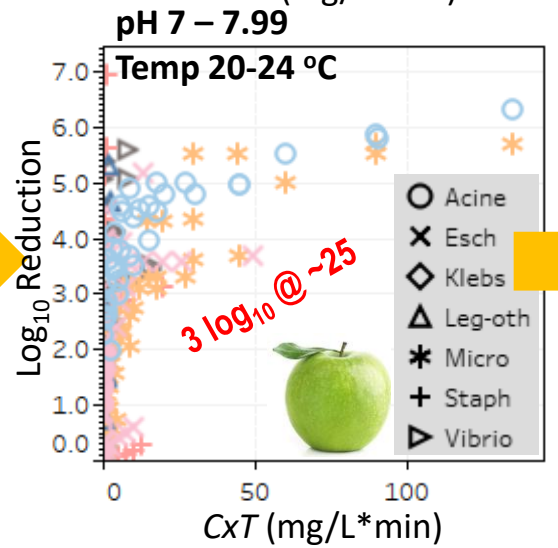


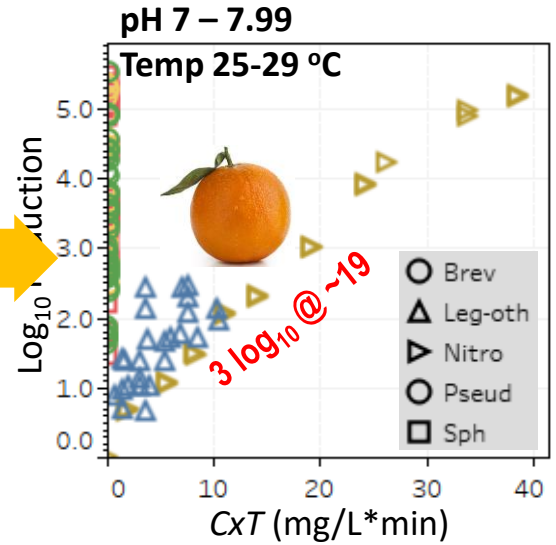
Within pH range, ⇧ temperature <u>might</u> show a decrease in *CxT* requirement

<u>Different organisms</u>









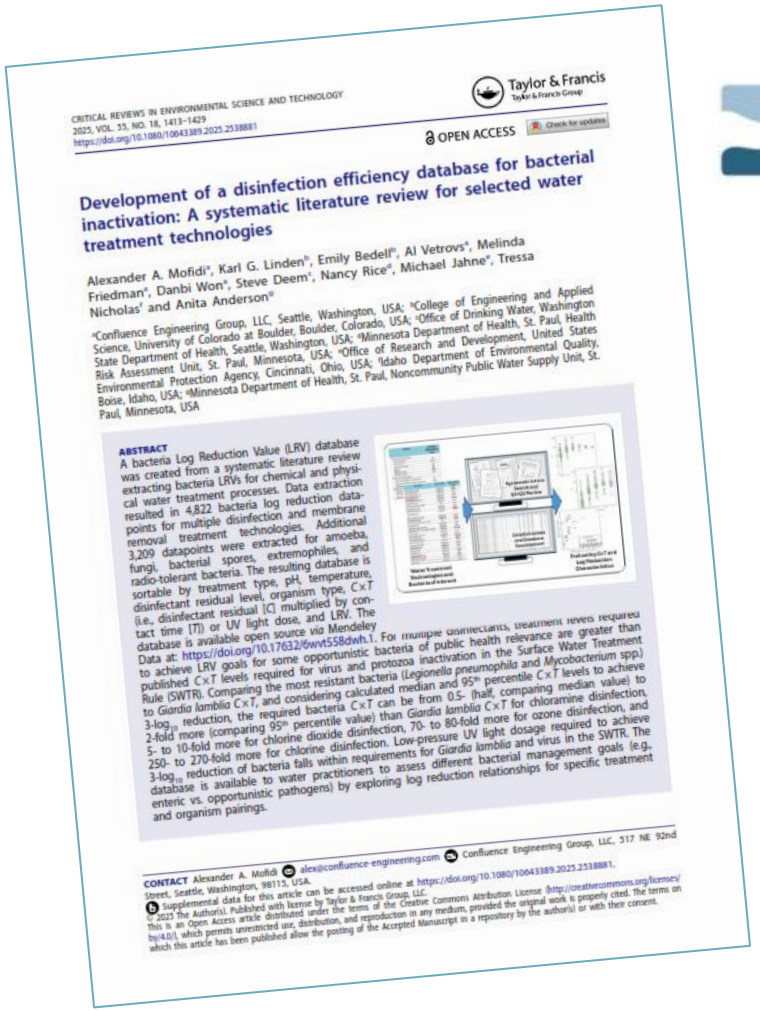
Data shown excludes *Legionella pneumophila* and *Mycobacterium* spp.

CxT values for 3-$\log_{10}$ reduction are estimated & depend on model/estimate method used.

Thank you!

Read more &
Geek out on data…

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CRITICAL REVIEWS IN ENVIRONMENTAL SCIENCE AND TECHNOLOGY
2025, VOL. 55, NO. 18, 1413–1429
https://doi.org/10.1080/10643389.2025.2538881

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Development of a disinfection efficiency database for bacterial inactivation: A systematic literature review for selected water treatment technologies

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ABSTRACT

A bacteria Log Reduction Value (LRV) database was created from a systematic literature review extracting bacteria LRVs for chemical and physical water treatment processes. Data extraction resulted in 4,822 bacteria log reduction datapoints for multiple disinfection and membrane removal treatment technologies. Additional 3,209 datapoints were extracted for amoeba, fungi, bacterial spores, extremophiles, and radio-tolerant bacteria. The resulting database is sortable by treatment type, pH, temperature, disinfectant residual level, organism type, C×T (i.e., disinfectant residual [C] multiplied by contact time [T]) or UV light dose, and LRV. The database is available open source via Mendeley Data at: https://doi.org/10.17632/6wvt558dwh.1. For multiple disinfectants, treatment levels required to achieve LRV goals for some opportunistic bacteria of public health relevance are greater than published C×T levels required for virus and protozoa inactivation in the Surface Water Treatment Rule (SWTR). Comparing the most resistant bacteria (*Legionella pneumophila* and *Mycobacterium* spp.) to *Giardia lamblia* C×T, and considering calculated median and 95th percentile C×T levels to achieve 3-log$_{10}$ reduction, the required bacteria C×T can be from 0.5- (half, comparing median value) to 2-fold more (comparing 95th percentile value) than *Giardia lamblia* C×T for chloramine disinfection, 5- to 10-fold more for chlorine dioxide disinfection, 70- to 80-fold more for ozone disinfection, and 250- to 270-fold more for chlorine disinfection. Low-pressure UV light dosage required to achieve 3-log$_{10}$ reduction of bacteria falls within requirements for *Giardia lamblia* and virus in the SWTR. The database is available to water practitioners to assess different bacterial management goals (e.g., enteric vs. opportunistic pathogens) by exploring log reduction relationships for specific treatment and organism pairings.

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Supplemental data for this article can be accessed online at https://doi.org/10.1080/10643389.2025.2538881.

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Critical Reviews in Environmental Sci. & Tech.
https://doi.org/10.1080/10643389.2025.2538881

Open-Source Dataset (Mendeley Data)
https://doi.org/10.17632/6wvt558dwh.1