Combined UV-Chlorine processes to improve the Disinfection of Drinking Water

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Figueres DWTP

The Figueres Drinking Water Treatment Plant is situated in the north of Girona treating **11000 m^3/day**.

The raw water is captured from **Darnius-Boadella** reservoir.

Reservoir Darnius Boadella

Drinking water treatment plant

City of Figures

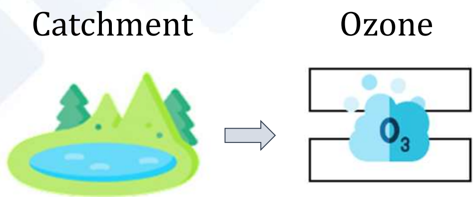
Why do we treat surface water

Surface water (rivers, lakes, reservoirs) are primary sources in many communities.

- **Pathogens**: bacteria, viruses and protozoa than can cause diseases
- **Turbidity**: Suspended particles
- **Natural Organic Matter**: materials that comes from plans and animals, not harmful by itself, but reacts with disinfectants!
- **Micropollutants**: persistent pharmaceuticals, pesticides and industrial chemicals that present long-term health risks

Surface water treatment is essential to ensure public health and provide safe and aesthetically pleasing water to costumers

Drinking Water Treatment Processes



Pre-oxidation with **ozone**:

- It is a powerful oxidant used to break down organic matter, reduce turbidity and inactivate pathogens
- Improves the efficiency of the subsequent processes altering the structure of the substances

Drinking Water Treatment Processes

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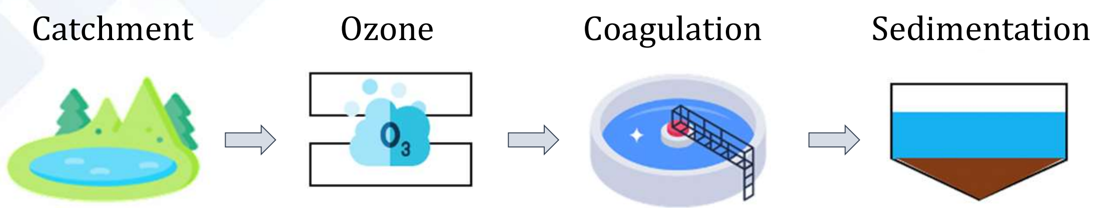
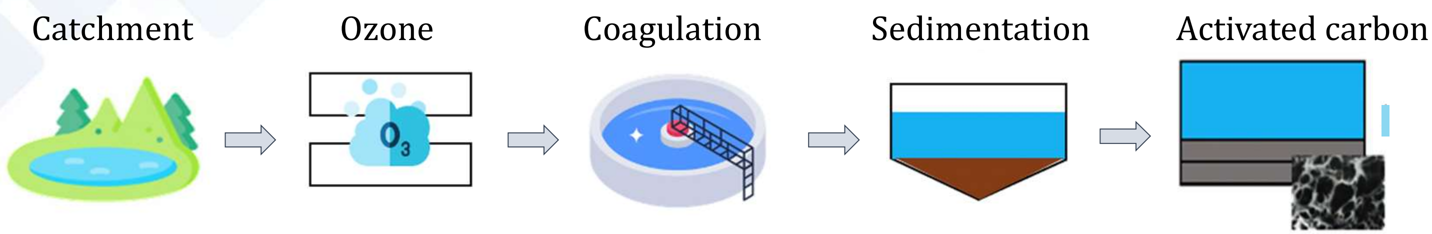


Coagulation and **Sedimentation**:

- Chemicals are added to destabilize small particles, that clump together to **form aggregates** and flocs
- The flocs settle at the bottom of the tank during sedimentation

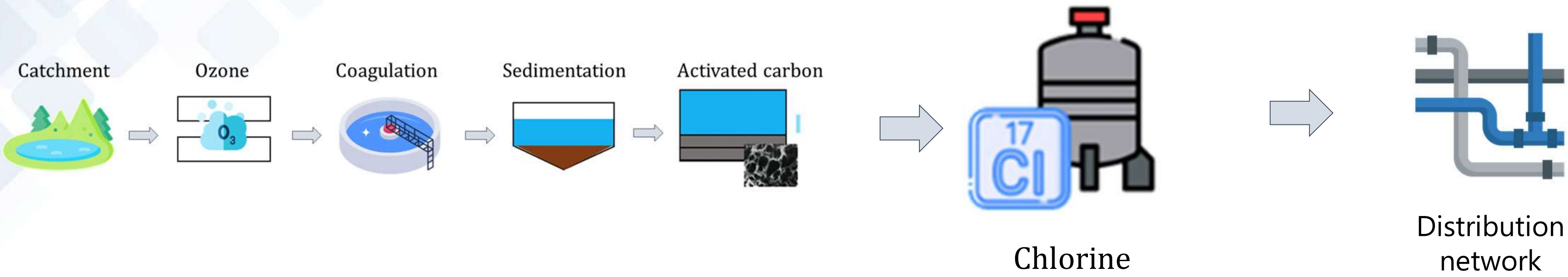
Drinking Water Treatment Processes



Adsorption onto **Activated Carbon**:

- Activated carbon is used to remove **dissolved** organic matter and **micropollutants**.
- This step is crucial because it minimizes the formation of disinfection by-products during chlorination.

Disinfection: why chlorine?



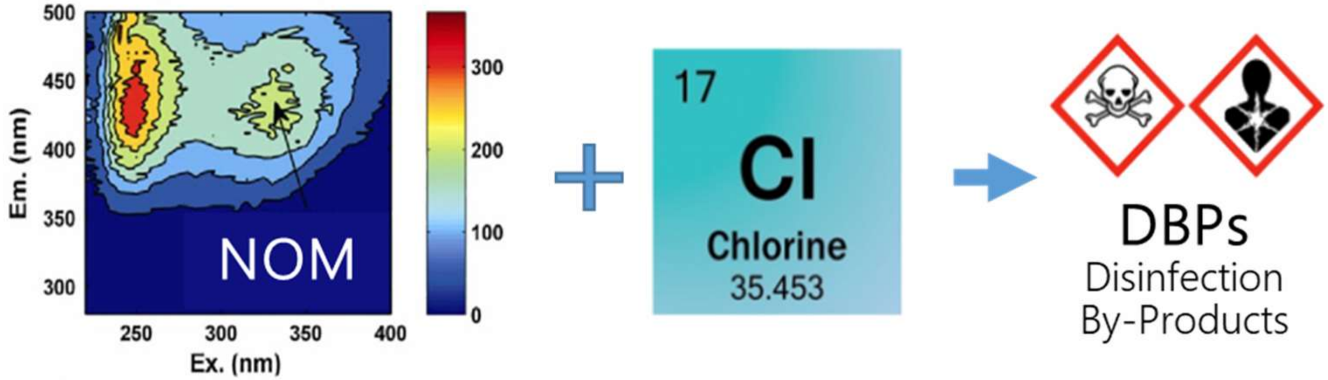
Chlorine has been standard of disinfection in water treatment for over a century. Why?

- It's **Effective**: it kills a wide range of pathogens, including bacteria and viruses.
- It's **Affordable**: it is cost-effective and widely available.
- **Residual-effect**: it remains in the water as it travels through the distribution system, offering continued protection.

Disinfection: why chlorine?

However, chlorine isn't perfect:

- Interaction with NOM to form Disinfection by-Products

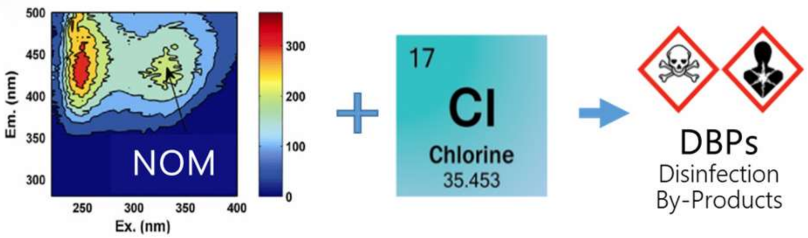


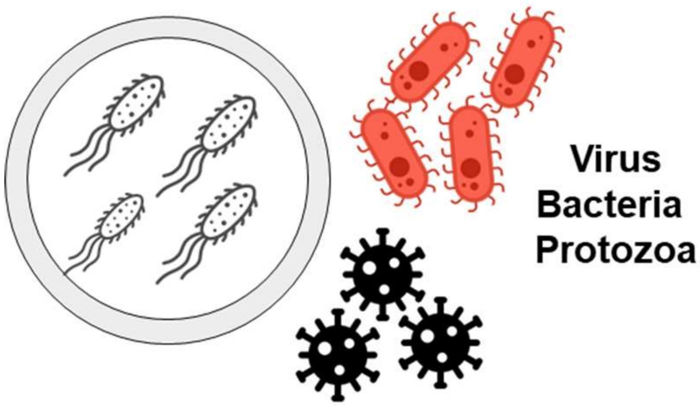
Trihalomethanes
Halo acetic acids
Among others

Disinfection: why chlorine?

However, chlorine isn't perfect:

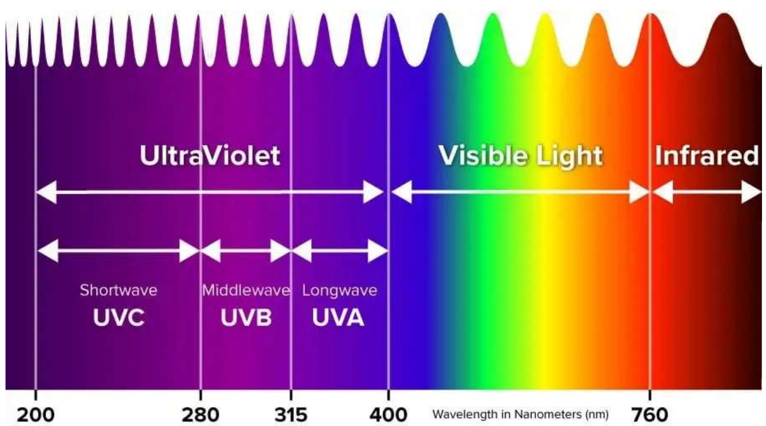
- Interaction with NOM to form Disinfection by-Products
- Increasing chlorine-resistant bacteria

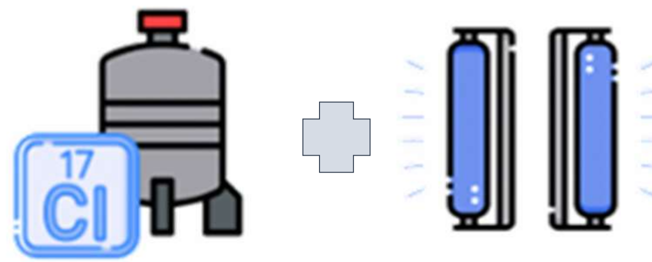




Why Combine UV with Chlorine?

Using UV light alongside chlorine has several advantages:





Chlorine

UV Radiation

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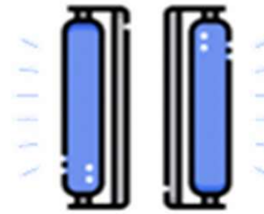
Chlorine



UV Radiation

- **Enhanced Disinfection**: UV light damages the DNA of microorganisms, making them unable to reproduce.
- **Reduced Chlorine Dosage**: Because UV inactivates many pathogens directly, less chlorine is needed, which can reduce the formation of DBPs.
- **Improved Water Quality**: UV also breaks down some contaminants that chlorine cannot, such as certain micropollutants.

But this combination introduces new complexities —specifically, **how UV affects chlorine decay**.

Evaluating Bacteria inactivation

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To study the effectiveness of chlorine and UV disinfection, we conducted **laboratory experiments** to measure bacterial inactivation

Evaluating Bacteria inactivation

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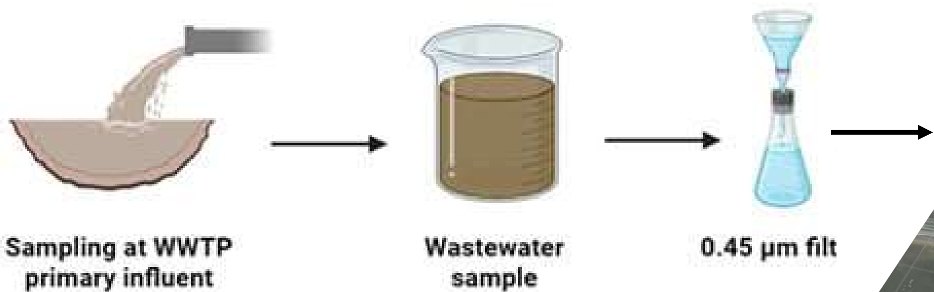
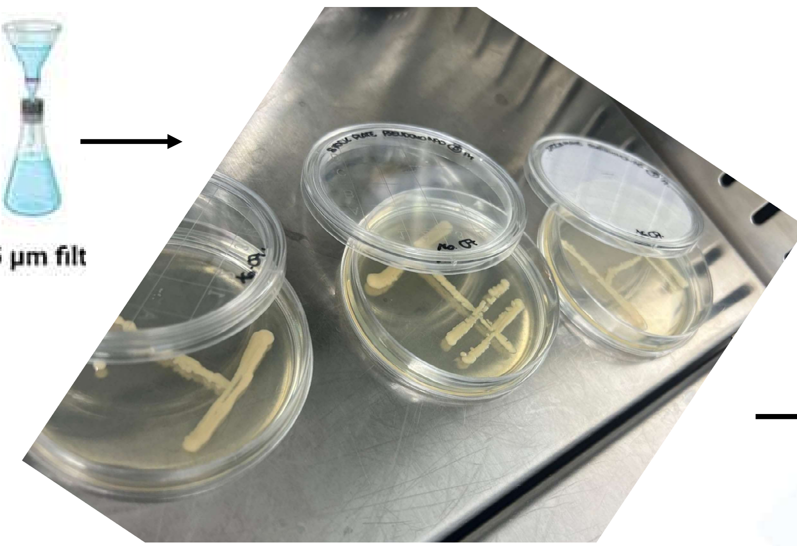
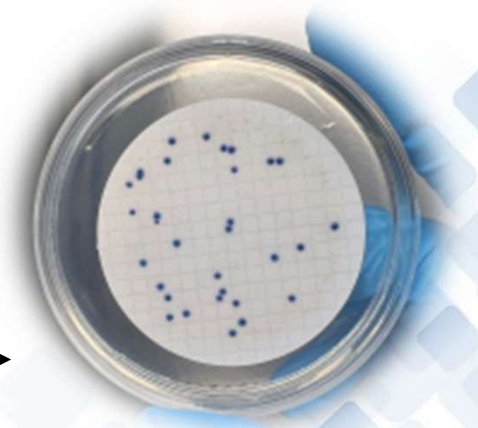
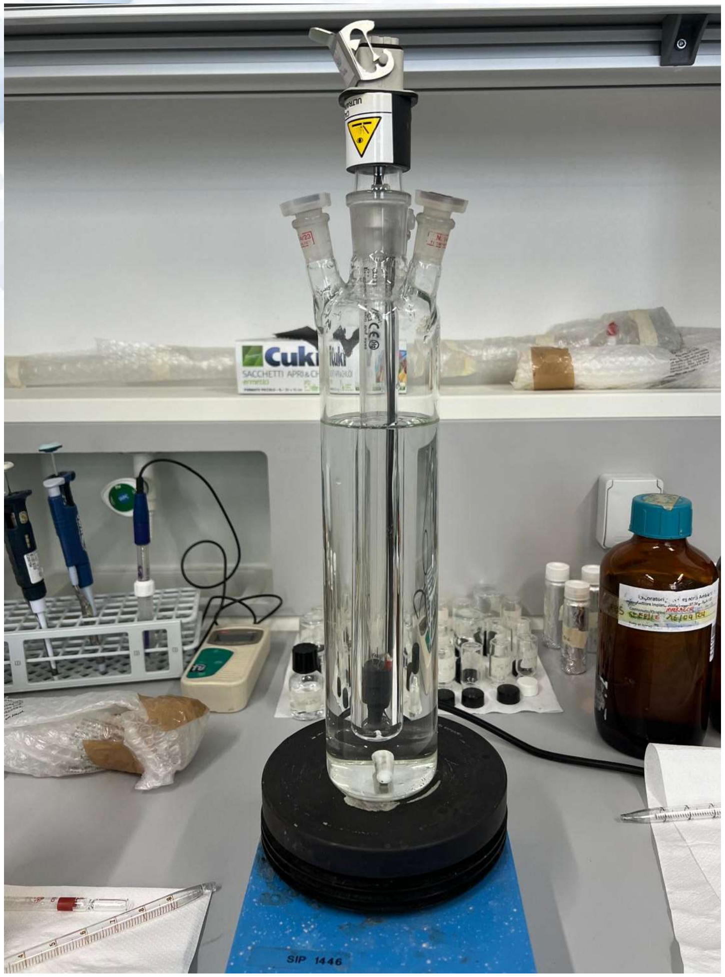
We obtain **chlorine resistant bacteria** isolated from wastewater

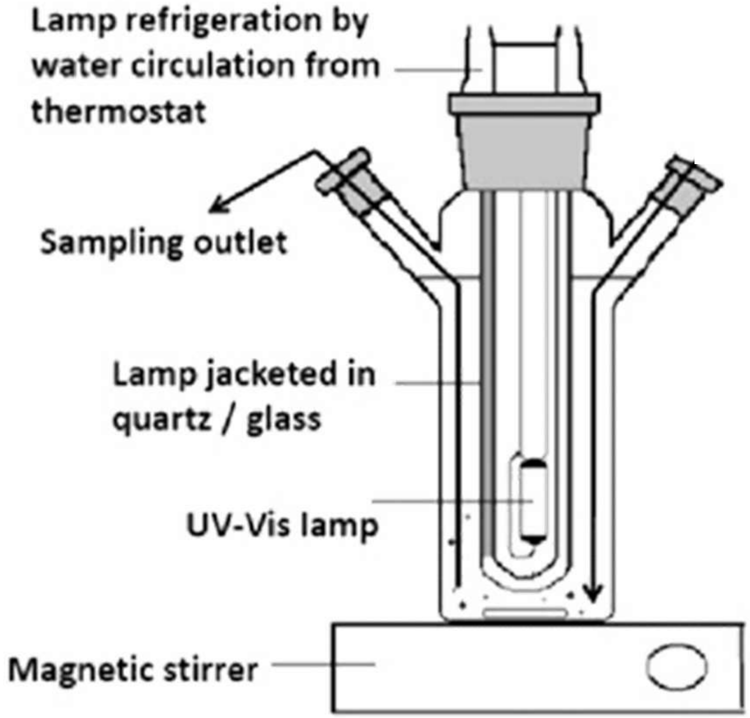






Lab scale photoreactor

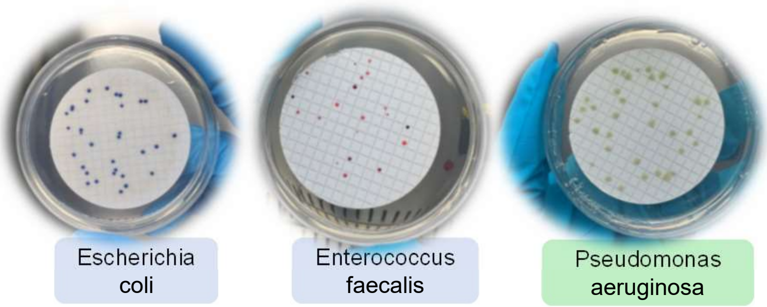




Evaluating Bacteria inactivation

Experimental Setup:

- Test Water: We spike with a known concentration of three resistant bacteria
  - Clean water: first for simplicity
  - Water with NOM: closer to real conditions



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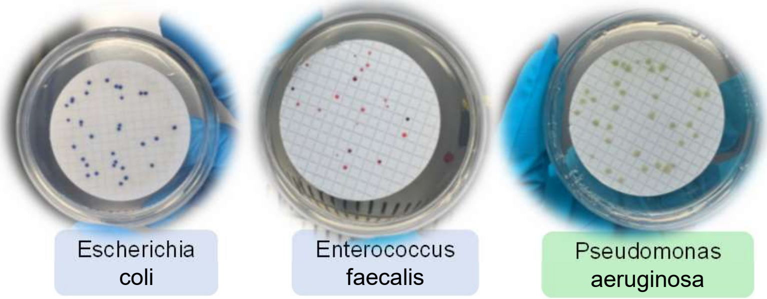
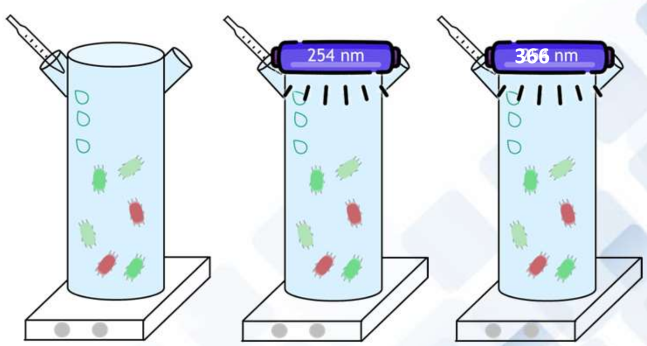
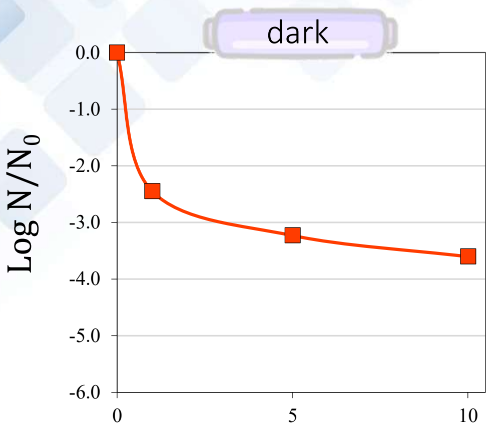


- Conditions:
  - **Chlorination only**: A fixed chlorine dose was added to the water.
    - HClO / ClO_2
  - **Chlorination + UV radiation**: Water was exposed to UV light while maintaining the same initial chlorine dose.
    - UV-C (254 nm) / UV-A (366 nm)



Results and Observations

Bacteria decay:

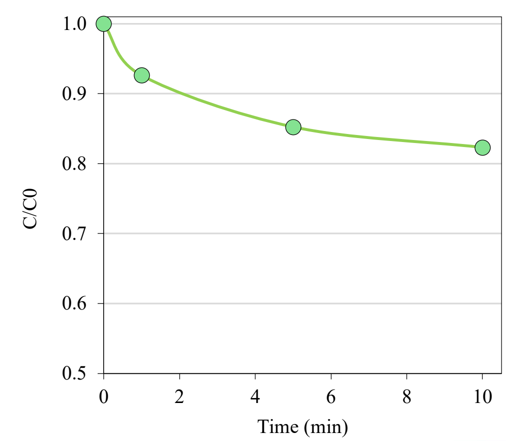


$$log\left(\frac{N_0}{N}\right) = k_d \cdot C \cdot t$$

Chick-Watson model

- Monitoring Parameters:
  - **Bacterial Inactivation**: Measured as *log reduction* of bacteria over time.
  - **Chlorine Decay**: Monitored by measuring the *residual chlorine concentration at regular intervals.*

Chlorine decay:

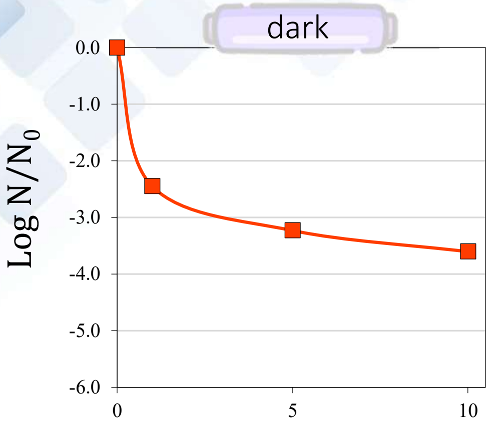


$$\frac{dC}{dt} = -k \cdot C$$

First order decay

Results and Observations - Clean Water

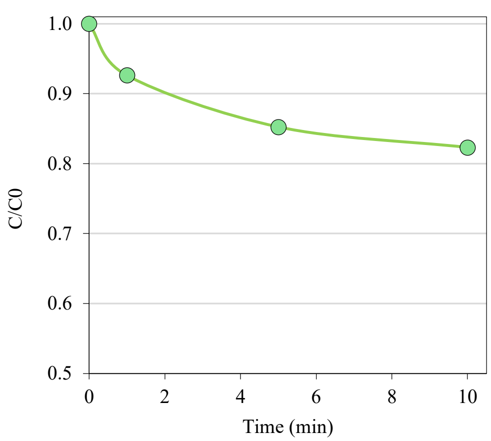
Bacteria decay:



Without UV Radiation:

- Chlorine alone was effective in inactivating bacteria, but the process slowed over time due to chlorine decay.
- The rate of inactivation decreased as the chlorine **concentration dropped**.

Chlorine decay:



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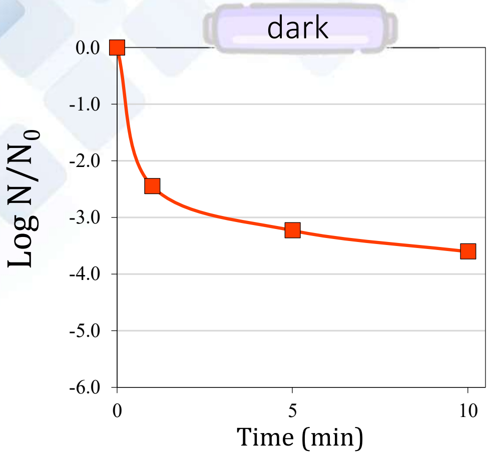
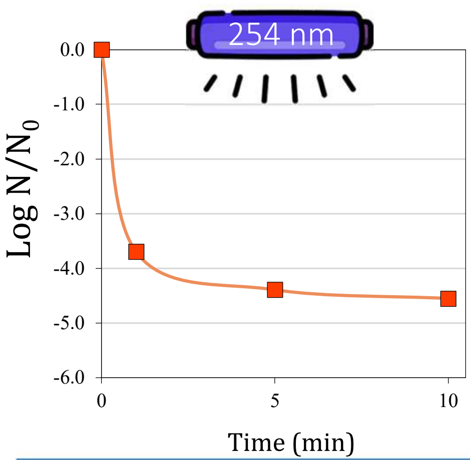




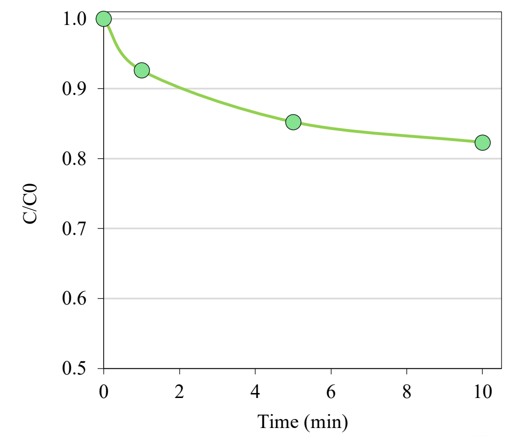
Without UV Radiation:

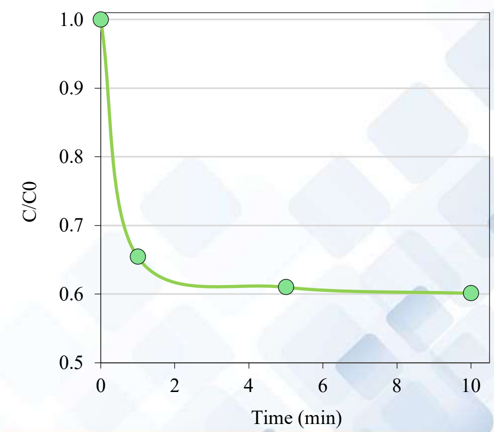
- Chlorine alone was effective in inactivating bacteria, but the process slowed over time due to chlorine decay.
- The rate of inactivation decreased as the chlorine concentration dropped.

With UV Radiation:

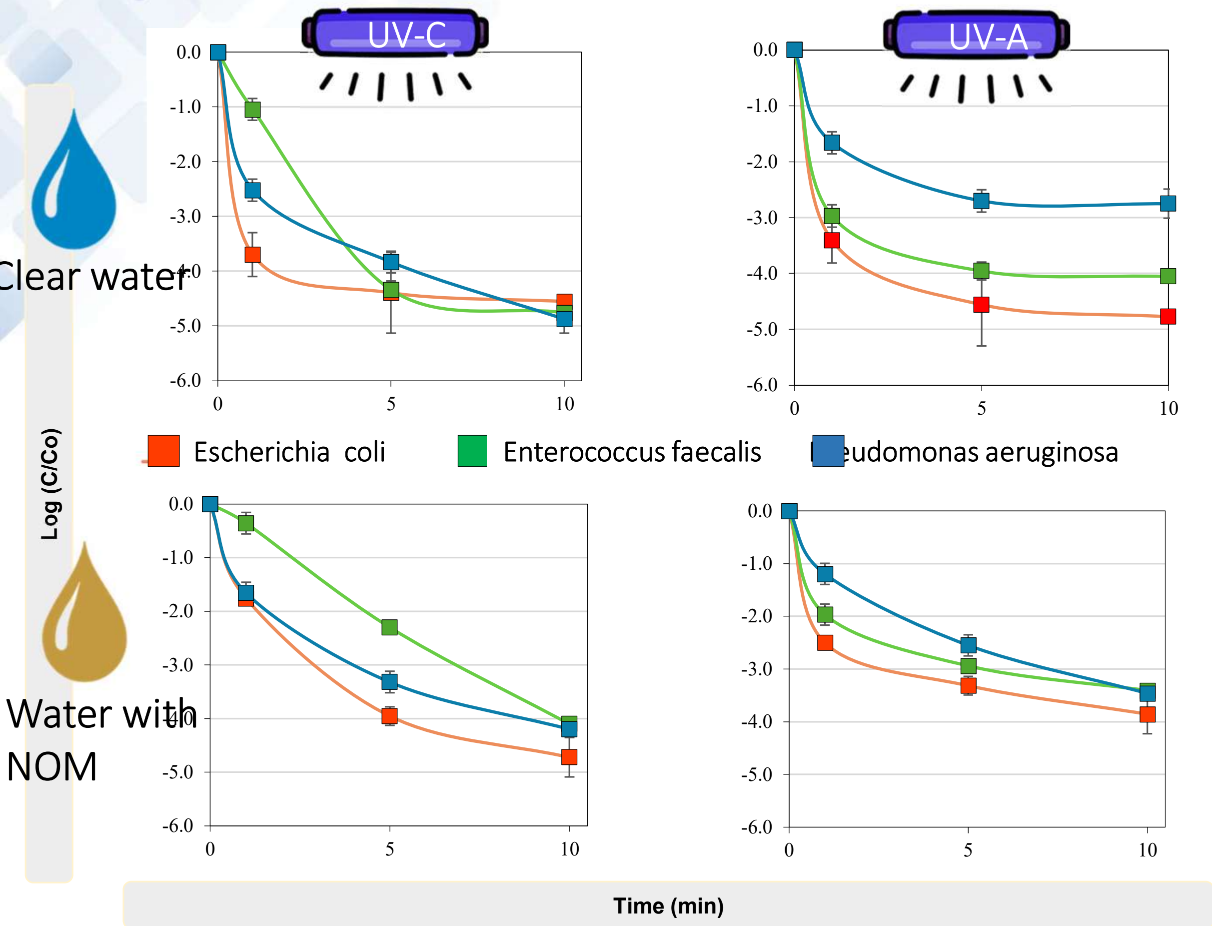
- Combining UV with chlorine accelerated bacterial inactivation, achieving higher log reductions in a shorter time.
- However, **chlorine decay was faster due to photolysis**, indicating a trade-off between increased UV disinfection efficiency and decreased chlorine.

Chlorine decay:

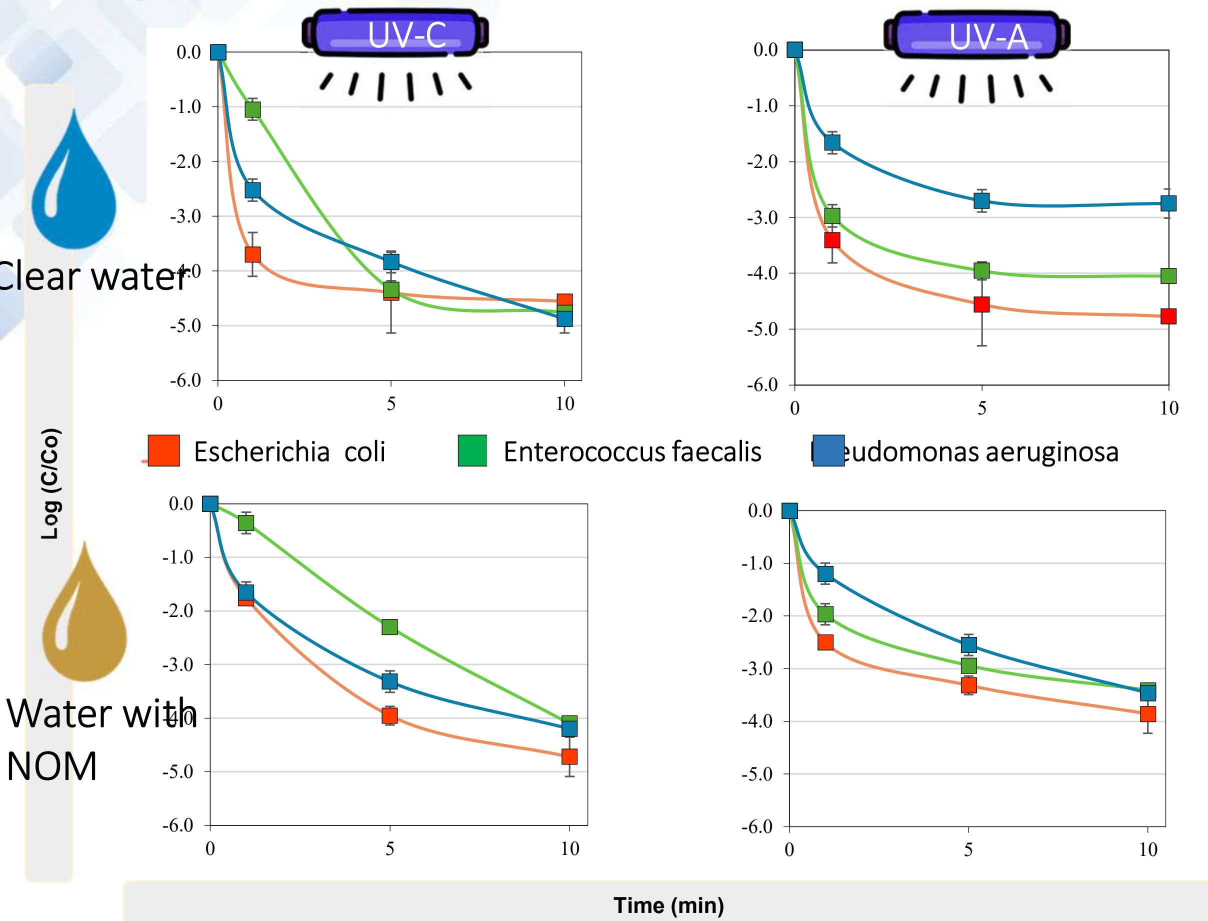




Results and Observations –Water with NOM



Results and Observations –Water with NOM



When Natural Organic Matter (NOM) is present in the water, the process slows down because:

- chlorine is consumed as it reacts with NOM
- UV light is further extinguished due to water turbidity

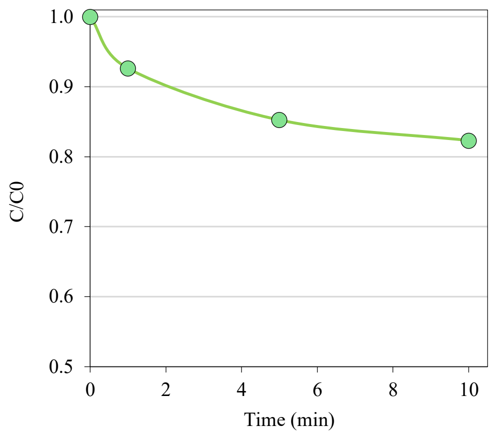
Some models available

Disinfection efficiency is often modeled using the **Chick-Watson equation**, which relates bacterial inactivation to disinfectant concentration and time:

$$log\left(\frac{N_0}{N}\right) = k_d \cdot C \cdot t$$

N_0 is the initial bacterial concentration,
N is the bacterial concentration at time t
C is the chlorine concentration
and k_d is the disinfection rate constant

Chlorine decay:



C is not constant!

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Environ. Sci. Technol. **1994**, *28*, 1367–1369

Disinfection under Dynamic Conditions: Modification of Hom's Model for Decay

Charles N. Haas* and Josh Joffe

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Hom's model for microbial disinfection kinetics is frequently applied to data showing deviations from Chick's law inactivation. However, the generally applied form of this model does not consider the possibility for disinfectant decay/demand. In this work, we derive the form of the Hom model under conditions of first-order demand; the integrated solution involves the incomplete γ function. We then propose a simpler approximation to this exact solution and explore its numerical adequacy, also showing

$$\ln(S) = -kC^n t^m \quad (1)$$

This can be derived from the following differential equation, under the assumptions of constant disinfectant residual, where N is the concentration of viable organisms at any one time:

$$\frac{dN}{dt} = -mkC^n t^{m-1} N \quad (2)$$

$$C = C_0 \exp(-k^* t) \quad (3)$$

First-order disinfectant decay has often been noted to describe the loss of chlorine residuals, at least in initial stages of exposure (*16–18*). On this basis, the use of a first-order assumption is often appropriate.

Exact Solution. By combining eqs 2 and 3 and collecting terms, the following equation can be derived for the survival ratio:

$$\ln(S) = -mkC_0^n \int_0^t \exp(-nk^* t) t^{m-1}\, dt \quad (4)$$

This equation can be integrated analytically only by employing the incomplete γ function, $\gamma(a,y)$, defined by the following integral:

$$\gamma(a,y) = \int_0^y \exp(-z) z^{a-1}\, dz \quad (5)$$

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$$log\left(\frac{N_0}{N}\right) = k_d \cdot C \cdot t$$

N_0 is the initial bacterial concentration,
N is the bacterial concentration at time t
C is the chlorine concentration
and k_d is the disinfection rate constant

Chlorine photolysis produces radicals, which are powerful oxidants that further enhance disinfection but **accelerate chlorine loss**.
Decay equation is modified to include UV effects:

$$\frac{dC}{dt} = -k \cdot C - kUV \cdot C$$

Key questions for investigation

Can mathematical modelling improve our understanding of disinfection efficiency and help optimize chlorine dosing?

Disinfection Efficiency:

- How can we model the combined effects of UV and chlorine dose to predict bacterial inactivation?

Distinguishing Chlorine Consumption Pathways:

- Can we mathematically separate chlorine consumption due to bacterial inactivation from its reactions with natural organic matter (NOM)?

Scaling from Laboratory to Real-World Conditions:

- How can the Beer-Lambert law, which describes the attenuation of UV light in water, be integrated into the models?