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Disinfection Of Drinking Water From E.Coli And Tmc Using A Combined Ultraviolet And Ultrasound Device

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Abstract: In this study, a combined ultraviolet (UV) and ultrasound (US) device was proposed for rapid and stable disinfection of drinking water from Escherichia coli and total microbial count (TMC). Experiments were conducted in a flow-through reactor in the range of US (40 kHz; 2.27 W/cm²; 0.28 s) and UV (≈26.7 W/m²; lamp depth 3.6 cm; 4.58 s) parameters. It was observed that the cavitation effects of US weakened cell walls and enhanced the damaging effect of UV radiation at the DNA level; as a result, E. coli and TMC were sharply reduced, and the microbiological stability of water (the period before regrowth) was significantly extended compared to single methods. Maintaining the UV intensity around ~28–30 W/m² and placing the lamp close to the water surface increased the efficiency; in US, frequencies close to 40 kHz gave the best results. The combined mode provided high disinfection efficiency and energy efficiency with low contact time; this creates a convenient platform for practical implementation in small and medium-capacity drinking water systems.

Keywords: drinking water disinfection, E. coli, TMC, ultraviolet (UV), ultrasound (US), synergistic effect, cavitation, flow reactor, optimal parameters, microbiological stability.

INTRODUCTION

The microbiological safety of drinking water is among the core requirements for public health and resilient infrastructure. Under international standards, the presence of *Escherichia coli* (*E. coli*) in drinking water is not permissible, and the total microbial count (TMC) must be strictly controlled. Although chlorination is widely used in practice for being inexpensive and effective, it increasingly raises concerns due to the formation of disinfection by-products (e.g., trihalomethanes, chloramines), taste/odor issues, and the evolution of microbial resistance mechanisms. Ultraviolet (UV) irradiation provides rapid inactivation without chemical addition; however, its efficiency can decline because of water turbidity, "shadowing" effects, biofilms, and—under certain conditions—photoreactivation. Ultrasound (US)–induced cavitation mechanically damages cell walls, enhances diffusion, and promotes coagulation, but US alone does not always ensure high-level sterilization.

In recent years, the combined use of UV and US (sonophotodisinfection) has emerged as a promising approach across various water systems. Cavitation bubbles generated by US create microstreaming and localized high-pressure/high-temperature zones that weaken the microbial envelope; as a result, UV can inflict greater DNA/RNA damage, i.e., a synergistic effect may be observed. Such an approach enables shorter contact times, reduced energy consumption, and a lower risk of post-treatment regrowth. Compact flow-through reactors are particularly valuable for small- and medium-capacity supply systems and in regions where chlorine-reagent logistics are challenging.

The relevance of this study is driven, on the one hand, by the need to increase the share of non-chemical methods in drinking-water disinfection and, on the other, by the need to maximize efficiency through optimal integration of multiple physical factors. To this end, we examine a flow-through reactor that combines UV and US and evaluate its microbiological performance with respect to *E. coli* and TMC.

Study objective. To determine the effectiveness of the combined UV–US device in inactivating *E. coli* and TMC, quantify the degree of synergy, and assess energy efficiency. The study focuses on:

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Comparing UV and US operated separately and in combination (dose/frequency/intensity–response relationships);
Assessing the effects of flow rate, contact time, lamp positioning, and transmission/turbidity on outcomes;
Calculating the synergy coefficient (combined outcome exceeding the sum of individual modes) and energy-per-log metrics (energy required for 1–3 $\log_{10}$ reductions);
Monitoring microbiological stability after disinfection (risk of regrowth).

Novelty. The work advances the field by: (i) integrating UV and US within a single housing as a compact flow-through reactor design; (ii) identifying an operating window that achieves high-level inactivation at short contact times; (iii) quantitatively evaluating the energy-consumption–performance trade-off; and (iv) developing practical recommendations for deployment in small/local water networks.

Article structure. The next section details materials and methods, followed by results and discussion; conclusions and practical recommendations are then presented. This approach contributes to improving drinking-water safety, enabling robust, reagent-free disinfection processes, and introducing energy-saving technologies adapted to local conditions.

RESEARCH MATERIALS AND METHODOLOGY

1. Materials

Water samples. Tap water collected from the distribution network was characterized by turbidity (NTU), pH, electrical conductivity, and UV transmittance at 254 nm (UVT254). To assess matrix effects, additional samples were prepared by kaolin spiking to achieve 0–20 NTU.

Microorganisms. A biosafety-approved laboratory strain of *Escherichia coli* (e.g., from the ATCC collection) was used. The initial concentration (N_0) was inoculated in the range of ~10^4–10^6 CFU/mL.

Culture media and enumeration. Standard growth media and 0.45 μm membrane-filtration sets were employed for *E. coli* and for total microbial count (TMC; heterotrophic plate count, HPC).

Equipment. Flow-through reactor; UVC module (≈254 nm band); ultrasound (US) piezoceramic transducer (≈35–45 kHz); peristaltic pump; UV radiometer; power meter (wattmeter); turbidimeter; UV/Vis spectrophotometer (for UVT254); thermometer (or PT100 probe); pH meter.

2. Apparatus and Reactor Design

Flow-through combined reactor. Stainless-steel housing with a centrally mounted UVC source enclosed in a quartz sleeve. Baffle elements were installed to establish flow either parallel or perpendicular to the lamp axis, while inducing swirl/recirculation to reduce "shadow zones."

US module. A piezoceramic transducer (≈35–45 kHz) attached either via a flange to the external wall or bonded to the inner shell of the reactor. Cavitation zones were positioned as close as possible to the UVC active region.

Module sequencing. Two configurations were tested: (i) US→UV (ultrasound first, then UV) and (ii) UV→US; these were compared to identify the optimal sequence.

Cooling and temperature control. To counteract heat generated by US, surface cooling or a water jacket was employed; the outlet temperature was maintained at $T \leq 30$ °C to avoid confounding by thermal inactivation.

3. Experimental Design and Factors

Design. A full factorial or central composite design within a response-surface methodology (RSM) framework was used to investigate the following factors:

- UV dose (H): ≈10, 30, 60 mJ/cm², computed from the radiometer-derived effective irradiance and exposure time ($H = I_{eff} \times t$).
- US power density (q_US): ≈0.5, 1.5, 3.0 W/cm², determined from the transducer power and the sonicated area.
- Residence time (t): ≈0.3, 1.0, 3.0 s, given by reactor volume and flow rate ($t = V/Q$).
- Flow rate (Q): adjusted to achieve the target contact times.
- Sequencing: US→UV and UV→US.

Control groups:

1. Untreated control (pump flow only);

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2. UV-only (UV-C irradiation only);
3. US-only (ultrasound cavitation only);
4. UV+US (combined mode).

Each condition was run with ≥3 replicates, and experiments were randomized.

4. Procedures

Inoculation. Under aseptic conditions, *E. coli* was spiked into the water samples, mixed, and immediately fed into the reactor.

Disinfection. Tests were conducted at the target values of flow rate (Q), US power density ($q_{(US)}$), and UV dose (H). In-reactor UVC intensity was calibrated with a radiometer, and the delivered dose was calculated ($H = I_e ff \times t$), accounting for $UVT_{(254)}$ over a 0–10 cm path length.

Sampling. Influent (N_0) and effluent (N) samples were collected in sterile containers; for each condition, at least three independent runs over time were performed.

Microbiological enumeration.

- *E. coli:* membrane filtration (0.45 μm) → selective medium → incubation at 37 ± 1 °C for 24 h → results reported as CFU/mL.
- TMC (HPC): plating on appropriate media → incubation at 22 °C for 72 h and/or 37 °C for 48 h → CFU/mL.

Regrowth assay. Disinfected water was stored in the dark at 22 ± 2 °C for 24/48/72 h, after which TMC (HPC) was re-measured.

Physicochemical measurements. pH, turbidity (NTU), $UVT_{(254)}$, and temperature (T) were monitored; temperature increases under US operation were recorded.

5. Statistical Analysis

After testing for normality (Shapiro–Wilk) and homogeneity of variances (Levene's test), data were analyzed using one- or two-way ANOVA with Tukey's HSD post-hoc comparisons ($\alpha = 0.05$). For LR and EPL, regression (or RSM) models were fitted to assess main effects and interactions (UV×US, UV×t, US×t). Results are reported as mean ± SD with 95% confidence intervals.

6. Quality Assurance and Calibration

UVC source. Lamps were allowed to stabilize for 10–15 min prior to operation; the radiometer was verified each test day against a calibration source.

US transducer. Output power and frequency were verified against the manufacturer's specifications and with an external power meter.

Controls. "Blank" (sterile) and "positive" (known-concentration) control samples were monitored for recovery and potential contamination.

Process monitoring. For every series, changes in turbidity (NTU), $UVT_{(254)}$, and temperature (T) were recorded and correlated with LR outcomes.

7. Safety Requirements

Biosafety. Biosafety Level 2 (BSL-2) practices were followed; spent liquids and consumables were autoclaved (121 °C, 15 psi, ≥20 min).

UVC safety. A light-tight enclosure, interlock switch, and eye/skin protection (UV-rated goggles, gloves) were mandatory.

Acoustic safety. During operation of the US module, noise and vibration were controlled; hearing protection and mechanical reinforcement measures were implemented.

8. Criteria for Comparing Results

Performance benchmarks. The combined mode's LR, synergy index (SI), and EPL are compared against **UV-only** and **US-only**. *(SI is reported as the difference index, $S = LR_{UV+US} - (LR_{UV-only} + LR_{US-only})$, and/or the fractional index, $FS = LR_{UV+US}/(LR_{UV-only} + LR_{US-only})$.)*

Operating window. Identify parameter ranges that deliver robust ≥2–3 $\log_{10}$ reduction of *E. coli* at low EPL under varying turbidity (NTU) and $UVT_{(254)}$.

Sequencing effect. Analyze differences in LR and SI between **US→UV** and **UV→US** configurations.

Regrowth. Assess post-treatment stability from TMC dynamics over 24–72 h (degree of regrowth delay or prevention).

RESULTS.

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1. Stability of reactor and operating regimes

UV intensity ($I_e$ff) remained stable within ±7% over the test period; after a 10–15 min lamp warm-up, deviations became minimal.

Mapping of the US acoustic field (35–45 kHz) showed cavitation-zone uniformity within ±8%, positioned as close as possible to the UVC active region of the reactor.

Under US operation, the temperature rise did not exceed 2–3 °C; the outlet temperature was kept at $T \leq 30$ °C, so thermal inactivation was excluded.

2. E. coli and TMC inactivation

UV-only ($H \approx 30$ mJ/cm², $t \approx 1.0$ s): 2.1 ± 0.3 $\log_{10}$ reduction for *E. coli*; 1.2 ± 0.2 log for TMC.

US-only (q_{US} ≈ 1.5 W/cm², $t \approx 1.0$ s): 0.6 ± 0.1 log for *E. coli*; 0.3 ± 0.1 log for TMC.

UV+US (US→UV, $H \approx 30$ mJ/cm², q_{US} ≈ 1.5 W/cm², $t \approx 1.0$ s): 3.5 ± 0.2 log for *E. coli*; 2.2 ± 0.3 log for TMC; synergy index (SI) = +0.8 ± 0.2 log.

At increased dose ($H \approx 60$ mJ/cm², q_{US} ≈ 3.0 W/cm², $t \approx 1.0$ s), *E. coli* reductions reached ≥4.5–5.0 log (below detection in some series).

The combined (sono-photo) mode significantly outperformed single modalities (ANOVA, $p < 0.05$).

3. Sequencing effect

The US→UV sequence yielded ~0.4 log higher LR for *E. coli* than UV→US ($p < 0.05$), consistent with US weakening cell envelopes and enhancing access for UV-induced photodynamic/DNA damage.

4. Effect of flow rate and contact time (t)

$t \approx 0.3$ s: 1.4–1.8 log (*E. coli*) with UV+US.

$t \approx 1.0$ s: 3.2–3.6 log (*E. coli*), 2.0–2.3 log (TMC).

$t \approx 3.0$ s: further gains observed, but EPL (kWh·m^{-3}·log^{-1}) worsened slightly; from an energy-efficiency standpoint, $t \approx 0.8$–1.2 s was selected as the optimal range.

5. Influence of water properties (UVT_{254} and turbidity)

At $UVT_{254} \geq 85\%$ and NTU ≤ 1, UV-only achieved ≥2 log, while UV+US reached ~3.5 log.

At NTU ≈ 5–10, UV-only efficiency declined by ~25–35%, whereas UV+US maintained ~2.5–3.0 log ($p < 0.05$).

With increasing turbidity, US-induced microstreaming and coagulation partially compensated for "shadowing" effects.

6. Energy metrics (EPL) and savings

For a 3-log target: EPL_{UV-only} ≈ 0.045 kWh·m^{-3}·log^{-1}; EPL_{UV+US} ≈ 0.031 kWh·m^{-3}·log^{-1}.

This corresponds to up to ~30% energy savings ($t \approx 1.0$ s, $H \approx 30$ mJ/cm², q_{US} ≈ 1.5 W/cm²).

7. Regrowth control

After disinfection and dark storage at 22 ± 2 °C for 24/48/72 h:

UV-only: TMC increased by +0.5 ± 0.2 / +0.8 ± 0.2 / +1.1 ± 0.3 log.

UV+US: held at +0.2 ± 0.1 / +0.3 ± 0.1 / +0.3 ± 0.2 log; regrowth was markedly slowed ($p < 0.01$).

This is likely attributable to additional sublethal damage and decreased dispersed biofilm due to US.

8. Optimal operating "window"

The following ranges balanced performance and energy use: $H \approx 30$–40 mJ/cm², q_{US} ≈ 1.0–2.0 W/cm², $t \approx 0.8$–1.2 s, US→UV sequencing. Under these conditions:

E. coli: ≥3–4 log; **TMC**: ≥1.8–2.5 log;

SI: +0.6…+1.0 log; **EPL**: ~25–35% lower than UV-only.

Table 1. Typical parameters and results (mean ± SD, n ≥ 3)

Operating mode	H (mJ/cm²)	q_{US} (W/cm²)	t (s)	LR (E. coli, log)	LR (TMC, log)	SI (log)	EPL (kWh·m^{-3}·log^{-1})
UV-only	30	–	1,0	2,1 ± 0,3	1,2 ± 0,2	–	0,045
US-only	–	1,5	1,0	0,6 ± 0,1	0,3 ± 0,1	–	0,067*

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UV+US (US→UV)	30	1,5	1,0	3,5 ± 0,2	2,2 ± 0,3	+0,8 ± 0,2	0,031
UV+US (UV→US)	30	1,5	1,0	3,1 ± 0,3	1,9 ± 0,3	+0,4 ± 0,2	0,033
UV+US (extended mode)	60	3,0	1,0	≥4,5	≥3,0	+0,9 ± 0,2	0,036

* For the **US-only** condition, EPL is reported for comparability (based solely on US power input); in practical applications, a standalone US mode is **not** recommended for disinfection.

The combined UV–US device achieved high $\log_{10}$ reductions of *E. coli* and TMC at short contact times, markedly suppressed regrowth, and reduced energy consumption. The US→UV sequence, a moderate UV dose (≈30–40 mJ/cm²), and a moderate US power density (≈1.0–2.0 W/cm²) were identified as the most practical operating conditions. These results provide a basis for deploying a robust, reagent-free disinfection technology in small- and medium-capacity drinking-water systems.

DISCUSSION

Nature of the synergistic effect. In this study, the UV+US combination outperformed the single modes (an additional +0.6…+1.0 $\log_{10}$ reduction for *E. coli*). The main contributing mechanisms are interpreted as follows:

Cavitation and microstreaming. Collapse of US-induced bubbles mechanically weakens the cell envelope, reduces hydraulic "shadow zones," and improves target accessibility for UV photons.

Sonoporation-like effect. Transient increases in membrane permeability facilitate deeper UV photochemical damage.

Localized oxidative phenomena. Short-lived radicals (e.g., •OH) may form within cavitation hotspots; although their overall contribution in drinking-water matrices is limited, they can add sublethal injuries that potentiate UV efficacy.

As a result, high log-reductions were achieved even at short contact times, and regrowth was markedly slowed.

Sequencing advantage (US→UV). Experimental results indicated that US→UV was more favorable than UV→US by ~0.4 log for *E. coli* ($p < 0.05$). Applying US first (i) partially disperses biofilm and agglomerates, lowering UV scattering; (ii) weakens the cell wall, enabling deeper DNA/RNA-level photodamage by UV; and (iii) reduces regrowth risk by further disrupting cellular recovery pathways.

Matrix effects: turbidity and UVT. As turbidity increased (NTU ≈ 5–10), UV-only performance declined, whereas UV+US partially compensated for "shadowing" and sustained ~2.5–3.0 log reduction. This underscores the practical value of the combination for small/local networks and moderately turbid waters. Nevertheless:

At very high NTU, **pre-treatment** (coagulation/filtration) remains necessary;

Optimal outcomes were obtained at **$UVT_{(254)} \geq 85\%$**; declining UVT requires adjusting the UV dose.

Energy efficiency and the operating "window."

An EPL gain of ~25–35% was observed: adding US allowed moderation of the UV dose, thereby lowering $kWh \cdot m^{-3} \cdot log^{-1}$ overall. A practical balance was found at **H ≈ 30–40 mJ/cm², q_{US} ≈ 1.0–2.0 W/cm², t ≈ 0.8–1.2 s, US→UV**, which delivered ≥3–4 log (*E. coli*) and ≥1.8–2.5 log (TMC) and allowed adaptation of the device to small- and medium-capacity applications. From an energy perspective, **diminishing returns** were evident for $q\_\{US\} > 2.0$ W/cm²: incremental log gains were small while heat and noise increased.

Regrowth control: advantage of the combination.

With UV-only, TMC regrowth over 24–72 h was evident; with UV+US, regrowth slowed by up to **threefold**. Likely mechanisms include (i) a higher burden of sublethal injuries (membranes and internal structures) and (ii) reduced re-colonization due to biofilm fragmentation and altered microenvironments. That said, the absence of a residual disinfectant in distribution systems with long conveyance distances can pose risks; therefore, **very low chloramine residuals** (or tight operational hygiene alongside UV+filtration) may be considered.

Operation and maintenance considerations.

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Quartz sleeve fouling depresses delivered UV dose; routine mechanical/chemical cleaning and UVT monitoring are required.
Acoustic regime monitoring (frequency, transducer coupling) helps ensure cavitation uniformity.
Temperature and vibration control: keeping US-induced ΔT to ~2–3 °C minimizes thermal confounding.
Hydraulics: baffles and guide vanes that enhance mixing **narrow the RTD**, directly affecting the "effective" UV dose received.
Limitations and future work.
This study focused on *E. coli* and TMC; broader testing is needed for **viruses** (e.g., MS2), **spores**, and **protozoan cysts** (*Giardia/Cryptosporidium*).
Long-term (months/quarters) operation should document lamp aging, transducer stability, and seal durability.
With respect to **DBPs**, UV+US generally entails low risk due to the absence of added chemicals, but potential **sonochemical** secondary effects warrant analytical verification.
Life-cycle cost (LCC) and cost–effectiveness analyses are needed to optimize configurations for small-town/rural systems.
Practical recommendations (brief).
Prefer **US→UV** sequencing; place the UV lamp near the flow axis in a geometry that minimizes shadowing.
Operating window: H = 30–40 mJ/cm², $q\_\{US\}$ = 1.0–2.0 W/cm², t = 0.8–1.2 s; monitor $UVT_{(254)}$ online.
If **NTU > 5**, add simple pre-treatment (coagulation/filtration).
In long distribution networks with regrowth risk, pair with a **low residual** or enforce strict sanitation (e.g., periodic tank/collector cleaning).
Maintenance: routinely clean the quartz sleeve; perform radiometric/acoustic calibration on a defined schedule.
Conclusion. Integrating UV and US in a flow-through configuration enabled rapid, robust, and energy-efficient disinfection of drinking water. Mutual reinforcement between mechanical (US) and photochemical (UV) processes achieved required log-reductions under modest conditions and reduced regrowth risk. This approach is ready for practical deployment as a **reagent-free, sustainable** technological platform for small- and medium-capacity systems.

CONCLUSIONS

1. The UV+US combination provided clear advantages over UV-only or US-only for drinking-water disinfection: ≥3–4 $\log_{10}$ reduction for *E. coli* and ≥1.8–2.5 log for TMC at short contact times ($t \approx$ 0.8–1.2 s); the synergy index (SI) typically ranged from +0.6 to +1.0 log.
2. In terms of energy performance, at a 3-log target the UV+US mode required ~25–35% lower EPL ($kWh \cdot m^{-3} \cdot log^{-1}$) than UV-only, which can reduce operating costs in small- and medium-capacity systems.
3. Regarding sequencing, **US→UV** delivered ~+0.4 log higher reduction than **UV→US**, attributable to cavitation and microstreaming that improve access for UV photodamage.
4. The recommended operating window is $H \approx$ 30–40 mJ/cm², $q\_\{US\} \approx$ 1.0–2.0 W/cm², $t \approx$ 0.8–1.2 s; this range sustains synergy while limiting excess power consumption.
5. For regrowth control, UV+US slowed bacterial rebound over 24–72 h by up to threefold, likely due to a higher burden of sublethal injuries and biofilm dispersion.
6. Under matrix effects (turbidity NTU ≈ 5–10 and reduced UVT_{254}), UV-only efficacy declined sharply, whereas UV+US partially compensated for "shadowing" and maintained stable performance. Nonetheless, at high NTU, simple pre-treatment (coagulation/filtration) is required.
7. From an O&M standpoint, quartz-sleeve cleanliness, UVC intensity monitoring, stable operation of the US transducer, and maintaining temperature at $T \leq$ 30 °C are critical for consistent results.
8. Safety measures were strictly observed: UVC shielding and interlocks, along with acoustic safety protocols (vibration/noise control).
9. Practical significance: the combined reactor is a reagent-free, compact, and energy-efficient solution, particularly suitable for areas with challenging chlorine logistics, local distribution networks, and modular systems.

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10. Limitations and future work: extended testing with viruses (MS2), spores, and protozoan cysts; long-term (monthly/quarterly) reliability; monitoring of potential sonochemical secondary effects on DBPs; pilot trials at **1–5 $m^3 \cdot h^{-1}$**, hydraulic/RTD assessment in real networks, and life-cycle cost (LCC) / cost–effectiveness analyses.

Overall conclusion. Integrating UV and US in a single housing enabled rapid, robust, and energy-efficient disinfection of drinking water. In the US→UV sequence with moderate UV dose and US power density, high log-reductions were achieved alongside markedly suppressed regrowth. The results indicate that the technology is mature for practical deployment in small- and medium-capacity systems.

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