

## Sustainable Fabrication of Alkali-Treated Aluminum Foil Using Agricultural Fertilizers for Filter-Free *Escherichia coli* Removal in Drinking Water

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### Abstract

Microbiological contamination of drinking water by *Escherichia coli* remains a major public health hazard in resource-limited settings. Conventional adsorptive technologies that utilize powdered materials pose post-treatment recovery challenges, whereas synthesis using analytical-grade chemicals is economically infeasible for point-of-use (POU) applications. Herein, we report a sustainable strategy for fabricating Alkali-Treated Aluminum Foil (ATA foil) as an integrated, filter-free sheet from commercial aluminum foil and agricultural fertilizers ( $\text{Mg}(\text{NO}_3)_2$  and wood ash extract). The influence of activation duration (6 h vs. 24 h) on phase transformation, surface topography, and bacterial capture performance was systematically investigated. X-ray diffraction (XRD) revealed that moderate synthesis pH (9.3) favored the formation of a disordered, amorphous aluminum (oxy)hydroxide active coating rather than crystalline Layered Double Hydroxides (LDH). Scanning Electron Microscopy (SEM) confirmed that extending activation to 24 h formed an interconnected, porous web across the surface. In batch assays, the 24-h ATA foil achieved a rapid and substantial reduction of culturable *E. coli* (from  $10^2$  CFU/mL to below the detection limit of  $< 1$  CFU/mL, corresponding to  $> 99\%$  efficiency) within 24 h in both synthetic water and real refill drinking water depot samples. The captured bacteria remained stably immobilized without desorption for up to 168 h. Atomic Absorption Spectrometry (AAS) confirmed non-detectable dissolved aluminum leaching ( $< 0.01$  mg/L), complying strictly with WHO and national drinking water standards (0.2 mg/L). This study highlights the ATA foil as a safe, cost-effective, and filter-free POU alternative for decentralized drinking water safety.

### Keywords

Amorphous Aluminum Oxyhydroxide, ATA Foil, *Escherichia coli*, Filter-Free Adsorption, Green Precursor, Point-of-Use Disinfection

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## 1. INTRODUCTION

Access to biologically safe drinking water is a fundamental prerequisite for human health and sustainable development (Arora and Mishra, 2022; Ejiohuo et al., 2025; Li et al., 2026). Nevertheless, microbial contamination predominantly driven by enteric pathogens such as *Escherichia coli* (*E. coli*) remains a major public health hazard worldwide (Gaur et al., 2026). Diarrheal diseases caused by contaminated water account for approximately 1.7 billion cases annually, representing a leading cause of morbidity and mortality in developing nations (World Health Organization, 2023). In regions where centralized water distribution systems are unreliable or non-existent, communities rely heavily on decentralized sources such as household storage and refill drinking water depots (Afonso et al., 2025; Nduli et al., 2025; Syahrir et al., 2026). However, water quality at these points of consumption frequently degrades due to inadequate local sanitation

infrastructure, improper storage, and contamination from secondary handling (Syahrir et al., 2026). This critical gap underscores the urgent necessity for decentralized point-of-use (POU) drinking water disinfection technologies that are accessible, effective, and safe for immediate household implementation.

To address microbial hazards at the household level, various POU treatment strategies have been developed, including boiling, chlorination, solar disinfection (SODIS), and ceramic filtration (Ihsan and Derosya, 2024). Although these methods offer decentralized alternatives to central plants, their real-world deployment is hampered by operational and safety drawbacks. Thermal boiling requires significant energy, chlorination can produce hazardous carcinogenic disinfection by-products (DBPs), and solar methods rely heavily on specific climatic conditions. In parallel, active aluminum-based electrochemical technologies, such as elec-

trocoagulation, have demonstrated strong capabilities for water purification, remediation of aquaculture effluents, and pathogen abatement (Abdul Rahman et al., 2026). However, electrocoagulation systems inherently require external electric power, continuous voltage regulation, and routine maintenance to counteract severe electrode fouling and anodic passivation, particularly in complex rural or brackish water environments (Abdul Rahman et al., 2025). These operational prerequisites make active electrochemical systems challenging to deploy for off-grid household-level batch water storage. In response, adsorptive inactivation utilizing functionalized inorganic materials has emerged as a promising alternative owing to its low energy requirement and operational simplicity. Specifically, aluminum (hydro)oxide-based compounds and Layered Double Hydroxides (LDHs) exhibit a strong electrostatic affinity toward the negatively charged lipopolysaccharide outer membranes of Gram-negative bacteria such as *E. coli*, facilitating effective microbial capture (Forano et al., 2018).

Despite these technical advantages, traditional adsorptive water treatment faces two major bottlenecks that limit practical field adoption. First, the vast majority of synthesized adsorbents are prepared as fine powders. Fine particles are difficult to remove from treated water and require secondary filtration or centrifugation to prevent ingestion by consumers. Second, conventional fabrication protocols depend heavily on analytical-grade chemical precursors (such as pure NaOH,  $\text{MgCl}_2$ , or  $\text{Al}(\text{NO}_3)_3$ ), which elevates production costs and creates supply chain dependencies that are unviable for resource-constrained or disaster-prone communities. Recent advances in functionalized media, such as polymer foams impregnated with nanocomposites (e.g., polysilicone coated with chitosan-nanosilver), have shown effective bacterial elimination in decentralized drinking water systems (Nisah et al., 2025). However, complex synthesis pathways and potential leaching of active nanoparticles during continuous filtration remain notable considerations. Addressing these structural and economic constraints requires developing integrated, sheet-form adsorbents synthesized from low-cost, locally accessible precursors, specifically tailored for passive, static household water storage rather than for pressurized, instantaneous filtration.

To bridge this research gap, this study offers a novel, sustainable strategy for engineering Alkali-Treated Aluminum Foil (ATA foil) as a filter-free, solid-sheet disinfectant. While previous exploratory studies established the baseline feasibility of modified aluminum surfaces using alkalized seawater or analytical-grade alkaline solutions, the novelty of the present work lies in the development of an entirely circular, fertilizer-assisted *in situ* synthesis protocol. By pairing commercial aluminum foil (which serves as both an active aluminum source and a durable structural support) with commercial agricultural-grade  $\text{Mg}(\text{NO}_3)_2$  and biomass-derived wood ash extract, we eliminate reliance on hazardous synthetic alkalis (such as analytical NaOH) and expensive chemical reagents.

Crucially, the natural buffering action of the wood ash extract establishes a self-regulating synthesis pH ( $\sim 9.3$ ) that selectively drives the room-temperature growth of an active, amorphous oxyhydroxide fibrous web directly on the foil surface, bypassing the need for energy-intensive hydrothermal crystallization. This ambient, low-temperature synthesis, using bulk fertilizer and waste biomass, substantially reduces raw-material overhead compared to analytical-grade chemical routes. This paper systematically investigates the structural evolution, phase transformation, and surface morphology of the foil across different activation durations (6 h vs. 24 h). Furthermore, the disinfection performance and binding stability are evaluated using both synthetic-inoculated water and naturally contaminated refill depot water. At the same time, chemical leaching safety is rigorously verified by atomic absorption spectrometry to ensure strict compliance with drinking water quality standards.

## 2. EXPERIMENTAL SECTION

### 2.1 Materials

Commercial aluminum foil (Cheffy, PT Altindo Mulia, Indonesia) was utilized as the primary metallic substrate and internal aluminum source. Agricultural-grade magnesium nitrate fertilizer ( $\text{Mg}(\text{NO}_3)_2$ , PT Saprotan Benih Utama, Indonesia) and commercial wood ash fertilizer (Tuturanugraha Mandiri, Indonesia) were obtained locally as low-cost, green chemical precursors. The alkaline extraction bath was prepared by dissolving 2.5 g of wood ash fertilizer in 1 L of deionized water, yielding a strongly basic solution with a pH of 10.0–12.0. A precursor salt solution of  $\text{Mg}(\text{NO}_3)_2$  (0.05 M, equivalent to 12.8 g/L) was prepared in deionized water.

For artificial water inoculation, pure-culture strains of *Escherichia coli* (*E. coli* ATCC 25922), maintained at a stock concentration of  $10^8$  CFU/mL, were employed. Microbiological culture media consisted of Eosin Methylene Blue (EMB) Agar (Merck, Germany), a selective and differential medium utilized specifically for the isolation, identification, and selective enumeration of *E. coli*.

Real drinking water matrix evaluations were performed using refill drinking water collected from a commercial food service facility in Padang, West Sumatra, Indonesia. The sample represents refill-depot water used in food preparation and storage, reflecting real-world post-distribution contamination risks during handling and storage. The baseline physicochemical characteristics of this water matrix were systematically measured prior to treatment: pH  $7.3 \pm 0.1$ , temperature  $25 \pm 1$  °C, electrical conductivity (EC)  $142 \pm 3.5$   $\mu\text{S}/\text{cm}$ , total dissolved solids (TDS)  $71 \pm 2.0$  mg/L, and turbidity  $0.85 \pm 0.08$  NTU, containing a natural background *E. coli* count of approximately  $\pm 80$  CFU/mL.

## 2.2 Methods

### 2.2.1 Fabrication of ATA Foil

The synthesis of Alkali-Treated Aluminum Foil (ATA foil) was performed via a two-step surface-modification process under ambient laboratory conditions. Initially, commercial aluminum foil sheets were cut into uniform square coupons measuring  $4 \times 4$  cm ( $16 \text{ cm}^2$  total exposed surface area). In the pre-treatment phase, the foil coupons were immersed in 100 mL of the prepared alkaline wood ash solution (pH > 10) at room temperature for 5 minutes. This controlled etching step partially dissolved the passive native  $\text{Al}_2\text{O}_3$  surface film, exposing reactive underlying metallic aluminum sites. Following oxide etching, the functional active layer was grown by transferring the etched foil coupons into a reaction mixture comprising 100 mL of 0.05 M  $\text{Mg}(\text{NO}_3)_2$  solution and 35 mL of alkaline wood ash extract, yielding a stable synthesis mixture pH of 9.3. Immersive aging was conducted at room temperature for two reaction times, 6 and 24 hours, to evaluate the structural maturation of the active coating. The fabricated materials, designated as ATA Foil-6h and ATA Foil-24h, were retrieved, thoroughly washed with deionized water to remove nonadhered species, and then dried at ambient conditions prior to characterization and performance testing.

### 2.2.2 Material Characterization Techniques

Crystallographic phase analysis was conducted via X-ray Diffraction (XRD; Bruker D8 Advance, Germany) using  $\text{Cu K}\alpha$  radiation ( $\lambda = 1.5406 \text{ \AA}$ ), with a  $2\theta$  scan range of  $10^\circ$ – $40^\circ$  and a step size of  $0.028^\circ$ . Surface microtopography, pore architecture, and active layer development were examined using Scanning Electron Microscopy (Carl Zeiss EVO 10, Germany) at accelerating voltages of 8.0–10.0 kV and magnifications up to  $100,000\times$ . Semi-quantitative mapping of surface elemental composition and spatial distribution was performed using Energy-Dispersive X-ray Spectroscopy (EDX) integrated directly with the SEM system.

### 2.2.3 Batch Disinfection Assays and Desorption Testing

Bacterial disinfection experiments were carried out in batch mode in sterile glass reactors, agitated on an orbital shaker at 80 rpm at ambient temperature. For controlled trials in a synthetic water matrix, deionized water was inoculated with *E. coli* stock culture to establish a standardized initial cell density of approximately  $10^2$  CFU/mL. Specifically, overnight bacterial cultures grown in nutrient broth were harvested, washed twice with sterile saline solution (0.9% NaCl), and diluted to an optical density ( $\text{OD}_{600}$ ) corresponding to a target cell density of  $\sim 10^2$  CFU/mL, representative of typical fecal contamination levels in unmanaged water sources.

Square coupons ( $4 \times 4$  cm, total exposed geometric area of  $16 \text{ cm}^2$ ) of ATA Foil-6h and ATA Foil-24h were individually placed into 100 mL inoculated samples, establishing

a standardized material surface area-to-water-volume ratio of  $0.16 \text{ cm}^2/\text{mL}$  ( $160 \text{ cm}^2/\text{L}$ ). Experimental reactors were tested alongside two distinct negative controls: (i) an untreated, unactivated commercial aluminum foil coupon to evaluate non-specific baseline attachment on native metallic aluminum, and (ii) an inoculated water reactor without foil to monitor spontaneous settling or natural bacterial die-off.

Aliquots (1 mL) were withdrawn at contact time intervals of 0 h, 3 h, and 24 h. For real water matrix validation, naturally contaminated refill drinking water collected from a food service facility (with an initial baseline concentration of approximately 80 CFU/mL *E. coli*) was treated with the optimized ATA Foil-24h under identical contact times. Evaluating water at the point of use in a catering setting is highly representative of practical field conditions, where secondary microbial contamination frequently occurs during transportation and storage rather than solely at the production source.

To verify long-term immobilization stability and eliminate the risk of bacterial detachment or regrowth, treated water systems were monitored for up to 168 hours (7 days). Bacterial survival was quantified using the Colony Forming Unit (CFU) total plate count method following national standard procedures (SNI 2897:2008) after 24 hours of incubation at  $37^\circ\text{C}$ . Aliquots of 1.0 mL were plated on selective EMB agar in triplicate, defining an analytical limit of detection (LOD) of 1 CFU/mL (100 CFU/mL). Samples yielding zero visible colonies were recorded as  $< 1$  CFU/mL.

All batch disinfection experiments were conducted in triplicate, and results were expressed as mean values  $\pm$  standard deviation. Statistical significance among experimental groups (blank control, untreated foil, ATA Foil-6h, and ATA Foil-24h) was evaluated using one-way Analysis of Variance (ANOVA) followed by two-sample *t*-tests for pairwise comparisons. Differences were considered statistically significant at  $p < 0.05$ , and all statistical computations were performed using Microsoft Excel 2019 (Microsoft Corp., USA).

### 2.2.4 Post-Treatment Metal Leaching Evaluation

To confirm chemical safety and ensure that the functional surface layer remains intact during operational contact, treated water samples (100 mL exposed to  $16 \text{ cm}^2$  ATA foil for 24 h) were collected for dissolved metal analysis. Dissolved aluminum ( $\text{Al}^{3+}$ ) concentrations were measured via Atomic Absorption Spectrometry (AAS, Shimadzu AA7000, Japan) in accordance with standard water testing methods (SNI 6989.34:2009). The analytical results were evaluated against the maximum allowable threshold of 0.2 mg/L stipulated by WHO guidelines and Indonesian drinking water quality standards (Ministry of Health of the Republic of Indonesia, 2023).

### 3. RESULTS AND DISCUSSION

#### 3.1 Structural and Morphological Evolution of ATA Foil

##### 3.1.1 Phase Identification

Figure 1 presents the XRD patterns of ATA Foil-6h and ATA Foil-24h. Both samples exhibit intense, sharp diffraction reflections at  $2\theta \approx 17^\circ$  and  $38^\circ$ – $39^\circ$ , corresponding to the underlying metallic aluminum substrate (Al). Remarkably, characteristic basal reflections of crystalline MgAl hydrotalcite/LDH structures typically expected at  $2\theta \approx 11.5^\circ$  (003) and  $23^\circ$  (006) were absent (Fukugaichi et al., 2022; Gama et al., 2022).

This crystallographic outcome is directly governed by the reaction chemistry: classic Mg–Al LDH precipitation requires a rigid, highly alkaline environment (pH 10.0–11.0) (Fukugaichi et al., 2022). Upon mixing the wood ash extract with  $\text{Mg}(\text{NO}_3)_2$ , the solution pH stabilized at 9.3 due to buffering effects. Under this moderate pH, co-precipitation of  $\text{Mg}^{2+}$  and  $\text{Al}^{3+}$  into structured LDH layers was restricted (Ihsan et al., 2025). Instead, hydroxide ions ( $\text{OH}^-$ ) etched the native  $\text{Al}_2\text{O}_3$  layer, inducing local dissolution-reprecipitation that yielded an amorphous aluminum oxyhydroxide ( $\text{AlOOH}/\text{Al}(\text{OH})_3$ ) surface phase (Cheng et al., 2021; Fukugaichi et al., 2024b), evidenced by the elevated, diffuse background profile between  $2\theta = 20^\circ$ – $35^\circ$ . Extending aging time to 24 h slightly sharpened the amorphous envelope features, indicating structural consolidation of the active oxyhydroxide layer. The structural assignment of this amorphous layer is further corroborated by the short-range coordination of disordered  $\text{AlO}_6$  octahedral units containing bridging oxo (Al–O–Al) and terminal hydroxyl (Al–OH) moieties, which typically lack long-range periodic lattice order while retaining a high density of reactive proton-accepting surface sites (Fukugaichi et al., 2024b; Johan et al., 2023). Compared to conventional protocols that employ strong analytical alkalis, which cause rapid, uneven metal pitting, the milder buffering capacity of the fertilizer-derived wood ash extract facilitates a controlled, continuous etching-reprecipitation cascade at ambient temperature, producing an active surface without requiring handling corrosive reagents or post-synthesis thermal activation.

##### 3.1.2 Surface Topography

Scanning Electron Microscopy (SEM) imaging revealed a dramatic morphological transition on the foil surface driven by the activation duration (Figure 2 and 3). Upon 6 hours of activation (Figure 2a), the foil surface remained relatively dense, compact, and featureless, accompanied by minor dispersed surface aggregates. At this early stage, the alkaline etching process was beginning, forming localized shallow surface pits rather than deep, interconnected porous networks (Johan et al., 2023). In stark contrast, extending the activation duration to 24 hours induced a profound topographical evolution, transforming the foil surface into a well-developed, highly porous, web-like network (Figure

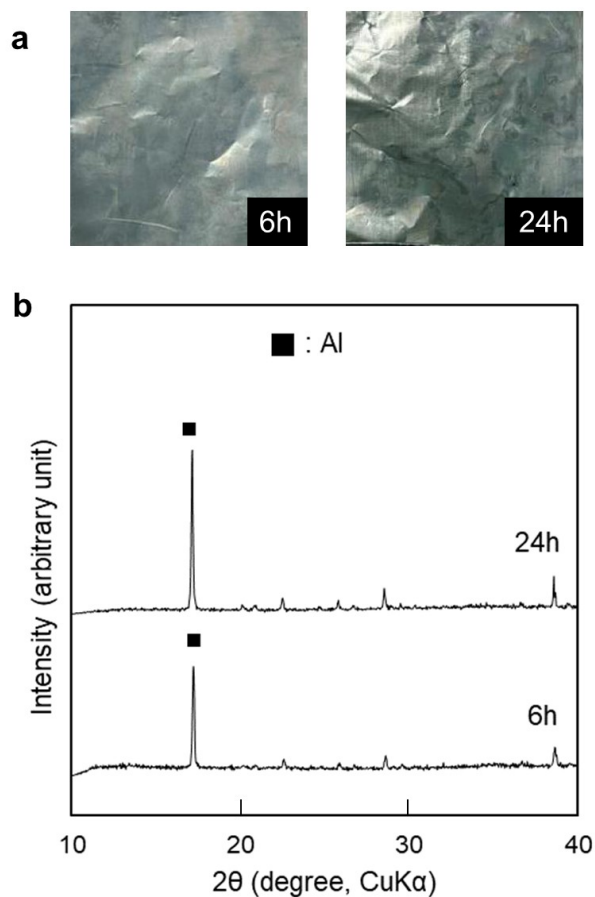


**Figure 1.** (a) The Physical Surface Changes of Commercial Aluminum Foil After 6 H and 24 H Alkali-Treatment; (B) X-Ray Diffraction (XRD) Patterns of ATA Foil-6h and ATA Foil-24h

2b). Prolonged exposure to the alkaline synthesis mixture facilitated continuous local dissolution of  $\text{Al}^{3+}$  cations from the metallic aluminum matrix, followed by localized reprecipitation of amorphous oxyhydroxide fibers (Fukugaichi et al., 2024b). This multi-porous, interconnected architecture greatly increases the exposed specific surface area and provides abundant accessible hydroxyl (Al–OH) functional groups (Ihsan and Bachtiar, 2026).

This morphological progression is strongly supported by the semi-quantitative Energy Dispersive X-ray Spectroscopy (EDX) elemental mapping results (Figures 2b, 2c, 3b, and 3c). As shown in the representative EDX spectra, the surface composition of ATA Foil-24h was heavily dominated by aluminum (75.20 wt%, 59.40 atomic%) and oxygen (7.72 wt%, 10.28 atomic%), confirming the growth and maturation of an oxygen-rich inorganic hydroxide active layer. Significantly, the atomic proportion of oxygen surged nearly 3.5-fold rising from 2.87 atomic% (2.77 wt%) at 6 hours (Figure 2c) to 10.28 atomic% at 24 hours (Figure 3c) demonstrating

progressive surface hydroxylation and condensation of the amorphous oxyhydroxide matrix over time. This marked increase in surface-bound oxygen atoms reflects the systematic proliferation of hydroxyl (Al–OH) and oxo (Al–O) functional linkages formed during the dissolution-precipitation cascade, providing the chemical foundation for electrostatic protonation under circumneutral aquatic conditions. Furthermore, a substantial decrease in surface carbon content was observed, declining from 48.51 wt% (67.12 atomic%) at 6 hours to 17.08 wt% (30.32 atomic%) at 24 hours. This marked reduction in detected carbon reflects the progressive coverage and masking of adventitious environmental carbon by the continuously growing, porous inorganic oxyhydroxide matrix

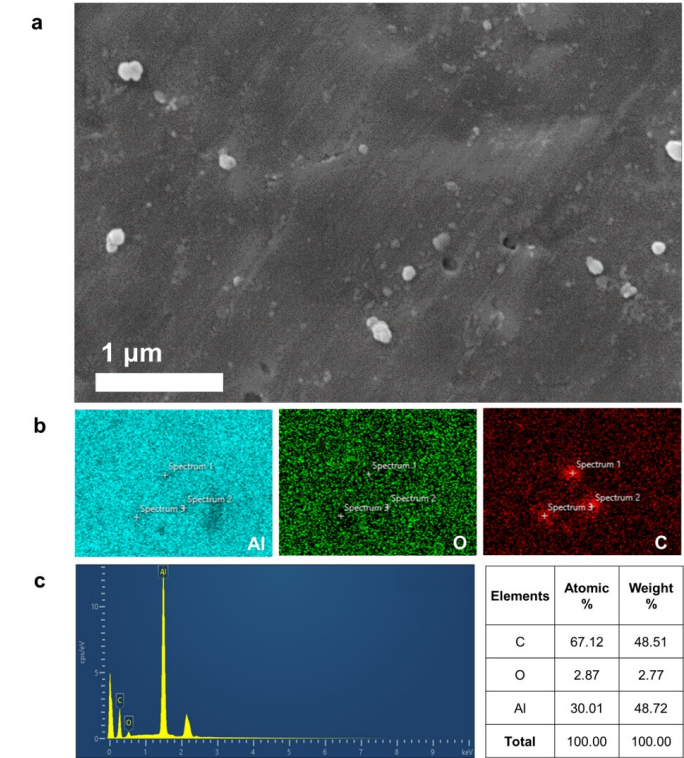


**Figure 2.** Surface morphological and elemental composition analysis of ATA Foil-6h: (a) SEM micro-topography; (b) elemental distribution mapping of Al, O, and C; (c) EDX spectrum and quantitative elemental composition table.

3.2 Batch Disinfection Assays and Desorption Testing

3.2.1 Performance in Controlled Synthetic Water Matrix

Batch disinfection assays conducted in synthetic water provided a clear baseline for evaluating the intrinsic bacterial capture efficiency of the functionalized foils under controlled conditions (Johan et al., 2023). Figure 4a illustrates the removal kinetics of *E. coli* starting from a standardized initial concentration of approximately 10<sup>2</sup> CFU/mL over

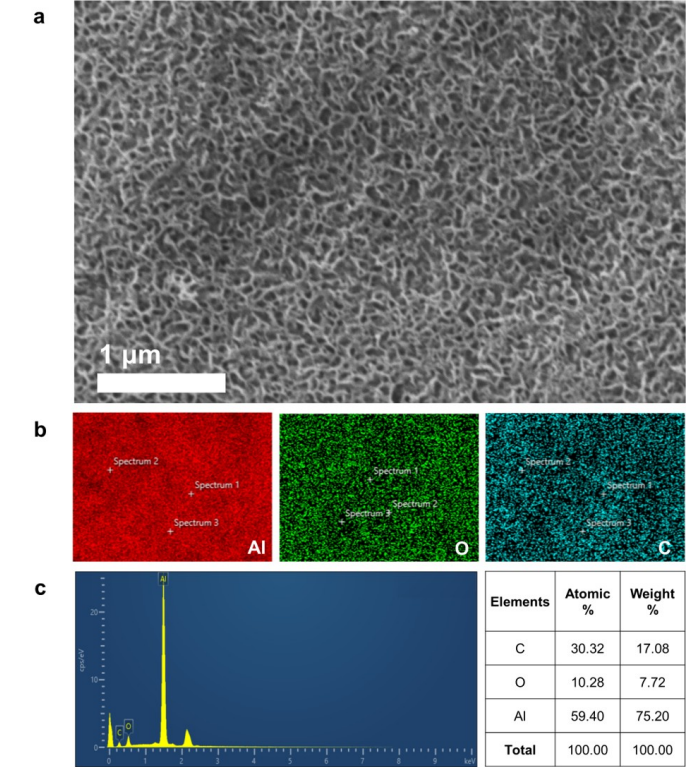


**Figure 3.** Surface morphological and elemental composition analysis of ATA Foil-24h: (a) SEM micro-topography; (b) elemental distribution mapping of Al, O, and C; (c) EDX spectrum and quantitative elemental composition table.

an extended exposure period of 168 hours (7 days). In the negative control system without the ATA foil, the bacterial population remained remarkably stable throughout the 168-hour monitoring window, fluctuating only between 1.15 × 10<sup>2</sup> and 1.44 × 10<sup>2</sup> CFU/mL. This persistence confirms that natural die-off or spontaneous settling in the unactivated aqueous medium was negligible, establishing that any observed reduction in bacterial density in the experimental reactors was directly attributable to interaction with the ATA foil materials. Similarly, reactors containing untreated commercial aluminum foil coupons exhibited negligible bacterial reduction (<5% removal over 24 h), maintaining viable counts at 1.10 - 1.25 × 10<sup>2</sup> CFU/mL, demonstrating that the native, smooth passivating Al<sub>2</sub>O<sub>3</sub> layer provides insufficient active sites and negligible microporosity for bacterial capture.

In contrast to the control, reactors containing ATA foil coupons demonstrated time-dependent reductions in bacterial counts, with the performance strongly influenced by the foil activation duration. The ATA Foil-6h material reduced the residual *E. coli* concentration to 2 ± 2.62 CFU/mL after 24 hours of contact, achieving an approximate removal efficiency of 98%. The ATA Foil-24h coupon exhibited superior performance, reducing culturable *E. coli* to below the

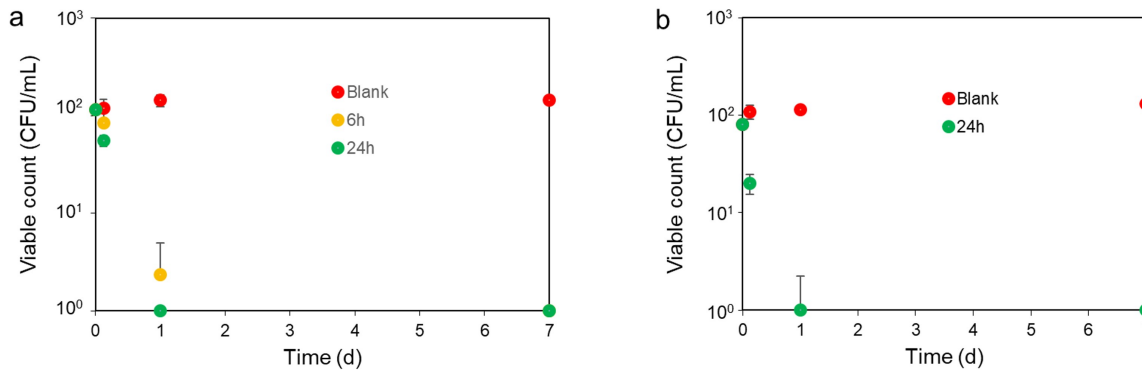


**Figure 4.** Viability of *E. Coli* as a Function of Contact Time Up to 7 Days (168 H): (A) Performance in Synthetic Water Inoculated With 10<sup>2</sup> CFU/mL *E. Coli*, Comparing Blank Control, ATA Foil-6h, and ATA Foil-24h; (B) Performance in Naturally Contaminated Commercial Food-Service Refill Drinking Water Matrix Treated With Optimized ATA Foil-24h Versus Blank Control. Data Represent Mean Values Standard Deviation N=3.

limit of detection (<1 CFU/mL; >99% removal efficiency) within 24 hours. One-way ANOVA confirmed statistically significant differences in residual bacterial counts among the treatment groups after 24 hours of contact ( $p < 0.001$ ). Pairwise comparisons further demonstrated that bacterial reductions by both ATA Foil-6h and ATA Foil-24h were significantly higher than those of the blank and untreated foil controls ( $p < 0.001$ ), with ATA Foil-24h exhibiting significantly greater bacterial removal than ATA Foil-6h ( $p < 0.05$ ). The higher efficacy of the 24-hour activated foil aligns directly with the SEM and XRD characterization findings, confirming that a fully developed, highly porous surface architecture with a mature amorphous oxyhydroxide coating provides a significantly higher density of exposed active sites for bacterial binding (Fukugaichi et al., 2024a). While a 24-h contact period is longer than rapid chemical dosing or membrane-based filtration, it represents an ideal operational window for static, overnight drinking water storage in household containers. In resource-constrained decentralized environments, water is conventionally fetched or refilled in batches and stored overnight before consumption; submerging the ATA foil directly into the storage vessel eliminates the need for power, consumables, or active intervention while ensuring microbial safety prior to daily use.

From a practical scaling perspective, the tested area-to-volume ratio of 160 cm<sup>2</sup>/L indicates that treating a typical 5 - 10 L household storage vessel would require an active foil surface of approximately 800–1600 cm<sup>2</sup>. Owing to the high mechanical flexibility and negligible thickness of commercial foil, such surface areas can be compactly configured as rolled cylinders, pleated cartridges, or suspended mesh sheets (e.g., a single 20 × 40 cm sheet per 5 L) that fit into standard domestic containers without occupying substantial storage volume. This highlights the real-world operational feasibility of the ATA foil for passive, decentralized batch

water disinfection.

### 3.2.2 Performance in Real Refill Drinking Water Matrix

To evaluate technological viability under practical field conditions, the optimized ATA Foil-24h material was tested against naturally contaminated refill drinking water collected from a commercial food service facility. Testing water at the point of use in a catering environment reflects a realistic scenario in which secondary microbial contamination frequently occurs during transportation, transfer, or secondary storage rather than solely at the primary refill depot (Loyola et al., 2020; Nowicki et al., 2021). The baseline *E. coli* concentration in this real water matrix was measured at ±80 CFU/mL, reflecting typical post-distribution contamination levels.

Upon exposure to ATA Foil-24h (Figure 4b), a rapid decline in viable bacterial counts was observed, dropping to  $20 \pm 4.54$  CFU/mL within 3 hours of contact. By 24 hours, the treatment brought culturable *E. coli* counts down to below the detection threshold (<1 CFU/mL on selective EMB agar plates), matching the removal performance observed in the synthetic water matrix. Notably, the presence of background inorganic ions, minor turbidity, and dissolved organic species typically present in commercial refill water did not noticeably hinder bacterial capture. These results demonstrate that the functionalized surface retains high selectivity and binding affinity for bacterial cells even within more complex real-world water matrices (Ihsan et al., 2025).

However, because this assessment was conducted using a single commercial refill source, these results provide a preliminary validation of practical field viability. Future studies should systematically evaluate the performance of ATA foils across a broader spectrum of natural water matrices, with greater variation in total hardness, natural organic matter (NOM) content, and competing multivalent anions (such

as phosphates and sulfates), to establish comprehensive operational envelopes.

### 3.2.3 Long-Term Retention and Desorption Resistance

A critical challenge in adsorptive water disinfection technologies is the risk of bacterial desorption where captured viable cells detach and return to the treated water or of microbial regrowth during household storage (Sidarenka et al., 2023). To rigorously assess the binding stability and durability of the ATA foil, experimental water systems in both synthetic and real water matrices were continuously monitored for up to 7 days post-treatment. Microbiological plating on selective EMB agar during this extended period confirmed that culturable *E. coli* remained below the detection limit ( $<1$  CFU/mL), proving that no secondary detachment, cell reactivation, or bacterial re-release occurred into the bulk water column over time.

The total absence of bacterial resurgence during the 7-day observation period indicates a robust immobilization stability between the bacterial cell envelope and the ATA foil surface under the tested conditions. Rather than relying on weak, transient physical adsorption, the interaction is governed by synergistic strong electrostatic attraction between the positively charged surface hydroxyl groups ( $\text{Al-OH}_2^+$ ) and the negatively charged lipopolysaccharide outer membrane of *E. coli* and mechanical micro-entrapment within the 3D interconnected porous network developed on the 24-h activated foil (Johan et al., 2023). This persistent immobilization demonstrates that captured pathogens remain stably retained without detectable re-release, thereby mitigating the risk of secondary contamination during typical multi-day household batch storage.

### 3.3 Proposed Disinfection Mechanism

Understanding the interfacial interactions between the functionalized aluminum surface and bacterial cells is essential for optimizing point-of-use adsorptive materials (Ihsan and Bachtiar, 2026). Based on the observed morphological evolution and established interfacial surface chemistry, the reduction of culturable *E. coli* by the ATA foil is hypothesized to proceed via a combined pathway involving surface electrostatic attraction and physical micro-entrapment within the porous surface architecture. Under circumneutral drinking water pH conditions (6.8 – 7.3), the surface hydroxyl groups ( $\text{Al-OH}$ ) on the amorphous aluminum oxyhydroxide ( $\text{AlOOH}/\text{Al}(\text{OH})_3$ ) layer undergo protonation to form positively charged active species ( $\text{Al-OH}_2^+$ ) (Fukugaichi et al., 2024a). Conversely, Gram-negative *E. coli* bacteria possess a net negative surface potential across their outer membrane due to the ionization of phosphate and carboxylate functional groups embedded within their lipopolysaccharide structure (Khan and Gupta, 2020). This marked charge gradient creates a strong long-range electrostatic attraction, driving the rapid migration and surface complexation of

bacterial cells toward the functionalized foil (Forano et al., 2018; Sidarenka et al., 2023).

In addition to electrostatic attraction, the structural evolution of the active layer plays a decisive physical role in bacterial immobilization. As demonstrated by the SEM micro-topographical analysis, extending the foil activation time to 24 hours transforms the dense metallic surface into a three-dimensional, interconnected porous web composed of amorphous oxyhydroxide fibers (Fukugaichi et al., 2024b). When *E. coli* cells (typically measuring 1.0-2.0  $\mu\text{m}$  in length and 0.5  $\mu\text{m}$  in diameter) approach the surface, they become mechanically entrapped within these porous micro-cavities (Johan et al., 2023). The spatial confinement provided by the web-like network, coupled with short-range hydrogen bonding between bacterial cell-wall functional groups and surface hydroxyls, effectively retains the cells in place (Forano et al., 2018). This dual mechanism prevents cell detachment and explains the exceptional stability observed during the 168-hour retention assays, without requiring post-treatment filtration or the addition of chemical disinfectants. Nevertheless, because surface zeta potential and in situ spectroscopic interactions were not quantified in this work, this dual pathway is presented as a plausible working model that warrants further direct interfacial verification in future investigations.

### 3.4 Chemical Safety and Metal Leaching Analysis

A paramount prerequisite for any point-of-use drinking water treatment technology is ensuring that operational contact does not induce secondary chemical contamination, adverse physicochemical shifts, or aesthetic degradation (Lindmark et al., 2022). In this study, key water quality parameters including pH, temperature, organoleptic properties (taste and odor), and dissolved metal levels were monitored before and after 24 hours of contact with the ATA foil materials. Experiments were conducted under ambient room temperature ( $25 \pm 2^\circ\text{C}$ ). The initial baseline pH values of the water matrices (pH  $6.8 \pm 0.1$  for synthetic water and pH  $7.3 \pm 0.1$  for food-service refill water) remained unchanged following extended exposure to ATA Foil-24h. This pH neutrality confirms that thorough post-synthesis rinsing successfully removed unreacted alkaline residues from the wood ash extract, preventing caustic leaching and ensuring that the water remains within the optimal drinking water range (6.5–8.5) (Ministry of Health of the Republic of Indonesia, 2023).

Importantly, organoleptic evaluation revealed no observable alteration in water taste, odor, or color post-treatment. The preservation of natural taste is directly associated with the ionic stability of the active layer and the controlled retention of magnesium species. Although magnesium nitrate fertilizer ( $\text{Mg}(\text{NO}_3)_2$ ) was utilized as a precursor, the magnesium cations ( $\text{Mg}^{2+}$ ) were strongly incorporated into the insoluble amorphous oxyhydroxide matrix rather than leaching freely into the solution (Li et al., 2022; Pattappan

**Table 1.** Dissolved Aluminum Concentrations in Water Before and After 7 Days of Immersive Contact With ATA Foils

| Water Sample Matrix                            | Pre-Treatment Al (mg/L) | Post-Treatment Al (mg/L) <sup>a</sup> |
|------------------------------------------------|-------------------------|---------------------------------------|
| Synthetic Water (Blank)                        | ND (< 0.0086)           | ND (< 0.0086)                         |
| Synthetic + ATA Foil-6h                        | ND (< 0.0086)           | ND (< 0.0086)                         |
| Synthetic + ATA Foil-24h                       | ND (< 0.0086)           | ND (< 0.0086)                         |
| Food-Service Refill Water (Blank) <sup>b</sup> | ND (< 0.0086)           | ND (< 0.0086)                         |
| Food-Service Refill Water + ATA Foil-24h       | ND (< 0.0086)           | ND (< 0.0086)                         |

Note: ND = Not Detected (below the AAS instrument limit of detection, LOD = 0.0086 mg/L).

<sup>a</sup>The maximum allowable aluminum threshold established by the WHO Guidelines and Permenkes RI No. 2/2023 is 0.2 mg/L.

<sup>b</sup>Refill drinking water collected at the point-of-use from a commercial food service facility.

et al., 2023). Excessive dissolution of  $Mg^{2+}$  typically imparts a metallic or bitter taste and artificially elevates total water hardness. The absence of taste impairment indicates that dissolved magnesium concentrations and overall water hardness remained well within acceptable sensory thresholds and the standards for drinking water aesthetics (Ministry of Health of the Republic of Indonesia, 2023).

Chemical safety regarding the dissolution of toxic metals was further validated using atomic absorption spectrometry (AAS). Dissolved aluminum ( $Al^{3+}$ ) levels in both synthetic and real water matrices post-treatment remained consistently non-detectable (<0.0086 mg/L), well below the instrument detection limit (Table 1). This confirms that the in situ-grown amorphous aluminum oxyhydroxide active layer is structurally resilient to chemical degradation and dissolution under ambient conditions. The non-detectable aluminum concentrations strictly comply with the maximum permissible threshold of 0.2 mg/L mandated by World Health Organization (WHO) guidelines and Indonesian national drinking water standards (Permenkes RI No. 2/2023). Nevertheless, it should be noted that the present evaluation was constrained to dissolved aluminum and general sensory/pH shifts. Because agricultural  $Mg(NO_3)_2$  and biomass wood ash extract were employed during fabrication, future comprehensive safety assessments should quantitatively measure other potentially soluble precursor-derived ions specifically residual nitrate ( $NO_3^-$ ), potassium ( $K^+$ ), and trace metal impurities to establish full chemical safety profiles. Collectively, these findings demonstrate that the fertilizer-assisted ATA foil achieves effective microbial removal while maintaining the specific chemical safety, physicochemical stability, and organoleptic palatability parameters measured in this study.

From a materials economy and processing standpoint, the current fabrication route offers clear resource advantages over traditional analytical synthesis. Conventional LDH and aluminum adsorbent synthesis typically relies on high-purity analytical salts (e.g., analytical  $Mg(NO_3)_2 \cdot 6H_2O$  at ~\$50–100/kg and pure NaOH at ~\$30–60/kg) coupled with elevated hydrothermal temperatures (80–150 °C). In contrast, our approach utilizes agricultural-grade fertilizer

$Mg(NO_3)_2$  (~\$0.30–0.50/kg), zero-cost biomass wood ash as an alkaline source, and room-temperature (25 °C) aging without external heating. For a single 16 cm<sup>2</sup> coupon, precursor chemical consumption is estimated at less than \$0.002 USD. Nevertheless, while these input metrics suggest favorable economic potential, rigorous techno-economic analysis (TEA) and life cycle assessment (LCA) including long-term foil regeneration cycles, mechanical durability over repeated deployments, and spent-material disposal pathways remain necessary to establish its commercial and environmental sustainability fully.

#### 4. CONCLUSIONS

This study successfully demonstrated an ambient, circular synthesis protocol to engineer Alkali-Treated Aluminum Foil (ATA foil) as an integrated, filter-free sheet for point-of-use bacterial removal using agricultural-grade  $Mg(NO_3)_2$  and biomass wood ash extract. Moderate synthesis conditions (pH 9.3) guided the growth of an active, disordered amorphous aluminum (oxy)hydroxide coating, which matured over 24 hours into a 3D interconnected porous network. In batch assays operated at an area-to-volume ratio of 160 cm<sup>2</sup>/L, the 24-h activated foil reduced culturable *Escherichia coli* from 10<sup>2</sup> CFU/mL to below the detection limit (< 1 CFU/mL, > 99% removal) within 24 hours in both synthetic water and naturally contaminated commercial refill drinking water. The captured bacteria remained stably immobilized without detectable resurgence or detachment over a 7-day (168-h) static monitoring window. Furthermore, post-treatment chemical analysis confirmed no detectable dissolved aluminum leaching (< 0.0086 mg/L), strictly meeting WHO and national drinking water standards without altering water pH or organoleptic quality. Overall, the fertilizer-assisted ATA foil provides a practical, zero-energy, filter-free sheet material well-suited for static overnight batch water storage in resource-limited decentralized settings.

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## REFERENCES

- Abdul Rahman, N., C. Jose Jol, A. Albania Linus, S. N. L. Taib, A. Parabi, C. Kwong Ming, A. S. L. Parabi, A. James, N. S. Samsol, S. B. John, A. A. Jitai, and D. F. A. Abang Abdul Hamid (2025). Unveiling Challenges of Aluminium Electrode Fouling and Passivation in Electrocoagulation Treatment System for Sustainable Water Management of Coastal Borneo Peatlands: A Focused Review. *Environmental Research*, **270**; 121005
- Abdul Rahman, N., C. Kwong Ming, C. Jose Jol, A. Albania Linus, S. N. L. Taib, A. Parabi, B. H. Mohamad Jan, A. S. L. Parabi, A. James, N. Abdul Mutalip, S. N. A. Samsul, J. Anyi Ngau, A. R. Stephen, A. A. Jitai, and D. F. A. Abang Abdul Hamid (2026). Sustainable Water Circularity Using Electrocoagulation System for Leptobarbus Hoevenii Aquaculture Wastewater Treatment in Rural Borneo. *Environmental Research*, **302**; 124557
- Afonso, A. C., M. J. Saavedra, I. B. Gomes, M. Simões, and L. C. Simões (2025). Current Microbiological Challenges in Drinking Water. *Journal of Water Process Engineering*, **72**; 107614
- Arora, N. K. and I. Mishra (2022). Sustainable Development Goal 6: Global Water Security. *Environmental Sustainability*, **5**(3); 271–275
- Bouali, A. C., M. Serdechnova, C. Blawert, J. Tedim, M. G. S. Ferreira, and M. L. Zheludkevich (2020). Layered Double Hydroxides (LDHs) as Functional Materials for the Corrosion Protection of Aluminum Alloys: A Review. *Applied Materials Today*, **21**; 100857
- Cheng, S., L. Lan, M. Li, X. Chu, H. Zhong, M. Yao, F. Peng, and Y. Zhang (2021). Pure Mg–Al Layered Double Hydroxide Film on Magnesium Alloys for Orthopedic Applications. *ACS Omega*, **6**(38); 24575–24584
- Ejiohuo, O., H. Onyeaka, A. Akinsemolu, O. F. Nwabor, K. F. Siyanbola, P. Tamasiga, and Z. T. Al-Sharify (2025). Ensuring Water Purity: Mitigating Environmental Risks and Safeguarding Human Health. *Water Biology and Security*, **4**(2); 100341
- Forano, C., F. Bruna, C. Mousty, and V. Prevot (2018). Interactions between Biological Cells and Layered Double Hydroxides: Towards Functional Materials. *The Chemical Record*, **18**(7-8); 1150–1166
- Fukugaichi, S., S. Maruyama, E. Johan, and N. Matsue (2024a). Facile Removal of Escherichia coli from Water Using Amorphous Membrane Fabricated on Aluminum Plate. *Emergent Materials*
- Fukugaichi, S., Y. Tomosugi, and H. Aono (2022). Facile Synthesis of Hydrophilic Layered Double Hydroxide Film on Aluminum Plate. *Inorganic Chemistry Communications*; 109647
- Fukugaichi, S., Y. Tomosugi, and H. Aono (2024b). Preparation of Hydrophilic MgAl Type Layered Double Hydroxide Films with Elevated Mg/Al Molar Ratio on Aluminum Substrates via a Facile Approach. *Discover Materials*, **4**(1); 3
- Gama, B. M. V. d., R. Selvasembian, D. A. Giannakoudakis, K. S. Triantafyllidis, G. McKay, and L. Meili (2022). Layered Double Hydroxides as Rising-Star Adsorbents for Water Purification: A Brief Discussion. *Molecules*, **27**(15)
- Gaur, N., S. Shankar, R. Chaudhary, N. Akhtar, and A. Vyas (2026). Fecal Contamination in Drinking Water: A Review of Detection Techniques, Pathogen Dynamics, and Sustainable Remediation Approaches. *Environmental Monitoring and Assessment*, **198**(4); 296
- Ihsan, T. and V. S. Bachtiar (2026). Fabrikasi Agen Antimikroba Ramah Lingkungan Berbasis Lapisan Ganda Hidroksida pada Substrat Aluminium Foil. *Jurnal Ilmu Lingkungan*, **24**(1); 1–6
- Ihsan, T. and V. Derosya (2024). Drinking Water Problems in Rural Areas: Review of Point-of-Use Methods to Improve Water Quality and Public Health. *Larhyss Journal*, **58**; 55–71
- Ihsan, T., F. Novia, V. Derosya, T. A. Ediharsi, and A. Az-zahra (2025). Sustainable Layered Double Hydroxide Foils: Calcium Hydroxide and Alternative Magnesium Sources for Rapid Point-of-Use Water Disinfection in Rural and Disaster Settings. *Journal of Ecological Engineering*, **26**(11); 342–350
- Johan, E., T. Ihsan, S. Fukugaichi, and N. Matsue (2023). Aluminum Foil Immersed in Alkalized Seawater Removes Escherichia coli from Household Drinking Water. *Journal of Water, Sanitation and Hygiene for Development*, **13**(9); 681–686
- Khan, F. M. and R. Gupta (2020). Escherichia coli (E. coli) as an Indicator of Fecal Contamination in Groundwater: A Review. In H.-Y. Jeon, editor, *Sustainable Development of Water and Environment*. Springer International Publishing, pages 225–235
- Li, A., Y. Zhang, W. Ge, Y. Zhang, L. Liu, and G. Qiu (2022). Removal of Heavy Metals from Wastewaters with Biochar Pyrolyzed from MgAl-Layered Double Hydroxide-Coated Rice Husk: Mechanism and Application. *Biore-source Technology*, **347**; 126425
- Li, S., Y. Wei, J. Zhou, Y. Li, L. Qiao, D. You, Y. Jiang, Z. Jiang, X. Wei, and X. Ma (2026). Unsafe Drinking Water and Human Health: A Global Umbrella Review of Disease Outcomes, Intervention Effectiveness, and Policy Implications. *Cell Reports Medicine*, **7**(2); 102588
- Lindmark, M., K. Cherukumilli, Y. S. Crider, P. Marcenac, M. Lozier, L. Voth-Gaeddert, D. S. Lantagne, J. R. Michelcic, Q. M. Zhang, C. Just, and A. J. Pickering (2022). Passive In-Line Chlorination for Drinking Water Disinfection: A Critical Review. *Environmental Science & Technology*, **56**(13); 9164–9181
- Loyola, S., J. F. Sanchez, E. Magaña, E. Canal, R. Castillo,

- M. Bernal, Y. Meza, D. H. Tilley, W. E. Oswald, K. Heitzinger, A. G. Lescano, and C. A. Rocha (2020). Fecal Contamination of Drinking Water Was Associated with Diarrheal Pathogen Carriage among Children Younger than 5 Years in Three Peruvian Rural Communities. *The American Journal of Tropical Medicine and Hygiene*, **102**(6); 1279–1285
- Ministry of Health of the Republic of Indonesia (2023). Regulation of the Minister of Health of the Republic of Indonesia Number 2 of 2023 Concerning Minimum Service Standards in the Health Sector
- Nduli, S., M. Tekere, V. Masindi, and S. Foteinis (2025). Assessment of the Water Quality and Microbial Regrowth in Drinking Water Treatment Plants and the Distribution Network. *Water Resources and Industry*, **33**; 100290
- Nisah, F. A., N. Winarsih, U. Nuraini, Y. U. Mubarak, M. R. Ramadhan, and F. Diaztu (2025). The Effectiveness of Polysilicone Coated Chitosan-Nanosilver as a Disinfectant in Drinking Water Treatment Processes. *Indonesian Journal of Environmental Management and Sustainability*, **9**(1); 12–19
- Nowicki, S., Z. R. deLaurent, E. P. de Villiers, G. Githinji, and K. J. Charles (2021). The Utility of *Escherichia coli* as a Contamination Indicator for Rural Drinking Water: Evidence from Whole Genome Sequencing. *PLOS ONE*, **16**(1); e0245910
- Pattappan, D., S. Kapoor, S. S. Islam, and Y.-T. Lai (2023). Layered Double Hydroxides for Regulating Phosphate in Water to Achieve Long-Term Nutritional Management. *ACS Omega*, **8**(28); 24727–24749
- Sidarenka, A. V., S. I. Leanovich, E. I. Kalamiyets, D. E. L. Vieira, J. P. V. Cardoso, J. Tedim, and A. N. Salak (2023). Commercial Synthetic Hydrotalcite as an Adsorbent Nanomaterial for Removal of Bacteria from Contaminated Water. *Environmental Engineering Research*, **28**(3); 220060–220063
- Syahrir, M., N. Sakati, H. Herawati, and D. W. Balebu (2026). Risk Assessment of Chemical Exposure through Consumption of Rainwater in. *Indonesian Journal of Environmental Management and Sustainability*, **10**(1); 112–119
- Tedim, J., T. L. P. Galvão, K. A. Yasakau, A. Bastos, J. R. B. Gomes, and M. G. S. Ferreira (2022). Layered Double Hydroxides for Corrosion-Related Applications—Main Developments from 20 Years of Research at CICECO. *Frontiers in Chemistry*, **10**; 1048313
- World Health Organization (2023). Drinking-Water. <https://www.who.int/news-room/fact-sheets/detail/drinking-water>