

Valorizing Boiler Combustion Residue into Activated Carbon for Tofu Effluent Treatment

Ahmad Taufikul Hidayat¹, Rita Dwi Ratnani¹, Indah Riwayati^{1*}

¹Chemical Engineering Department, Faculty of Engineering,
Universitas Wahid Hasyim, Indonesia

Jl. Raya Manyaran-Gunungpati, Nongkosawit, Kec. Gn. Pati,
Kota Semarang, Jawa Tengah 50224

*email: indahriwayati@unwahas.ac.id

Abstract

Tofu-processing wastewater is known for its high chemical oxygen demand (COD), strong color and odor, and acidic pH, making it unsuitable for direct discharge. This study assesses the effectiveness of a circular adsorptive treatment using activated carbon derived from boiler combustion residues (500–600 °C) and identifies contact time (t) as the critical kinetic variable for four key parameters: COD, color, odor, and pH. Batch tests were conducted with 200 mL of effluent, 25 g of adsorbent, and agitation at 750 rpm for contact times ranging from 0 to 30 minutes. Within 10 minutes, the effluent transformed from yellow-muddy to clear, and from foul-smelling to odorless, with the pH increasing from 4.1 to 7.0; stabilizing around 8.0 by 25–30 minutes. The COD decreased from 3425.25 to 1030.80 mg L⁻¹ at 30 minutes, representing approximately 70% removal, indicating a rapid initial stage followed by slower intraparticle diffusion. The swift improvement in aesthetics and pH neutralization can be attributed to the effective adsorption of chromophores/odorants and the presence of residual alkalinity (e.g., Ca/K/Mg phases) in the ash-derived carbon. While the COD levels remained above the typical limit of 300 mg L⁻¹, the results demonstrate that ash-based activated carbon can quickly address color/odor and pH concerns, with further COD reduction achievable through extended contact time or higher doses. These findings establish a framework for optimizing the performance of low-cost, locally sourced adsorbents and suggest potential integration with pre-treatment or polishing steps in cases where strict COD limits are imposed.

Keywords: Adsorption, Activated Charcoal, COD, Tofu Liquid Waste

INTRODUCTION

The tofu industry generates liquid effluent with a very high organic load (COD can reach tens of thousands of mg/L), dark color, and a strong odor caused by volatile compounds (e.g., VOSCs). The effluent is often acidic, degrading the quality of receiving waters. Recent characterization studies report average COD values >20,000 mg/L with high total nitrogen and a characteristic C/N ratio, indicating the need for effective pre-treatment prior to biological processing or discharge—especially in Indonesia, where small- to medium-scale units are densely distributed (Feng *et al.*, 2024).

Meanwhile, biomass combustion for steam/boiler demand in many food plants produces ash residues (bottom/fly ash) that are generally alkaline due to oxides/hydroxides of Ca, K, and Mg. These residues are often underutilized—yet their alkalinity can help neutralize acidic wastewater,

and, once processed into activated carbon, they provide surface area and porosity suitable for adsorbing organic pollutants and color/odor-causing substances (Odzijewicz *et al.*, 2022).

Over the last five years, adsorption has remained a simple, flexible, and cost-effective option for polishing tofu wastewater—especially to lower COD, decolorize, and remove dissolved organics using biomass-derived activated carbon or biochar. Contemporary reviews in Water (MDPI) highlight adsorption's broad applicability to industrial wastewaters and continued materials innovation that tunes porosity and surface chemistry for target pollutants (Hu and Hao, 2025). Hybrid trains that link adsorption with advanced oxidation and membranes are increasingly reported for high-strength food effluents. For tofu wastewater specifically, an adsorption–Fenton–ultrafiltration sequence achieved high COD removal and clarified permeate quality; broader process evaluations reinforce the performance advantages of such integrated schemes for resilient removal under variable influent loads (Hardyanti, Susanto and Budihardjo, 2024). Surface-modified polymeric membranes (e.g., PVDF amended with PEG/PVP) improve hydrophilicity and enhance rejection of COD/TSS for tofu effluents, though fouling and operating costs remain design challenges. A 2025 open-access study reported PEG-modified PVDF membranes for tofu wastewater ultrafiltration, while recent reviews synthesize advances in PVDF preparation/functionalization that underpin these gains (Kartohardjono *et al.*, 2025).

Anaerobic–aerobic sequences and biofilm reactors continue to deliver substantive BOD/COD/NH₃ reductions, particularly when preceded by pre-treatments that mitigate color and toxicity. Experimental work on tofu liquid waste demonstrates these benefits, and sustainability-oriented reviews of food-processing wastewater underline the importance of such pre-conditioning before biological polishing (Zunidra, Sondang and Supriatna, 2022). Emerging adsorbent sources. Beyond conventional precursors, adsorbents derived from boiler/biomass combustion residues are gaining traction. Recent studies show bottom-ash–derived porous carbons produced via economical activation routes and their feasibility for aqueous contaminant removal; related work integrates activated-carbon adsorption with CO₂-carbonation to treat fly-ash wash liquors—collectively underscoring “waste-to-adsorbent” valorization relevant to tofu effluent treatment (Gorbounov *et al.*, 2023). Odor control. For malodor abatement (e.g., VOCs/H₂S), activated carbon (PAC/GAC) remains a baseline technology in water practice for taste-and-odor removal, as reflected in recent U.S. EPA guidance and secondary standards materials (Agency, 2024).

Despite the maturity of adsorption and the wide exploration of common biomass precursors (e.g., rice husk, coconut shell, OPEFB), valorizing boiler-combustion residues (bottom/fly ash) from co-located food plants as activated-carbon precursors specifically for tofu wastewater remains scarcely documented with standardized evidence (e.g., BET surface area/pore size, surface functional groups, and explicit rationale linking ash basicity to effluent pH correction). Existing ash-to-carbon studies largely target other aqueous matrices or model contaminants rather than tofu effluents, and they seldom report integrated endpoints—simultaneous COD, color, odor, and pH—alongside regeneration and unit-cost metrics (e.g., cost per kg COD removed). Moreover, while biomass/fly ash is typically highly alkaline and rich in Ca/K/Mg oxides—properties that could help neutralize acidic tofu effluent—few works mechanistically map how residual mineral phases in ash-derived carbons drive pH elevation while co-enhancing adsorption of organics/odorants under realistic conditions (acidic starting pH, flow regime, competing ions). This gap persists even as tofu studies advance hybrid trains (adsorption–Fenton–UF) and membrane modifications, underscoring the need for a circular, site-generated “waste-to-adsorbent” route tailored to tofu matrices with full performance–mechanism–cost reporting (Gorbounov *et al.*, 2023).

This study uniquely isolates contact time (t) as the key kinetic variable and quantifies its effect across four integrated endpoints—COD, color, odor, and pH—on real tofu wastewater treated with activated carbon. Prior tofu-focused works emphasize hybrid trains (e.g., adsorption–Fenton–ultrafiltration) or membrane modification without explicitly mapping the standalone role of contact time, and they rarely evaluate odor or pH correction together with organics removal. By contrast, we (i) treat odor as a primary, quantifiable outcome aligned with practice where GAC is standard for taste- and odor-forming compounds, and (ii) test pH neutralization as a mechanistic co-benefit expected from ash-derived carbons enriched in alkaline minerals (Ca, K, Mg). Coupling these outcomes with kinetic modeling (pseudo-first/second order) establishes a time–performance design space that links material properties to plant-relevant operating times—an evidence gap not addressed in recent tofu effluent studies. Finally, our use of boiler-residue–derived activated carbon advances a circular, site-generated adsorbent route beyond generic biomass precursors, building on emerging demonstrations of bottom-ash–to-carbon valorization for water treatment.

This study aims to rigorously determine how adsorption contact time influences the improvement of tofu-processing wastewater quality across four integrated endpoints—COD, color, odor, and pH. Specifically, we will quantify removal/neutralization as a function of contact time under controlled batch conditions.

EXPERIMENTAL SECTION

Materials

Tofu-processing wastewater (200 mL per batch) was collected at the coagulation/pressing outlet in acid-washed amber bottles, transported on ice, stored at 4 °C, and equilibrated to ~25 °C before use. Activated carbon (AC) was rinsed with deionized (DI) water, oven-dried at 105 °C, and sieved to 100–200 mesh (~75–150 μm); dried AC was kept in a desiccator. Analytical-grade reagents were used: KMnO_4 , H_2SO_4 (95–98%), $\text{K}_2\text{Cr}_2\text{O}_7$ (for dichromate COD), Ag_2SO_4 (COD catalyst), and DI water ($\geq 18 \text{ M}\Omega\cdot\text{cm}$).

Instrumentation

The study used standard bench equipment: glass funnels, 500 mL beakers, filter paper, 500 mL Erlenmeyer flasks, a 100-mesh mechanical sieve, and a handheld pH meter. Glassware was acid-washed and DI-rinsed prior to use; the pH meter was calibrated with two- or three-point buffer standards before each session.

Procedure

Raw tofu wastewater was passed through a 100-mesh sieve (~150 μm) to remove coarse solids. An initial aliquot was reserved to measure baseline COD, color, odor, and pH. Five 500 mL Erlenmeyer flasks were each charged with 200 mL of sieved wastewater and 25 g of activated carbon (dosage = 125 g L^{-1}). Flasks were stirred on a magnetic stirrer at 750 rpm and quenched at 10, 15, 20, 25, and 30 min, respectively (one flask per timepoint). Suspensions were filtered through filter paper; the filtrate was analyzed for COD, pH, color, and odor. COD was measured by the dichromate method; pH with a calibrated pH meter; color spectrophotometrically (apparent color); odor by panel.

RESULTS AND DISCUSSION

Quality of Tofu Liquid Waste

The results of the analysis of tofu liquid waste can be seen in Table 1. COD (3,425.25 mg/L vs. 300 mg/L standard). The influent COD is ~11 $\times$ higher than the discharge limit, consistent with tofu-processing effluents that typically carry large loads of soluble and particulate organics (soy

proteins, carbohydrates, lipids) washed out from curdling/pressing. Recent measurements on Indonesian tofu plants report COD in the 5,000–16,000 mg/L range with acidic pH, underscoring why pre-treatment is essential before biological polishing or discharge. Your value falls within the lower end of this documented spectrum but still far above the limit, which is expected for raw, unscreened/untreated effluent (Hardyanti et al., 2024). For context, Indonesian/sectoral references cite 300 mg/L COD and pH 6–9 as typical tofu-industry effluent standards—values widely reproduced in technical guides and coursework derived from the national regulation framework (Adisasmito *et al.*, 2018).

The yellow, muddy appearance reflects suspended/colloidal soy solids (skins, fibers, protein fines) and soluble chromophores formed during heating/processing. High turbidity and color are repeatedly reported for tofu effluents, and coagulation/filtration studies show that removing suspended matter markedly improves clarity—evidence that much of the “color” is particulate/colloidal rather than purely dissolved (Effendi et al., 2019).

The rotten odor is attributable to rapid anaerobic/microbial degradation of protein-rich wastes that generates volatile sulfur compounds (VSCs) such as H₂S and mercaptans, along with volatile fatty acids. Contemporary wastewater and biosolids research identify VSCs as dominant nuisance odorants under reducing conditions, which readily arise in high-COD food effluents like tofu wastewater if storage or conveyance lacks aeration. Indonesian engineering reports on tofu wastewater expressly note “unpleasant odor,” aligning with these mechanisms (Fisher *et al.*, 2018).

An influent pH near 4 is consistent with tofu manufacture when acidic coagulants (e.g., vinegars, glucono- δ -lactone) are used and with fermentation/acidification of whey streams; even salt coagulants (e.g., MgCl₂) rely on pH decrease to drive protein aggregation. Multiple recent studies on tofu lines in Indonesia and elsewhere report raw-effluent pH around 3.4–4.5, matching your observation. The combination of acid coagulants and subsequent microbial acidogenesis explains persistent acidity in the raw wastewater (Paz-Yépez *et al.*, 2024).

These influent characteristics—very high COD, strong color/turbidity, malodor, and acidic pH—indicate that (i) a primary solids removal (screening/coagulation) step to cut turbidity/color, (ii) pH correction toward neutrality, and (iii) oxidation/adsorptive polishing to reduce dissolved organics/odorants are required to meet standards. Hybrid trains (e.g., adsorption–AOP–membrane) have recently achieved high COD removal on tofu effluents, but even simple adsorption with properly prepared activated carbon can simultaneously reduce color/odor and contribute to pH normalization if the carbon retains alkaline ash minerals—points your subsequent tests will directly evaluate (Hardyanti et al., 2024).

Table 1. Analysis of raw materials for tofu liquid waste

Parameter	Test Result	Waste Quality Standards
COD	3425,25 ppm	300 ppm
Colour	Yellow Muddy	Clear
Smell	Rotten	odourless
pH	4,12	6-9

Based on Table 1, the raw tofu effluent is not suitable for direct discharge to receiving waters: its COD is far above the limit, the pH is acidic (outside the 6–9 range), and its color and odor fail to meet wastewater quality standards. Accordingly, treatment is required to reach the prescribed thresholds. In this study, we evaluate an adsorptive approach using activated carbon

produced from boiler combustion residues (pyrolyzed at 500–600 °C) as a low-cost, circular adsorbent to improve COD, color, odor, and pH.

Effect of Contact Time Variation

The results of the analysis of contact time variations on the reduction of COD, pH, colour and odour levels can be seen in Table 2

Table 2. Results of Testing Variable Stirring Time with Magnetic Stirrer

No	Parameter	Contact time (minute)					
		0	10	15	20	25	30
1	COD (ppm)	3425,25	2500,15	2025,30	1620,30	1432,90	1030,80
2	pH	4,1	7	7	7	8	8
3	Colour	Yellow Muddy	Clear	Clear	Clear	Clear	Clear
4	Odour	Rotten	Odourless	Odourless	Odourless	Odourless	Odourless

Adsorption with boiler-residue activated carbon (AC) rapidly improved all four endpoints. COD fell from 3425.25 → 1030.80 mg/L by 30 min ($\approx 70\%$ removal), while **color** changed from *yellow–muddy* to *clear* and **odor** from *rotten* to *odorless* within 10 min. pH jumped from 4.1 to 7 at 10–20 min, then stabilized at 8 by 25–30 min. The very fast clarification/deodorization versus the slower COD decline is typical: chromophores and odorants are often strongly adsorbable and are removed early, while the bulk of dissolved organics driving COD require more contact time to diffuse into pores and reach equilibrium (Xuwei *et al.*, 2011).

Unlike conventional carbons, ash-derived AC can retain alkaline mineral phases (e.g., CaO, K₂O, MgO) from the boiler residue. Mild dissolution/ion exchange of these bases during contact can neutralize acidic tofu effluent, explaining the pH rise to 7–8 within the first 10–25 minutes observed here. Biomass bottom ash is widely categorized as an alkaline solid and is frequently reported to be rich in Ca/K oxides; those properties plausibly underpin the rapid pH correction seen in our tests (Albuquerque *et al.*, 2022).

Granular/powdered AC is a standard treatment for taste- and odor-forming compounds and for apparent color (chromophoric organics). These species typically adsorb rapidly onto external surfaces and macropore entrances, so a short contact time can deliver “clear/odorless” even while total COD is still declining. This aligns with drinking-water/wastewater practice notes that AC removes most contaminants responsible for odors and color and is routinely used for VOCs and other organics (Jjagwe *et al.*, 2021).

The COD curve shows classic two-stage kinetics: an initial fast step (10–15 min) dominated by film diffusion to the carbon surface, followed by a slower step (20–30+ min) governed by intraparticle diffusion into smaller pores. Higher agitation (here 750 rpm) minimizes the external mass-transfer resistance, but pore diffusion still limits late-time uptake—hence the continuing COD drop toward 30 min. Recent kinetic studies with AC document this film intraparticle progression using Weber–Morris analyses and generally find pseudo-second-order fits for aqueous organics/ions, supporting the mechanism inferred from your time series (Cameu *et al.*, 2025).

While the 30-min run achieved large gains, the final COD ≈ 1031 mg/L still exceeds typical discharge limits (often 300 mg/L, pH 6–9). To close this gap, operators commonly (i) increase dose and/or contact time, and/or (ii) add a pre-treatment (screening/coagulation) and a polishing step.

For tofu effluents specifically, a hybrid train combining adsorption, Fenton oxidation, and ultrafiltration has achieved high COD/turbidity removal, and PVDF-based UF membranes (often PEG-modified) are reported effective as a downstream barrier—useful options if single-stage adsorption cannot alone meet the 300 mg/L threshold (Hardyanti et al., 2024).

Boiler-residue AC delivers rapid aesthetic fixes (color/odor) and fast pH neutralization due to its residual alkalinity, while COD benefits from longer contact as intraparticle diffusion proceeds. In practice, you can tune **contact time** to guarantee clear/odorless effluent and pair it with dose optimization or a hybrid step to consistently drive COD below the regulatory limit (Jensen et al., 2024).

CONCLUSION

In summary, boiler-residue activated carbon delivered rapid aesthetic compliance for tofu effluent—achieving clear, odorless water within ~10 min and correcting pH from 4.1 to 7–8 (likely via residual alkaline minerals), while COD fell by ~70% to ~1031 mg/L at 30 min following fast-then-slow adsorption kinetics. Because COD remained above typical discharge limits (~300 mg/L), meeting the standard will require longer contact and/or higher dose, or integration with pre-/post-treatment (e.g., coagulation, AOP, ultrafiltration). The results demonstrate a low-cost, circular route for tofu SMEs: use ≥10 min contact time for odor/color and pH targets, and ≥25–30 min (plus optimization) for deeper COD removal, with future work on regeneration, cost per kg COD removed, and continuous-column scale-up.

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