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Decolorization of Treated Municipal Wastewater for Non-Potable Reuse Using a Household UV/H_2O_2 Process

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ABSTRACT

Color remaining in treated municipal wastewater can limit its acceptance for non-potable reuse. This study evaluated a simple UV/H_2O_2 step for decolorization of secondary effluent from three Bangkok Metropolitan Administration (BMA) wastewater treatment plants. Experiments were performed in a 0.75 L batch reactor equipped with a single low-pressure UV lamp (254 nm, 16 W); H_2O_2 doses of 33, 100, 167, and 333 mg/L were tested at ambient 25-30°C and unadjusted pH. Reaction times were 0-10 minutes with sampling at 0, 3, 5, and 10 min. Color (ADMI) decreased rapidly in the first minutes: >65% removal at 5 min for 100 mg/L H_2O_2, and a maximum of 76% at 10 min for 333 mg/L H_2O_2. Linearized kinetic fits showed that a pseudo-second-order model ($R^2 \approx 0.953$-0.966) described the data better than pseudo-first-order ($R^2 \approx 0.909$-0.921), indicating apparent bimolecular behavior under the tested conditions. A screening-level reagent cost based on commercial 50% w/w H_2O_2 pricing was 5.8 THB/m^3 at 100 mg/L (≈0.179 USD/m^3 using 32.4 THB: USD). These results demonstrate that a household-scale UV/H_2O_2 configuration can provide fast decolorization of municipal secondary effluent under short contact times, with a simple kinetic descriptor and an initial cost benchmark relevant to building-level non-potable reuse.

HIGHLIGHTS

- A household UV/H_2O_2 system removed over 65% of wastewater color in 5 minutes.
- Maximum decolorization of 76% was achieved with 333 mg/L H_2O_2 after 10 minutes.
- Reaction followed pseudo-second-order kinetics, indicating a bimolecular mechanism.
- Treatment cost at 100 mg/L H_2O_2 was approximately 5.8 THB/m^3—economically feasible.
- The system is suitable for non-potable reuse in large buildings (e.g., toilet flushing, cleaning).

1. INTRODUCTION

Water reuse is a practical strategy for addressing water scarcity, particularly for non-potable applications. In Bangkok, more than 2.6 million cubic meters of domestic wastewater are generated daily, of which only about 60-70% is treated before discharge (BMA, 2022). However, less than 1% of treated wastewater is reused, indicating substantial potential for reclamation. Given growing water demand and urban expansion, promoting the reuse of treated effluent in non-potable applications has become increasingly important. Treated domestic wastewater is a significant resource with potential for non-potable reuse, offering an environmentally sustainable solution and supporting applications like agricultural irrigation, street cleaning, and environmental restoration, commonly referred to as "water reclamation" (Institute for Environment and Sustainability, 2014; Duckett et al., 2024). The idea of using treated wastewater is to reduce potable water consumption in buildings, especially large-scale buildings, such as shopping malls, office buildings, universities, government offices. Many activities such as floor washing, toilet flushing, and garden irrigation do not need high quality water, so the use of treated wastewater is a practical solution. However, treated

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wastewater contains color consisting of organic compounds, particularly humic and fulvic substances which are generated by microorganisms in the biological wastewater treatment processes (Park et al., 2005; Puspita et al., 2011). These soluble organic compounds are resistant to biological degradation and cause a light yellow to brown coloration in the effluent. This color creates an unpleasant impression on users and causes staining on sanitary fixtures.

Various advanced treatment methods have been applied to remove residual color from wastewater. Among them, the UV/H_2O_2 process—a type of Advanced Oxidation Process (AOP)—has shown promising decolorization performance. Several studies have reported high efficiency of this method. For instance, Caretti and Lubello (2010) achieved up to 90% and 80% color removal within 10 minutes when treating wastewater treatment effluent using a 150 W-medium pressure UV lamp and a 15W-low pressure UV lamp, respectively. Sugha and Bhatti (2022) observed 86% dye degradation and 78% COD reduction after 120 minutes of UV/H_2O_2 treatment (50 mg/L dye, initial pH 4). More recently, Son et al. (2024) demonstrated over 99% color removal in actual textile wastewater using UV/H_2O_2 with 5 mM H_2O_2, 26.6 W/m² UV intensity, and 180 minutes of irradiation, identifying H_2O_2 concentration as the most critical operating variable. Moreover, Jennifer et al. (2024) showed that UV/H_2O_2 effectively removed anionic surfactants from tertiary treated effluent, achieving over 90% removal. These findings highlight the consistent performance of the UV/H_2O_2 process across different wastewater types and emphasize its potential for practical application.

The UV/H_2O_2 process generates powerful oxidizing hydroxyl radicals. Hydrogen peroxide (H_2O_2) reacts with UV to create OH· as the following reaction: $H_2O_2 + hv \rightarrow 2OH$. The UV/$H_2O_2$ process has been applied in various fields, including drinking water, water treatment, wastewater treatment, organic contamination removal, and groundwater remediation (Puspita et al., 2011; Lhotský et al., 2017; Pamuła et al., 2022; Sugha and Bhatti, 2022). It can improve the wastewater quality by removing micropollutants, which are difficult to treat by conventional treatments including pharmaceuticals in domestic wastewater and pesticides (Kim et al., 2009; Luo et al., 2014; Afonso-Olivares et al., 2016; Pamuła et al., 2022; Mukherjee et al., 2023). This process can reduce chemical oxygen demand (COD) and promote disinfection in water reuse applications (Pamuła et al., 2022; Yang et al., 2024). Several studies have reported the application of the UV/H_2O_2 process to remove color from wastewater including dye and textile industries (Papić et al., 2006; Zawadzki and Deska, 2021; Sugha and Bhatti, 2022). Moreover, several studies have applied this process for decolorization of treated wastewater from activated sludge wastewater treatment (Park et al., 2005; Puspita et al., 2011). However, most of studies have not explored key engineering aspects, such as the optimal sizing of UV systems, comparative operational and installation costs with other water reuse technologies, and the cost of water supply.

Beyond UV/H_2O_2, several post-treatment options have been used to reduce residual color in treated effluents, including coagulation-flocculation, granular activated carbon (GAC) adsorption, ultrafiltration (UF), ozonation, Fenton/photo-Fenton oxidation, and TiO_2 photocatalysis. Coagulation and GAC can remove humic-like chromophores cost-effectively but generate sludge or require media regeneration and breakthrough management (Barloková et al., 2023; Knap-Bałdyga and Żubrowska-Sudoł, 2023). UF provides consistent decolorization but entails higher capital/operating costs and membrane fouling that necessitate chemical cleaning (Zhang et al., 2023). Ozonation is effective for color and other chromophores but can form bromate in bromide-containing waters, requiring careful control or downstream mitigation (Morrison et al., 2023). Fenton/photo-Fenton processes often achieve high decolorization but typically require acidic condition (pH~3), produce iron sludge, and have higher reagent demand (Ziembowicz and Kida, 2022). TiO_2 photocatalysis shows high laboratory performance but faces catalyst recovery and scale-up challenges in full-scale applications (Kumari et al., 2023).

Recent work has advanced UV/H_2O_2 for challenging effluents and tertiary polishing—for example, actual textile wastewater achieving very high decolorization under optimized UV fluence and peroxide dose (Son et al., 2024), and hybrid tertiary sequences that couple UV or UV/H_2O_2 with nature-based units for effluent polishing (Miguel et al., 2024), alongside costed UV/H_2O_2 applications in high-strength industrial streams (Kim et al., 2023). Building on these advances, our study operationalizes UV/H_2O_2 for building-scale reuse by deploying a household UV device on municipal secondary effluent at neutral pH, demonstrating rapid visible-color reduction, and developing a bottom-up treatment cost appropriate for

building or campus applications. In terms of sustainability, the design avoids sludge-forming coagulants and relies on modular, readily available UV equipment. It also reduces the need for potable water in non-potable applications, as shown in recent decentralized/tertiary studies of compact UV-AOP systems (Jennifer et al., 2024).

2. METHODOLOGY

2.1 Treated municipal wastewater

Treated municipal wastewater samples were collected from three wastewater treatment plants operated by the Bangkok Metropolitan Administration (BMA). The characteristics of the treated wastewater are summarized in Table 1. Turbidity levels ranged from 1.30 to 6.54 NTU, with an average of 5.03 NTU, while the pH averaged 7.56. The five-day biochemical oxygen demand (BOD_5) ranged from 1.67 to 4.50 mg/L, with a mean value of 2.69 mg/L. Chemical oxygen demand (COD) ranged from 19.8 to 29.3 mg/L, averaging 23.2 mg/L. After filtration through 20-micron filter paper, the average color value was 25 ADMI. All parameters complied with Thailand's effluent discharge standards for buildings and factories within typical ranges for secondary effluents (Royal Gazette, 2017; Royal Gazette, 2018).

Table 1. Baseline characteristics of secondary-effluent grab samples from three BMA WWTPs

Source of sample	Turbidity (NTU)	pH	BOD_5 (mg/L)	COD (mg/L)	Color (ADMI)
Plant A	6.54	7.60	1.67	19.8	24.0
Plant B	7.24	7.49	4.50	29.3	29.0
Plant C	1.30	7.60	1.90	20.3	22.0
Range (min-max)	1.3-7.24	7.49-7.60	1.67-4.50	19.8-29.3	22.0-29.0

Note: Single grab per plant; SD is not reported to avoid conflating inter-plant variability with replicate precision. Inter-plant variability is shown as the range (min-max).

2.2 Chemicals and materials

Treated municipal wastewater (secondary effluent) was obtained as grab samples from three wastewater treatment plants operated by the Bangkok Metropolitan Administration (BMA). The oxidant used was hydrogen peroxide (H_2O_2, 30% w/w, CAS 7722-84-1; CARLO ERBA Reagents), from which working solutions in the range 33-333 mg/ L were prepared. H_2O_2 30% w/w was used for laboratory dosing and kinetic experiments. For cost estimation, unit prices refer to commercial-grade H_2O_2 50% w/w commonly sold in the local market; costs are normalized to the pure H_2O_2 dose and then converted to the equivalent mass of 50% stock for pricing. For sample pre-filtration, qualitative ashless filter paper (Whatman No. 41, GE Healthcare Life Sciences; nominal particle retention≈20 µm) was employed. Ultraviolet irradiation was provided by a low-pressure 16-W household UV unit (commercial supplier) equipped with a quartz sleeve; the manufacturer's rated flow is 453 L/h. Samples from the three wastewater treatment plants were analyzed and treated separately; no compositing was performed.

2.3 Pre-treatment and filtration

Secondary effluent samples were passed through a 20-micron filter paper prior to UV/H_2O_2 testing. This step was introduced to emulate the simple pre-filtration commonly used upstream of small UV systems to limit lamp sleeve fouling and reduce light shielding by suspended solids and standardize the optical conditions for kinetic evaluation by focusing on the dissolved/colloidal chromophore fraction. No coagulants or adsorbents were added, and pH was not adjusted. Filtration was performed immediately before each experiment. (Note: this pre-filtration is equivalent to the role typically served by cartridge/sand filters in building-scale reuse systems.) Dissolved organic carbon (DOC) was not measured in this study; kinetics therefore emphasize the dissolved color fraction under a fixed UV setting.

2.4 Reactor and operating conditions

2.4.1 Selection of H_2O_2 dose and experimental plan

To define a usable range for small, building-scale systems, four H_2O_2 concentrations were selected: 33, 100, 167, and 333 mg/L, corresponding to approximately 0.97, 2.94, 4.91, and 9.79 mM (MW(H_2O_2)=34 g/mol). This 1-10 mM range encompasses doses commonly reported for UV/H_2O_2 decolorization in tertiary polishing and dye-laden wastewaters, with 5 mM frequently identified as effective under optimized UV fluence (Son et al.,

2024). Experiments followed a one-factor-at-a-time plan at a fixed low-pressure UV setting (254 nm, 16 W), varying H_2O_2 dose and contact time (0, 3, 5, 10 min). All tests were performed in triplicate (n=3), and concentration-time data were analyzed using kinetic models (pseudo-first- and pseudo-second-order) to support design-level sizing. We did not conduct a formal design of experiments (e.g., factorial/response-surface varying UV fluence, H_2O_2 dose, and contact time); this will be undertaken in future work to optimize performance and cost for scale-up.

2.4.2 Operating conditions

Experiments were conducted in a batch reactor (working volume=0.75 L) equipped with a single low-pressure 254 nm, 16 W UV lamp in a quartz sleeve (household UV device). After dosing H_2O_2 (30% w/w stock) to the target concentration, samples were mixed (~300 rpm, 30 s) before UV exposure. Contact times were 0-10 min (0, 3, 5, 10 min sampling). Tests were run at ambient temperature (~25-30°C) and neutral pH characteristic of the effluent (no pH adjustment). All tests were performed in triplicate (n=3). Irradiance at the liquid surface was not measured; experiments used a single low-pressure 254 nm, 16 W lamp in a fixed geometry for all tests, so comparisons across H_2O_2 doses and contact times were made at the same UV setting. Color (ADMI) and turbidity (NTU) were measured by standard methods; glassware was rinsed with deionized water between runs as see Figure 1. Residual H_2O_2 was not measured in this screening study. In practical non-potable reuse configurations, a short post-UV holding period is provided to allow decay of H_2O_2 prior to distribution.

2.5 Color measurements

The American Dye Manufacturers Institute (ADMI) method was used to measure the color of water samples in this study, in accordance with U.S. EPA Method 110.1 (USEPA, 1978). The principle of ADMI color measurement involves the use of a spectrophotometer to determine absorbance at multiple wavelengths, specifically 436, 525, and 620 nanometers, which correspond to key regions of the visible light spectrum as perceived by the human eye. These absorbance values are mathematically combined to yield a single ADMI value, providing a standardized and quantitative representation of color intensity in wastewater samples. In this study, color measurements were performed using a HACH DR6000 UV-Vis spectrophotometer.

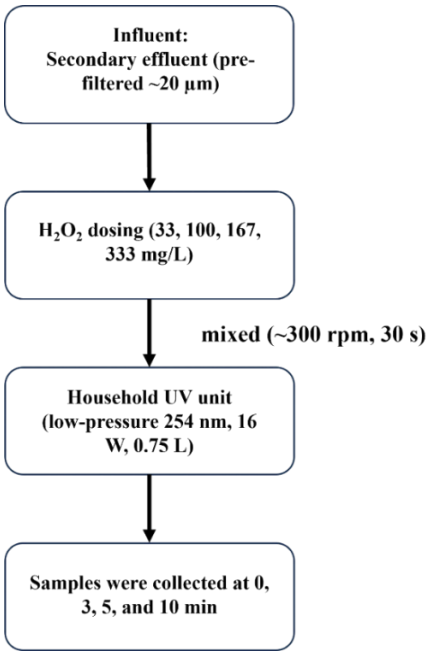

Figure 1. Experimental process and conditions for UV/H_2O_2 tests

2.6 Chemical kinetics of color removal

The kinetics of the color removal reaction were investigated to evaluate the potential application of the UV/H_2O_2 process. Two kinetic models, namely pseudo-first order and pseudo-second order, were applied to describe the degradation behavior, using the following rate equations:

$$\text{Pseudo-First-order model: } \frac{dC}{dt} = -k'C \quad (1)$$

$$\text{Intregated from: } \ln\left(\frac{C}{C_0}\right) = -k't \quad (2)$$

$$\text{Pseudo-Second-order model: } \frac{dC}{dt} = -k''C^2 \quad (3)$$

$$\text{Intregated from: } \frac{1}{C_0} - \frac{1}{C} = -k''t \quad (4)$$

Where; C is the color concentration (ADMI), t is the reaction time (minutes), k' is the pseudo-first-order rate constant (min^{-1}), and k" is the pseudo-second-order rate constant ($ADMI^{-1} \cdot min^{-1}$).

Because samples were filtered prior to treatment, the reported kinetics emphasize the dissolved/colloidal color fraction under reduced light-scattering conditions. At full scale, pre-filtration is typically included upstream of UV to protect lamps and improve UV transmittance; nevertheless, performance on unfiltered effluent may be lower due to shielding by suspended solids. Accordingly, design for building-scale reuse should include a basic 1-5 µm pre-filter ahead of the UV/H_2O_2 unit, and site-specific performance testing is recommended.

2.7 Cost calculation (reagent-only)

The reported cost covers H_2O_2 only. Doses are expressed as mg/L of pure H_2O_2. For pricing with 50% w/w commercial stock, the required stock mass per cubic meter is:

$$m_{stock,50\%} = \frac{D \times 10^{-3}}{0.50} \left(kg/m^3\right) \quad (5)$$

And the reagent cost is:

$$C_{H_2O_2} = m_{stock,\ 50\%} \times P_{50\%} \left(THB/m^3\right) \quad (6)$$

Where; D is the pure- H_2O_2 dose (mg/L) and $P_{50\%}$ is the market price of 50% w/w H_2O_2 (THB/kg). If a different stock strength is procured on site, replace 0.50 by the corresponding mass fraction p. Calculations were performed in Microsoft Excel and reported to three significant figures. All THB values were converted to USD using an exchange rate of 32.4 THB=1 USD on 16 June 2025.

2.8 Data analysis

All data processing and plotting were performed in Microsoft Excel (Home edition). Replicate measurements are reported as mean±standard deviation (SD) with n=3. Fits were performed by ordinary least squares in Excel on the linearized kinetic models. Model selection used R^2 and residual patterns. Numerical results are rounded to three significant figures.

3. RESULTS AND DISCUSSION

3.1 Characteristic of color reduction

Color dropped quickly in the first 3-5 min at all H_2O_2 doses. At 5 min, 100 mg/L removed >65% of color, and the best case was 76% at 10 min with 333 mg/L (Figure 2). The fast early drop likely occurs because hydroxyl radicals quickly attack the color-forming compounds. After that, removal slows as the easiest compounds are used up and other substances in the water compete for radicals. Raising H_2O_2 from 33 to 167 mg/L clearly improves removal at 3-5 min but increasing to 333 mg/L gives only a small extra benefit by 10 min, indicating diminishing returns at higher dose.

These trends are consistent with previous UV/H_2O_2 reports on secondary effluents and dye-laden wastewaters, which often show fast initial decolorization followed by slower tails (Park et al., 2005; Puspita et al., 2011; Sugha and Bhatti, 2022; Son et al., 2024). Here, a household low-pressure UV unit still achieved operationally relevant decolorization within minutes, supporting building-scale non-potable reuse where short retention and simple equipment are preferred. The time-course data in Figure 2 were subsequently used for kinetic fitting in Section 3.2, which quantifies the observed behavior. In contrast, the H_2O_2-only control (without UV irradiation) showed no measurable color loss at any dose (results not shown).

In addition, visible color disappearance was observed in the water samples, consistent with the study's objectives (Figure 3). For example, at 100 mg/L H_2O_2, the water sample appeared colorless after just 3 minutes of UV irradiation, corresponding to a color value of 11 ADMI or 54% removal (Figure 3(a)).

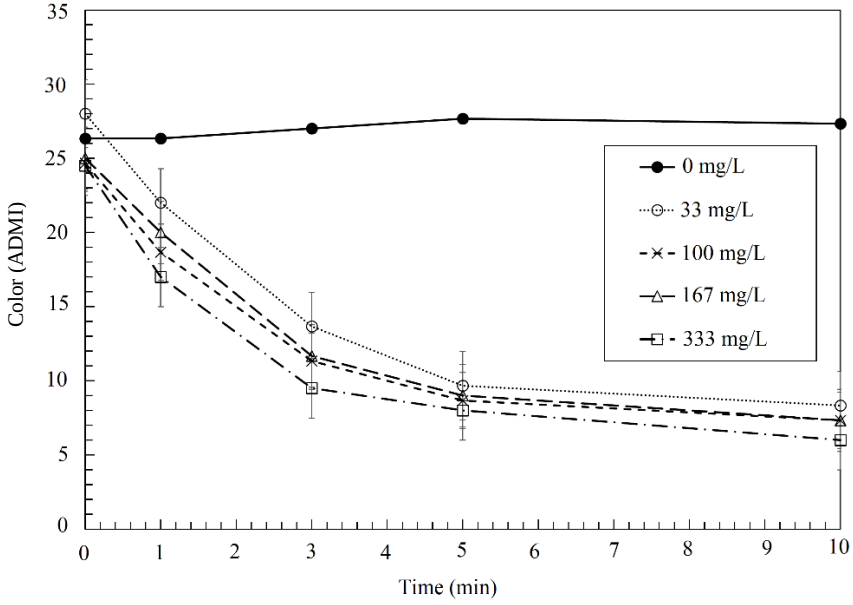

Figure 2. Color of the treated wastewater samples using UV/H_2O_2. Error bars show±SD (n=3). (Data shown as ADMI; initial values differ by plant (as shown in Table 1).

In practical terms, it is important to note that typical UV systems for water and wastewater disinfection are designed with retention times of approximately 30 to 60 seconds to effectively inactivate viruses (Tchobanoglous et al., 2003). Based on the experimental results, the decolorization reaction showed minimal changes after 5 minutes. Furthermore, the combination of H_2O_2 and UV irradiation for just 3 to 5 minutes was sufficient to render the water visibly colorless (Figure 3). Therefore, an irradiation time of 3 to 5 minutes (equivalent to 6-10 times the typical UV disinfection retention time) may be considered a practical design choice for UV systems targeting color removal, balancing efficiency with energy consumption and operational cost. No significant changes were observed in other parameters, including pH, conductivity, and turbidity, across all samples after irradiation. The visual panels (Figure 3(a-b)) emphasize that low H_2O_2 doses (33-100 mg/L) are sufficient to remove visible color within 3-5 min; the 333 mg/L performance is shown quantitatively in Figure 2.

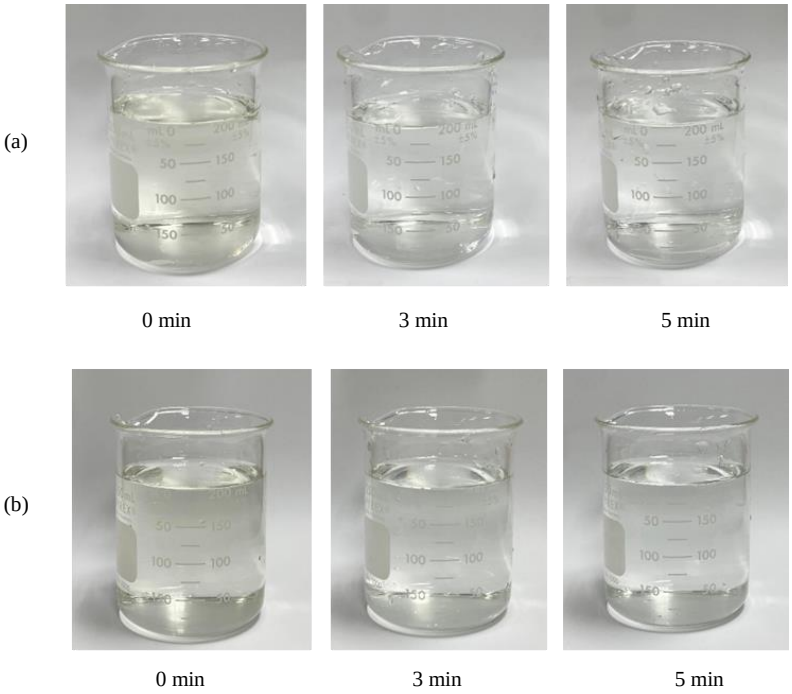

Figure 3. Comparison of the color of treated wastewater and color removal using H_2O_2 in combination with UV irradiation a) 100 mg/L of H_2O_2 and b) 33 mg/L of H_2O_2.

3.2 Chemical kinetics

Experiments were conducted under fixed conditions (Low-pressure lamp UV 254 nm, 16 W; neutral pH; ambient temperature at 25-30°C). Within this setting, we assess peroxide effects as observed trends rather than statistical claims. Time-course data are presented as absolute ADMI. Kinetic fits were obtained from the linearized forms $\ln(C/C_0)$ vs time for pseudo-first order model and $(1/C-1/C_0)$ vs time pseudo-second order model using the run-specific C_0 as mentioned in section 2.6. Linearized plots of $\ln(C/C_0)$ versus time and $(1/C_0-1/C)$ versus time are shown in Figure 4(a) and Figure 4(b), respectively. Across all H_2O_2 doses, the pseudo-second order model provided consistently higher R^2 (0.953-0.966) than pseudo-first order (0.909-0.921) with more uniform residuals; therefore, pseudo-second order was selected for reporting and interpreted as apparent bimolecular control under our conditions (Park et al., 2005; Puspita et al., 2011; Sugha and Bhatti, 2022; Son et al., 2024). Linear regression analysis was conducted for both kinetic models, and the calculated rate constants are presented in Table 2. To maintain readability, R^2 of all fitted models are reported in Table 2 rather than overlaid on Figure 4; the figure displays the fitted lines, while Table 2 lists the numerical parameters. Across the tested range, increasing H_2O_2 from 33 to 167 mg/L was associated with higher fitted pseudo-Second order rate constants, while the increment to 333 mg/L gave only modest additional gain (Table 2). We therefore describe a positive dose-response trend under the fixed UV setting; formal significance testing

was not performed in this screening study. A limitation of this study is that lamp irradiance was not measured; while this does not affect the within-study kinetic comparisons at a fixed setting, inter-laboratory reproducibility will benefit from reporting irradiance/fluence in future pilots.

Higher lamp power/UV fluence generally accelerates decolorization at fixed contact time, as reported for treated effluents and dye-rich matrices (Caretti and Lubello, 2010; Puspita et al., 2011; Sugha and Bhatti, 2022; Son et al., 2024). At neutral pH, bicarbonate or carbonate and natural organic matter can scavenge ·OH, moderating apparent kinetics (Park et al., 2005; Puspita et al., 2011). Tests here were at 25-30°C; temperature can modestly enhance rates but was not isolated. A future design-of-experiments study will explicitly vary UV fluence (lamp power), H_2O_2 dose, pH, and temperature to quantify main/interaction effects and optimize performance.

Table 2. Kinetic constants of pseudo-first order and pseudo-second order

H_2O_2 (mg/L)	Pseudo-First order constant		Pseudo-Second order constant	
	k' (min^{-1})	R^2	k'' ($ADMI^{-1}·min^{-1}$)	R^2
33	0.147	0.918	0.010	0.954
100	0.148	0.910	0.011	0.953
167	0.147	0.921	0.011	0.963
333	0.169	0.909	0.014	0.966

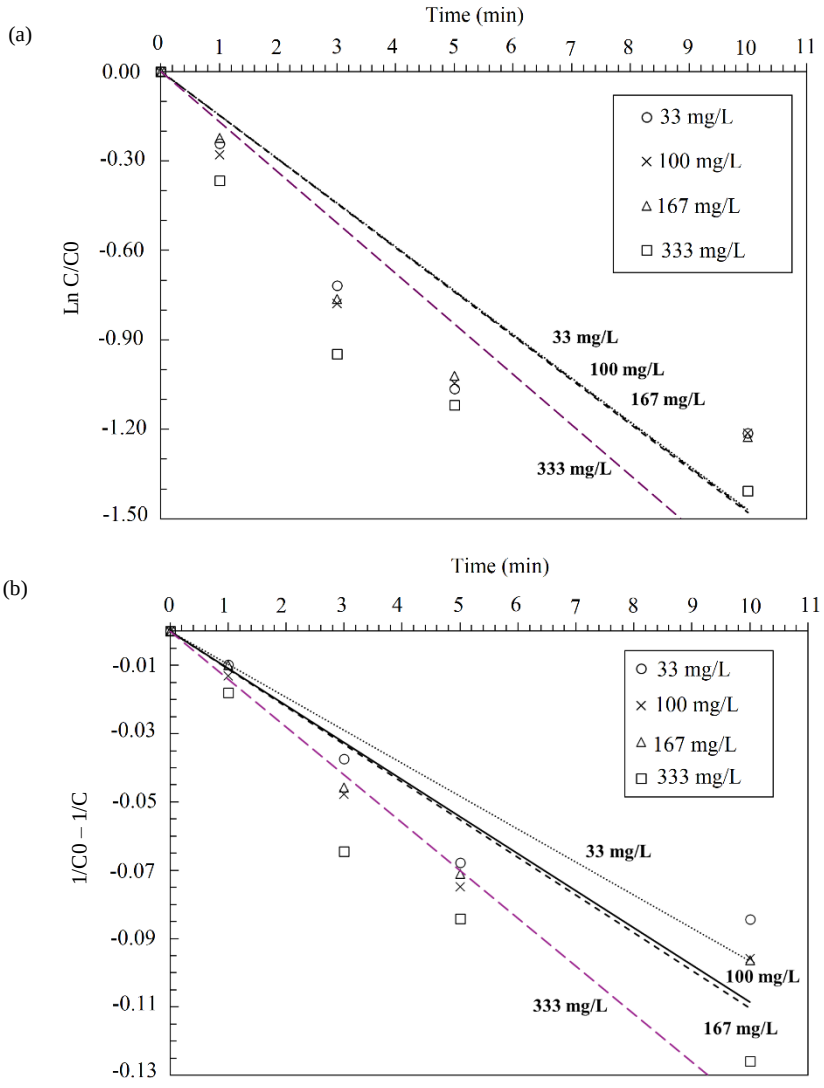

Figure 4. Reaction kinetic models (a) Pseudo-First order reaction and (b) Pseudo-Second order reaction. Rate constants and R^2 for all fits are provided in Table 2

The high coefficient of determination (R^2>0.95) indicates that the reaction kinetics in this study closely follow the pseudo-second-order model, consistent with findings from previous research (Zawadzki and Deska, 2021). This model suggests that the rate of color removal is influenced by both the concentration of hydroxyl radicals and the concentration of color, implying a bimolecular reaction mechanism, which indicates the involving of both concentration on hydroxyl radical and color. Such behavior typically occurs when the concentration of hydroxyl radical changes throughout the reaction. Hydroxyl radicals in this process are primarily generated through the photolysis of H_2O_2 under UV irradiation. The strong fits to the pseudo-second order model (Table 2) indicate apparent bimolecular behavior, where the observed rate reflects both chromophore concentration and the effective ·OH exposure (Park et al., 2005; Puspita et al., 2011). Under our fixed UV condition, the positive dose-response is consistent with increased radical availability (Caretti and Lubello, 2010; Sugha and Bhatti, 2022). However, other variables—not varied here—also influence rates, including UV fluence/lamp power (Son et al., 2024), pH and radical scavenging by carbonate and natural organic matter (Sugha and Bhatti, 2022), and temperature (Park et al., 2005). We therefore interpret the peroxide effect as a trend specific to these operating conditions. Despite these complexities, the primary aim of this study is to evaluate the effectiveness of the UV/H_2O_2 process in eliminating residual color from treated wastewater. The results presented in the previous section demonstrate that this widely available UV equipment exhibits sufficient performance to achieve this objective. Moreover, the proposed kinetic model offers a practical foundation for future engineering applications in water reused processes. However, matrix constituents (e.g., NOM/DOC) can scavenge radicals and reduce UV transmittance, moderating apparent rates under otherwise identical conditions.

3.3 Comparison with previous studies

Under a fixed Low pressure UV setting (254 nm, 16 W; neutral pH; ambient 25-30°C), this study achieved >65% color removal at 5 min with 100 mg/L H_2O_2 and around 76% at 10 min with 333 mg/L. The pattern—rapid early decolorization followed by diminishing gains at longer contact/higher dose—is consistent with UV/H_2O_2 behavior reported for municipal secondary effluents and dye-laden matrices, where fast radical attack on chromophores is followed by slower tails due to scavenging and depletion of the most reactive moieties (Park et al., 2005; Caretti and Lubello, 2010; Puspita et al., 2011; Sugha and Bhatti, 2022). Recent work on actual textile wastewater under optimized fluence and higher peroxide has shown very high ultimate decolorization (Son et al., 2024); by contrast, our household-UV configuration emphasizes short retention and simple hardware for building-scale effluent reuse, yielding practically meaningful removal within minutes. Table 3 compares UV/H_2O_2 color-removal performance reported in prior studies with the results of the present study. The reviewed studies vary in wastewater type, H_2O_2 concentration, UV exposure conditions, and irradiation time. Reported decolorization efficiencies range from approximately 78% to over 99%, depending on experimental setups (Park et al., 2005; Caretti and Lubello, 2010; Puspita et al., 2011; Sugha and Bhatti, 2022; Son et al., 2024).

In this study, approximately 65% color removal was achieved within 5 minutes using 100 mg/L H_2O_2 and a household-scale low-pressure UV system treating municipal wastewater. This performance is comparable to other studies on treated municipal or domestic effluents—for example, Caretti and Lubello (2010) reported 80-90% removal within 10 minutes at 50 mg/L H_2O_2, while Puspita et al. (2011) and Park et al. (2005) achieved >90% removal after 20-30 minutes of treatment at high-energy lamp. Despite the relatively simple and low-energy setup used in this work, the efficiency falls within the reported range, highlighting the practicality of the UV/H_2O_2 process for decentralized color removal in non-potable water reuse. In comparison, studies using industrial wastewaters—such as textile effluents—report higher color removal (>99% removal) but typically require longer treatment times, higher H_2O_2 doses. These differences emphasize the importance of using the UV/H_2O_2 process with wastewater characteristics and reuse goals. A brief cost perspective for this dose-time window is provided in Section 3.4, where reagent costs are reported in THB and USD (conversion per Section 2.7). For building-scale reuse, a basic pre-filter is typically installed upstream of UV (as used here). A downstream, low-cost polishing step (e.g., granular activated carbon) could target residual chromophores and potentially increase overall color removal and enabling lower H_2O_2 doses with minimal added complexity. Evaluation of such UV/H_2O_2 + GAC trains will be included in future pilot testing.

Table 3. Summary of UV/H_2O_2 color removal performance from previous studies and this work

Study	Sample type	UV lamp	H_2O_2 (mg/L)	Irradiation time (min)	Color removal (%)
Park et al. (2005)	Municipal secondary effluent	75 W	44	20	>90%
Caretti and Lubello (2010)	Municipal secondary effluent	15 W	50	10	80-90%
Puspita et al. (2011)	Municipal secondary effluent	40 W	32	30	>90%
Sugha and Bhatti (2022)	Synthetic dye wastewater	11 W	425	10	65%
Son et al. (2024)	Actual textile wastewater	4 W	170	180	91%
This study	Municipal secondary effluent	16 W	100	5	65%

3.4 Reagent cost (H_2O_2)

Based on the commercial-grade price of H_2O_2 at 50% w/w, the estimated chemical costs for the UV/H_2O_2 process are summarized in Table 4. In this study, the cost of H_2O_2 usage ranged from 1.93 to 19.31 baht per cubic meter of treated wastewater, depending on the applied concentration. The total operational cost of the UV/H_2O_2 process includes the cost of the UV system, electricity consumption, and the H_2O_2 reagent. According to Metropolitan Waterworks Authority (MWA) of Thailand, the starting price of water supplied to large commercial buildings or industrial users is 9.5 baht per cubic meter (Thailand Metropolitan Waterworks Authority (MWA), 2022). In comparison, using 100 mg/L of H_2O_2—identified as an effective concentration in this study—acquires an approximate cost of 5.8 baht per cubic meter, which is considered economically feasible. As discussed in the previous section regarding system sizing, a 3-minute UV retention time, achieving 52-58% color removal (Figure 2), may serve as a reasonable operational target. This design would allow the combined cost of system installation and chemical usage to remain competitive with the price of municipal water supply, supporting practical implementation of the UV/H_2O_2 process for wastewater treatment.

Table 4. Reagent cost of H_2O_2 per m^3 of treated wastewater (priced with 50% w/w stock). Values shown in THB and USD (conversion per Section 2.7)

H_2O_2 concentration (mg/L)	Cost per m^3 of wastewater (THB/m^3)	Cost (USD/m^3)
33	1.9	0.059
100	5.8	0.179
167	9.7	0.300
333	19.3	0.596

Note: Experimental dosing used 30% w/w H_2O_2, but costs are normalized to pure H_2O_2 and priced using 50% w/w commercial stock (conversion via mass fraction). Reported values represent reagent cost only; electricity and UV capital are excluded.

A recent study by Cai et al. (2020) evaluated various advanced oxidation processes (AOPs) for treating reverse osmosis concentrate from industrial wastewater and reported that the UV/H_2O_2 process had comparatively higher operational costs (1.44 USD/m^3 as 0.30 USD/m^3 for chemical cost) than alternatives like the Fenton process (0.519 USD/m^3), primarily due to energy-intensive UV systems and higher reagent consumption. While such costs may be acceptable in large-scale industrial treatment, they can be prohibitive in small-scale or building-scale applications. In contrast, this study demonstrates that using a simple, low-pressure household UV system and 100 mg/L of H_2O_2 achieves 65% color removal within 5 minutes at a cost of approximately 5.8 THB/m^3 (USD ~0.179/m^3) for chemical cost. These results emphasize the economic feasibility of the UV/H_2O_2 process for decentralized municipal wastewater reuse, especially in urban buildings where cost-efficiency and operational simplicity are essential.

In Thailand, treated wastewater is typically discharged into public sewer systems. However, increasing environmental concerns and growing water scarcity have heightened public awareness and interest in sustainable practices, such as water reclamation, water reuse, and green building initiatives. Over the past several years, recycling treated wastewater has gained significant attention. Many large buildings equipped with on-site wastewater treatment systems—such as condominiums, shopping malls, and government buildings—are now exploring the reuse of treated wastewater to reduce dependence on the public water supply. The initial strategy focuses on utilizing reclaimed water for non-potable purposes, such as landscape irrigation, floor washing, toilet flushing, and other activities where direct human contact is minimal. Nevertheless, the light-yellow coloration often present in treated wastewater raises concerns regarding its acceptability for reuse. Conventional post-treatment methods, including sand filtration,

activated carbon filtration, and chlorine disinfection, are frequently insufficient to effectively remove this residual color. To resolve this issue, advanced treatment methods, such as ultrafiltration (UF), have been recommended. Although UF is highly effective in color removal, it involves high capital investment and requires intensive maintenance, which creates wastewater during washing the membrane. An alternative approach involves the application of the UV/H_2O_2 advanced oxidation process. While this method requires scaling up the UV system to approximately six times its standard size, the overall capital cost remains lower than that of ultrafiltration. Furthermore, unlike UF, which still requires a separate disinfection step, the UV/H_2O_2 process simultaneously achieves both color removal and effective disinfection. Therefore, the UV/H_2O_2 process represents a practical, efficient, and cost-effective solution for color removal, making it a promising option for the reuse of treated municipal wastewater in large buildings. Furthermore, its modularity, low maintenance requirements, and absence of waste residuals offer practical advantages over conventional technologies, especially in urban settings promoting sustainable and decentralized water reuse.

To contextualize costs relative to common reuse trains, recent technology-economic assessments report operating expenditures (OPEX) for tertiary ultrafiltration (UF) polishing of \$0.129-\$0.152/m^3 (converted from 0.11-0.13 €/m^3), whereas full-scale ozonation-based tertiary treatment is \$1.01-\$2.85/m^3 (converted from 0.86-2.44 €/m^3) (Clem and Mendonça, 2022; Echevarría et al., 2022). These ranges reflect the higher capital intensity and energy/oxidant demand characteristic of membrane and ozone systems. By comparison, the household-scale UV/H_2O_2 configuration evaluated here—achieving ≈65% color removal in 5 min with 100 mg/L H_2O_2—yields an estimated treatment cost of ≈\$0.179/m^3 (converted from 5.8 THB/m^3), which is competitive for building- or campus-level non-potable reuse where simplicity, modularity, and low maintenance are priorities.

While our analysis centers on reagent-only cost for a compact UV/H_2O_2 step, literature indicates that membrane polishing (e.g., UF) and ozonation-based trains generally carry higher capital intensity and/or energy/oxidant demand at full scale; see cited studies for comparative ranges and drivers (Caretti and Lubello, 2010; Cai et al., 2020). Our screening window (≤167 mg/L H_2O_2; 3-5 min) is therefore intended as a low-complexity option for building-level reuse, with full TEA (energy + lamp replacement) to be developed in future work.

3.5 Regulatory context for non-potable reuse

Non-potable reuse for building or district applications (e.g., toilet/urinal flushing, laundry, street cleaning) is typically governed by "fit-for-purpose" specifications that target microbiological safety, clarity, and operational reliability. Representative criteria compiled by the USEPA and state programs include (USEPA, 2024):

- Microbiological: Total coliform ≤2.2 MPN·100 m/L (7-day median) with 23 MPN·100 m/L single-sample maximum for Class A reclaimed water; demonstration of ≥4-log virus removal/inactivation via treatment and disinfection.
- Clarity (Turbidity): For coagulation/ filtration treatment, 2 NTU monthly average (5 NTU max); for membrane filtration, 0.2 NTU monthly average (0.5 NTU max).
- Disinfection operation: Free chlorine ≥1 mg/L with ≥30 min contact at peak flow or validated UV disinfection dose meeting target log-credits.

For onsite (single-building) non-potable reuse, USEPA resources emphasize end-use specific controls and, in some local authorities, conformance with product standards such as NSF/ANSI 350 for graywater systems; similar "fit-for-purpose" principles guide centralized non-potable reuse categories summarized in the EPA's REUSExplorer (USEPA, 2024). For irrigation-type end uses, ISO 16075 provides international guidance on project design and monitoring for the safe use of treated wastewater, complementing WHO risk-based approaches (International Organization for Standardization, 2020). While Thailand's reclaimed-water specifications are evolving, recent reviews indicate growing interest and pilots in municipal reuse. Therefore, we present the above criteria as representative targets for Thai urban/building contexts, consistent with non-potable reuse benchmarks discussed in previous studies in Thailand (Chiemchaisri et al., 2015; Kanchanapiya and Tantisattayakul, 2022).

Residual H_2O_2 naturally decomposes to H_2O and O_2 in typical effluents. In practice, several treatment systems include a short post-UV residence time, so the residual is non-detectable before distribution. Because lamp-based UV/H_2O_2 provides

no disinfectant residual—and this study did not measure residual H_2O_2 or microbiological indicators—regrowth control is treated as an operational matter (e.g., storage turnover, light-blocking storage tanks, routine sanitation) in line with non-potable reuse practice. These controls, together with residual/microbial monitoring, will be verified in future pilot testing.

4. CONCLUSION

This study evaluated color removal from treated municipal wastewater using a household low-pressure UV unit (254 nm, 16 W) combined with H_2O_2 under neutral pH and ambient temperature (25-30°C). Color decreased rapidly within the first 3-5 min across doses, with >65% removal at 5 min for 100 mg/L H_2O_2 and a maximum of ~76.0% at 10 min for 333 mg/L. Linearized kinetic fitting showed that the pseudo-second-order model (R^2≈0.953-0.966) described the data better than the pseudo-first-order model (R^2≈0.909-0.921), indicating apparent bimolecular behavior under the tested conditions.

A screening-level cost calculation (reagent-only, priced using 50% w/w commercial H_2O_2) yielded 1.90, 5.80, 9.70, and 19.3 THB/m^3 at 33, 100, 167, and 333 mg/L, respectively; using 32.4 THB=1 USD (Section 2.7), these correspond to 0.059, 0.179, 0.300, and 0.596 USD/m^3. These values reflect chemical reagent cost only; electricity and UV capital were not included.

Results were obtained at a fixed lamp power with pre-filtration, neutral pH, and ambient temperature. Microbiological indicators were not measured, and the cost analysis excluded energy and capital. Accordingly, conclusions are limited to color removal performance, kinetic description, and reagent cost under the reported conditions. Residual H_2O_2 was not measured; future pilot work will apply a post-UV holding step and verify non-detectable residual prior to reuse. No microbiological enumeration or regrowth assessment was performed; these will be included in future pilot studies.

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AUTHOR CONTRIBUTIONS

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DECLARATION OF CONFLICT OF INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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