Comparison of ferrate (FeO$_4^{2-}$) and ultrasonic waves ability as Coliform antibacterial in Kahayan River water Central Kalimantan

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Abstract. This study aims to compare ferrate (FeO$_4^{2-}$) and exposure of ultrasonic waves as an antibacterial coliform in the Kahayan River water in Central Kalimantan. Sampling in this study used the Grab Sampling method with the Kemmerer Sampler tool. Ferrate (FeO$_4^{2-}$) was made by reacting to a solution of Fe(NO)$_3$ with NaOCl in alkaline conditions. Application of Ferrate (Fe(VI)) done by varying the concentration (0.03125; 0.0625; 0.125; 0.25; 0.5 mmol/L) to get the best concentration, and follow by varying times (0, 5, 10, 15, 20, 25, 30 minutes) at optimum concentration. Ultrasonic wave exposure was carried out with varying frequencies to get the optimum frequency and followed by variations in the exposure time at the optimum frequency. The coliform test was carried out by the MPN method with stages of detection tests, affirmation tests, and colony counting. The MPN analysis showed that ferrate could kill coliform bacteria at a concentration of 0.0625 mmol/L during the 5 minutes stirring time with 100% efficiency. Ultrasonic wave exposure could kill coliform bacteria optimally at a 40 kHz frequency during 3 hours of exposure time with 96% efficiency. These results showed that ferrate was more effective in killing coliform bacteria compared with ultrasonic wave exposure.

1. Introduction

Water is essential for human life. The source of water used is not always clean. For drinking water purposes, water must be treated to reduce odor, taste, clarity, or eliminate diseases caused by pathogens [1]. More than 1 billion people cannot get clean water sources. Many people suffer from illness and even death due to water contamination [2]. Un-disinfected water triggers the development of Escherichia coli and causes gastroenteritis in Walkerton, Ontario (2000), cryptosporidiosis in Milwaukee, Wisconsin (1993), and cholera in Peru (1991) [3,4].

The Indonesian Central Bureau of Statistics reports that 75% of Indonesia's rivers are polluted by pollutants, just as the Kahayan river water in 2008 was heavily polluted [5]. Coliform bacteria contaminate the Kahayan River. The biological indicator indicates that water is trash, or fecal contamination is coliform bacteria in the water [6].
One way to deal with coliform bacteria contamination is by utilizing exposure to ultrasonic waves. Ultrasonic waves reproduce sound waves with frequencies above 20 kHz. Ultrasonic waves propagate in a diffuse pattern, while the angle of spread of the waves is inversely proportional to the working frequency. Ultrasonic waves can be generated by using a piezoelectric transducer or a ferroelectric transducer. This transducer will produce high-frequency sound waves [7].

In 1960, the discovery that the ship's sonar emitted sound waves could cause fish to die. Since then, various researches have been developed on the ultrasonic potential to kill bacteria [8]. Acoustic cavitation generated by ultrasonic waves can inactivate bacteria through several physicals, mechanical and chemical effects. When collapsed, cavitation bubbles generate enough energy to weaken or irritate through the following processes:
- The induction of cavitation produces a force as a result of resonance on the surface of bacterial cells. This force creates pressure and pressure gradient due to the collapse of gas bubbles entering or near the bacterial cell wall. Within a certain time, this mechanical fatigue causes damage to the bacterial cells. It also depends on the frequency.
- A shear force formed, which is induced by microstreaming in the bacterial cell.
- Chemical groaning occurs due to the formation of radicals (H• and OH•) during cavitation in water media, on bacterial cell walls, and weakens the cell walls to disintegration.
- The end product of this water's sonochemical degradation is hydrogen peroxide (H₂O₂), which is a potent bactericide [9].

A study on ultrasonic waves to kill bacteria was carried out by Zhou et al. in 2009 to kill E. coli bacteria on spinach leaves [10]. Besides, there is the use of ultrasonic waves to reduce the amount of Salmonella typhimurium in milk [11], study the effect of ultrasonic waves on beef broth [12], and control microbes in water [13–15].

Research on the sterilization of Kahayan River water was previously carried out by Suastika et al. in 2015 [7]. Based on this research, it was reported that the optimum frequency of deactivating E. coli in water samples was 27.6 kHz with an efficiency of 37.8%.

The accepted treatment method to protect public health apart from ultrasonic treatment is filtration and disinfection [2]. The filtration method is considered a weakness in removing viruses or spores that are small in size. Filtration may not be able to 99% reduce contamination. A disinfectant is a chemical treatment that is adopted to remove harmful and safe microorganisms. Some of the disinfectants that have been used include hydrogen peroxide, UV light, permanganate, or a combination of chloramine [16,17]. However, there are several obstacles to applying this disinfectant because it can cause side effects [18–21].

Ferrate [FeO₄²⁻] is an environmentally friendly treatment that can be used in drinking water treatment. Several studies have used ferrates in the field of water treatment technology and the wastewater industry. The nature of ferrate can kill various viruses and bacteria in water and wastewater treatment processes. The potassium ferrate was reported to reduce 50% color, 30% COD, and kill 10% bacteria in the water than aluminum sulfate and ferric sulfate [22]. There is still limited research on the experimental of ferrate(VI) as a disinfectant focused only on drinking water is available in our acknowledgment.

Iron, which has an oxidation number of +2 and +3, can be strongly oxidized in the environment, iron with a higher oxidation number such as +4, +5, and +6, too [23]. Ferrate, which is iron with an oxidation state of +6, is of concern because it can be synthesized in an environmentally friendly manner [24,25]. Several papers published the Fe(VI) reaction mechanism (especially the FeO₄²⁻ oxidation). For example, ferrate can oxidize lactam antibiotics, and ferrate is very effective in reducing lactam antibacterial activity. Fe(VI) as an inorganic compound, is more stable in the pH range 9-10 but reacts slowly in water because it forms ferrate and oxygen ions[26–28], as in equation 1.

\[
2\text{FeO}_4^- + 5\text{H}_2\text{O} \rightarrow 2\text{Fe} + \frac{3}{2}\text{O}_2 + 10\text{OH}^- \tag{1}
\]
Fe (VI) is unstable at pH below nine, and ferrate ion will quickly auto-decompose within seconds to minutes. This reaction follows second order kinetics. The auto-decomposition rate of Fe (VI) increases with increasing pH, experiencing protonation from the more reactive FeO₄²⁻ [29]. The potential advantage of using Fe (VI) in the water treatment process is that it does not produce harmful toxicological side effects [30].

Disinfectants designed to kill harmful organisms (e.g., bacteria and protozoa) and oxidizers degrade various contaminants. Fe (VI) is useful in deactivating (escherichia coli, sphaerotilus, bacillus subtilis, bacillus licheniformis RB1-1B, mycobacterium frederiksiergense M8-6, mycobacterium setense M9-4) [31–33], viruses (f2 coliphage, Q -coliphage and Bacteriophage MS2) [32,34,35], algae (Microcystin-LR) [36] and other pathogens [37] in synthetic buffer solutions and secondary effluents. Besides, even Fe(VI) in low doses can inactivate 99.9% of various microorganisms, both on a laboratory scale or in early experiments [38]. Many researchers have used Fe(VI) to remove fecal contamination from various world regions with coliform mortality rates above 99.9% [39,40].

Fe (VI) is a powerful disinfectant and oxidant useful for treating drinking water in the U.S. for more than a decade[41]. In many ways, it can be considerably affordable, a sample alternative to ozonation, and thus it is well suited for use in small systems. Like ozone and other disinfectants such as chlorine dioxide and chloramines, Fe (VI) is a highly selective oxidant, but it does not lead to the formation of any know hazardous by-products (brominated or chlorinated DBPs), bromate or chlorite). Ferrate is considered a ‘‘green’’ chemical for water treatment, because it does not produce any known toxic by-products [40]. In this paper, the synthesis of ferrate (Fe(VI)) was analyzed using the wet synthesis method as a disinfectant in the Kahayan river water treatment.

2. Materials and methods
This study’s method is divided into three stages: water sampling and coliform bacteria examination, sonication using ultrasonic, and oxidation using ferrate (Fe (VI)).

2.1. Water sampling and coliform bacteria examination
Kahayan River water sampling was carried out by varying several sampling points by taking into account the river depth, river width, and water discharge. Kahayan River has a depth of 7 m, a width of 500 m, the most massive water discharge is 2,716 m³/s, and the smallest water discharge is 26.30 m³/s. Kahayan River water sampling was carried out in January-April when the water discharge reached its most massive water discharge. Based on these data, the Kahayan River water sampling carried out at 6 points, namely 3 points from the width of the Kahayan River at the 125 m point; 250 m; 375 m and 2 points from the depth of the Kahayan River at a point of 1.4 m; 5.6 m [42,43].

Coliform bacteria examination uses a quantitative examination, with the following stages:

a. Estimation Test. The estimation test is a specific test for the detection of Coliform bacteria. This is a preliminary test of coliform bacteria’s presence or absence based on the formation of acids and gases caused by lactose fermentation by Coli bacteria. The method used was the three tubes series Most Probable Number (MPN) method. The principle of the MPN method is to calculate the closest estimate through the estimator test [44].

b. Confirmative Test. The positive results in the prediction test for raw water were followed by a reinforcement test using the MPN series three methods. The media used was Brilliant Green Lactose Bile (BGLB). This medium is a selective medium for coliform, so it can inhibit other bacteria’s growth and increase growth for coliform. The observation of river water samples in the MPN tube tested with three series of tubes using BGLB media where the air bubbles formed in the durham tubes after 24 hours in the form of carbon dioxide gas produced due to lactose fermentation in BGLB media by coliform bacteria.

c. Complimentary Test. This test is a final analysis of a water sample to detect the presence of coliform. The medium used was Eosin Methyylene Blue (EMB) [45].
d. The calculation of the efficiency of reducing the number of bacterial colonies was then carried out to see the percentage of reduction in bacterial colonies using equation 2:

\[
\text{% Efficiency} = \frac{\text{MPN}_{\text{str}} - \text{MPN}_{\text{per}}}{\text{MPN}_{\text{str}}} \times 100
\]  

(2)

where % efficiency is the percentage reduction in bacteria, MPN<sub>str</sub> is the control MPN index, and MPN<sub>per</sub> is the treatment's MPN index [43].

2.2. Oxidation using ferrate (Fe (VI)).

2.2.1 Synthesis of ferrates (Fe (VI)) and the Kahayan River water treatment. Ferrate was synthesized in the following way:
1. Manufacture of 5.25% NaOCl solution
2. NaOCl solution with a 5.25% concentration was made by diluting 43.75 mL of 12% NaOCl from the bleach solution to 100 mL.
3. Making FeCl<sub>3</sub> 0.3 M solution
4. The solution of FeCl<sub>3</sub> with a concentration of 0.3 M was prepared by dissolving 4.058 grams of FeCl<sub>3</sub>·6H<sub>2</sub>O with aquabides to 50 mL.
5. Synthesis of ferrates from clothing bleach solutions
6. Ferrate synthesis was carried out by reacting 40 mL of clothes whitening solution containing 5.25% NaOCl with 12 grams of NaOH. The solution is stirred until NaOH is completely dissolved, then added 1 mL FeCl<sub>3</sub>. The solution is stirred again until the solution turns purple, then closed and allowed to stand for a day. Furthermore, it was analyzed by UV-Vis spectrophotometer to determine the maximum wavelength of ferrate.

2.2.2 The Kahayan River water treatment using ferrate as disinfectant. Solution containing ferrate ions. This solution was used as a disinfectant in the Kahayan river water by adding a volume of ferrate solution to the Kahayan river water sample. First, the optimum dosage of effective ferrate ions was determined as a disinfectant for coliform bacteria that lived in the Kahayan river water under natural environmental conditions, by adding a solution of ferrate ions to 250 mL of Kahayan river water with a concentration of 0.5; 1.5; 2.5; and 3.5 mmol/L [46], with stirring for 30 minutes [1]. Then, each sample was planted into MPN media for 24 hours to identify the remaining coliform bacteria after treatment.

Then, the optimization of the contact time of ferrate ions with coliform in the Kahayan river water was carried out. The concentration used in this optimization referred to [1] which is 0.03125 mmol/L with stirring variations at time 0; 5; 10; 15; 20; 25 and 30 minutes. Furthermore, each sample was planted into MPN media for 24 hours to identify coliform bacteria left after treatment.

2.3. Sonication using ultrasonic

At this stage, the Kahayan River water samples treated with ultrasonic waves. The stages of sonication are as follows:
1. The water sample was placed in a beaker, and at the top of the glass, an ultrasonic speaker was placed. To prevent other waves' attenuation during the ultrasonic exposure process, the sample glass and speaker were placed in a glass container filled with sterile water.
2. Generating ultrasonic waves using a piezo tweeter speaker with a frequency of 20 kHz. The activation of the speaker operation used an ultrasonic wave generator (signal generator).
3. Place the piezo speaker on the top of the container containing the Kahayan River water sample for 2 hours.
4. The process repeated for 20 kHz, 30 kHz, 40 kHz, 50 kHz, and 60 kHz [42].
5. Based on the optimum frequency data above, processes 1 and 2 repeated with time variations of 1, 2, 3, 4, and 5 hours [43].
3. Results and discussion

3.1. Oxidation using ferrate (Fe (VI)).

3.1.1. Synthesis of ferrate. Ferrate synthesis was carried out by dissolving NaOH solids with a clothes whitening solution containing 5.25% NaOCl. Furthermore, the solution Fe(III) was added later with the iron species intention to be oxidized by NaOCl in an alkaline atmosphere. In the oxidation reaction of Fe(III) to Fe(VI), FeCl₃ was added drop by drop. This reaction produced a dark purple solution which showed that Fe (III) has been oxidized to Fe (VI). The following reaction shows ferrate formation reaction in equation 3.

\[
2\text{Fe}^{3+} + 3\text{ClO}^- + 10\text{OH}^- \rightarrow 2\text{FeO}_4^{2-} + 3\text{Cl}^- + 5\text{H}_2\text{O}
\]  

(3)

This solution is allowed to stand for a day with the aim that the fermentation produced is stable. The stability of ferrate was shown by the color of the solution formed. This solution was then analyzed by UV-Vis spectroscopy to determine the maximum wavelength of ferrate in the visible wave. The measurement results obtained that the maximum wavelength was 510 nm, as reported by Karelius and Asi (2017) showed in figure 1 [47].

![Figure 1. Maximum wavelength of ferrate.](image)

3.1.2. Quantification of Fe(VI). Electrochemical, volumetric, and various spectrophotometric methods are some of the methods used for the quantitative determination of Fe (VI), [48,49]. Of these various methods, the UV-Vis spectral method offers simple steps, fast experimental work, and accurate results [49], to determine the concentration and purity of Fe (VI) using this method. The determination of the concentration and purity of Fe (VI) is as follows,

- Determination of the concentration of Fe (VI) in water by absorbance of UV-Vis based on Beer's law;
- Fe (VI) ion in water appeared dark purple with a maximum absorbance peak at 510 nm;
- The molar absorbance coefficient (ε) was determined to be 1070 M⁻¹cm⁻¹;
- Calculating the concentration of Fe (VI) using the following equation 4 [48],

\[
\varepsilon = \frac{A}{BC}
\]

(4)

where the notation “ε” equals 1070 M⁻¹cm⁻¹ (molar absorbance coefficient), “A” is UV-Vis absorbance by sample, “B” represents Fe (VI) concentration (M) in the examined sample, and “C” was the light path (cm) of the quartz cell used in this study. The concentration of ferrate ions in the solution was 365.85 mmol/L.
3.1.3 Ferrate ions as disinfectants. The initial condition of the Kahayan river water in pH of 5.39 has a total suspended solid (TSS) of 849 mg/L, turbidity of 420 mg/L, and iron, sodium and chlorine total content respectively of 0.229; 1.67; 3.30 mg/L. The presence of coliform in the Kahayan river was carried out using the MPN method and BGLB media. This is the community that uses the Kahayan River for various activities including being used as a latrine so that fecal *coli*form bacteria can ensure pollution.

This study used ferrate ions as a disinfectant for *coli*form bacteria that lives in the Kahayan river water, a source of raw water for PDAM of Palangka Raya. The first step taken was to determine the optimum dose of effective ferrate ions as a disinfectant for *coli*form bacteria that live in the Kahayan river water under natural environmental conditions, by adding ferrates to 250 mL of Kahayan river water at a concentration of 0.5; 1.5; 2.5 and 3.5 mmol/L[46], stirring for 30 minutes [1]. The results of the treatment can be seen in the following figure 2.

Figure 3 was based on the data generated from observations of effective ferrate as a disinfectant. Observation of river water samples in MPN tubes treated with ferrates' addition at a concentration of 0.5; 1.5; 2.5 and 3.5 mmol/L with stirring for 30 minutes did not show a positive test for the presence of *coli*form bacteria in 4 treatments with the addition of ferrate. No carbon dioxide gas was formed in the Durham tube with BGLB media after 24 hours (figure 3).

The use of Fe (VI) in several water sources in several cities in the world is known to kill almost 99.9% of the total *coli*forms in water sources. The effect of significant Fe(VI) as a disinfectant on effective microorganisms against environmentally safe *coli*forms is not mutagenic or carcinogenic [50].

![Figure 2. Calculation of ferrate treatment as disinfectant.](image)

![Figure 3. The MPN tube of river water sample using ferrate after 24 hours. Concentration of (a) 0.5; (b) 1.5; (c) 2.5; (d) 3.5 mmol/L.](image)
Figure 2, the calculation of coliform bacteria in several variations of ferrate concentration after 24 hours calculation of the number of coliform bacteria showed that ferrate was very effective as a disinfectant for coliform bacteria in the Kahayan river water. Ferrate ions with the lowest concentration of 0.5 mmol/L could function as a disinfectant for coliform bacteria in the Kahayan river water with 100% inactivation efficiency. Based on these results it is deemed necessary to re-optimize the concentration of ferrate ions added to the Kahayan river water as a disinfectant. The concentration used refers to Nguema [1] which is 0.03125 mmol/L with variations in the stirring time varying 0; 5; 10; 15; 20; 25 and 30 minutes.

The results of the treatment can be seen in figure 4. Stirring time at 0.03125 mmol/L ferrate ion concentration was found to affect the efficiency of inactivation. Figure 5 shows that at the time of stirring 0 minutes (without stirring) it turns out that ferrate ions at a concentration of 0.03125 mmol/L still gave positive test results on coliform bacteria with an efficiency of 88.97%. While from the stirring time 5 minutes onwards, the test did not give positive results for coliform bacteria. These results indicated that at the stirring time of only 5 minutes ferrate ions with a concentration of 0.03125 mmol/L were able to inactivate coliform bacteria in the Kahayan river water with 100% efficiency.

The final goal of this research is to find out the concentration of ferrate which can inactivate coliform bacteria in the Kahayan river water optimally under natural environmental conditions, which can later be applied to water treatment processes in PDAM Palangka Raya city by minimizing mechanical processes such as stirring. One possible way to achieve this is to find the concentration of ferrate that is able to inactivate coliform bacteria in the Kahayan river water optimally even without stirring.

Following figure 5 are the results of the ferrate treatment at a concentration of 0.03125; 0.0625; 0.125; 0.25; 0.5 mmol/L without stirring. The results of the addition of ferrate ions at various concentrations in the Kahayan river water containing coliform bacteria show that at the concentration of ferrate ions 0.03125; 0.0625; 0.125 mmol/L, still gave positive test results on coliform bacteria, with each inactivation efficiency of 76.92%, 85.725 and 99.42%. Ferrate ions with these concentrations had not inactivated coliform bacteria in the Kahayan river water to 100%. In contrast, the ferrate ion concentration of 0.25 and 0.5 mmol/L without stirring did not give positive test results on coliform bacteria. These results indicated that at a concentration of 0.25 mmol/L the ferrate ion could inactivate coliform bacteria in the Kahayan river water without stirring with 100% efficiency.

![Figure 4. The inactivation efficiency of coliform bacteria in the variation of stirring.](image1)

![Figure 5. The inactivation efficiency of coliform bacteria in the variation of ferrate concentration.](image2)
3.2. Sonication using ultrasonic

The first stage in this research was to determine the optimum frequency of exposure to ultrasonic waves. Water samples of 250 mL were exposed to ultrasonic waves for 2 hours [12], with variations of 20 kHz, 30 kHz, 40 kHz, 50 kHz, and 60 kHz. The water sample was placed in a beaker, and at the top of the glass, an ultrasonic speaker was placed. To prevent other waves' attenuation during the ultrasonic exposure process, the sample glass and speaker were placed in a glass container filled with sterile water. Then the bacteria count was checked after 2 hours of exposure.

The raw data obtained from the examination was the MPN index, from this data, it was used to calculate the inactivation efficiency of coliform bacteria, the higher the efficiency value indicated the high level of coliform bacteria inactivation. Figure 6 shows the results of the examination of coliform bacteria in water samples with variations in the frequency of exposure to ultrasonic waves. The highest efficiency to reduce the number of bacteria was at a frequency of 40 kHz which reached a value of 85.72%, which means that after 2 hours of treatment there were 85.72% of bacteria lost from water samples, this shows that ultrasonic waves could be used as anti-bacterial in river water Kahayan with sufficient frequency 40 kHz.

Based on the results of efficiency of coliform colony reduction with frequency, water samples were exposed to ultrasonic waves with a frequency of 40 kHz, with variations in an exposure time of 1 hour, 2 hours, 3 hours, 4 hours, and 5 hours. After that, the water sample removed, and the number of coliform colonies examined.

![Figure 6](image-url)  
**Figure 6.** Graph of the efficiency of coliform colony reduction with frequency.

![Figure 7](image-url)  
**Figure 7.** Effect of exposure time on the efficiency of the number of bacterial colonies.
The results of the coliform examination after incubation for 24 hours presented in figure 7. It shows that by comparing the number of bacterial colonies in control, the reduction in the number of \textit{coliforms} was at least when exposed to 3 hours, while at 5 hours, there was no change in the number of bacterial colonies. From the graph we can see, the highest efficiency for reducing the number of bacteria at 96% exposure time. This data shows that after 3 hours of treatment, 96% of bacteria had lost from water samples, this shows that ultrasonic waves with a 40 kHz frequency could be used as anti-bacteria in Kahayan River water with an optimal exposure time of 3 hours. However, these results show that ferrate was more effective in killing coliform bacteria than ultrasonic wave exposure.

4. Conclusion
Fe (VI) is an effective disinfectant for the treatment of The Kahayan river water. Laboratory research the application of Ferrate (Fe (VI)) in the MPN test results showed that at the concentration of Ferrate (Fe (VI)) 0.03125 mmol/L positive results were only seen at 0 minutes contact time. The inactivation efficiency of Ferrate (Fe (VI)) in this treatment was 88.97%. The variation of concentration treatment showed at the 0 minutes contact time the MPN test were positive at concentration of 0.03125; 0.0625; and 0.125 mmol/L and negative at concentration of 0.25; 0.5 mmol/L. This study’s result shows that the concentration of 0.25 mmol/L Ferrate (Fe (VI)) could function as a disinfectant for \textit{coliform} bacteria in Kahayan river with 100% inactivation efficiency.

After the ultrasonic wave exposure treatment with a 40 kHz frequency by varying the exposure time, the sufficient time to reduce the number of coliform colonies was 3 hours, with 96% efficiency. Based on this study’s result, it is concluded that ultrasonic waves can also be used as coliform anti-bacteria, but these results show that ferrate is more effective in killing coliform bacteria compared with ultrasonic wave exposure.

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References
[1] Nguema P F and Jun M 2016 Application of Ferrate (VI) as Disinfectant in Drinking Water Treatment Processes: A Review 11
[2] Rose J B 2002 Viewpoint: Water Quality Security \textit{Environ. Sci. Technol.} \textbf{36} 246A-50A
[3] Richardson S D, Simmons J E and Rice G 2002 Peer reviewed: disinfection by products: the next generation
[4] Hunter P R 2003 Drinking water and diarrhoeal disease due to Escherichia coli \textit{J. Water Health} \textbf{1} 65–72
[5] Badan Pusat Statistik 2017 Status Kualitas Air Sungai, 2007 - 2016
[6] Hujjatusnaini N 2009 Kajian Tentang Kualitas Mikrobiologi Berdasarkan Nilai MPN Coliform, Coliform fekal, dan Jumlah Koloni Bakteri Escherihia coli, Kualitas Fisik dan Kimia Air Minum Isi Ulang Di Kota Palangkaraya Sebagai Bahan Penunjang Praktikum Mikrobiologi. (Tesis) \textit{Disertasi dan Tesis Program Pascasarj. UM}
[7] Suastika K G, Martani N S and Hartanto T J 2015 Rancang Bangun Sistem Pembangkit Gelombang Ultrasonik Sebagai Metode Alternatif Menurunkan Jumlah Bakteri E. Coli Pada Proses Penjernihani Air \textit{Pros. Simp. Fis. Nas. XXVII Univ. Udayana Bali} \textbf{1} 546–52
[8] Gao S, Lewis G D, Ashokkumar M and Hemar Y 2014 Inactivation of microorganisms by low-frequency high-power ultrasound: 1. Effect of growth phase and capsule properties of the bacteria \textit{Ultrason. Sonochem.} \textbf{21} 446–53
[9] Joyce E, Phull S S, Lorimer J P and Mason T J 2003 The development and evaluation of ultrasound for the treatment of bacterial suspensions. A study of frequency, power and sonication time on cultured Bacillus species Ultrason. Sonochem. 10 315–8
[10] Zhou B, Feng H and Luo Y 2009 Ultrasound Enhanced Sanitizer Efficacy in Reduction of Escherichia coli O157 : H7 Population on Spinach Leaves J. Food Sci. 74 M308–13
[11] Juraga E, Šalamon B S, Herceg Z and Jambrak A R 2011 Application of High Intensity Ultrasound Treatment on Enterobacteriae Count in Milk Mljekarstvo J. Dairy Prod. Process. Improv. 61 11
[12] Puspasari N, Surtono A and Warsito W 2014 Efek Frekuensi Gelombang Ultrasonik Terhadap Mikroba Pada Air Kaldhu Daging Sapi J. Teori Dan Apl. Fis. 2 171–7
[13] Al-Juboori R A, Aravinthan V and Yusaf T 2015 Impact of pulsed ultrasound on bacteria reduction of natural waters Ultrason. Sonochem. 27 137–47
[14] Jiang J-Q and Lloyd B 2002 Progress in the development and use of ferrate (VI) salt as an oxidant and coagulant for water and wastewater treatment Water Res. 36 1397–408
[15] Jeannot C, Malaman B, Gerardin R and Oulladiaf B 2002 Synthesis, crystal and magnetic structures of the sodium ferrate (IV) Na4FeO4 studied by neutron diffraction and Mössbauer techniques J. Solid State Chem. 165 266–77
[16] Lee D G and Gai H 1993 Kinetics and mechanism of the oxidation of alcohols by ferrate ion Can. J. Chem. 71 1394–400
[17] Cho M, Lee Y, Choi W, Chung H and Yoon J 2006 Study on Fe(VI) species as a disinfectant: Quantitative evaluation and modeling for inactivating Escherichia coli Water Res. 40 3580–6
[31] Makky E A, Park G-S, Choi I-W, Cho S-I and Kim H 2011 Comparison of Fe (VI)(FeO42-) and ozone in inactivating Bacillus subtilis spores Chemosphere 83 1228–33
[32] Jiang J-Q, Wang S and Panagoulopoulos A 2007 The role of potassium ferrate (VI) in the inactivation of Escherichia coli and in the reduction of COD for water remediation Desalination 210 266–73
[33] Gombos E, Felföldi T, Barkács K, Vértes C, Vajna B and Záray G 2012 Ferrate treatment for inactivation of bacterial community in municipal secondary effluent Bioresour. Technol. 107 116–21
[34] Kazama F 1994 Inactivation of coliphage Qb by potassium ferrate FEMS Microbiol. Lett. 118 345–9
[35] Karaatli T 1998 Disinfection of surface waters by ferrate (MS thesis, Middle East Technical University, Turkey)
[36] Kanari N, Ostrosi E, Ninane L, Neveux N and Evrard O 2005 Synthesizing alkali ferrates using a waste as a raw material JOM 57 39–42
[37] Licht S, Naschitz V and Ghosh S 2002 Silver mediation of Fe (VI) charge transfer: Activation of the K2FeO4 super-iron cathode J. Phys. Chem. B 106 5947–55
[38] Jiang J-Q, Stanford C and Alsheyab M 2009 The online generation and application of ferrate (VI) for sewage treatment—A pilot scale trial Sep. Purif. Technol. 68 227–31
[39] Ling F, Wang J-G, Liu Q-F, Li M, Ye L-T and Gong X-N 2010 Prevention of Ichthyophthirius multifilis infestation in goldfish (Carassius auratus) by potassium ferrate (VI) treatment Vet. Parasitol. 168 212–6
[40] Lee Y and von Gunten U 2010 Oxidative transformation of micropolllutants during municipal wastewater treatment: Comparison of kinetic aspects of selective (chlorine, chlorine dioxide, ferrateVI, and ozone) and non-selective oxidants (hydroxyl radical) Water Res. 44 555–66
[41] Lee Y, Um I and Yoon J 2003 Arsenic (III) oxidation by iron (VI)(ferrate) and subsequent removal of arsenic (V) by iron (III) coagulation Environ. Sci. Technol. 37 5750–6
[42] Hakim L, Sunariyati S, Karelius, Kurniawati N, Krestina W and Wardani D A P 2020 Ultrasonic wave as anti-bacteria of coliform in the Kahayan River, Palangka Raya, Indonesia J. Phy. Conf. Ser. 1517 012054
[43] Neny Kurniawati K, Luqman Hakim D A P W and Dwi Tyas Setiawan F P 2020 Pengaruh Variasi Waktu Paparan Gelombang Ultrasonik dalam Mengurangi Jumlah Bakteri coliform pada Sampel Air Sungai Kahayan Risal. Fis. 4 9–13
[44] Putri A M and Kurnia P 2018 Identifikasi Keberadaan Bakteri Coliform dan Total Mikroba dalam Es Dung-Dung di Sekitar Kampus Universitas Muhammadiyah Surakarta [Identification of Coliform Bacteria and The Total Mikrobes in Dung-Dung Ice around Universitas Muhammadiyah Surakarta Campus] Media Gizi Indones. 13 41–8
[45] Pradhika I 2019 Hubungan MPN dan CFU Lab. Mikrobiol. Standar
[46] Zahari A, Tazi A and Blaghen M 2015 Study of the antibacterial activity of the potassium permanganoferrate K3Fe3Mn5O8 Int. J. Innov. Sci. Res. 13 523–9
[47] Karelius K and Asi N B 2017 Sintesis Ferrat (FeO42-) dari Fe (NO3) 2 dan NaOCl sebagai Pendedegadasi Methyylene Blue J. Sains Dan Terap. Kim. 10 1–7
[48] Licht S, Naschitz V, Halperin L, Halperin N, Lin L, Chen J, Ghosh S and Liu B 2001 Analysis of ferrate (VI) compounds and super-iron Fe (VI) battery cathodes: FTIR, ICP, titrimetric, XRD, UV/VIS, and electrochemical characterization J. Power Sources 101 167–76
[49] Luo Z, Strouse M, Jiang J-Q and Sharma V K 2011 Methodologies for the analytical determination of ferrate (VI): a review J. Environ. Sci. Health Part A 46 453–60
[50] Sharma V K, Kazama F, Jiangyong H and Ray A K 2005 Ferrates (iron (VI) and iron (V)): environmentally friendly oxidants and disinfectants J. Water Health 3 45–58