Original article[1]

Ferrate (VI) technology in water and wastewater treatment

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ABSTRACT

This study explores the effectiveness of metal ferrates in treating water and wastewater from Demerara and Berbice counties in Guyana. Conventional chlorination, though widely applied, poses limitations: it can generate carcinogenic by-products when reacting with organic matter, and pathogens such as anthrax and *Cryptosporidium* remain resistant. Consequently, ferrates were investigated as an alternative disinfectant. Their multifunctional properties—oxidizing, coagulating, flocculating, and disinfecting—make them superior to traditional methods. Potassium, barium, cesium, and magnesium ferrates were synthesized and characterized using spectral techniques. Samples included tap water from Berbice, surface water from the University of Guyana pond, and wastewater from Banks DIH Ltd. and Bosai Mining Company. Key water quality indicators—turbidity, pH, alkalinity, hardness, chloride, iron, and color—were measured before and after treatment to assess performance. Among the synthesized ferrates, potassium ferrate demonstrated the highest treatment potential, while magnesium ferrate showed the lowest efficiency compared with other tested compounds.

RESUMEN

Tecnología de ferrato (VI) en el tratamiento de agua y aguas residuales. Esta investigación evalúa el potencial de los ferratos metálicos para tratar agua y aguas residuales en los condados de Demerara y Berbice, Guyana. La cloración, aunque ampliamente utilizada, presenta limitaciones: genera subproductos cancerígenos al reaccionar con materia orgánica, y patógenos como el ántrax y *Cryptosporidium* resisten su acción. Por ello, se analizaron los ferratos como desinfectantes alternativos. Sus propiedades multifuncionales—oxidantes, coagulantes, floculantes y desinfectantes—los hacen superiores a los métodos convencionales. Se sintetizaron y caracterizaron ferratos de potasio, bario, cesio y magnesio mediante estudios espectrales. Las muestras incluyeron agua potable de Berbice, agua superficial del estanque de la Universidad de Guyana y aguas residuales de Banks DIH Ltd. y Bosai Mining Company. Se midieron parámetros de calidad—turbidez, pH, alcalinidad, dureza, cloruros, hierro y color—antes y después del tratamiento. Los resultados mostraron que el ferrato de potasio tuvo la mayor eficacia, mientras que el de magnesio presentó el rendimiento más bajo.

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INTRODUCTION

Water is essential for health, hygiene and the productivity of our community and a satisfactory supply must be available to all. Water has always played a prominent role in human civilization. The water sources used for supplying water were not always clean however and treating drinking water to improve smell, taste, clarity, or to remove disease – causing pathogens has occurred in one form or another throughout record history. Many people in the world suffer illness and death each year due to drinking water contamination[1 2]. Iron commonly exists in two oxidation states, +2 and +3, however, in a strong oxidizing environment, higher oxidation states of iron +6 can be obtained[3]. The chemistry of iron with high oxidation states [Fe (VI)] in aqueous solution has been of interest because of his implication in numerous hydroxylation/oxidation reactions of environmental, industrial and biological importance[4]. The high valent iron species, which are commonly called ferrates Fe (IV), Fe (V) and Fe (VI), possess stronger oxidation ability than most traditional water treatment oxidants (*e.g.*, O_3, Cl_2, H_2O_2, $KMnO_4$), and the concentrations of toxic byproducts resulting from ferrates oxidation are generally low[5 6 7].

Fe (VI) ion is a powerful oxidizing agent throughout the entire pH range with a reduction potential varying from + 2. 2 to + 0.7 V in acidic and basic solutions, respectively[8]. With its high oxidizing power which is greater than any other disinfectants (Table 1[9]) and it is potentially the strongest of all the oxidants/disinfectants realistically applicable to water treatment. The redox potential of iron (VI) drops to +0.7 V under alkaline conditions. The decrease in the redox potential of Fe (VI) with increasing pH can be ascribed to the shift of Fe (VI) species with pH. Fe (VI), with its three pKa values (1.5, 3.5, and 7.3), has four protonation states: H_3 Fe O_4^+, H_2 Fe O_4, H Fe O_4^- and Fe O_4^{2-} (Equations 1 - 3)[10 11].

$$H_3Fe^{VI}O^+_4 \rightleftharpoons H^+ + H_2\,Fe^{VI}\,O_4 \qquad pK_{a1} = 1.5 \qquad (1)$$

$$H_2Fe^{VI}\,O_4 \rightleftharpoons H^+ + HFe^{VI}\,O_4^- \qquad pK_{a2} = 3.5 \qquad (2)$$

$$HFe^{VI}\,O^-_4 \rightleftharpoons H^+ + Fe^{VI}\,O^{2-}_4 \qquad pK_{a3} = 7.3 \qquad (3)$$

Under environmentally – relevant conditions (pH 4.0 – 9.0), $HFeO^-_4$ and FeO_4^{2-} are the dominant Fe (VI) species (Figure 1). Using calculations based on the density functional theory (DFT), Kamachi et al.[12] found that the monoprotonated Fe (VI), (HFe O_4^-) has a larger spin density on the oxo – ligands than the deprotonated Fe (VI), (Fe O_4^{2-}) does, resulting in higher oxidation ability of H FeO_4^- compared to FeO_4^{2-}. Consistent with the finding of Kamachi et. al.[12], the reaction rate constants of HFe O_4^- with most compounds are reported to be 1 to 4 orders of magnitude higher than those of FeO_4^{2-} with various compounds[13 14].

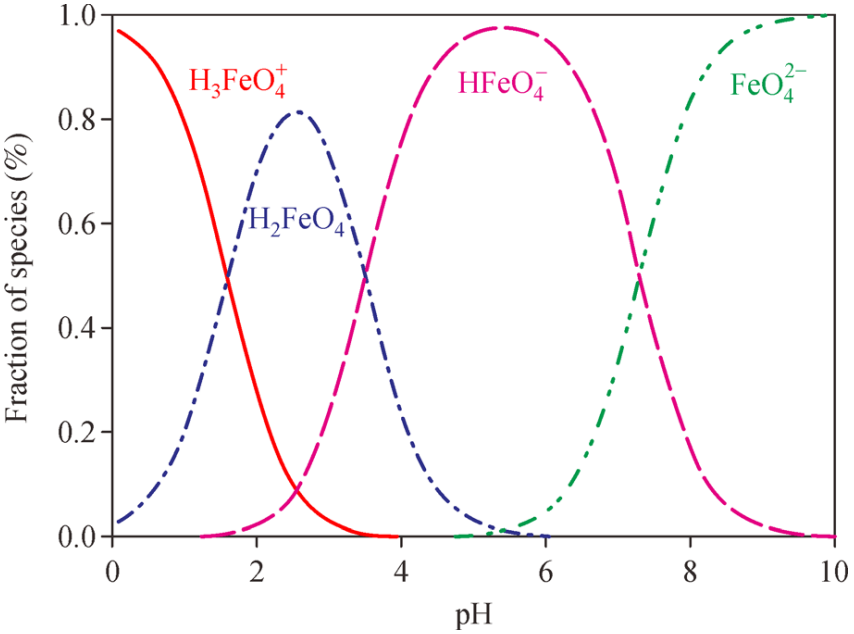


Figure 1: Influence of pH on the specification of ferrate (VI)

Table 1. Oxidation potential of different disinfectants

Disinfectants	Reaction	E* (V)
Chlorine	Cl_2 (g) + 2e ⇌ $2Cl^-$	1.358
	ClO^- + H_2O + 2e ⇌ Cl^- + $2OH^-$	0.841
Hypochlorite	HClO + H^+ + 2e ⇌ Cl^- + H_2 O	1.482
Chlorine dioxide	ClO_2 (aq) + e ⇌ ClO_2^-	0.954
Perchlorate	ClO_4^- + $8H^+$ + 8e ⇌ Cl^- + $4H_2$ O	1.389
Ozone	O_3 + $2H^+$ + 2e ⇌ O_2 + H_2O	2.076
Hydrogen peroxide	H_2O_2 + $2H^+$ + 2e ⇌ $2H_2$ O	1.776
Dissolved oxygen	O_2 + $4H^+$ + 4e ⇌ $2H_2O$	1.229
Permanganate	MnO_4^- + $4H^+$ + 3e ⇌ MnO_2 + $2H_2O$	1.679
	MnO_4^- + $8H^+$ + 5e ⇌ Mn^{2+} + $4H_2O$	1.507
Fe (VI)	FeO_4^{2-} + $8H^+$ + 3e ⇌ Fe^{3+} + $4H_2O^-$	2.20

E* (V) Oxidation potential in Volts

The objectives of present research work are to

(i) Synthesize and characterize barium cesium, magnesium and potassium ferrates.

(ii) Collection of water and wastewater samples from various sources of country, Guyana.

(iii) Test the collected samples for pH, alkalinity, turbidity, total iron, colour, total chloride and hardness parameters at pre and post treatment with synthesized ferrates.

(iv) Water samples were collected from selected region of the country due to importance of the need for the clean and safer water.

Jiang et al.[15] has investigated the practical feasibility of ferrate (VI) used as an alternative to the existing coagulant (*e.g.* ferric chloride/sulphate) for both drinking water and domestic sewage treatment via series of pilot plant trials. The five technical barriers which prevent the water industry from establishing the necessary credibility for the full-scale application of ferrate (VI) in water and wastewater treatment has been described by Deng and Abdel – Shafy[16]. Homonnay et al.[17] has successfully determined the Mossbauer – Lamb factors for the ferrate (VI) and three most common iron (III) degradation products formed in electrochemically produced potassium ferrate for wastewater treatment. Fe^{57} Mossbauer spectroscopy is an excellent tool for checking the ratio of ferrate (VI) to the degradation product iron (III) in a sample. Calcium ferrate was synthesized and characterized using XRD, FT – IR, UV – Vis, TEM, SEM, Raman and redox titration by Ndzungu et al.[18]. FT – IR analysis confirmed the presence of the Fe – O stretching vibrations in all the freeze – dried $CaSO_4$ powders, signifying the successful preparation of the materials. The physicochemical characteristics of the raw water such as turbidity, colour, COD, pH, EC, and TDS, were analyzed before and after treatment with $CaFeO_4$.

Modern alternative methods of water purification based on sodium ferrate, has been discussed by Petkova et al.[19]. Nguema and Jun[20] has presented a review on the application of Fe (VI) as disinfectant in the treatment of drinking water and also its possible future applications in drinking water technology. A short review on uses of potassium ferrate (VI) for the removal of selected pollutants from water and wastewater has been described by Klis et al.[21]. Jiang et al.[22] has discussed online generation and application of ferrate (VI), for sewage treatment, from pilot to full scale trials at Hailsham North Wastewater Treatment Plant of Southern Water Ltd. of UK. Uses of ferrate as an all-in-one alternative for the removal of chlorine – consumed compositions such as organic, colour, turbidity, iron, manganese in river water for water supply purposes has been studied by Khoi et al.[23]. Ivanenko et al.[24] has investigated the efficiency of potassium ferrate application in water conditioning processes: oxidation of pollutants of different composition by ferrate compounds; clarification of model solutions by coagulation; reduction of corrosive aggressiveness of aqueous solutions. A review on ferrate (VI) production, measurement, stability and utilization in water and wastewater treatment has been described by Talaiekhozani et al.[25]. Application of metallic iron and ferrates in water and wastewater treatment for Cr (VI) and organic contaminants removal has been reported by Samiotis et al.[26].

Due to the disadvantages of ferrate (VI) such as oxidation selectivity and instability Yu et al.[27] has investigated three hyphenated techniques of ferrate (VI) viz; ferrate (VI) – photocatalytic synergistic coupling, ferrate (VI) – PAA synergistic coupling and ferrate (VI) – PMS synergistic coupling. Wang et al.[28] has systematically reviewed the important modes in developing methods to improve the performance of ferrate (VI) as oxidant or disinfectant in the past two decades and proposed the future research needs for the developments of Fe (VI) technologies. System and material design based on slow – release ferrate (VI) combined with ultrasound for ballast water treatment has been studied by Laksono et al.[29]. Dar et al.[30] has evaluated the use of ferrate, being a green coagulant, sustainable and reactive oxidant, to remove micro pollutants contaminated water. Jiang[31] has presented a review on the research progress of using ferrate (VI) in the following fields of environmental remediations: (i) water disinfection; (ii) degradation of synthetic organic pollutants; (iii) treatment of emerging organic pollutants, (iv) oxidation of inorganic pollutants, (v) removing humic substance, (vi) wastewater treatment and disinfection, (vii) sewage sludge treatment.

RESULTS

The synthesized barium, cesium magnesium and potassium ferrates were observed to have red – brown, dark – red, purplish and reddish color, respectively. Barium, cesium magnesium and potassium ferrates were also found to have percentage yield of 81.07 %, 72.10 %, 97.54 % and 69.74 %, respectively.

pH

pH test result for initial and potassium, barium, cesium and magnesium ferrates (50 mg, 250 mg and 500 mg per 100 mL) treated water samples from four different locations (Bosai wastewater, Linden; Banks DIH wastewater, Georgetown; University of Guyana Pond water; Berbice tap water of county, Guyana are given in Table 2 and Figure 2, respectively, at the end of the text.

Alkalinity

Alkalinity test results in initial and potassium, barium, cesium and magnesium ferrates (50 mg, 250 mg and 500 mg per 100 mL) treated water samples from four different locations (Bosai wastewater, Linden; Banks DIH wastewater. Georgetown; University of Guyana Pond water; Berbice tap water) of country, Guyana are given in Table 3 and Figure 3, respectively, at the end of the text.

Turbidity

Turbidity test results in initial and potassium, barium, cesium and magnesium ferrates (50 mg, 250 mg and 500 mg per 100 mL) treated water samples from four different locations (Bosai wastewater, Linden; Banks DIH wastewater, Georgetown; University of Guyana Pond water; Berbice tap water) of county, Guyana are given in Table 4 and Figure 4, respectively, at the end of the text.

Total Iron

Total iron test results in initial and potassium, barium, cesium and magnesium ferrates (50 mg, 250 mg and 500 mg per 100 mL) treated water samples from four different locations (Bosai wastewater, Linden; Banks DIH wastewater, Georgetown; University of Guyana Pond water; Berbice tap water) of country, Guyana are given in Table 5 and Figure 5, respectively, at the end of the text.

Colour

Colour test results in initial and potassium, barium, cesium and magnesium ferrates (50 mg, 250 mg and 500 mg per 100 mL) treated water samples from four different locations (Bosai wastewater, Linden; Banks DIH wastewater, Georgetown; University of Guyana Pond water: Berbice tap water) of country, Guyana are given in Table 6 and Figure 6, respectively. at the end of the text.

Total Chloride

Total chloride test results for initial and potassium, barium, cesium and magnesium ferrates (50 mg, 250 mg and 500 mg per 100 mL) treated water samples from four different locations (Bosai wastewater, Linden; Banks DIH wastewater, Georgetown; University of Guyana Pond water; Berbice tap water) of county, Guyana are given in Table 7 and Figure 7, respectively, at the end of the text.

Total Hardness:

Total hardness test results for initial and potassium, barium, cesium and magnesium ferrates (50 mg, 250 mg and 500 mg per 100 mL) treated water samples from four different locations (Bosai wastewater, Linden; Banks DIH

wastewater, Georgetown; University of Guyana Pond water; Berbice tap water) of county, Guyana are given in Table 8 and Figure 8, respectively. at the end of the text.

DISCUSSION

The four water samples collected were treated with barium, cesium, magnesium and potassium ferrates at varying concentrations: 50 mg/L, 250 mg/L and 500 mg/L. The concentration was varied so as to examine how the concentration affects the treatment efficiency and thus, determine the optimum amounts of ferrates requires to effectively treat all water samples.

pH

It is observed from Table 2 and Figure 2 that all the water samples analyzed showed an increase in pH after treatment with metal ferrates. This suggest that the basicity of the solution has increased. This is due to the formation of hydroxide ions during the reduction of the ferrate ion as represented below:

$[FeO_4]^{2-} + 4H_2O + 3e^- \rightarrow Fe(OH)_3 + 5\ OH^-$.

It was also observed that the pH increased as the amount of ferrate was increased. At 50 mg/L all ferrates did not meet the World Health Organization pH specification (6.5 – 8.5). Bosai wastewater samples did not meet WHO specification when treated with any amounts of the ferrates. However, at 250 mg/L and 500 mg/L the WHO specification was met for some samples, while other did not meet the WHO specification. All metal ferrates at 50 mg/L were seen to be effective at controlling pH except for Bosai wastewater.

Alkalinity

It is clear from Table 3 and Figure 3 that alkalinity of all water samples has increased after treatment with metal ferrates. Also, as the quantity of ferrate increased the alkalinity was found to increase accordingly. The alkalinity refers to the capacity of an aqueous solution to neutralize acid. Alkalinity is related to the pH of a solution but measures a different property. The increase in alkalinity can be attributed to the ferrate ion being reduced and producing the basic hydroxide ion. The highest alkalinity was observed at 500 mg/L but all samples were found to be within WHO range. So, none of the ferrates were effective in reducing alkalinity of the water samples but instead did the reverse since alkalinity increased, in a sense we can say that all ferrates were not effective at controlling pH at all concentration.

Turbidity

High turbidity affects light penetration and productivity. Turbidity results from particles either suspended or dissolved in water appears cloudy. In steams where particulate matter is dominant, increased sedimentation and siltation can occur, which can result in harm to habitat areas for fish and other aquatic life, additionally particles provide attachment places for other pollutant, notably, method and bacteria. For this reason, turbidity readings can be used on an indicator of potential pollution in a water body.

It is clear from Table 4 and Figure 4 that turbidity was generally reduced by all metal ferrates at amounts 50 mg/L, 250 mg/L and 500 mg/L. However, potassium ferrate was observed to be most effective at reducing turbidity in all samples. However, when compared to the WHO standards many were found to be out of range. This might have been due to their treatment time, the presence of impurities that might have been present at the time of treatment. Samples treated with 500 mg/L of metal ferrate showed the greatest reaction in turbidity. As the quantity of ferrate increased the turbidity decreased. More ferrate means the more ferrate ion will be available for reduction of ferric hydroxide, whose function is to remove waste particles out of solution by coagulation and flocculation.

Total Iron

Total iron test for untreated and barium, cesium, magnesium and potassium ferrates treated contaminated water sample is shown in Figure 5 and values are given in Table 5. The ferrates displayed an exceptional ability to remove iron from the water samples. Potassium ferrate was found to be must efficient at removing iron from Bosai wastewater, UG pond water and Berbice tap water at all three quantities of ferrates used for treatment, while barium ferrate was found to be best of removing iron from Banks wastewater alone. The samples treated with 500 mg/L were found to be most effective for removing iron. However, it was observed that magnesium ferrate was the most effective for treating Banks wastewater at amounts 50 mg/L and 250 mg/L.

Colour
Color test for untreated and metal ferrates treated contaminated water samples is shown in Figure 6 and values are given in Table 6. All metal ferrate functioned well to remove colour from contaminated water. All metal ferrate caused a reduction in colour at all three concentrations of ferrates. The more ferrate used resulted in a higher reduction in colour. Potassium ferrate was found to be most effective at reducing colour in Bosai wastewater and Berbice tap water, but barium ferrate was most effective at reducing Banks wastewater and UG pond water. The ferric hydroxide is formed when the ferrate ion is reduced functions to remove the many particles and metals that gives water its colour.

Total Chloride
It is clear from Figure 7 and Table 7 that total chloride was reduced by all ferrate treatment. However, potassium ferrate was found to be slightly more effective than the other ferrates. Removal of chloride seemed to be most effective at 50 mg/L and 250 mg/L although Berbice tap water displayed greatest effectiveness at 500 mg/L.

Total Hardness:
It is observed from Table 8 and Figure 8 that water hardness reduction is seen in all the water samples treated with each ferrate, potassium ferrate is seen to be most effective for treating Bosai wastewater, Banks wastewater and UG pond water. While cesium ferrate was found to be most effective for treating Berbice tap water and Bosai wastewater. The quantity of ferrate used in each instance did not appear to effect much, the total hardness reduction in each scenario.

CONCLUSIONS

The following conclusions can be drawn from the present studies.

1. All the metal ferrate synthesized improved water quality to some degree except for the alkalinity, although the quality of treatment did not meet the World Health Organization water quality standard on some instance. Even so, they displayed great potential and further research into using the metal ferrates to treat water and wastewater is required.
2. The quality of treatment seemed to vary with quantity of ferrate used. As the quantity of ferrate increased from 50 mg/L to 250 mg/L and finally 500 mg/L a corresponding increase was observed for alkalinity and pH. However, other parameter such as colour, turbidity, iron and total chloride decreased. Total hardness did not seem to be phased much by alteration in concentration.
3. All the ferrates demonstrated relatively good treatment of water sample, it was found that overall, potassium ferrate displayed the greatest treatment efficiency and magnesium ferrate had the lowest treatment efficiency.

EXPERIMENTAL

Material
Sodium hypochlorite, sodium hydroxide, ferric chloride, ferric nitrate, potassium hydroxide, potassium permanganate, barium acetate, cesium chloride, magnesium chloride, hexane, diethyl ether, petroleum sprit, ethanol was obtained from Aldrich.

Synthesis of Ferrates:
Potassium, barium, cesium and magnesium ferrates were prepared according to the method reported in chemical literature[32].

Potassium Ferrate:
A 50 g of sodium hydroxide was added slowly to 100 mL of distilled water in an ice bath further 40 g of $FeCl_3$ was added to this solution still in the ice bath as this reaction is extremely exothermic. This mixture was removed from ice bath and 500 mL of NaOCl was added while stirring. The resulting mixture was then allowed to stand for 40 mins, and vacuum filtered using Whatman No.1 filter paper. The filtrate was discarded, and precipitate was washed with 25 mL cold 1. 0 M KOH. The precipitate was then added to a beaker containing 80 mL of saturated KOH solution. This was mixed and allowed to stand for 10 mins. This mixture was re-filtered as above, and residue was placed in a petri dish and stored in a desiccator. The chemical reaction can be given as:

$2\ FeCl_3 + 3NaOCl + 10\ NaOH \rightarrow 2Na_2Fe\ O_4 + 9NaCl + 5H_2O$

$Na_2FeO_4 + 2KOH \rightarrow K_2\ Fe\ O_4 + 2NaOH$

Barium Ferrate
A 50 g of barium acetate was dissolved in 300 mL of distilled water, further 37 g of potassium ferrate was added to this solution, which was carefully stirred then allowed to stand for 25 mins. The resulting mixture was vacuum filtered, and residue was placed in a petri dish and stirred in a desiccator. The chemical reaction can be given as:

$K_2\ Fe\ O_4 + Ba\ (CH_3\ COO)_2 \rightarrow Ba\ Fe\ O_4 + 2\ CH_3\ COOK$

Cesium Ferrate
A 50 g of cesium chloride was dissolved in 300 mL of distilled water, further 37 g of potassium ferrate was added to this solution, which was carefully stirred then allowed to stand for 25 mins. The resulting mixture was vacuum filtered, and residue was placed in a petri dish and stored in a desiccator. The chemical reaction can be given as:

$K_2Fe\ O_4 + 2CsCl \rightarrow Cs_2\ Fe\ O_4 + 2\ KCl$

Magnesium Ferrate
A 40 g of magnesium chlorine was dissolved in 500 mL of distilled water , further 60 g of potassium ferrate was added to this solution, which was carefully stirred then allowed to stand for 25 mins. The resulting mixture was vacuum filtered, and residue was placed in a petri dish and stored in a desiccator. The chemical reaction can be given as:

$K_2\ Fe\ O_4 + Mg\ Cl_2 \rightarrow Mg\ Fe\ O_4 + 2\ KCl$

Purification of Ferrates
Potassium, barium, cesium and magnesium ferrates were purified according to method reported in literature[33]. Ferrates were washed with 15 mL of n-hexane 4 times. It further washed with 10 mL methanol 3 times. It further washed with 5 mL diethyl ether, 4 times. Precipitates were dried and stored in a desiccator.

Characterization of Ferrates
Synthesized ferrates have demonstrated typical ferrate (VI) characteristic absorption at 505 nm and 790 nm, which is consistent with literature[34 35]. Prominent UV-VIS spectral absorption band for cesium and magnesium ferrates were also observed at 320 nm and 380 nm, respectively.

Collection of Water Samples

Water samples were collected in 1000 mL, stoppered bottles from four different location of the country (Guyana). The order of water sampling is as follows:

1. Bosai wastewater (Linden)
2. Banks DIH wastewater (Georgetown)
3. University of Guyana (UG) Pond water (East Coast)
4. Tap water (Berbice)

Method for Testing Water Samples
Water samples were tested via pre and post treatments with barium, cesium, magnesium and potassium ferrates for pH, alkalinity, turbidity, total iron, color, total chloride and hardness.

pH
pH tests were done using the HACH HQseries portable meter. pH meter was calibrated prior to each use.

Alkalinity
A 0.5 g of sodium carbonate was accurately weighted in a 100 mL volumetric flask and made up to mark with deionized water. This was primary standard. The 0.05 M HCl solution was standardized by titrating 10 mL of the primary standard with HCl to a methyl orange endpoint (orange to faint pink). A 100 mL of the sample was transferred via pipette to a 250 mL Erlenmeyer flask. This was then titrated with the standardized 0.05 M HCl to a methyl orange endpoint. Alkalinity of water samples were calculated with the help the of equation:

= (t x 0.05 x 100.086 x 1000)/V x 2

Where t = titer of HCl used

V = Volume of sample used

Turbidity
Turbidity test was carried out using a Portable Turbidimeter (model 2100 P). Turbidimeter was calibrated with the standard range from 0.01 – 3000 Nephelometric Turbidity Unit (NTU). The 15 mL sample vial was filled, read off and recorded for all samples (pre and post treatment).

Total Iron Test
Iron test for the untreated and treated water samples were done at Guyana Water Incorporation, Central Laboratory, using the portable data login spectrophotometer. A 10 mL sample was used for the iron test, 5 mL for zeroing the meter, the indicators phenanthroline was added to the remaining 5 mL water sample then read off.

Colour
Color test for the untreated and treated water samples were done at Guyana Water Incorporation Central Lab, using the portable data login spectrophotometer. A 25 mL sample was used after being calibrated with 25 mL of distilled water. The color of samples was measured in unit of Pt Co Alpha.

Determination of Total Chloride:
Measure out 25 mL portion of sample into Erlenmeyer flask. If sample is highly coloured add 3 mL aluminum hydroxide suspension, mix, let settle and filter. Adjust the pH of samples between 7.0 to 10.0 with sulfuric acid or sodium hydroxide. Add 1.0 mL potassium chromate indicator solution. Titrate to a pinkish yellow end point. Standardize silver nitrate titrant according to titration method using 10mL of the primary standard sodium chloride solution diluted to 100 mL. Blank values were established by titrating the same volume of distilled water that was used for water samples according to titration method outlined above. Total chlorides were calculated by using the formula

$$\text{Chloride ion [mg/L]} = \frac{\{(V_s - V_b) \times N \times 35.45\} \times 1000}{V_{sample}}$$

Where

V_s = Volume of $AgNO_3$ for sample

V_b = Volume of $AgNO_3$ for blank

N = Normality of $AgNO_3$

V_{sample} = Volume of sample used

Determination of Water Hardness:
Prepare a primary standard solution from AnalaR Grade sodium carbonate, previously dried at 260^0 C, by accurately weighing about 0.5 g of that into a 100 mL volumetric flask and make up to mark with deionized water. Standardized the 0.05 M HCl solution by titration 10 mL of the primary standard solution with the HCl to a methyl orange end point. Titration was repeated until to achieve experimental agreement. A 25 mL sample was transferred to Erlenmeyer flask using pipette. Sample was titrated with standardized 0.05 HCl to a methyl orange end point. Total hardness was calculated by using formula:

Concentration of HCl x volume of HCl = Concentration of Na_2CO_3 x Volume of Na_2CO_3

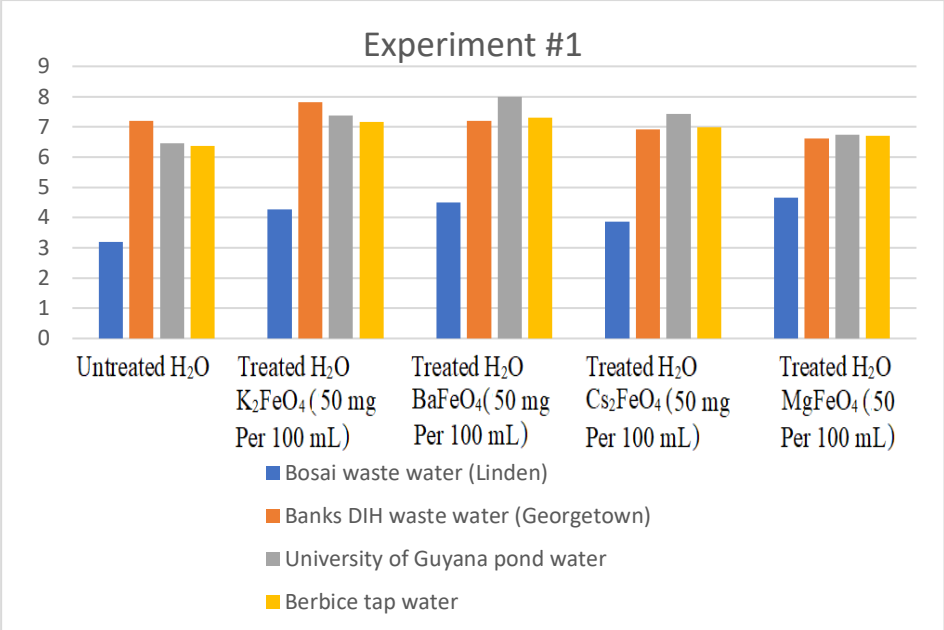
Tables and figures

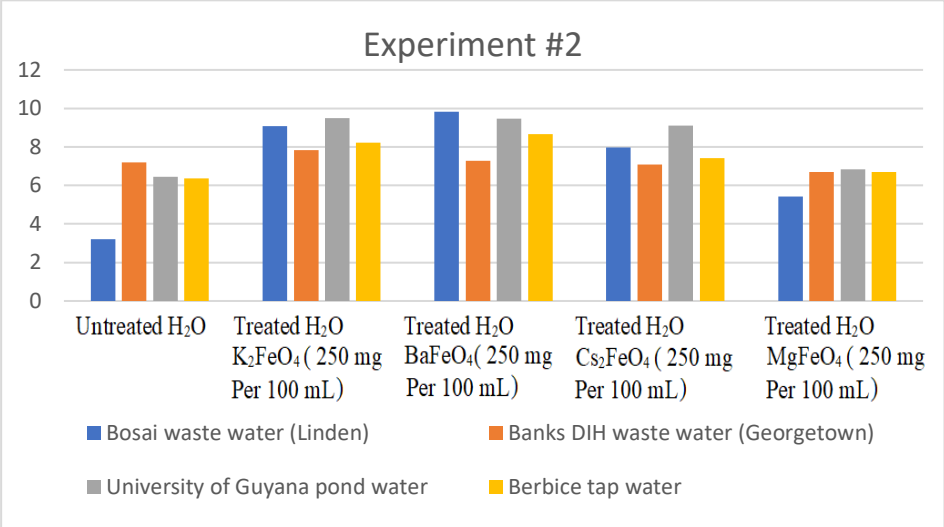
Table 2. pH of untreated and metal ferrates treated water samples

Experiment No. 1	Untreated H_2O	Treated H_2O K_2FeO_4 (50 mg per 100 mL)	Treated H_2O $BaFeO_4$ (50 mg per 100 mL)	Treated H_2O Cs_2FeO_4 (50 mg per 100 mL)	Treated H_2O $MgFeO_4$ (50 mg per 100 mL)

Bosai Waste Wate (Linden)	3.20	4.27	4.49	3.86	4.65
Banks DIH Wast Water (Georgetown)	7.20	7.81	7.19	6.91	6.62
University of Guyan Pond water	6.45	7.37	7.99	7.42	6.74
Berbice tap water	6.36	7.16	7.31	6.99	6.70
Experiment No. 2	**Untreated H_2O**	**Treated H_2O K_2FeO_4 (250 mg per 100 mL)**	**Treated H_2O $BaFeO_4$ (250 mg per 100 mL)**	**Treated H_2O Cs_2FeO_4 (250 mg per 100 mL)**	**Treated H_2O $MgFeO_4$ (250 mg per 100 mL)**
Bosai Waste Wate (Linden)	3.20	9,08	9.82	7.97	5.42
Banks DIH Wast Water (Georgetown)	7.20	7.84	7.27	7.08	6.21
University of Guyan Pond water	6.45	9.49	9.46	9.12	6.84
Berbice tap water	6.36	8.23	8.66	7.41	6.71
Experiment No. 3	**Untreated H_2O**	**Treated H_2O K_2FeO_4 (500 mg per 100 mL)**	**Treated H_2O $BaFeO_4$ (500 mg per 100 mL)**	**Treated H_2O Cs_2FeO_4 (500 mg per 100 mL)**	**Treated H_2O $MgFeO_4$ (500 mg per 100 mL)**
Bosai Waste Wate (Linden)	3.20	10.36	10.55	9.17	6.49
Banks DIH Wast Water (Georgetown)	7.20	7.86	8.68	7.30	6.85
University of Guyan Pond water	6.45	7.37	10.65	9.83	6.99
Berbice tap water	6.36	9.61	9,70	9.01	6.76

Figure 2: PH of untreated and metal ferrates treated water samples





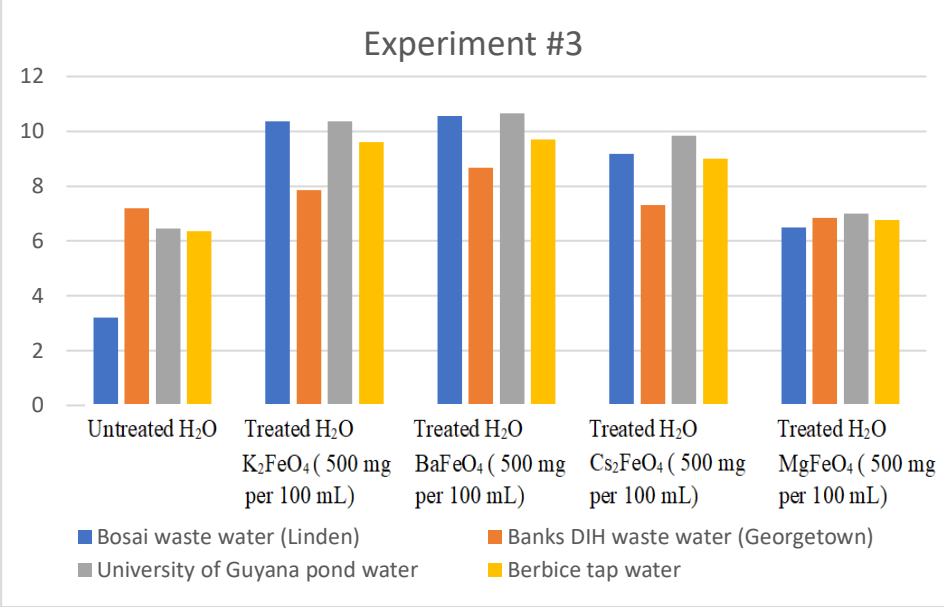
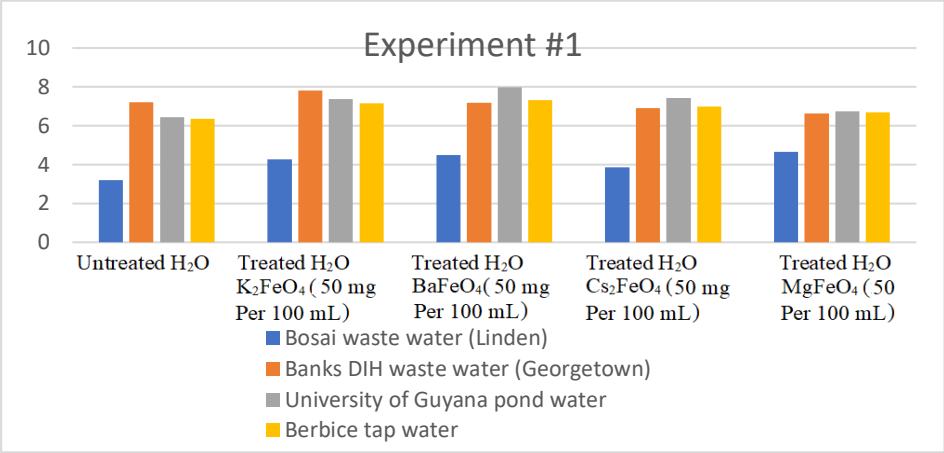


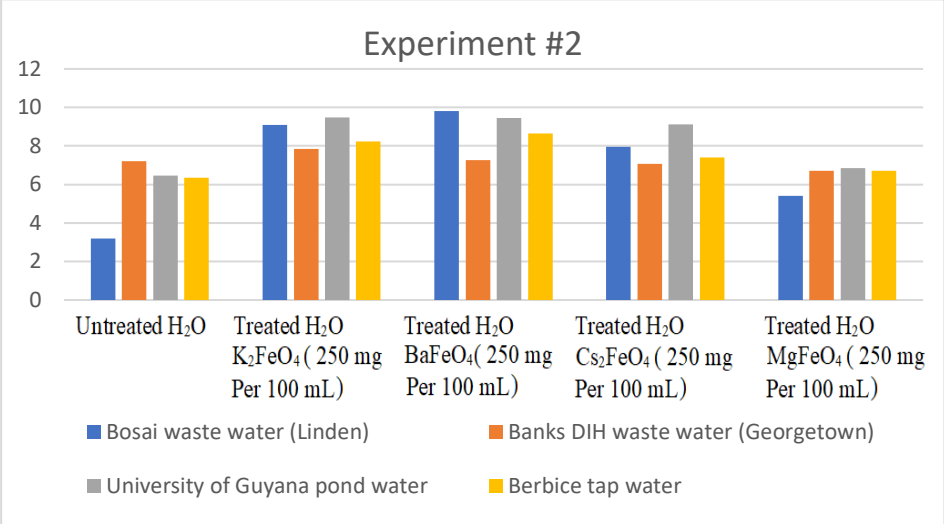
Table 3. Alkalinity of untreated and metal ferrates treated water samples

Experiment No. 1	**Untreated H_2O (mg/L)**	**Treated H_2O K_2FeO_4 (50 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFeO_4$ (50 mg per 100 mL) (mg/L)**	**Treated H_2O Cs_2FeO_4 (50 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFeO_4$ (50 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	18.00	20.50	6.00	30.00	30.20
Banks DIH Waste Water (Georgetown)	45.00	120.50	60.00	60.00	120.00
University of Guyana Pond water	36.00	60.23	36.00	35.5	60.00
Berbice tap water	18.00	60.90	61.00	45.00	60.00
Experiment No. 2	**Untreated H_2O (mg/L)**	**Treated H_2O K_2FeO_4 (250 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFeO_4$ (250 mg per 100 mL) (mg/L)**	**Treated H_2O Cs_2FeO_4 (250 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFeO_4$ (250 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	18.00	6010	30.00	36.15	150.00

Banks DIH Waste Water (Georgetown)	45.00	150.50	91.00	91.00	180.00
University of Guyana Pond water	36.00	90.00	60.50	60.00	180.00
Berbice tap water	18.00	90.00	60.00	180.00	180.00
Experiment No. 3	**Untreated H_2O (mg/L)**	**Treated H_2O K_2FeO_4 (500 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFeO_4$ (500 mg per 100 mL) (mg/L)**	**Treated H_2O Cs_2FeO_4 (500 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFeO_4$ (500 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	18.00	75.00	60.00	90.00	330.00
Banks DIH Waste Water (Georgetown)	45.00	155.23	195.00	120.00	329.50
University of Guyana Pond water	36.00	150.00	90.00	90.00	271.50
Berbice tap water	18.00	150.00	75.00	120.00	330.50

Figure 3: Alkalinity of untreated and metal ferrates treated water samples





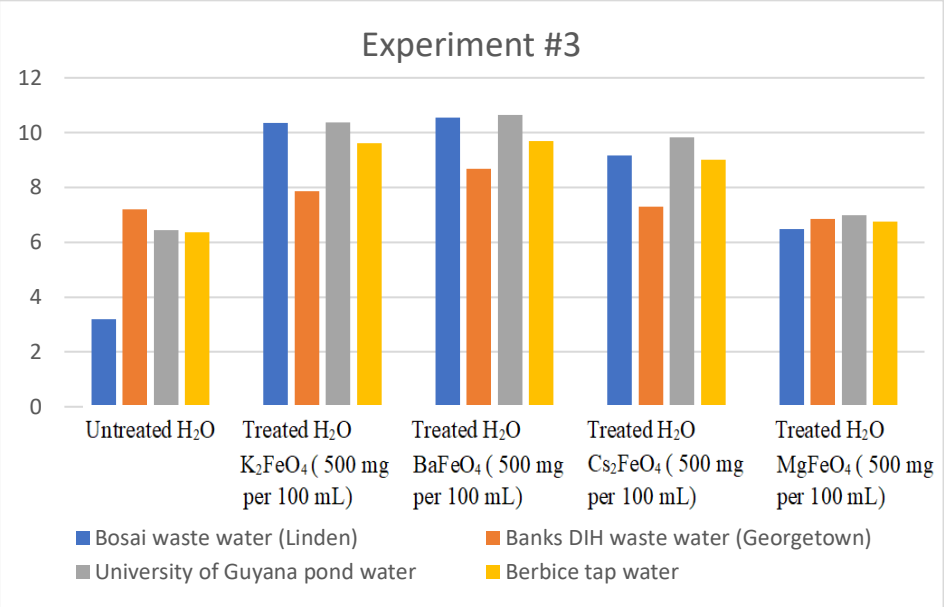
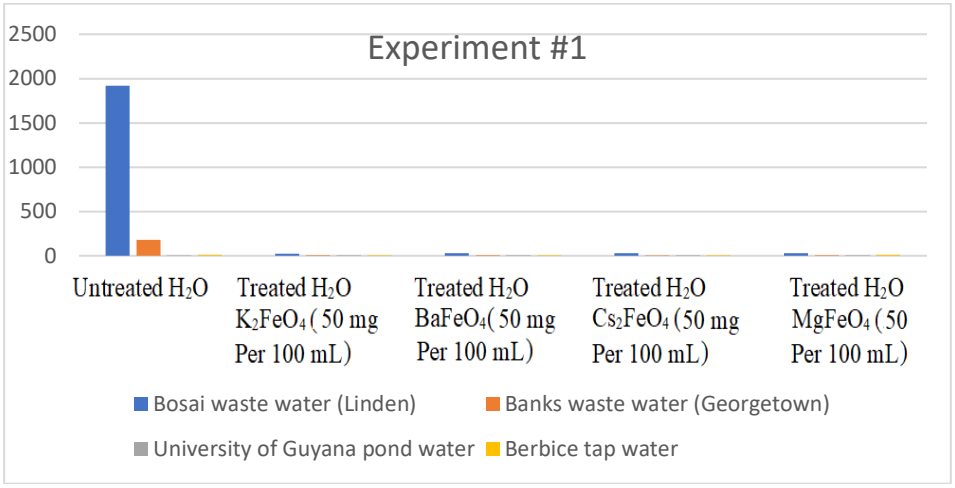
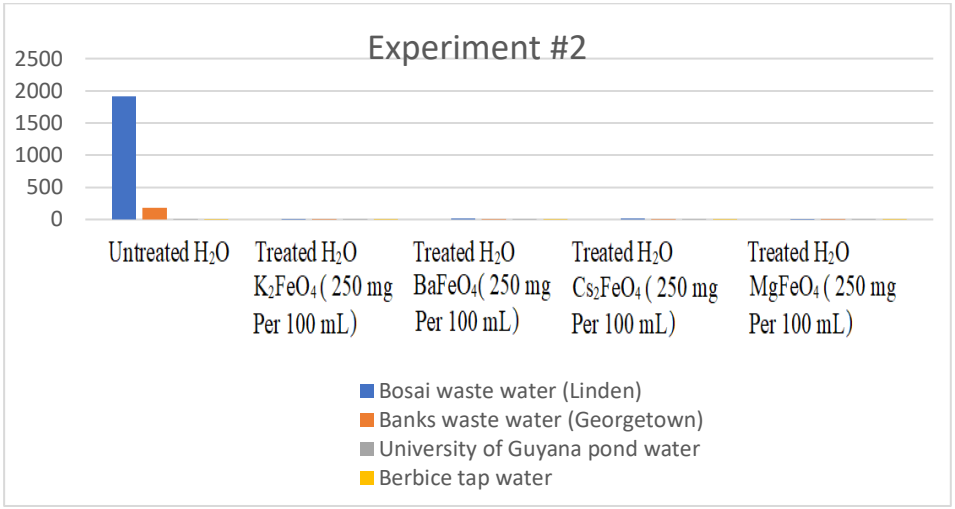


Table 4. Turbidity of untreated and metal ferrates treated water samples

Experiment No. 1	**Untreated H_2O (NTU)**	**Treated H_2O K_2FeO_4 (50 mg per 100 mL) (NTU)**	**Treated H_2O $BaFeO_4$ (50 mg per 100 mL) (NTU)**	**Treated H_2O Cs_2FeO_4 (50 mg per 100 mL) (NTU)**	**Treated H_2O $MgFeO_4$ (50 mg per 100 mL) (NTU)**
Bosai Waste Water (Linden)	1916.00	22.40	26.58	30.75	26.10
Banks DIH Waste Water (Georgetown)	179.00	323	4.39	6.51	5.99
University of Guyana Pond water	7.23	2.23	4.99	5.04	5.99
Berbice tap water	70.10	2.03	3.73	4.90	9.23
Experiment No. 2	**Untreated H_2O (NTU)**	**Treated H_2O K_2FeO_4 (250 mg per 100 mL) (NTU)**	**Treated H_2O $BaFeO_4$ (250 mg per 100 mL) (NTU)**	**Treated H_2O Cs_2FeO_4 (250 mg per 100 mL) (NTU)**	**Treated H_2O $MgFeO_4$ (250 mg per 100 mL) (NTU)**
Bosai Waste Water (Linden)	1916.00	6.75	15.15	17.04	23.21
Banks DIH Waste Water (Georgetown)	179.00	2.10	2,42	4.36	5.81
University of Guyana Pond water	7.23	7.10	1,86	3.84	4.83
Berbice tap water	70.10	1.88	2.52	4.13	7.20
Experiment No. 3	**Untreated H_2O (NTU)**	**Treated H_2O K_2FeO_4 (500 mg per 100 mL) (NTU)**	**Treated H_2O $BaFeO_4$ (500 mg per 100 mL) (NTU)**	**Treated H_2O Cs_2FeO_4 (500 mg per 100 mL) (NTU)**	**Treated H_2O $MgFeO_4$ (500 mg per 100 mL) (NTU)**
Bosai Waste Water (Linden)	1916.00	5.61	11.30	14.74	13.71
Banks DIH Waste Water (Georgetown)	179.00	0.87	1.55	3.16	2.99
University of Guyana Pond water	7.23	0.86	0.99	2.80	2.82
Berbice tap water	70.10	0.90	1.97	3.88	5.07

Figure 4: Turbidity of untreated and metal ferrates treated water samples





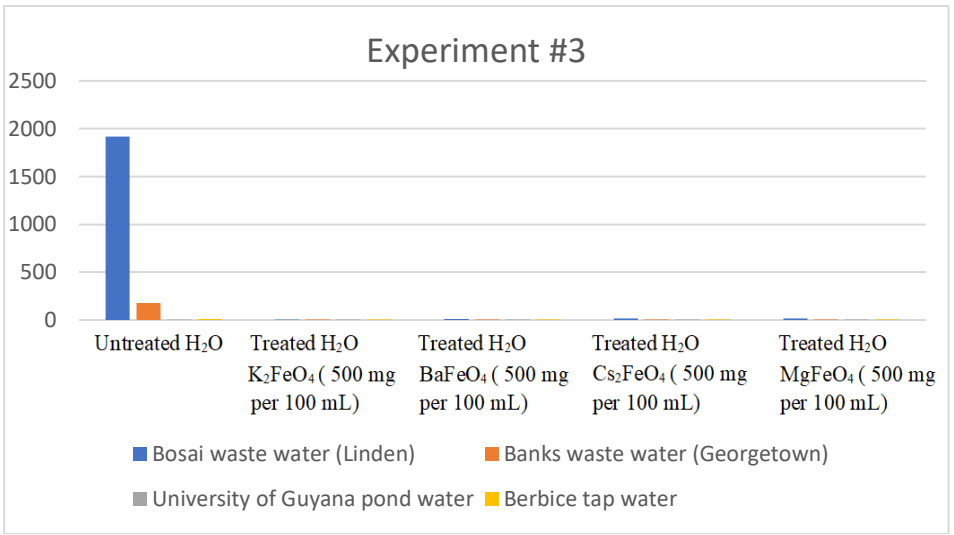
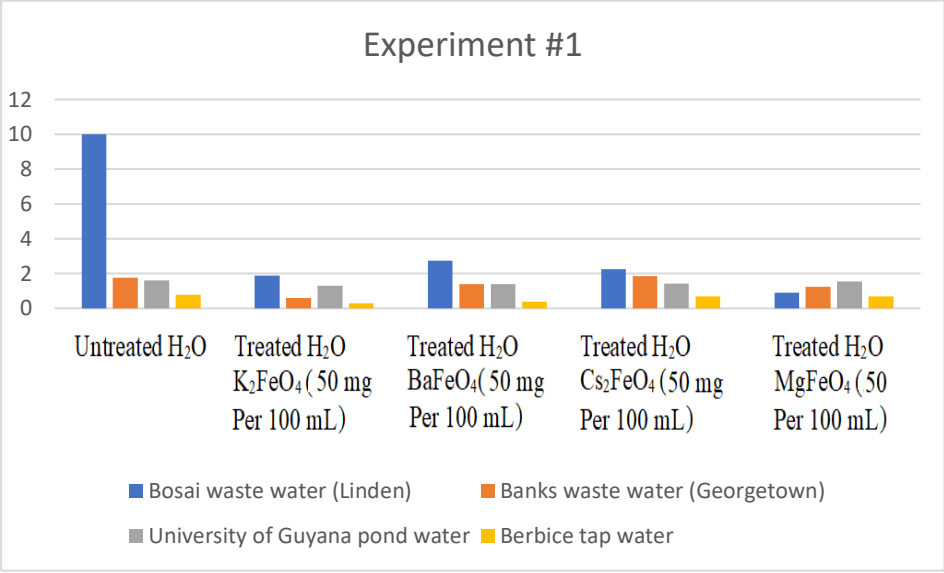
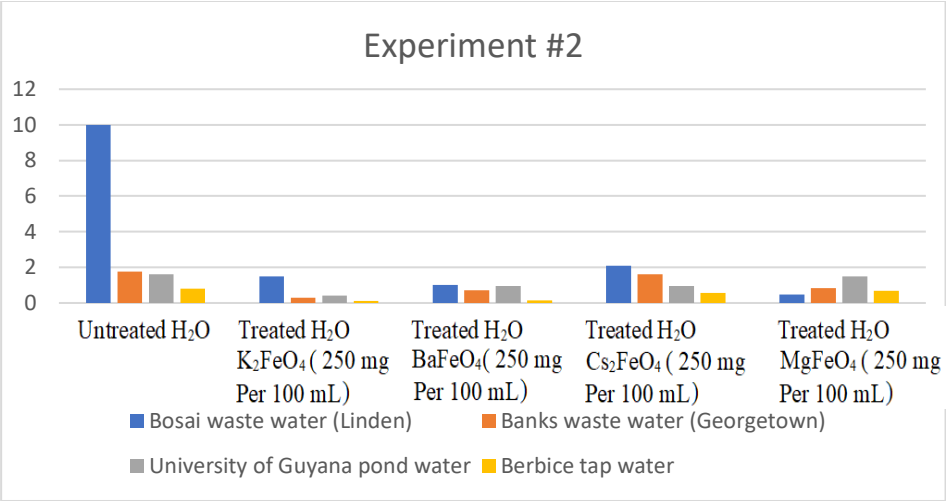


Table 5. Iron content of untreated and metal ferrates treated water samples

Experiment No. 1	**Untreated H_2O (mg/L)**	**Treated H_2O K_2FeO_4 (50 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFeO_4$ (50 mg per 100 mL) (mg/L)**	**Treated H_2O Cs_2FeO_4 (50 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFeO_4$ (50 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	10.00	1.90	2.75	2.25	0.90
Banks DIH Waste Water (Georgetown)	1.75	0.61	1.40	1.84	1.23
University of Guyana Pond water	i.62	1.30	1.40	1.43	1.55
Berbice tap water	0.79	0.30	0.37	0.69	0.70
Experiment No. 2	**Untreated H_2O (mg/L)**	**Treated H_2O K_2FeO_4 (250 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFeO_4$ (250 mg per 100 mL) (mg/L)**	**Treated H_2O Cs_2FeO_4 (250 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFeO_4$ (250 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	10.00	7.50	1.00	2.10	0.48
Banks DIH Waste Water (Georgetown)	1.75	0.31	0.70	1.62	0.82
University of Guyana Pond water	i.62	0.42	0.95	0.96	1.50
Berbice tap water	0.79	0.11	0.16	0.56	0.68
Experiment No. 3	**Untreated H_2O (mg/L)**	**Treated H_2O K_2FeO_4 (500 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFeO_4$ (500 mg per 100 mL) (mg/L)**	**Treated H_2O Cs_2FeO_4 (500 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFeO_4$ (500 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	10.00	0.06	0.20	1.80	0.30
Banks DIH Waste Water (Georgetown)	1.75	0.21	0.03	0.80	0.70
University of Guyana Pond water	1.62	0.20	0.51	0.61	0.49
Berbice tap water	0.79	0.07	0.11	0.39	0.61

Figure 5: Total iron of untreated and metal ferrates treated water sample





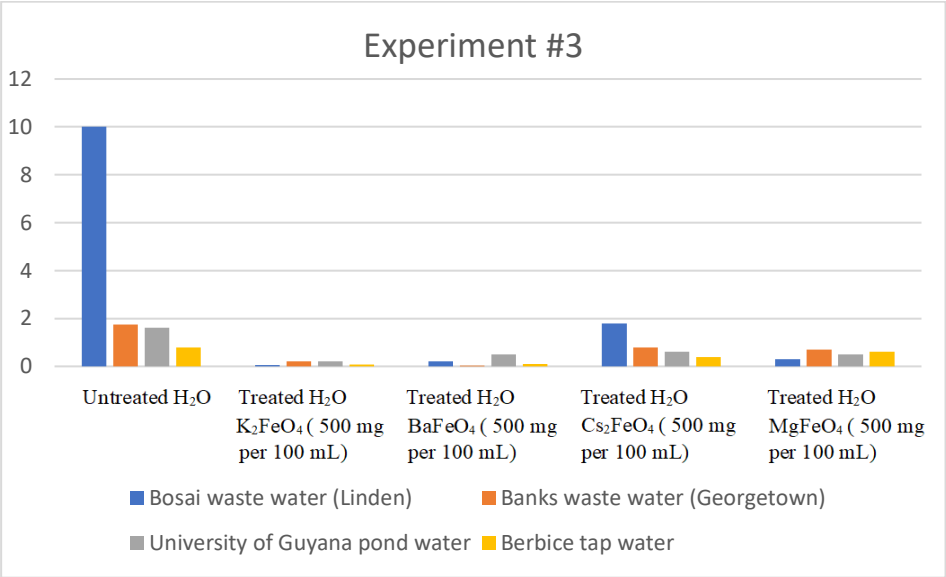
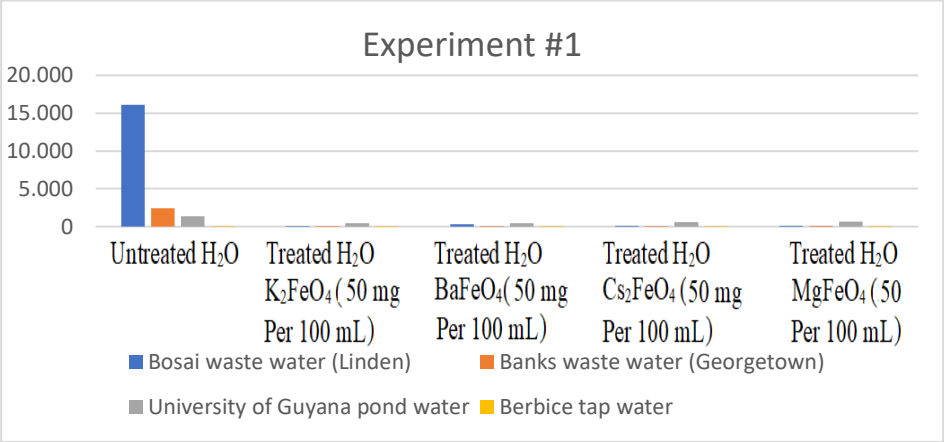


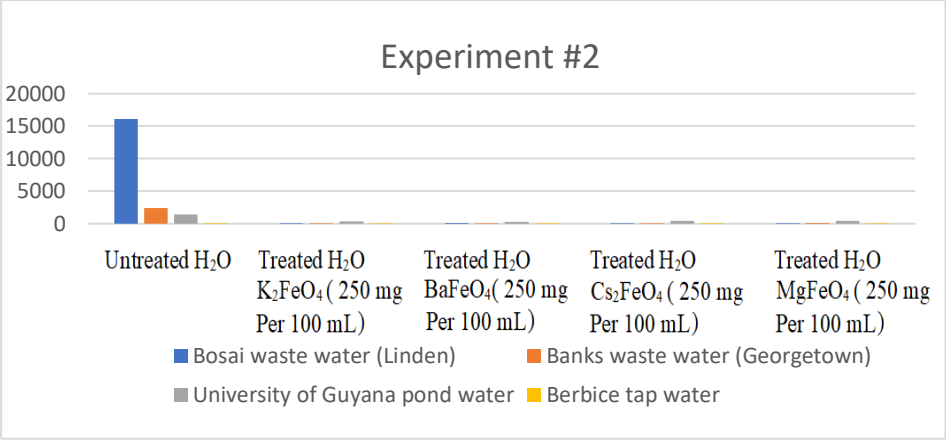
Table 6. Colour contentsof untreated and metal ferrates treated water samples

Experiment No. 1	**Untreated H_2O (Pt-Co)**	**Treated H_2O K_2FeO_4 (50 mg per 100 mL) (Pt-Co)**	**Treated H_2O $BaFeO_4$ (50 mg per 100 mL) (Pt-Co)**	**Treated H_2O Cs_2FeO_4 (50 mg per 100 mL) (Pt-Co)**	**Treated H_2O $MgFeO_4$ (50 mg per 100 mL) (Pt-Co)**
Bosai Waste Water (Linden)	16,100.00	35.50	330.50	102.50	84.50
Banks DIH Waste Water (Georgetown)	2400.00	62.50	59.50	70.50	120.50
University of Guyana Pond water	1400.00	463.00	426.00	563.00	641.00
Berbice tap water	39.00	13.00	26.50	31.00	35.00
Experiment No. 2	**Untreated H_2O (Pt-Co)**	**Treated H_2O K_2FeO_4**	**Treated H_2O $BaFeO_4$**	**Treated H_2O Cs_2FeO_4**	**Treated H_2O $MgFeO_4$**

		(250 mg per 100 mL) (Pt-Co)	(250 mg per 100 mL) (Pt-Co)	(250 mg per 100 mL) (Pt-Co)	(250 mg per 100 mL) (Pt-Co)
Bosai Waste Wate (Linden)	16,100.00	24.00	90.00	77.00	77.00
Banks DIH Wast Water (Georgetown)	2400.00	35.00	56.00	69.00	116.5
University of Guyan Pond water	1400.00	320.50	271.50	438.0	478.5
Berbice tap water	39.00	9.50	20.00	27.00	28.50
Experiment No. 3	**Untreated H_2O (Pt-Co)**	**Treated H_2O K_2FeO_4 (500 mg per 100 mL) (Pt-Co)**	**Treated H_2O $BaFeO_4$ (500 mg per 100 mL) (Pt-Co)**	**Treated H_2O Cs_2FeO_4 (500 mg per 100 mL) (Pt-Co)**	**Treated H_2O $MgFeO_4$ (500 mg per 100 mL) (Pt-Co)**
Bosai Waste Wate (Linden)	16,100.00	16.00	56.00	65.50	19.50
Banks DIH Wast Water (Georgetown)	2400.00	24.00	41.00	63.00	105.50
University of Guyan Pond water	1400.00	281.00	97.50	329.50	434.50
Berbice tap water	39.00	2.50	18.00	2050	24.00

Figure 6. Colour of untreated and metal ferrates treated water samples





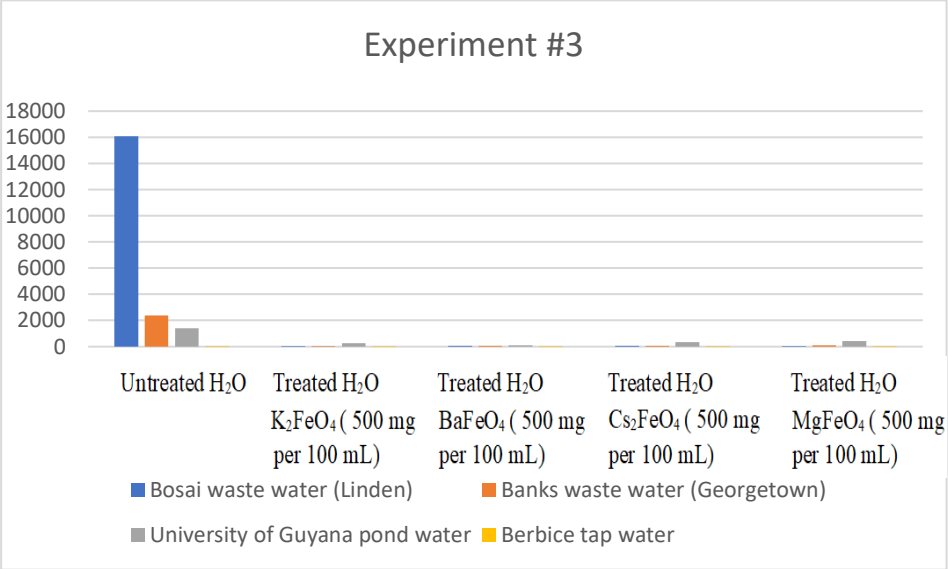
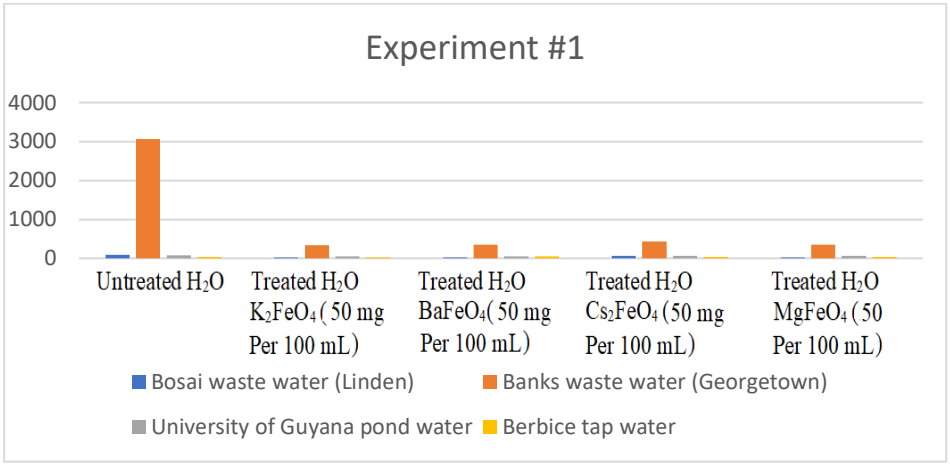
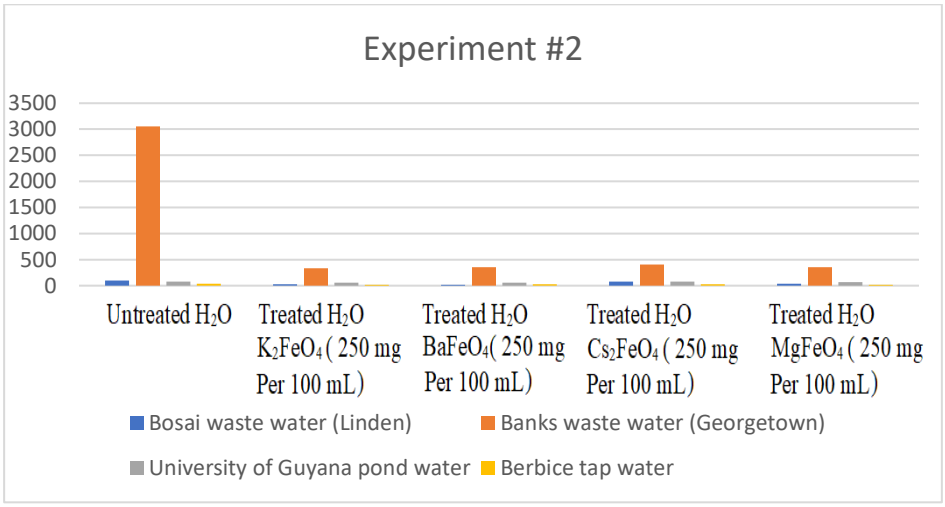


Table 7. Total cholride of untreated and metal ferrates treated water samples

Experiment No. 1	**Untreated H_2O (mg/L)**	**Treated H_2O K_2FeO_4 (50 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFeO_4$ (50 mg per 100 mL) (mg/L)**	**Treated H_2O Cs_2FeO_4 (50 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFeO_4$ (50 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	93.31	20.30	18.82	69.13	22.19
Banks DIH Waste Water (Georgetown)	3058.79	339.50	352.00	431.40	352.55
University of Guyana Pond water	80.37	50.30	49.80	66.89	59.13
Berbice tap water	33.26	18.09	50.53	30.83	31.49
Experiment No. 2	**Untreated H_2O(mg/L)**	**Treated H_2O K_2FeO_4 (250 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFeO_4$ (250 mg per 100 mL) (mg/L)**	**Treated H_2O Cs_2FeO_4 (250 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFeO_4$ (250 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	93.31	22.17	17.78	73.24	40.65
Banks DIH Waste Water (Georgetown)	3058.79	333.00	352.00	400.50	351.71
University of Guyana Pond water	80.37	59.12	59.12	75.73	68.35
Berbice tap water	33.26	13.45	26.59	23.81	68.35
Experiment No. 3	**Untreated H_2O (mg/L)**	**Treated H_2O K_2FeO_4 (500 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFeO_4$ (500 mg per 100 mL) (mg/L)**	**Treated H_2O Cs_2FeO_4 (500 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFeO_4$ (500 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	93.31	20.41	31.94	79.11	55.49
Banks DIH Waste Water (Georgetown)	3058.79	390.00	400.12	434,58	448.52
University of Guyana Pond water	80.37	70.21	76.59	77.45	77.60
Berbice tap water	33.26	17.59	26.52	24.39	8.16

Figure 7: Total chloride of untreated and metal ferrates treated water samples





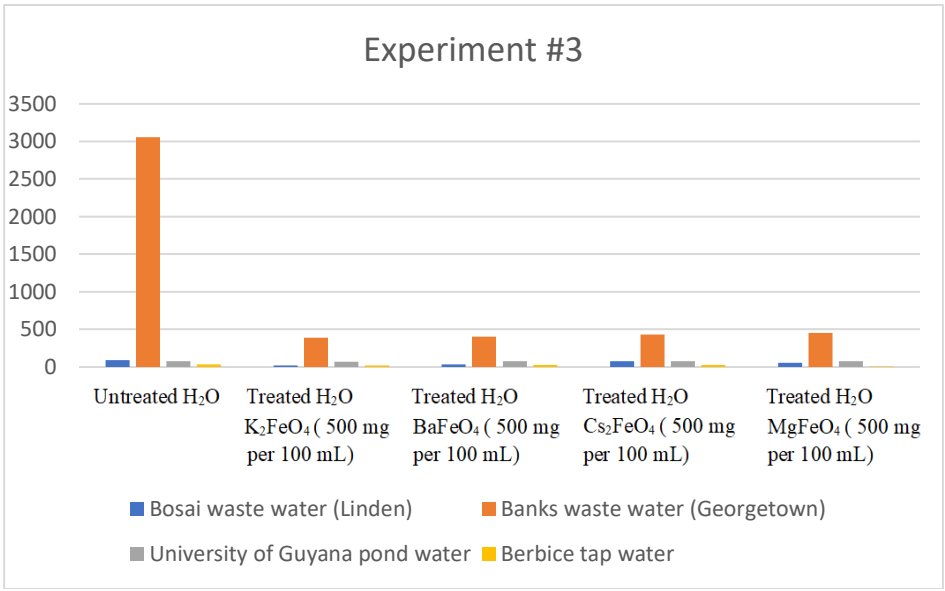
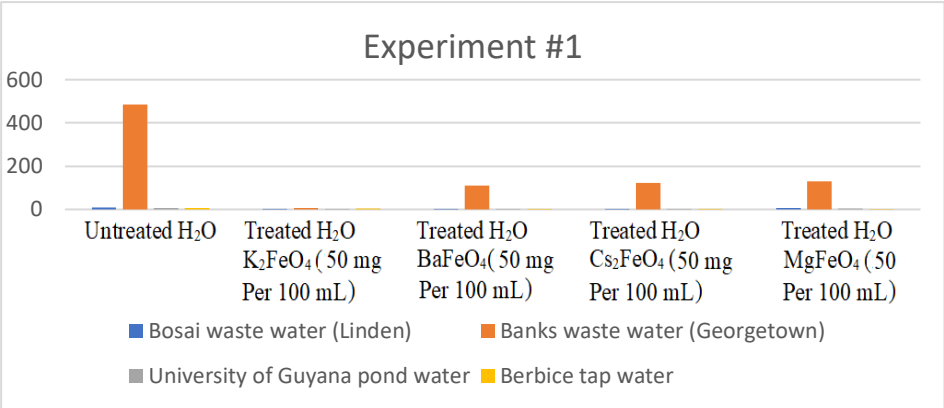
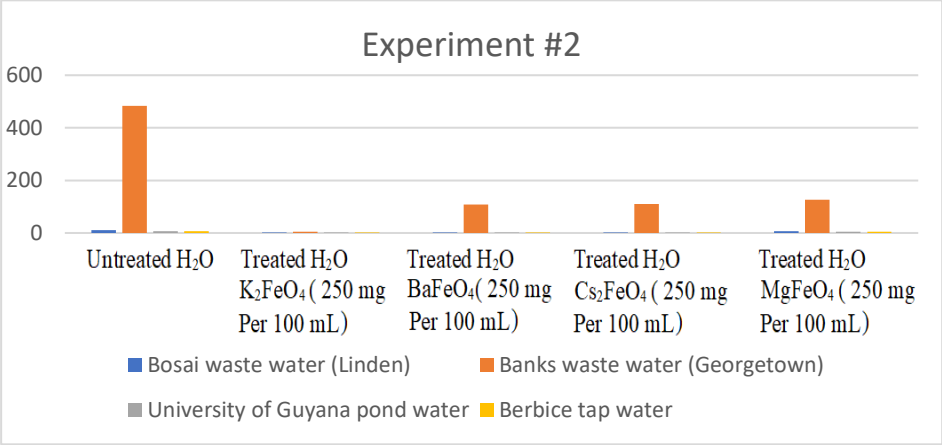


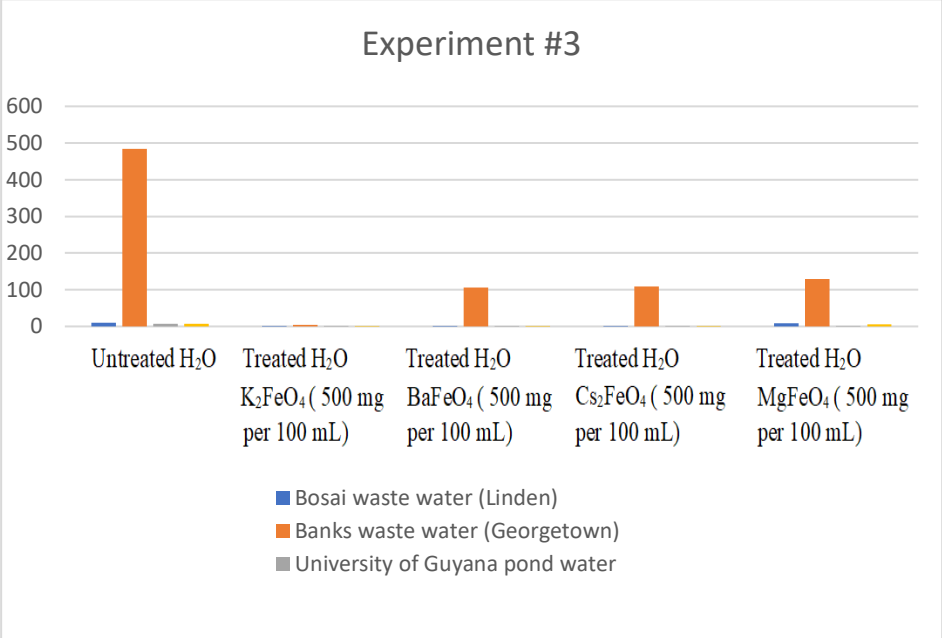
Table 8. Hardness of untreated and metal ferrates treated water samples

Experiment No. 1	**Untreated H_2O (mg/L)**	**Treated H_2O K_2FeO_4 (50 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFeO_4$ (50 mg per 100 mL) (mg/L)**	**Treated H_2O Cs_2FeO_4 (50 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFeO_4$ (50 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	10.33	1.30	1.30	0.61	6.56
Banks DIH Waste Water (Georgetown)	484.04	6.50	109.72	122.26	129.99
University of Guyana Pond water	7.74	0.64	1;61	0.97	3.87
Berbice tap water	7.10	3.32	1.94	0.97	2.58
Experiment No. 2	**Untreated H_2O(mg/L)**	**Treated H_2O K_2FeO_4 (250 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFeO_4$ (250 mg per 100 mL) (mg/L)**	**Treated H_2O Cs_2FeO_4 (250 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFeO_4$ (250 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	10.33	1.29	1.29	0.60	6.45
Banks DIH Waste Water (Georgetown)	484.04	5.81	109.04	110.37	126.41
University of Guyana Pond water	7.74	0.71	2.00	0.65	5.80
Berbice tap water	7.10	1.61	1.94	1.29	4.15
Experiment No. 3	**Untreated H_2O (mg/L)**	**Treated H_2O $K_2Fe\ O_4$ (500 mg per 100 mL) (mg/L)**	**Treated H_2O $BaFe\ O_4$ (500 mg per 100 mL) (mg/L)**	**Treated H_2O $Cs_2Fe\ O_4$ (500 mg per 100 mL) (mg/L)**	**Treated H_2O $MgFe\ O_4$ (500 mg per 100 mL) (mg/L)**
Bosai Waste Water (Linden)	10.33	1.29	1.29	0.60	8.07
Banks DIH Waste Water (Georgetown)	484.04	4.52	106.50	109.08	129.09
University of Guyana Pond water	7.74	0.71	1.94	0.97	5.80
Berbice tap water	7.10	1.61	1.29	1.27	5.06

Figure 8: Total hardness of untreated and metal ferrates treated water samples







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