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SCHOOL OF CHEMICAL & BIO-ENGINEERING

COMPARISON OF LABORATORY SYNTHESIZED IRON (II) SULPHATE WITH INDUSTRIAL COAGULANTS FOR REMOVING COLLOIDAL SUBSTANCES IN DRINKING WATER

A Thesis Submitted to the School of Chemical and Bio-engineering
In Partial Fulfillment of the Requirements for the Degree of Master of Science
in Chemical Engineering (Environmental Engineering Stream)

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As members of the examining board for the final M.Sc. thesis open defense, we hereby certify that we have duly read and assessed the thesis prepared by Hayu Baliste, entitled: **“**comparison of laboratory synthesized iron (II) sulphate with industrial coagulants for removing colloidal substances in drinking water.” We have found the thesis to meet the necessary academic standards and recommend its acceptance as fulfilling the requirements for the Degree of Master of Science in Chemical Engineering (Environmental Engineering stream).

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DECLARATION

I hereby declare that this research entitled “comparison of laboratory synthesized iron (II) sulphate with industrial coagulants for removing colloidal substances in drinking water” is a result of my own original work. All sources and references used during the preparation of this research have been duly acknowledged, and no part of this work has been submitted for any other degree or qualification in any academic institution.

I do further affirm that this piece of work is presented with total integrity; hereby, I take full responsibility for the methodology, data analysis, and the conclusion drawn therein.

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LIST OF ABBREVIATIONS AND ACRONYMS

AAS	Atomic Absorption Spectroscopy
Adeq Precision	Adequate Precision
Adj R^2	Adjusted Coefficient of Determination
ANOVA	Analysis of Variance
AOPs	Advanced Oxidation Processes
ASTM	American Society for Testing and Materials
BBD	Box-Behnken Design
BOD	Biological Oxygen Demand
C.V	Coefficient of Variation
CI	Confidence Interval
COD	Chemical Oxygen Demand
FTIR	Fourier Transform Infrared Spectroscopy
G/cm^3	Grams per cubic centimeter
GSE	Geological Survey of Ethiopia
HACH	Hach Company (manufacturer of water quality testing equipment)
MC	Moisture Content
Mt	Metric Ton
NTU	Nephelometric Turbidity Units
PACl	Polyaluminum Chloride
pH	Potential of Hydrogen (the measure of acidity or alkalinity)
Pred R^2	Predicted Coefficient of Determination
R^2	Coefficient of Determination
Rpm	Revolutions per minute
RSM	Response Surface Methodology
Std. Dev	Standard Deviation
UN	United Nations
UV	Ultraviolet
VIF	Variance Inflation Factor
WHO	World Health Organization
WWDR	World Water Development Report
XRD	X-ray diffraction

Abstract

Pollution from both natural and anthropogenic sources is increasingly degrading surface water quality, posing significant risks to human health and ecosystems. To address this, cost-effective and efficient water treatment methods are urgently needed. Coagulation is one of the most effective and simple techniques for removing colloidal and suspended solid pollutants from water. This thesis work evaluates and compares the removal efficiency of laboratory synthesized iron sulphate with industrial coagulants, alum and ferric chloride, in treating surface water. A batch jar test experiment was conducted to assess the impact of coagulant dose, pH, and settling time on turbidity removal. Varying doses (3, 6, 9 g/L) and pH levels (3, 7, 11) were tested, with rapid and slow mixing followed by settling periods of 35, 45, and 55 minutes. The results showed that ferrous sulphate achieved a maximum turbidity removal efficiency of 98.8% at 6 g/L, pH 3, and settling time 55 min, with optimal conditions at dose 5.834 g/L, pH 3.617, and 48 minutes of settling time, resulting in 99.03% removal. Ferrous sulphate performed similarly to ferric chloride (99.24%) and alum (99.61%) but offered additional benefits such as lower cost, reduced toxicity, and minimal impact on pH and water coloration. This study demonstrates that ferrous sulphate is a promising, low-cost alternative for water treatment, especially in developing countries like Ethiopia, where it can be locally sourced and produced efficiently. The optimization of coagulant dosage and pH is crucial for maximizing treatment performance, positioning ferrous sulphate as a sustainable solution for water purification in resource-limited settings. The study underlines the potential of ferrous sulphate as a feasible alternative for drinking water treatment, especially in developing countries like Ethiopia, where it can be produced locally and at a lower cost. Moreover, it identifies optimization of the dosage of coagulant and pH as necessary for the best treatment performance of ferrous sulphate, thus proving to be one of the promising solutions for low-cost and sustainable water purification in settings with limited resources.

***Keywords**: Coagulation, Ferrous sulfate, Surface water, pollution, turbidity removal*

1. INTRODUCTION

1.1. Background

Surface water is an essential part of human requirements for drinking, agriculture, industry, and sanitation throughout the world. However, surface water has been increasingly subject to a multitude of substances that threaten ecosystems, human health, and economic life. According to world health organization (2017), “surface waters contribute significantly to the international freshwater supply because alternative sources can be scarce in developing countries”. It is estimated that over two billion people still depend on surface water that is either untreated or poorly treated, thus exposing them to waterborne diseases such as cholera, dysentery, and typhoid fever.

Surface water resources are most vulnerable to pollution due to their accessibility for waste disposal contamination. Pollution originates from point and nonpoint sources, including anthropogenic activities like industrialization, urbanization, agricultural runoff, and domestic waste, as well as natural processes such as climate change, soil erosion, and sedimentation (Reddythota & Teferi, 2022). The World Water Development Report (2018) highlights that around 80% of industrial and municipal wastewater is released untreated, further deteriorating water quality with harmful effects on human health and ecosystems. Growth in population and economic development is adding to the exposure by pollution, which, on a larger scale, occurs in low- and middle-income countries (WWDR, 2018). These contaminants include chemicals, pesticides, pathogens, and particulates that have significant impacts on human health and aquatic ecosystems (Kurniawan et al., 2020).

Safe access to clean water remains one of the biggest challenges faced by many African countries, including Ethiopia. The United Nations estimates that 1.1 billion people globally lack access to adequate drinking water, many of whom reside in some of the poorest countries (Yimer & Dame, 2021). Poor water quality is usually related to bad health and poverty; approximately 80% of diseases in developing countries are caused by water contamination (Yimer & Dame, 2021). In Ethiopia, for instance, water drawn from rivers, particularly during the rainy season, is often characterized by high turbidity, which presents a significant challenge for water treatment (Karnenam & Saritha, 2021). The contamination of surface water is primarily caused by the direct disposal of industrial and municipal wastewaters, along with runoff from agricultural activities (Zegeye, 2020).

To control this water quality deterioration, several treatment technologies are being applied to transform raw water into potable water and treat wastewater before discharge into water bodies (Kurniawan et al., 2020). Conventional treatment processes include screening, sedimentation, coagulation-flocculation, filtration, and disinfection (Ugwu et al., 2017). Coagulation is a critical step in this process, used to remove suspended particles, colloids, and dissolved chemical species by aggregating them into larger flocs that can then be removed via sedimentation or filtration. Coagulation is an economical, simple, and reliable method that consumes less energy compared to other treatments (Karnenam & Saritha, 2021).

Some of the common coagulants used in water treatment include aluminum sulfate, ferric chloride, and ferrous sulfate (Mbaenet et al., 2017). In coagulation, the electrical bonding of suspended particles is neutralized, enabling them to form clumps. Coagulation efficiency depends on several factors such as coagulant type, its dosage, pH, feed concentration, and chemical additive (Mohamad et al., 2022). Optimum dosing and pH value of the solution is highly essential for better coagulation. Inadequate and excess dosage results in poor floc formation (Agarwal et al., 2020).

In Ethiopia, where iron ore is abundant but no chemical coagulant-producing factories exist; coagulants are usually imported, adding a lot of costs to the processes (Asmare et al., 2021). In such a case, locally produced ferrous sulfate has emerged as a cost-effective and sustainable alternative. It was indicated that ferrous sulfate is an efficient coagulant in the removal of pollutants like chrome, suspended solids, and other impurities from wastewater (Asmare et al., 2021; Mohamad et al., 2022).

The main objective of this research is to compare the coagulation efficiency of laboratory synthesized ferrous sulfate against that of the conventional industrial coagulant, alum and ferric chloride in surface water treatment. The research is also targeted at finding the potential of ferrous sulfate as an inexpensive locally available coagulant that might provide a sustainable solution for water purification, especially in resource-poor countries like Ethiopia.

1.2. Statement of the Problem

Water is a substance highly crucial to support life, industry, agriculture, and ecosystems. However, this resource is facing increasing pollution and over-extraction from rivers and aquifers, resulting in major environmental challenges. In turn, the setting of lower water tables, shrinking lakes, and degraded ecosystems contribute to the decline in water quality, harm aquatic life, and lose ecosystem services (Walker et al., 2019). As a result, water has become one of the most critically stressed resources in an increasingly unstable world, hence demanding immediate attention from policy makers, resource managers, and governments around the world. Clean and reliable water supplies are an imperative component of human subsistence and economic development. Water is nonetheless mismanaged, becoming wasted and polluted, thus worsening the global water crisis (Walker et al., 2019).

The problem is especially acute in developing countries, where rapid population growth, industrialization, and increased fertilizer and pesticide use further worsen the water quality. About 80% of all industrial and municipal wastewater is discharged untreated into the environment, causing severe impairment to ecosystems and seriously threatening human health (WWDR, 2018).

In Ethiopia turbidity and shortage of water is the key problems of the society especially in rural and semi-rural areas. More than 85% of the peoples of Ethiopia are living in rural and semi-rural areas of the country who are suffered from unsafe or turbid water. These problems are arisen from different causes. The main cause is poor water management skills and regulations. To solve these problems different methods and coagulants have been used in water treatment plants (Mihretie D., 2022)

Traditional water treatment processes often rely on the importation of chemicals such as alum (aluminum sulfate), beyond the affordability of developing countries such as Ethiopia. The high chemical cost and environmental impacts associated with alum, including the generation of huge amounts of hazardous sludge besides possible deleterious health effects, make the methods unsustainable Abatneh et al., 2014; Yimer & Dame, 2021. Iron-based coagulants, in contrast, produce less sludge with fewer health risks but are less well explored for application.

Iron-based treatments are, however, underutilized in Ethiopia's surface water treatment systems due to a lack of thorough study, low awareness, inadequate infrastructure, and inadequate training. As a result, less effective and perhaps hazardous techniques are still used to achieve the rising standards for water quality

Ethiopia, being rich in iron ore deposits, stands a better chance of producing locally sourced iron sulfate as a coagulant that could minimize the cost and environmental impact of water purification. Moreover, iron-based sludge could also be utilized as organic fertilizer because of its potential to improve iron deficiencies in the soil, particularly where agricultural production is significant. This is in agreement with Kurniawan et al. (2020) and Ngteni et al. (2020). The main objective of this study, therefore, is to evaluate the effectiveness of coagulation using laboratory synthesized iron sulfate for possible environmental and economic sustainability as an alternative to conventional coagulants in surface water treatment systems within Ethiopia.

1.3. Objective of the study

1.3.1. General objective

- The general objective of this study is to investigate and compare the removal efficiency of laboratory synthesized iron sulphate with that of industrial coagulants, specifically alum and ferric chloride, for the removal of colloidal substances from drinking water.

1.3.2. Specific objective

- To prepare iron (II) sulfate using sulfuric acid (H_2SO_4) as a dissolvent solution in the leaching process.
- To characterize the physicochemical properties of the produced iron (II) sulfate.
- To evaluate the effect of key operating parameters, namely coagulant dose, pH, and settling time, on the performance of coagulation process.
- To optimize the coagulant dose, pH, and settling time for the best coagulation performance of the produced iron (II) sulfate.
- To compare the coagulation efficiency of the produced iron (II) sulfate with that of conventional coagulants, such as ferric chloride and alum.

1.4.Significance of the study

Iron (II) sulfate was used as a coagulant in this research, which was prepared from iron ore obtained locally, instead of using imported chemical coagulants. By replacing conventional coagulants with locally sourced alternatives, the study aims to decrease import and transportation cost, ultimately contributing to the country’s self-sufficiency. If successfully implemented, the research is expected to have the following significant impacts:

- Cost reduction: Lowering the cost of chemical coagulants for water and wastewater treatment.
- Academic Contribution: Providing foundation for future research in this field.
- Investment opportunity: Attracting potential investments in local resource utilization and water treatment technologies.
- Employment: Crating job opportunities for local communities through the production and application of locally available coagulants.

1.5. Scope of Study

This research focuses on assessing key water quality parameter such as, pH and Turbidity, using three coagulants:-ferric chloride, alum, and local produced iron sulphate. The study compares the performance of these coagulants in treating surface water. The characterization of water quality (pH, Temperature and turbidity) before and after treatment is conducted through coagulation experiments using a jar test apparatus. All experiments are carried out at a laboratory scale. It is important to note that this study does not include cost of coagulant analysis, and characterization or quantification of sludge generated during the coagulation process. In addition the coagulation experiment was done only for dry season.

2. LITERATURE REVIEW

2.1. Overview of Surface Water

Rivers, lakes, and reservoirs constitute a huge portion of the earth's freshwater resources. Surface water accounts for approximately 0.3% of the planet's total water, with 69% of this fraction locked in glaciers and ice caps. This leaves only a small fraction accessible for human use (UN Water, 2023). Surface water is a vital resource, directly used for consuming purposes, irrigation, hydropower generation, and various other uses, particularly in African. Major rivers such as the Nile, Congo, and Zambezi support millions of people, providing water for drinking, irrigation, and energy production. However, only around 4% of the Africa's total surface water is effectively utilized, largely due to infrastructural constraints and uneven distribution (African Development Bank, 2023).

Ethiopia is endowed with abounds surface water resources, including major rivers such as Blue Nile, Awash, and Omo which support agriculture, hydropower, and water supply systems. The country's average annual surface water availability is estimated at 122 billion cubic meters. However, the distribution of these sources is highly uneven, leading to seasonal water shortage in some regions (World Bank, 2022). Managing these resources has become increasingly challenging due to pollution growth, climate change, and poor infrastructure development. Effective management of surface water sources is important in ensuring sustainable development, particularly in rural and neglected areas (Tadesse et al., 2023).

2.2.Sources of Surface Water Contamination

Surface water contamination arises from a wide variety of human activities and natural phenomena, compromising water quality and posing significant risks to public health. Industrial discharges, agricultural runoff, and urban wastewater are among the primary sources of surface water pollution. Industrial activities such as mining, chemical manufacture, and oil refinery release heavy metals, toxic chemicals, and particulate matter into rivers and lakes. Agricultural runoff, laden with fertilizers, pesticides, and herbicides, contribute to eutrophication and disrupting aquatic ecosystem (United Nations, 2023).

Rapid urbanization has exacerbated the problem, with the untreated sewage and wastewater from growing cities introduces organic matters, pathogens, and pharmaceuticals into surface waters. Globally, approximately two billion people rely on water sources contaminated with feces, significantly increases the risk of waterborne diseases (WHO, 2023).Furthermore, climate change and deforestation have intensified surface waters contamination by increasing the frequency and severity of flooding events, which transport pollutants from the land into water systems (Smith et al., 2023). Addressing surface water pollution requires comprehensive monitoring, regulation, and sustainable management practices in order to minimum pollutants and ensure water quality for both human consumption and ecosystem health.

2.3.Surface Water Treatment Methods

Due to the increasing scarcity and high cost of drinking water, industries and municipalities are increasingly relying on treated surface water. However, surface water typically contains high level of suspended solids, bacteria, algae, organic matter, creating bad taste and odor. As a result, treatment is essential to achieve the required water quality. Several treatment technologies are used to convert raw surface water into drinking water and to treat wastewater before it is discharged back into water bodies. These technologies can be broadly categorized into conventional and advanced methods (Kurniawan et.al, 2020).

Conventional treatment methods have been widely used for decades and remain fundamental in ensuring the safety and quality of drinking water. These methods typically include:

i. Coagulation: Chemicals such as alum are used to; destabilize suspended particles, allowing them to clump together.
ii. Flocculation: Gentle mixing encourages the formation of large flocs from the destabilize particles.

iii. Sedimentation: The flocs settle out of the water due to gravity, forming sludges at the bottom of the tank.
iv. Filtration: Remaining particulate matter is removed using sand, gravel, or activated carbon filters.
v. Disinfection: Pathogenic microorganisms are killed using chlorination, ozone, or other disinfectants (Crittenden et al., 2012). While these methods are effective in removing many contaminants, they have limitations in addressing emerging pollutants such as pharmaceuticals, personal care products, and micro plastics, which are increasingly detected in surface waters (Haas et al., 2019).

Advanced technologies are being increasingly adopted to tackle complex and emerging contaminants in surface water. These include:

i. Membrane filtration: Removes pathogens, dissolved solids, and heavy metals through processes such as reverse osmosis and ultra-filtration.
ii. Advanced Oxidation Process: Breaks down organic pollutants, such as pharmaceuticals and pesticides, using powerful oxidants such as hydroxyl radicals.
iii. Ultraviolet Disinfection: inactive microorganisms without the use of chemicals, avoiding harmful disinfection byproducts.
iv. Electrochemical Treatments: Methods such as electrocoagulation effectively remove suspended solids, oils, and toxic metals, offering a sustainable alternative for water treatment (Zhang et al., 2023; Pereira et al., 2021; Kumar & Bansal, 2024; Xu et al., 2023). These advanced methods provide more comprehensive solutions for modern water treatment challenges, ensuring safer and higher-quality water for both human consumption and environmental protection.

2.4. Coagulation-Flocculation

Coagulation is a crucial process in treating surface water, removing dissolved chemical species, and turbidity. Coagulation is used as a pre-treatment to remove a significant amount of colloidal and particulate organic matters in residual waters. This process is effective due to its operation, relatively simple design, and low energy consumption (Mohamad et al., 2022). Furthermore, it is a proven process for removing suspended, colloidal, and dissolved particles by aggregating macro and micro particulate to large size, which eventually settled by sedimentation. In addition, coagulation is also applicable for removing various impurities, including micro-pollutants, organic compounds, color-causing compounds, oil and fats (Karnena& Saritha, 2021).

The coagulation process destabilizes suspended particles and reacts with organic materials in raw water. Common coagulants include aluminum sulfate, ferric chloride, polyaluminum chlorides, and synthetic polymers. Alum, for instance, reduces the repulsive force between particulate matter, promoting particle collisions and the formation of floc (Yimer & Dame, 2021).Coagulation essentially consists of destabilization and aggregation of stable small colloidal contaminations to larger particles known as floc, that are effectively removed by physico-chemical processes such as rapid mixing, slow mixing, separation of solid-liquid stages in sedimentation and filtration. Colloidal impurities generally include viruses, bacteria, protozoans, color producing substances, inorganic solids and organic matter (Karnena&saritha 2021).

In practice, coagulation destabilizes the colloidal particles through charge neutralization after dosing of the coagulant, whereas in flocculation aggregation the colloids (ranging from micrometers to millimeters in size). Although coagulation and initial stages of flocculation occur rapidly, the overall process is gradual and requires careful control. In full-scale water treatment facilities, the coagulation processes are usually followed by flocculation and sedimentation. The optimal coagulant dose is often determined empirically using jar tests, studies, which involve adjustments of water pH, coagulant type, and dosage based on raw water quality (Jiang, 2015).

2.5. Types of Coagulants and Flocculants

A coagulant is a chemical compound, typically with positive charges (mostly divalent), that interacts with suspended particles inside the solution to neutralize their charges and form combined compounds that can be easily removed (Kurniawan et al., 2020).The selection of an appropriate coagulant is one of the most critical decisions in water or wastewater treatment, as different coagulants perform optimally under varying water quality parameters (Sahu & Chaudhari, 2013).

The most commonly used metal coagulants in the coagulation-flocculation process are aluminum-based and iron-based compounds (Mohamad et al., 2022; Karnena& Saritha, 2021). The aluminum-based coagulants include aluminum chloride, aluminum sulfate, sodium aluminate, PAC. The iron-based coagulants include ferric chloride, ferric chloride sulfate, ferric sulfate, and ferrous sulfate. These coagulants are effective across a wide range of pH levels, temperatures, and colloidal concentrations, compared to commonly used coagulants.

2.5.1. Aluminum-Based Coagulants

The most commonly used aluminum-based coagulants are aluminum sulfate (i.e., alum, $Al_2 (SO_4)_3 \cdot 18H_2O$) and polyaluminum chloride (PACl) in surface water treatment. These coagulants are highly effective in removing turbidity, suspended solids, heavy metals, and organic matter. Their mechanism involves neutralizing the negative charges on colloidal particles, causing them to aggregate into larger flocs that can be removed through sedimentation or filtration. Aluminum sulfate, specifically, is favored for its high coagulation efficiency and cost-effectiveness, especially in treating waters with high turbidity (Chowdhury et al., 2021).

Recent studies have highlighted the advantages of PACl over alum, which require lower doses and result in reduced sludge generation (Zhao et al., 2022). PACl is effective in treating low-turbidity, high-organic waters, making suitable for specific surface water sources (Li et al., 2023). However, aluminum-based coagulants are not without drawbacks. Residual aluminum in treated water has raised health concerns, as extensive exposure has been linked to neurotoxicity and other health conditions (Shao et al., 2023). To address these concerns, recent research has focused on optimizing dosage strategies and integrating aluminum-based coagulants with other treatment technologies, such as electrocoagulation and advanced oxidation processes, to enhance performance and reduce aluminum residues in treated water (Zhao et al., 2023).

2.5.2. Iron-Based Coagulants

Iron-based coagulants, including ferric chloride ($FeCl_3$), ferric sulfate ($Fe_2(SO_4)_3$), and ferric hydroxide ($Fe(OH)_3$), have extensively replaced other coagulants due to their effectiveness in removing suspended particles, turbidity, and contaminants such as organic matter, phosphorus, and heavy metals. These coagulants destabilize colloidal particles through hydrolysis, forming flocs that can be removed via sedimentation and filtration. Ferric chloride, in particular, is widely used for its ability to treat high turbidity waters effectively (Kaur et al., 2021). Iron-based coagulants also work better under acidic (low pH) conditions, making them versatile for various water sources. Recent studies explored the benefits and challenges of iron-based coagulants in water treatment. One significant benefit is their ability to remove heavy metals such as arsenic, more effectively than traditional coagulants (Li et al., 2022). However, a noticeable disadvantage is the generation of iron sludge, which can increase the costs of operations (Shao et al., 2023).

2.6.Factors Affecting the Coagulation Process

The efficiency of the coagulation process in water treatment is influenced by different factors, which affect particle removal and overall water quality. These factors must be carefully managed to optimize coagulation performance.

i. pH Level: The pH of water significantly affects the effectiveness of coagulants .Aluminum-based coagulants, such as aluminum sulfate, perform better under slightly acidic to neutral conditions, while iron-based coagulants are more effective in low pH (acidic) environments. The optimal pH range varies depending on the coagulant used, and deviations can reduce coagulation efficiency (Zhao et al., 2023).

ii. Temperature: higher water temperature conditions usually enhance coagulation by increasing the kinetic energy of particles and coagulant molecules, speeding up floc formation (Kaur et al., 2022).

iii. Concentration of suspended solids and organic matters: High concentrations of suspended solids or organic matters can interfere with the coagulation process by competing for coagulant chemicals or hindering floc formation. This may require higher coagulant doses or adjustments to the treatment process (Li et al., 2023).

iv. Particle characteristics: the size and charge of particles is also influences coagulation. Large or more negatively charged particles may need a higher coagulant dose or specific type of coagulants to achieve effective removal (Shao et al., 2023).

v. Mixing speed and time: proper mixing speed and time during the coagulation phase is critical for effective floc formation because poor mixing does not allow proper aggregation of particles. By carefully controlling all these factors, the efficiency of the coagulation process can be significantly improved, leading to better quality and treatment performance.

2.7. Effectiveness of Coagulants Used in Surface Water Treatment

The performance of coagulants during the treatment of surface water is vital for removing suspended solids, turbidity, organic matter, and even some dissolved pollutants. The most common used coagulants include aluminum-based coagulants, such as aluminum sulfate and polyaluminum chloride, and iron-based coagulants, such as ferric chloride and ferric sulfate. Their effectiveness depends on factors such as water quality, pH, temperature, and the specific nature of pollutants found in water.

The commonly used aluminum-based coagulants include alum and PACl due to their efficiency in removing suspended particles and turbidity. PACl has gained attention for its advantages over traditional alum, because it requires lower doses and results in reduced sludge production, making it cost-effective and environmentally friendly (Zhao et al., 2023). PACl is also more effective in treating low-pH waters and those that have high organic matter content, where alum may underperform (Li et al., 2023). However, the main disadvantage of aluminum-based coagulants is the potential health risks related to residual aluminum in treated water, which has been related to neurotoxic effects at very high concentrations (Shao et al., 2023).

Iron-based coagulants, such as ferric chloride and ferric sulfate, are multipurpose coagulants and effective to remove a wide variety of contaminants, including heavy metals such as arsenic and other organic pollutants. For instance, ferric chloride is an ideal coagulant for the treatment of water with high turbidity; therefore, acidic applicable reservoir conditions favor its use compared to some aluminum-based coagulants (Kaur et al., 2021). Iron-based coagulants produce dense, easily removable flocs but generate greater volumes of iron sludge, which requires careful disposal to avoid environmental contamination (Zhao et al., 2023). Despite this, they are increasingly preferred for industrial applications and waters contaminated with phosphates and metals (Zhao et al., 2022).

Comparative studies have shown that both aluminum and iron-based coagulants can actively lower turbidity but vary significantly in the removal of dissolved contaminants such as phosphorus, metals and certain organics from the water bodies. For example, Li et al. (2022) have shown that iron coagulants are better in phosphorus removal from surface water than aluminum. This is more relevant to water bodies that are impacted by eutrophication. Aluminum-based coagulants, however, remain popular in drinking water treatment due to their cost-effectiveness and having well-established operational procedures.

In recent years, there has been an increasing interest in the utilization of iron-derived coagulants, such as ferric chloride or ferric sulfate, as a low-cost, locally sourced alternative to conventional coagulants. This approach is particularly advantageous in developing countries, where the costs and logistics of importing chemicals are prohibitive (Bekele et al., 2016). Coagulants derived from iron ore have demonstrated effectiveness in removing turbidity, organic matter, and pathogens, making them a promising option for improving water quality in resource-constrained settings.

2.8.Iron Ore

Iron ores are naturally occurring rocks and minerals from which iron has been extracted, primarily for industrial application such as steel production. These ores are rich in iron oxides and a variety of colors, such as dark grey, bright yellow, deep purple, and rusty red, depending on their specific mineral composition. The most common forms of iron ore include: magnetite (Fe_3O_4), hematite (Fe_2O_3), goethite ($FeO(OH)$), limonite ($FeO(OH)\bullet n(H_2O)$), and siderite ($FeCO_3$). Among these, hematite and magnetite are most economically important ones because of the higher iron content and ease of extraction (Tavares et al., 2023). Goethite and limonite do often occur in lateritic deposits, and they cannot extract usable iron without more complex processing methods because they contain lower amounts of iron (Simms et al., 2023). Siderite is not very common, but it is an iron-bearing carbonate mineral in sedimentary deposits, and it requires that iron carbonate be subjected to reduction for the iron metal to be produced (Moges, 2021).

Metallic iron is rare on Earth's surface, with the exception of iron-nickel alloys found in meteorites and rare deep mantle xenoliths. As the fourth most abundant element in the Earth's crust, iron is primarily bound in silicate or carbonate minerals (Simms et al., 2023). Extracting pure iron from these minerals is thermodynamic challenging and energy-intensive. The iron industry primarily uses iron oxide minerals, with hematite being the most commonly exploited due to its high iron content and favorable physical properties. Magnetite, are also mined, but requires more complex processing (Tavares et al., 2023. Mining methods for iron ore vary depending on the type and location of deposit. Hematite is typically extracted through open-pit mining, while magnetite often requires underground mining or drilling and blasting due to their deeper location and more complex geological formations (Moges, 2021). Innovations are continually sought to reduce environmental impacts and improve the efficiency of iron ore mining.

2.9. Iron Resources in Ethiopia

Ethiopia is endowed with significant iron ore deposits, primarily located in regions such as Wollega, Kaffa, Sidamo, and Tigray. Some of the Wollega reserves are Chago (1.2Mt at 64% Fe), Dha (0.05Mt at 65% Fe), Gordona-Korree (0.27Mt at 63% Fe), Worakalu (0.15Mt at 62%

Fe), among others, summing to huge potential extent for exploitation of iron ore. In Kaffa, there are deposits like Garo (12.5 Mt), Melka Sedi (12.5 Mt), and Dombowa (12.5 Mt), these all have huge possibilities of iron ore extraction, while the Mai Guda (40% Fe) is one falling short of expected value. Among the Sidamo areas is Melka Arba, having an estimated reserve of 4.63Mt. Besides, in the Tigray region, there are areas with combined iron content in the range of 5Mt at Adua, Axum and Enticho, though lower in grade (30% Fe) (Solomon, 2013). These deposits represent a substantial potential source for the country, though challenges related to infrastructure and processing technology have limited their full exploitation.

2.10. Production of Iron Ore in Ethiopia

Ethiopia has significant reserves of iron ore, which are found in various regions of the country, including Wollega, Gambela, Oromia, and Tigray. The country has been exploring the potential of its iron ore resources to boost its industrial sector, particularly for steel production, which could have downstream benefits for water treatment and other industries. Large iron ore deposits in the Western Ethiopia region, including the Adola and Daro Lebu mines, have been of particular interest for commercial extraction (Mulugeta, 2010). The government of Ethiopia has been working on enhancing the mining sector to better utilize these resources, with the aim of increasing domestic production and reducing reliance on imports.

Currently, iron ore extraction in Ethiopia is limited, with the majority of the ore being used for domestic consumption in steel plants. However, there is a growing interest in expanding the use of locally sourced iron ore for applications beyond steel production, such as in water treatment. The availability of iron ore in Ethiopia presents an opportunity to reduce the cost of coagulants for water treatment and support the country's broader water infrastructure goals.

3. MATERIAL AND METHOD

3.1.Materials

The following are the equipment and chemicals that were used throughout the experiments to achieve the objective of the study: Jar test apparatus (IC 142 D), Four 1000ml beakers, a dropper, a measuring cylinder, beakers, a weight balance, a pipette, cross beater mill, jaw crusher, a sieve, electric thermostatic heater dry box (202OA), filter paper, a 1000ml volumetric flask, and an HACH turbid meter (model 2100N), gloves, 3505 pH meter and lega dadi surface water (sample source).

Chemicals used were lithium etaborate (LiBO2), nitric acid (HNO3), lanthanum chloride (LaCl3), potassium chloride (KCl2), and distilled water (H2O) for characterization of iron ore. Distilled water to mitigate the acid and for washing of materials**,** Detergent for cleaning, iron ore (Fe2O3), sulfuric acid (H2SO4), and hydrochloric acid (HCL) for iron sulfate production; ethanol (CH3CH2OH), phenolphthalein (C2OH14O4), 0.5N sodium hydroxide (NaOH), and 0.5N sulfuric acid (H2SO4) solution for pH adjustment surface water. Alum, ferric chloride, and ferrous sulphate as coagulants**.**

3.2.Method

The following subsections outline the strategies employed to accomplish each of the study’s specific objectives.

3.2.1. Iron Ore Collection and Characterization

Local iron ore from Horo Guduru, Oromia Region, was utilized as the raw material for the production of iron sulfate. The Geological Survey of Ethiopia (GSE) has identified numerous iron deposits in regions such as Oromia and Tigray. However, for this study, iron ore was collected from Abe Dengoro woreda in the Horo Guduru Wallaga zone, and the Walage Kebele special area FALLE.

The collection process involved collecting information from local people and visually identifying areas with abundant iron ore. The ore was then excavated, bagged, and transported for the next analysis. The characterization experiments were carried out at the Geological Survey of Ethiopia laboratory in Mekanisa, Addis Ababa. Techniques such as $LiBO_2$ fusion, HF attack, gravimetric analysis, colorimetric analysis, and atomic absorption spectroscopy (AAS) were used to characterize the iron ore.

3.2.2. Production of Iron Sulphate as Coagulant from Locally Collected Iron Ore

Before the chemical reaction, the collected iron ore was washed with water to remove impurities and prepared for crushing. The sample was crushed using a jaw crusher and motor mill in the Chemical Engineering Size Reduction Laboratory in Addis Ababa Institute of Technology. The resulting sample, with a particle size of less than 2 mm, was then ready for the next stage of the reaction process.

3.2.2.1.Reaction of Iron Ore with Acid

The crushed iron ore, with a particle size of less than 2 mm, was placed in a beaker and reacted with concentrated hydrochloric acid (35%). The chemical reaction is represented by the following equation (Equation 3.1):

$$Fe_2O_3 + 6HCl \rightarrow 2FeCl_3 + 3H_2O --------(Equation\ 3.1)$$

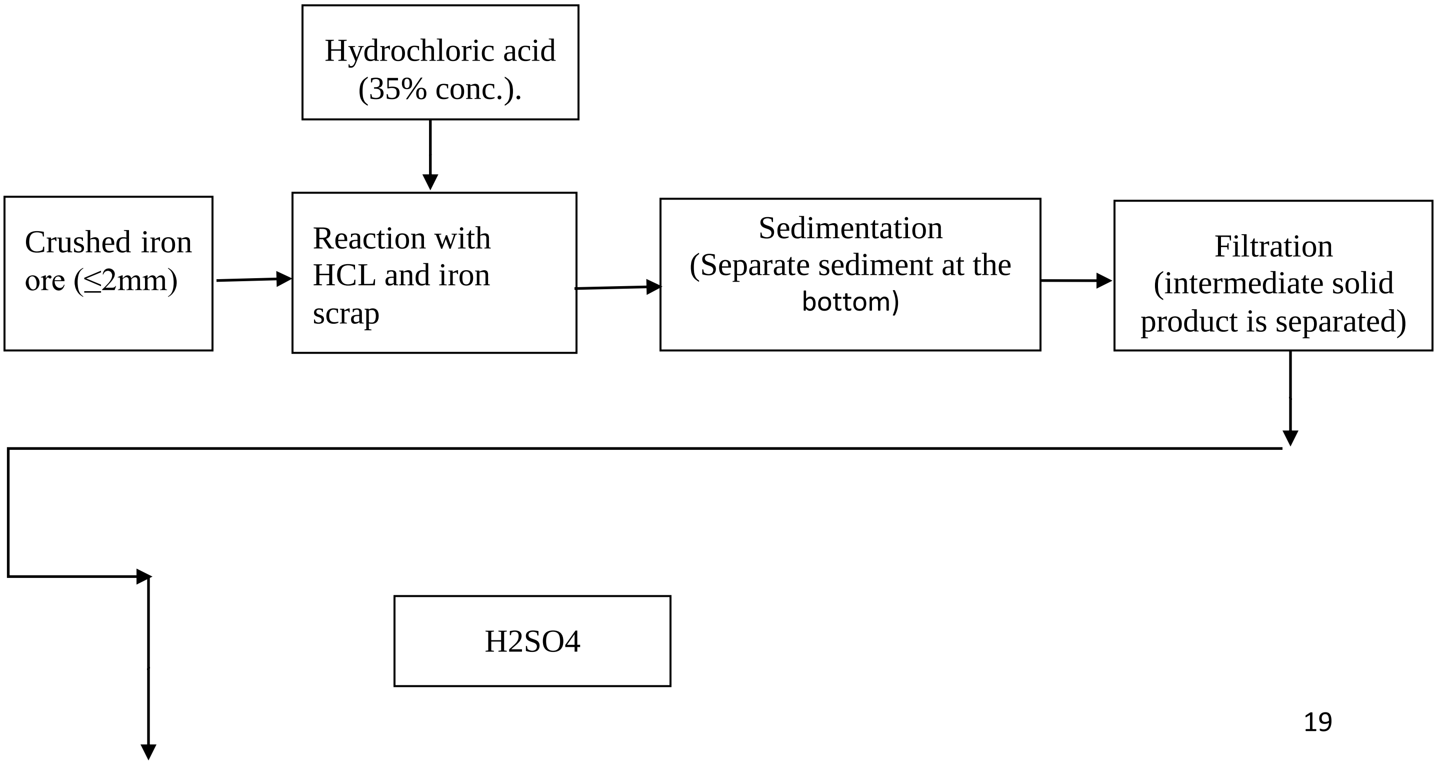
After the reaction, the unreacted solid ore and ferric chloride ($FeCl_3$) solution were separated using sedimentation followed by vacuum filtration. To produce ferrous sulphate, the ferric chloride solution was first reduced to ferrous chloride ($FeCl_2$) by adding an equivalent amount of porous iron scrap. The reduction reaction is exothermic and proceeds as follows:

$$2FeCl_3 + Fe \rightarrow 3FeCl_2 - - - - - - - - - - (Equation\ 3.2)$$

The resulting ferrous chloride solution was then dried in an oven at 105℃ for one hour. After drying, the ferrous chloride crystals were crushed and reacted with sulfuric acid (H_2SO_4) to produce ferrous sulfate ($FeSO_4$). The reaction is represented by the equation:

$$FeCl_2 + H_2SO_4 \rightarrow FeSO_4 + 2HCl - - - - - - - - - - -(Equation\ 3.3)$$

The mixture of the powdered ferrous chloride and sulfuric acid was heated at constant temperatures (50℃, 75℃, and 95℃) for 30, 60, 90 minutes to produce iron sulphate, by following the procedure outlined by (Birhan, 2017). The solution was then filtered using filter paper to separate undissolved waste from the ferrous sulfate solution. Finally, the filtered solution was cooled in a water bath at room temperature to allow the crystallization of ferrous sulfates ($FeSO_4$).



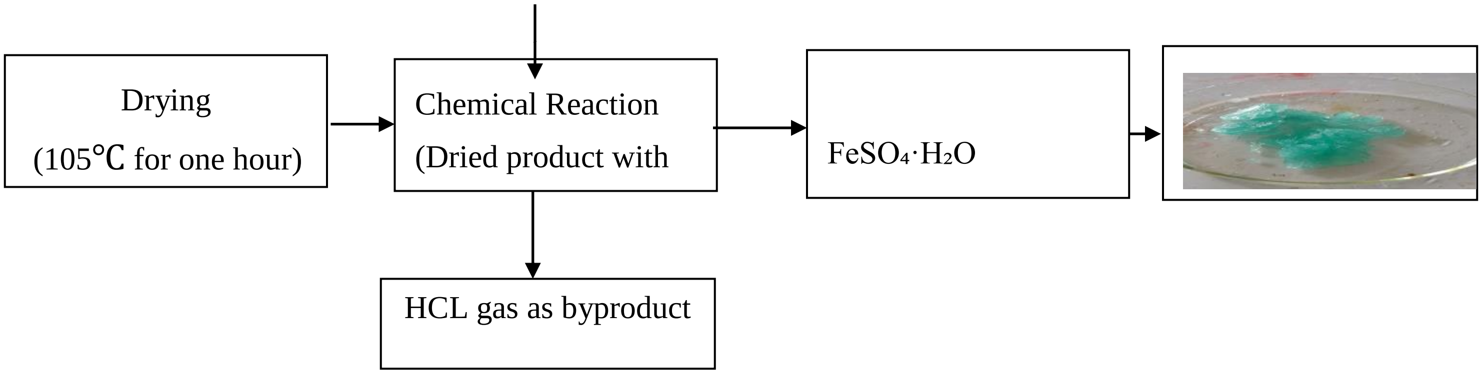


Figure 3-1: Sequential preparation flow chart of ferrous sulphate.

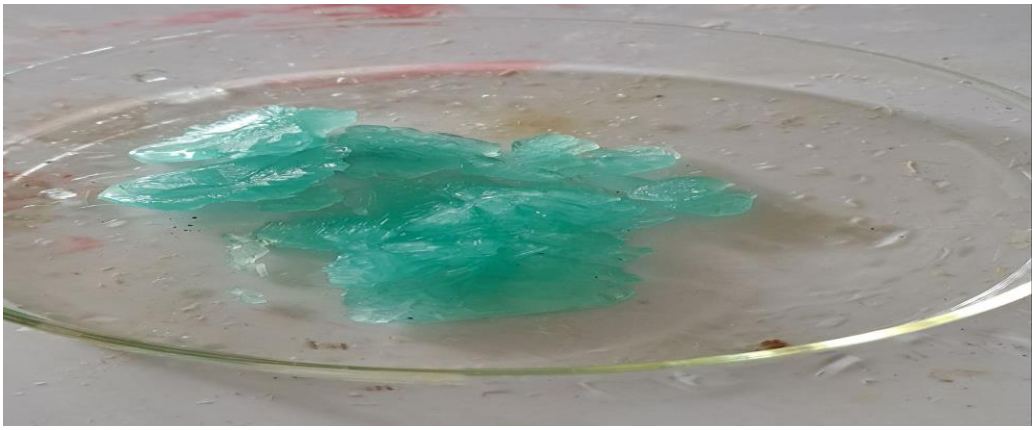


Figure 3.2: The photographic image of crystal ferrous sulphate

3.2.3. Characterization of Iron Sulphate (Physicochemical Properties)

3.2.3.1.Determination of Moisture Content

The moisture content of iron sulphate samples was determined by drying the samples in an oven until a constant weight was obtained. The 5 grams of samples were accurately weighed and placed in Petri dish. The dish was then dried at the 105℃, and the process was repeated until a constant weight was obtained. The moisture content was determined using following equation:

$$MC\ (\%) = \frac{W_1 - W_2}{W_1} * 100 ----------- (Equation\ 3.4)$$

Where: w_1= weight of the sample before drying

w_2 = weight of the sample after drying

MC= Moisture Content

3.2.3.2.Determination of density

The density of iron sulfate was measured using a standard pycnometer with a 25ml capacity. First empty pycnometer was weighed then weighed with half full iron sulfate; the pycnometer with iron sulfate crystal was filled with toluene and weighed. The volume of toluene was calculated using its known mass and density. The volume of iron sulfate was then determined by subtracting the volume of toluene from the total volume of the pycnometer. The density of iron sulfate was calculated using the following equation:

$$\text{Density} = \frac{mass\ of\ iron\ sulphate}{volume\ of\ iron\ sulphate} --------- (Equation\ 3.5)$$

3.2.3.3.Determination of pH

5 grams of iron sulfate were weighed and transferred to a 250ml resistant glass beaker. Then, 100 ml of distilled water was added, and the mixture was stirred thoroughly. After allowing the solution to settle briefly, the pH was measured using a potentiometric pH meter.

3.2.3.4.X-Ray Diffraction (XRD) Structure Analysis

X-Ray Diffraction (XRD) is a powerful analytical technique used for determining the crystalline phase of materials by measuring the diffraction patterns of X-rays from atomic planes. It is widely utilized in material science, chemistry, geology, pharmacy, and nanotechnology for phase identification, crystal size determination, structural defect determination, and compound purity verification. XRD provides precise lattice parameter and atomic arrangement data, and therefore it plays an important role in the characterization of natural and synthetic crystalline materials.

The crystalline structure of iron (II) sulphate (ferrous sulphate) nanoparticles was examined using XRD technique. Prior to analysis, the iron sulfate sample was prepared to ensure accurate and reproducible results. The sample was purified by washing with distilled water and dried at 105°C for 90 minutes. The dried sample was finely ground into a uniform powder, as XRD analysis requires a homogeneous crystalline powder for precise diffraction results.

3.2.4. Water Quality Analysis Method (Analytical Procedure)

3.2.4.1.PH and Temperature

The pH of the water samples was measured using a properly calibrated 3505 pH meter. About 200 milliliters of the sample water were transferred into a beaker, and the pH meter probe was immersed into the sample to obtain the reading. PH is a measure of the hydrogen ion concentration in a solution, expressed as a negative logarithm. It indicates the acidity or alkalinity of the solution, with a pH of 7 being neutral, values below 7 indicating acidity, and values above 7 indicating alkalinity. Temperature was measured using a thermometer with a range of 0–50 °C. Temperature is a critical parameter as it affects the solubility of dissolved oxygen in water. Higher water temperatures reduce the availability of dissolved oxygen, which impact aquatic life.

3.2.4.2.Turbidity

Turbidity measurements were taken using a 2100 Turbidimeter. The Turbidimeter was calibrated using standard solution of 4000 NTU, 1000 NTU, 100 NTU, and 20 NTU. Before measurement, the cuvette was rinsed three times with the sample to be analyzed. The cuvette was then firmly placed into the optical well, and the Turbidimeter was indexed to the lowest reading. The measurement was initiated by pressing the arrow button, and the turbidity value was recorded once the display stabilized. Turbidity is an optical property that measures the clarity of water by comparing the intensity of light scattered by the sample to that of a standard reference suspension. According to the WHO, water with a turbidity of less than 5 NTU is generally acceptable for consumption, although regional circumstances may affect this guideline.

3.2.5. Experimental Design

A batch experiment was conducted to evaluate the statistical significance and impact of study variables-coagulant dose, pH, and settling time-on the percentage turbidity removal from surface water. The experiment was carried out using four 1000 mL beakers, each filled with500 mL of turbid surface water and the respective coagulant. The selected variables and their corresponding levels appear suitable for the experiment, with accurate references to standardized protocols. The pH levels of 3, 7, and 11, regulated by 0.5M sodium hydroxide (NaOH) and 0.5M sulfuric acid (H_2SO_4), follow the procedure by Abidin et al. (2013). The 3, 6, and 9 g/l coagulant concentrations are favorable for testing as the levels fall in the ranges that are commonly examined in similar water treatment experiments. The experimental operating conditions like rapid mixing at 130 rpm for 2 minutes and slow mixing at 30 rpm for 20 minutes are pursuant to the procedure outlined by Rossini, M., Garrido, J. G., & Galluzzo, M. (1999). Finally, settling times of 35, 45, and 55 minutes are in accordance with guidelines provided by Ahmad et al. (2021), so the selected levels are well-established by the literature.

Finally, the turbidity of the suspension after settling within the given settling time, the turbidity was measured with Turbidimeter. The turbidity of water (initial turbidity of surface water) was measured, and the turbidity removal efficiencies (% turbidity removal efficiencies) were calculated using the following formula:

$$\%\,Turbidity\ Removal = \frac{Raw\ Water\ Turbidity - Treated\ Water\ Turbidity}{Raw\ Water\ Turbidity} x100$$

Source: Hameed, E., & Abdullah, R. (2023).

Then the samples of supernatant taken 2 cm below the water surface from each beaker were tested for turbidity.

Table 3.1: The variables and their levels in coagulation process

Variables	Unit	Levels		
		Low(-1)	Middle(0)	High(+1)
Coagulant dose	g/l	3	6	9
pH	-	3	7	11
Settling time	min	35	45	55

The table illustrates the experimental variables, units, and levels corresponding to each of the variables. The experimental conditions to be changed are the levels of each variable, where a common low (-1), middle (0), and high (+1) scale is used. It is a usual setup for an experiment to investigate the impact of these variables on a particular result using different values to determine the effect of each factor at differing levels.

3.2.6. Optimizing Coagulation Experiments

The optimization of coagulation experiments using 500 mL of raw water an initial turbidity of surface water 445 NTU. The experiments were conducted at room temperature, at optimum pH, coagulant doses (g/l), and with optimum settling time (min). The pH of the test solution was adjusted to 3.61 using 0.5 M sulfuric acid and/or 0.5 M sodium hydroxide solutions. The raw water was mixed with 5.834 g/l of the produced ferrous sulfate coagulant. The jar test procedure involved rapid mixing at 130 rpm for 2 min, followed by slow mixing at 30 rpm for 20 min. The mixture was then allowed to settle for 48 minutes. After settling, the supernatant was sampled from 2 cm below the water surface by syringe, and the turbidity was measured using a Turbidimeter.

3.2.7. Comparison of Removal Efficiency of Produced Iron Sulphate with Conventional Coagulant (Alum and Ferric Chloride)

The primary goal of this experiment was to compare the turbidity removal efficiency of the produced iron(II) sulfate (ferrous sulfate) with that of conventional coagulants, namely alum, and ferric chloride, under controlled experimental conditions. The performance of each coagulant was evaluated based on its ability to remove suspended particles, organic matter, and other contaminants from water. The jar test experiments were conducted using the optimized operating parameters for ferrous sulfate (coagulant dose = 5.834 g/l, pH=3.61,and settling time of 48 minutes).The coagulation and flocculation process involved rapid mixing at 130 rpm for 2 min, followed by a low mixing of 30 rpm for 20 minutes. After the settling period, the turbidity of the decanted supernatant was measured for each coagulant to determine its removal efficiency.

3.2.8. Data Analysis

The experimental data were analyzed using Design-Expert 13.0.5.0 software. Analysis of variance (ANOVA) was used to determine statistical significance of the results, with a p-value of < 0.05. Because the ANOVA test does not reveal patterns (i.e., how the response variables are affected), it simply shows which response variables are significantly impacted by various factors.

3.2.9. Statistical Experimental Design

A set of statistical and mathematical methods known as the response surface methodology (RSM) was used to construct empirical models and optimize process systems with curvatures that represent the response surfaces. The purpose of this study is to assess the effects of the variables' interactions and to identify the set of variables that, when combined, would produce the best outcome. The Box-Behnken designs (BBD) always have three levels for each factor, are effective at estimating the first- and second-order coefficients, have fewer design points, are less expensive to run with the same number of factors, and never include runs in which all factors are set to their most extreme values. As a result, the BBD was assigned to the response surface design in accordance with Tech In Sight's (2019) methodology.

Among study parameters, statistical experimental design serves as a systematic method to identify the interaction effects. This approach facilitates the investigation and optimization of the most significant study parameter, while also establishing a mathematical relationship with predictive capabilities. With limited resources, time, money, and labor, it's also critical to gather as much information as possible. The BBD and the response surface method (RSM) experimental methods were used in the current work to remove turbidity from turbid water by using produced iron sulfate as a coagulant. The software for experimental design, called Design Expert 13.0.5.0, was utilized and there were three variables in this study: pH, settling time, and coagulant dosage with one response, called turbidity removal efficiency.

Table 3-2: Build Information

File Version	13.0.5.0		
Study Type	Response Surface	Subtype	Randomized
Design Type	Box-Behnken	Runs	17.00
Design Model	Quadratic	Blocks	No Blocks

Briefly, the table dictates the primary elements of the experimental setup, i.e., the nature of study, design technique, and experimental run number, all of which hint towards a systematic exploration of system behavior through a Box-Behnken design.

Table 3-3: Design Expert Experimental run planned

Std	Run	Factor 1	Factor 2	Factor 3	Experimental Response
		A:coagulant dose	B:PH	C:settling time	turbidity removal efficiency %
		g/l	-	Min	%
12	1	6	11	55	
13	2	6	7	45	
15	3	6	7	45	
14	4	6	7	45	
7	5	3	7	55	

16	6	6	7	45
5	7	3	7	35
6	8	9	7	35
11	9	6	3	55
17	10	6	7	45
2	11	9	3	45
1	12	3	3	45
8	13	9	7	55
10	14	6	11	35
9	15	6	3	35
3	16	3	11	45
4	17	9	11	45

The table 3.3 presents the experimental run information for the thesis, with three factors coagulant dose (Factor 1), pH (Factor 2), and settling time (Factor 3) of the following values across 17 experimental run. A set of distinct combinations of these factors in each row and the corresponding turbidity removal efficiency (%) as each run's experimental response are presented. The factors differ at different levels for each run, and the turbidity removal efficiency is recorded as the outcome.

4. RESULTS AND DISCUSSION

4.1.Characterization of the Raw Materials

4.1.1. Physical Characterization

First, the collected raw material was characterized by touching and observing visually. The physical properties of the raw material are summarized in Table 4.1

Table 4.1: Physical characterization of the raw materials

Properties	Physical character
Density	5.567g/cm3
Color	Dull to bright red

4.1.2. Chemical Characterization

The chemical composition of the collected samples was analyzed at the central laboratory of the Geological Survey of Ethiopia (GSE) in Mekanisa. The results of the chemical analysis are presented in Table 4.2, which provides detailed information on the compound composition of the raw material.

Table 4.2: The complete silicate analysis for the compositional content of the ores.

Compound	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI
Amount (%)	2.86	3.72	77.12	0.26	0.32	<0.01	<0.01	0.32	<0.01	15.3	0.28	<0.01

4.2. Characterization of iron sulphate (Physicochemical properties)

4.2.1. Determination of Moisture Content

Table 4.3: Moisture Content

Run	Weight of the sample before drying (g)	Weight of the sample after drying (g)	Weight Difference (g)	Moisture content (%w/w).
1	5	3.099	1.901	38.02
2	5	3.101	1.899	37.98
3	5	2.998	2.002	40.04
average	5±0.00	3.066±0.627	1.934±0.627	38.68±0.125

The moisture content of iron sulfate was measured and found to be between 38.555 and 38.805% (by weight). The maximum value is acceptable when compared to the ASTMA standard (38.84%), as the average of the measured data aligns closely with the theoretical value.

4.2.2. Specific Gravity

The density of the generated iron sulfate varied between 1.6 to 1.9 g/cm³ depending on process conditions. These values are considered satisfactory when compared to the ASTM standard for iron sulfate (1.6672 g/cm³).

4.2.3. pH Determination

The pH of iron sulphate was measured three times using a pH meter, and the results are summarized in Table 4.4. From the table below, the pH value of iron sulfate was slightly acidic. The preferable pH value is in the range of 4.94-5.12, and the obtained values falls within the acceptable ASTMA standard.

Table 4-4: pH determination

Run	**pH values**
1	4.96
2	4.89
3	4.98
Mean value	4.9433

4.2.4. X-Ray Diffraction Structure Analysis

X-ray crystallography is the tool for identification of the atomic and molecular structure of a crystal in which the crystalline atoms cause a beam of incident X-rays to diffract into different specific directions. The XRD analysis of $FeSO_4$ showed characteristic peaks corresponding to its crystal structure. The sample can exist in multiple forms, such as anhydrous ferrous sulfate ($FeSO_4$) and ferrous sulfate heptahydrate ($FeSO_4.7H_2O$), both of which crystallizes in a monoclinic structure. The observed the XRD pattern well matches the expected diffraction positions for ferrous sulfate heptahydrate, confirming the presence of hydrated form of the sample. The sharp and well-defined peaks indicate a high degree of crystallinity, with minimum amorphous scattering. This suggested that the material contains very few amorphous fractions or impurities. The presence of hydrated ferrous sulphate is further confirmed by characteristics diffraction peaks at 2θ = 19.1°, 25.1°, and 32.6°, which agree with previously reported data by Lee et al. (2004) and Zhang et al. (2009). Furthermore, the XRD results obtained in this work were consistent with the diffraction data reported by Birhan, G. (2017) for ferrous sulfate heptahydrate. In addition, no significant peaks corresponding to impurity phases, such as iron oxides or other sulfate salts were observed, indicating that the sample is relatively pure. Figure 4.1 shows the XRD analysis results of the iron sulfate sample.

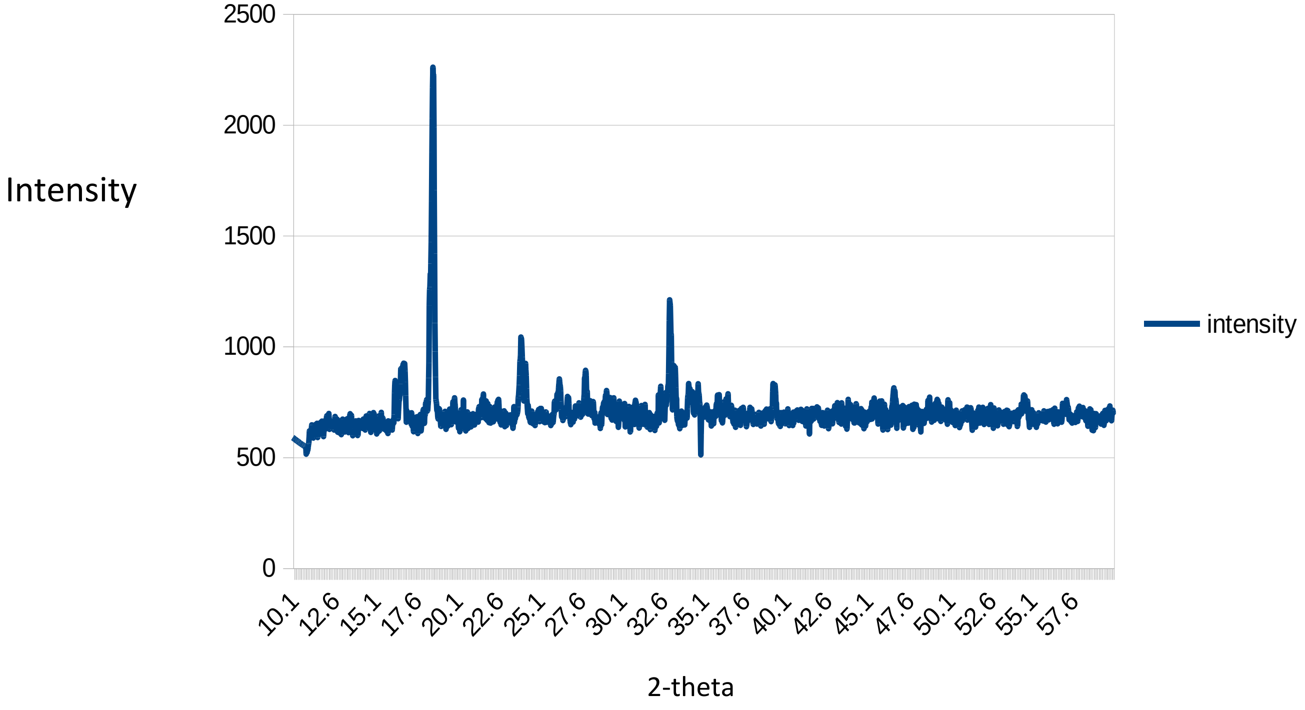


Figure 4.1: The XRD pattern of ferrous sulphate sample.

4.3. Experimental Analysis on Turbidity Removal by Jar Test

The experimental results were done through the sequential process involving three main factors: coagulant dose, pH, and settling time with the measured response. Table 4.5 shows both actual and expected responses. Following the above series of procedure, the experimental evaluation also included the measurement of turbidity removal efficiency for real surface water samples collected from the Legedadi water treatment plant. The results obtained from the experiment are summarized in table 4.5 below.

Table 4.5: The actual and the predicted synthetic turbidity removal efficiency of BBD design.

Std	Run	Factor 1	Factor 2	Factor 3	Experimental Response	Predicted Response
		A:coagulant dose	B:PH	C:settling time	turbidity removal efficiency %	turbidity removal efficiency %
12	1	6	11	55	85.66	84.11
13	2	6	7	45	90.4	89.69
15	3	6	7	45	87.2	89.69
14	4	6	7	45	90.68	89.69
7	5	3	7	55	47.8	47.38
16	6	6	7	45	91.23	89.69
5	7	3	7	35	51.76	51.94

6	8	9	7	35	77.14	77.56
11	9	6	3	55	98.8	100.95
17	10	6	7	45	88.92	89.69
2	11	9	3	45	95.7	93.73
1	12	3	3	45	70.8	69.07
8	13	9	7	55	83.25	83.07
10	14	6	11	35	86.88	84.73
9	15	6	3	35	97.84	99.39
3	16	3	11	45	45.34	47.31
4	17	9	11	45	82.25	83.98

This section discusses the overall impact of the three working parameters-coagulant dose, pH, and settling time on turbidity removal efficiency, as presented in Table 4.4. The table summarizes the experimental results of turbidity removal from actual water samples treated with various doses of iron sulfate (ferrous sulfate) coagulant, ranging from 3 g/l to 9 g/l. Turbidity removal efficiency rises from 70.8% to 98.8% at a constant pH of 3 as ferrous sulfate dosage increases from 3 g/l to 6 g/l. however, as the dose rises further to 9 g/l at the same pH, the turbidity removal efficiency begins to decline from 98.8% to 95.7%.This decline is due to the saturation of Fe^{2+} ions, which neutralizes the negative charges on suspended particles, enabling them to settle and coagulate. The removal efficiency reaches its maximum as the dosage rises. Beyond the optimum dosage, increasing the dose further leads to decreasing results. Various studies demonstrate that increasing coagulant dosages was not economically feasible and did not considerably improve contaminants removal.

According to Table 4.5, the lowest turbidity removal efficiency of 45.34% was observed at pH=11, the maximum turbidity removal efficiency ranged from 95.7% to 98.8% at pH=3, and the medium turbidity removal efficiency ranged from 70% to 90% at pH=7. This demonstrates that ferrous sulfate is more effective at lower pH values, which well aligns with previously reported literature. Similar studies, such as Irfan et al., 2017, demonstrated that optimal turbidity reduction at pH values below 4 when using ferrous sulfate.

The effect of settling time on turbidity removal efficiency was also examined as shown in Table 4.5. The experimental work was done between pH 3 and 11, and the turbidity removal efficiency at a constant dose of 9 g/l and pH of 7 with different settling times of 35 to 55 was 77.14% to 83.25%, respectively. The turbidity removal efficiency at constant dose = 6 g/l and pH = 3 with different settling times of 35 to 55 was 97.84% to 98.8%, respectively. These results show that settling time has a slight effect on turbidity removal. Thus, it's necessary to give the coagulant adequate time to settle in order to ensure that it reduces turbidity. Increasing the coagulant content, on the other hand, improved turbidity removal and reduced the required settling time until it reached an ideal position where it had no effect at all.

The resulting data obtained from the table above were analyzed using Design Expert 13.0.5.0 software to decide the effects of operating parameters: coagulant dose, pH, and settling time. The dependent variable used as a response parameter was the percentage of removal. All experiments were carried out in a randomized order to minimize the effect of unexpected variability in the observed response due to extraneous factors. Response surface methodology (RSM) of Box-Behnken Design (BBD) Design Expert 13.0.5.0 software is used to create the design model for the tests.

4.4.Statistical Analysis of the Experimental Result

In this section experimental results are discussed briefly based on the date obtained in RSM of BBD.

4.4.1. Analysis Variance (ANOVA) for Turbidity Removal

Table 4-6: ANOVA response table for turbidity removal

Source	Sum of Squares	df	Mean Square	F-value	p-value	
Model	4574.51	9	508.28	91.44	< 0.0001	significant
A-coagulant dose	1880.07	1	1880.07	338.21	< 0.0001	
B-PH	496.28	1	496.28	89.28	< 0.0001	
C-Settling time	0.4465	1	0.4465	0.0803	0.7851	
AB	36.06	1	36.06	6.49	0.0383	
AC	25.35	1	25.35	4.56	0.0701	
BC	1.19	1	1.19	0.2137	0.6579	
A^2	1989.19	1	1989.19	357.84	< 0.0001	
B^2	130.72	1	130.72	23.52	0.0019	
C^2	36.97	1	36.97	6.65	0.0365	
Residual	38.91	7	5.56			
Lack of Fit	28.26	3	9.42	3.54	0.1269	not significant
Pure Error	10.65	4	2.66			
Cor Total	4613.42	16				

Factor coding is coded.

Sum of squares is Type III - Partial

The Model F-value of 91.44 indicates that the model is significant. There is only a 0.01% probability that such a large F-value could occur due to noise. The P-values less than 0.0500 indicate that the corresponding model terms are statistically significant. In this case, the significant model terms are A, B, AB, A^2, B^2 and C^2. P-Values greater than 0.1000 indicate that the model terms are not significant. If a model contains many insignificant terms (not counting those required to support hierarchy), model reduction may improve its predictive accuracy. The Lack of Fit F-value of 3.54 implies that the lack of fit is not significant relative to the pure error. There is a 12.69% probability that a Lack of Fit F-value this large could occur due to noise. Non-significant lack of fit is good. So, the model is necessary to fit.

To determine whether the model is suitable for making predictions, the following statistical metrics are considered: Coefficient of Variation (CV%): The standard deviation expressed as a percentage of the mean; Predicted Residual Error, Sum of Squares: which is a measure of how the model fits each point in the design; the R-Squared: The measure of the amount of variation around the mean explained by the model; Adjusted R-Squared: Is a measure of the amount of variation around the mean explained by the model, Predicted R-Squared: A measure of the amount of variation in new data explained by the model, and Adequate Precision: Is a signal to disturbance ratio due to random error, presented in the table below, are used to decide whether the model can be used or not.

Fit Statistics

Table 4-7**:** Model adequacy measures for turbidity removal

Std. Dev.	2.36	R^2	0.9916
Mean	80.69	Adjusted R^2	0.9807
C.V. %	2.92	Predicted R^2	0.8984
		Adeq Precision	29.6628

The Predicted R^2 of 0.8984 is in reasonable agreement with the Adjusted R^2 of 0.9807; i.e. the difference is less than 0.2.Adeq Precision measures the signal to noise ratio. A ratio greater than 4 is desirable. The ratio of 29.663 indicates an adequate signal. This model can be used to navigate the design space.

Table 4.8: Coefficients in Terms of Coded Factors

Factor	Coefficient Estimate	df	Standard Error	95% CI Low	95% CI High	VIF
Intercept	89.69	1	1.05	87.19	92.18	
A-coagulant dose	15.33	1	0.8336	13.36	17.30	1.0000
B-PH	-7.88	1	0.8336	-9.85	-5.91	1.0000
C-Settling time	0.2362	1	0.8336	-1.73	2.21	1.0000
AB	3.00	1	1.18	0.2149	5.79	1.0000
AC	2.52	1	1.18	-0.2701	5.31	1.0000
BC	-0.5450	1	1.18	-3.33	2.24	1.0000
A^2	-21.74	1	1.15	-24.45	-19.02	1.01
B^2	5.57	1	1.15	2.86	8.29	1.01

C^2	-2.96	1	1.15	-5.68	-0.2460	1.01

The coefficient estimate represents the expected change in response per unit change in factor value when all remaining factors are held constant. The intercept in an orthogonal design represents the overall average response of all experimental runs. The coefficients adjustment this average based on the factor settings. When the factors are orthogonal the VIFs are 1; VIFs greater than 1 indicate multicollinearity, the higher the VIF the more severe the correlation of factors. As a rough rule, VIFs less than 10 are tolerable. The results of response (Turbidity removal efficiency) was correlated with three factors (coagulant dosage, effluent pH and settling time) using the second order polynomial. From the experimental data in Table 4-5, the following quadratic models were obtained for produced ferrous sulphate turbidity removal efficiency. The response variables represented as Y (Turbidity removal efficiency), were obtained through experiment using BBD. Upon statistical analysis using the experimentally generated response on BBD implementing RSM, the following equations was derived as depicted in equations 4.1 and 4.2. Final Equation in Terms of Coded Factors is:

Turbidityremoval=+89.69+15.33*A-7.88*B-0.2362*C+3.00*AB+2.52*AC-0.5450*BC-21.74*A^2+5.57 *B^2-2.96*C^2…………………………………………………..… (Equation 4.1)

The equation in terms of coded factors can be used to make predictions about the response for given levels of each factor. By default, the high levels of the factors are coded as +1 and the low levels are coded as -1. The coded equation is useful for identifying the relative impact of the factors by comparing the factor coefficients. Final equation in terms of actual factors is:

Turbidity removal efficiency = - 29.25781+28.56296 coagulant dose-7.73269 PH+2.28220 Settling time+0.250208 coagulant dose * PH+0.083917 coagulant dose * Settling time-0.013625 PH * Settling time-2.41506 coagulant dose^2+0.348250 PH^2-0.029630 Settling time^2……………………………………………………………………..…. (Equation 4.2)

The equation in terms of actual factors can be used to make predicting the response for given levels of each factor. Here, the levels should be specified in the original units for each factor. This equation should not be used to determine the relative impact of each factor because the coefficients are scaled to accommodate the units of each factor, and the intercept is not at the center of the design space.

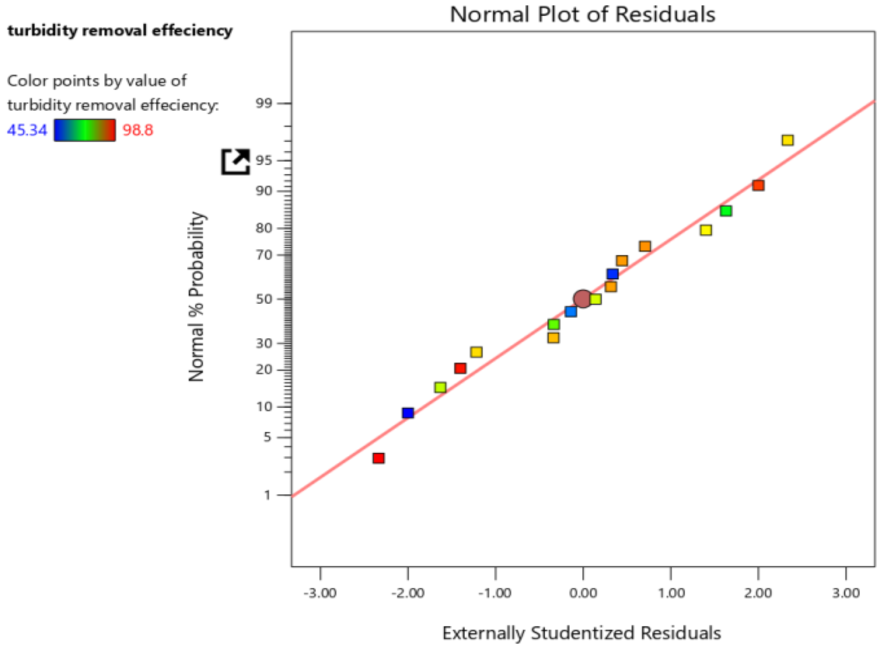


Figure 4-2: Normalized plots of residuals for Turbidity removal

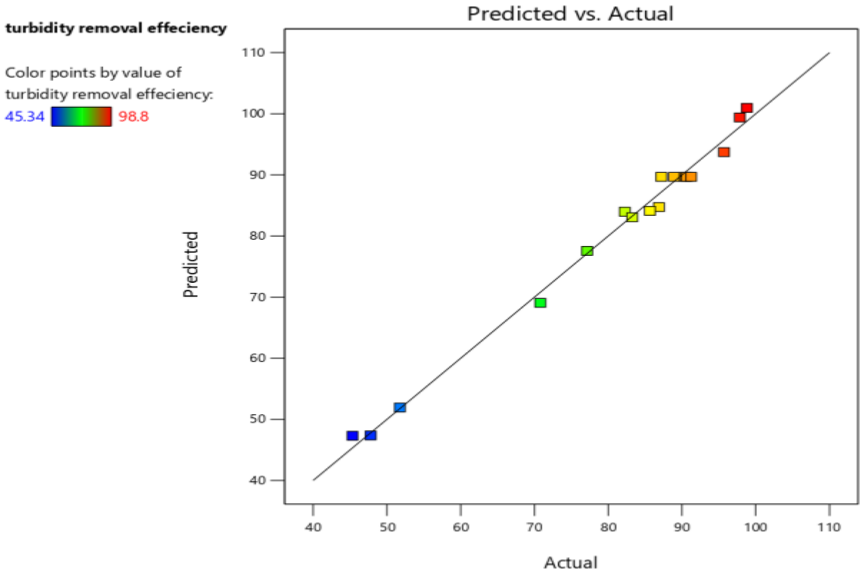


Figure 4-3: Predicted vs. actual plot for turbidity removal

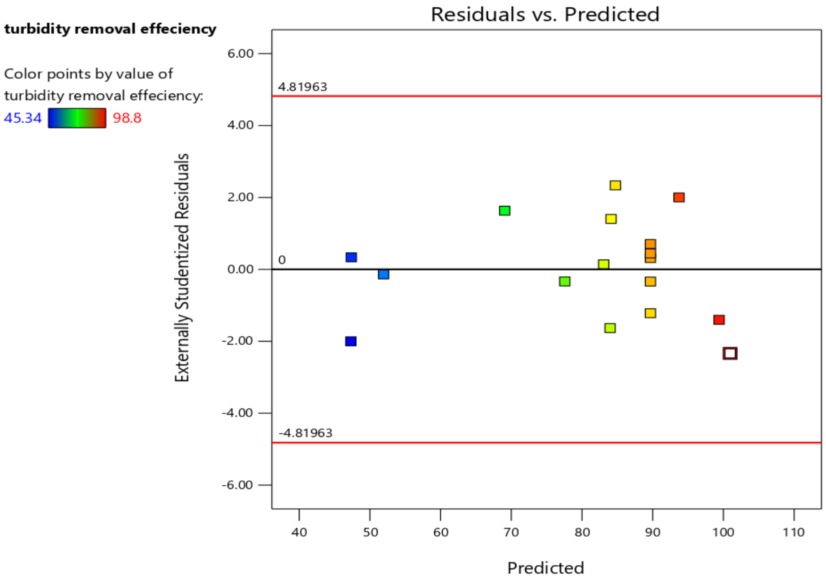


Figure 4-4: Residual vs. predicted plot for turbidity removal

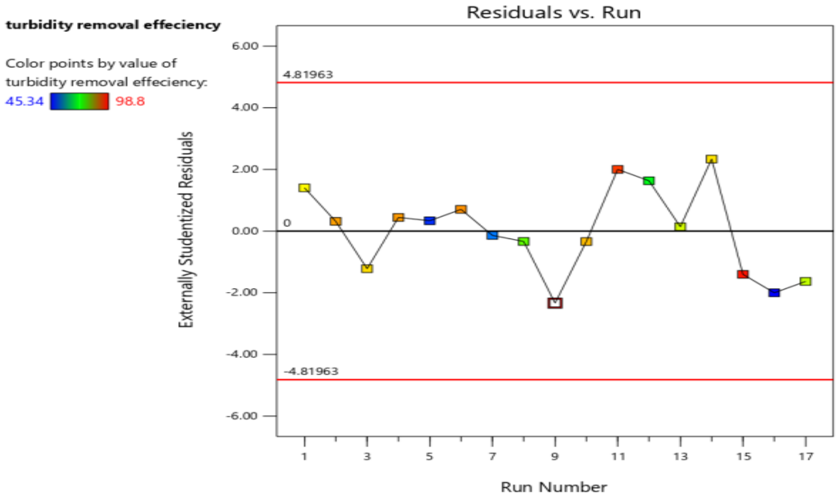


Figure 4-5: Residual vs. run plot for turbidity removal

4.5.Effect of Operating Parameters and Their Respective Interactions Using Ferrous Sulphate

4.5.1. Effect of Dose of Ferrous Sulphate on Turbidity

Figure 4.6 Turbidity removals as a function of coagulant dose illustrates that the appropriate dosage is the most important factor in optimal coagulation and flocculation performance. It is in line with results of other studies demonstrating how too small and excessively large doses of coagulant may result in poor performance, besides the fact that the dose will affect the efficiency of the coagulation-flocculation process. Both insufficient and excessive coagulant dosages have been shown to result in poor treatment performance. Many literatures also prove this observation; when the dose is out of the optimum range, the efficiency decreases. In the treatment of water with ferrous sulfate, for example, Aksu and Kabasakal (2018) observed that maximum turbidity removal occurred at the optimum dose of the coagulant; efficiencies were lower in both lower and higher dosages. Overdosing may cause re-dispersion of flocs, hence reducing the efficiency of the settling process. According to Khaled et al. (2020) excess doses of coagulant hinder the aggregation and sedimentation of particles.

This is evident in the work, as the turbidity removal efficiency increases steadily up to a coagulant dose of 6g, which agrees with the optimum dose range identified by Ahmad et al. (2021), where a similar coagulant dose of 6g yielded the highest turbidity removal in surface water. Beyond this dosage, the efficiency of removal started to decrease, which agreed with the information given by Sarioglu and Kocak (2018), whereby it was said that at higher doses of coagulant, already destabilized particles start re-agglomeration and re-dispersion, leading to poor settling and thus poor turbidity removal.

This study had the highest turbidity removal of 89.68% with a dose of 6g, which is in agreement with Rossini et al. (1999) that optimization of coagulant dosage is important to minimize excess sludge production and chemical cost for efficient removal of turbidity. These studies collectively indicate determination of optimal dose of coagulant is fundamental to cost efficiency, minimal sludge production, and effective treatment of water. These findings on the optimal dose of ferrous sulfate, 6g, for maximum turbidity removal and the decline in performance at both lower and higher doses are in agreement with a wide body of research on coagulation-flocculation processes. The optimum coagulant dose is vital for maximum turbidity removal, minimum sludge formation, and cost reduction of operation, as widely reported in the literature.

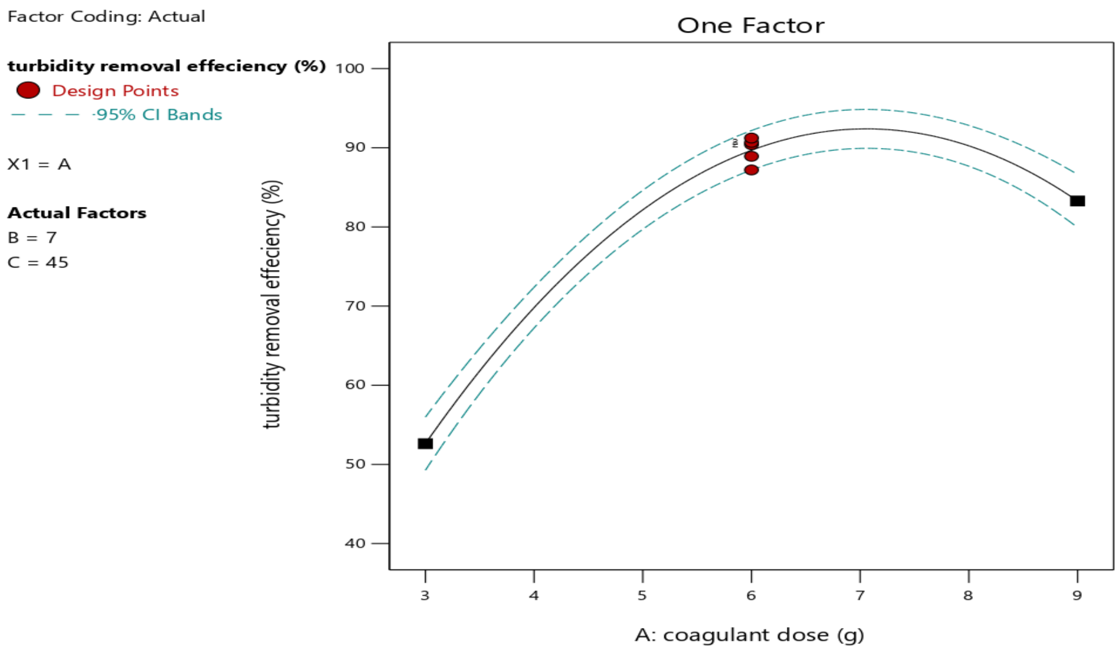


Figure 4-6: The effect of coagulant dose on percentage of turbidity removal

4.5.2. Effect of pH on Percentage Removal of Turbidity

According to this study, the influence of pH on turbidity removal using ferrous sulfate as a coagulant is considered important in coagulation efficiency. It was also observed from the study that the maximum turbidity removal occurred at acid pH value close to pH 3, while the minimum turbidity removal was observed to occur at pH 7. The result thus agreed with a general observation where coagulants like ferrous sulfate would normally perform in an acidic environment, as has also been variously reported.

For instance, Khan et al. (2020) found that the removal efficiency of ferrous sulfate for turbidity elimination was significantly higher at lower pH values. Indeed, their findings showed that within a wide pH range from 3 to 5, the charge density of ferrous sulfate was more appropriate for effective colloidal particle destabilization, thus allowing high removal efficiencies. Mojiri et al. (2019) also reported similar results, where the coagulation process with ferrous sulfate had the best performance at acidic pH, while its efficiency significantly decreased at neutral and alkaline pH values.

On the other hand, Ahmad et al. (2021) found that the pH had a significant effect on coagulation, where the removal efficiency was decreased at pH 7 or above. That agrees with what was observed in this study, where the neutral pH of 7 produced the lowest turbidity removal efficiency. The pH would affect turbidity removal because of changes in the coagulant's chemical behavior. Under an acidic environment, ferrous sulfate undergoes hydrolysis more effectively into iron-based flocs, which acts to efficiently aggregate the suspended particles. Moving up the pH scale from acid towards neutral and basic, the effectiveness of the coagulant in floc formation is reduced, hence the removals.

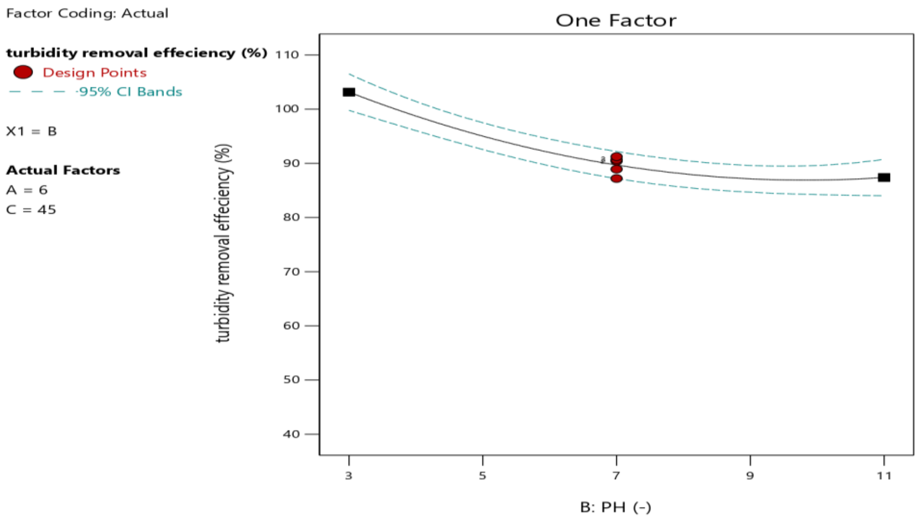


Figure 4-7: The effect of pH on percentage of turbidity removal

4.5.3. Effect of Settling Time on Percentage Removal of Turbidity

In general, with a longer settling time, more flocs will be allowed to settle; therefore, the better the reduction in turbidity. Indeed, this effect is not significant beyond a certain value, as confirmed by a p-value greater than 0.05. In all, studies, such as by Ahmad et al. (2021) and Ogunbiyi and Oladipo (2019), indicate that the turbidity removal increases with the increase in settling time up to a certain point, usually within 30-45 minutes, after which its benefits diminish. Sarioglu and Kocak (2018) reported that the optimum turbidity removal efficiency can be achieved within 45 minutes of settling time, beyond which further settling provides little additional benefit. This underlines the concept of diminishing returns whereby a balance must be struck between efficient particle removal and operational efficiency.

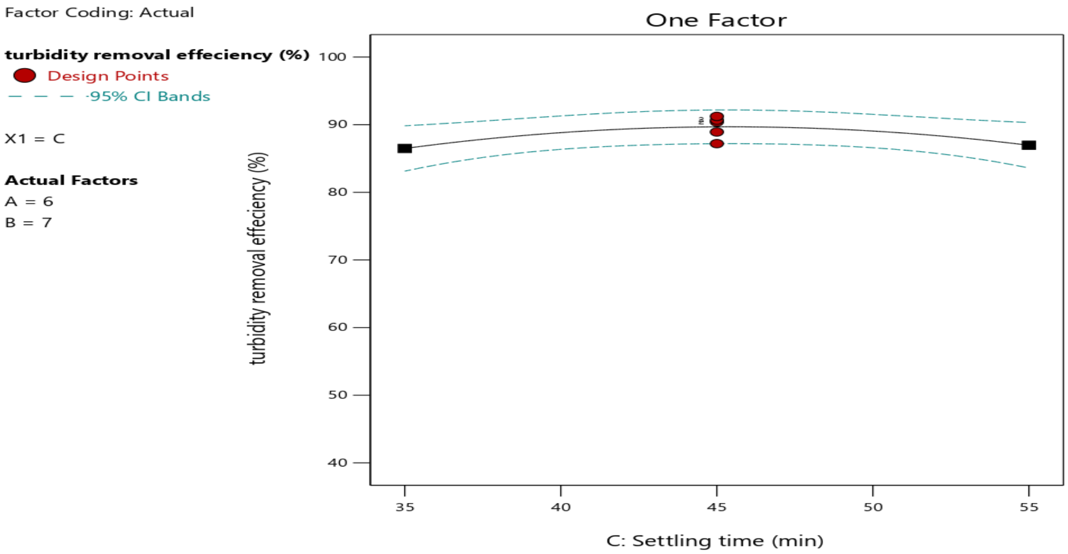


Figure 4-8: The effect of settling time on percentage of turbidity removal

4.5.4. Effect of Coagulant Dose and pH on Percentage of Turbidity Removal

The possible interactions that can affect the percentage removal of turbidity were pH and coagulant dose. Figure 4.7 and Table 4.6 from analysis of variance; demonstrate the significant interaction effects that exist between the processing variables. As observed from the Figure and Table, the only significant interaction that affects percentage removal of turbidity is between pH and coagulant dose. Accordingly the interaction between pH and coagulant dose, have increased the percentage removal of the turbidity.

The result, show that the interaction between pH and coagulant dose significantly influences turbidity removal, is in good agreement with the general trend observed in water treatment studies, where both parameters act synergistically to optimize coagulation and flocculation processes. Aksu and Kabasakal (2018) found that there was a significant interaction between pH and dosage of coagulant in water treatment with ferrous sulfate. They observed that at lower pH values of 3-5, higher dosages of coagulant were effective in destabilizing the colloidal particles and ensured better removal of turbidity.

Khan et al. (2020) also reported that both pH and coagulant dose were significant factors affecting turbidity removal. Their study reported that a low pH, around 3 to 5, with an optimum dose of coagulant, around 6g/L, resulted in maximum turbidity removal. They also identified that pH and coagulant dose are interacting in such a way that any rise or fall influences the performance of other parameters; rather, the optimal balance exists that gives high flocculation and settling efficiencies. These two factors, that the interaction between pH and coagulant dose significantly influences turbidity removal, are supported by the general literature on coagulation processes. In such cases, the studies reviewed indicate that pH and coagulant dose need to be optimized together for maximum turbidity removal efficiency.Therefore, the understanding and modulation of these factors in performance may provide more effective and cost-efficient solutions for water treatment.

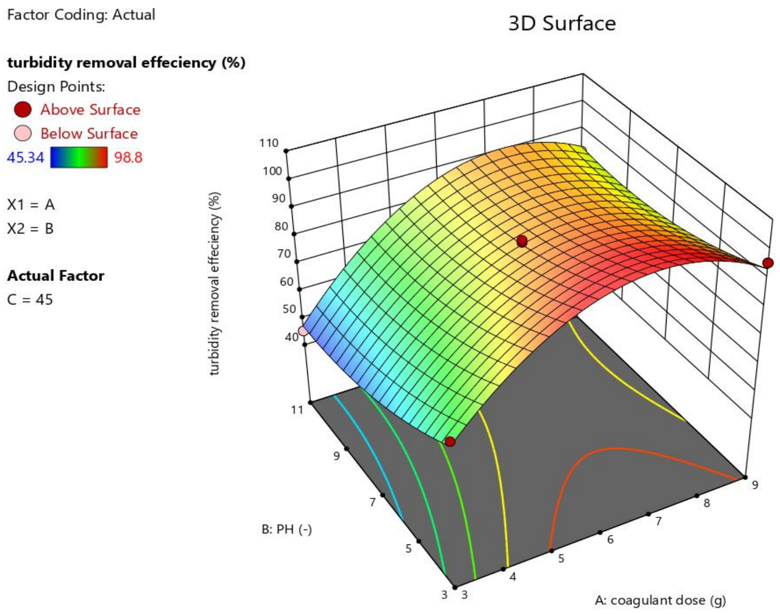


Figure 4-9: 3D plot of the interaction of dose and pH on turbidity removal

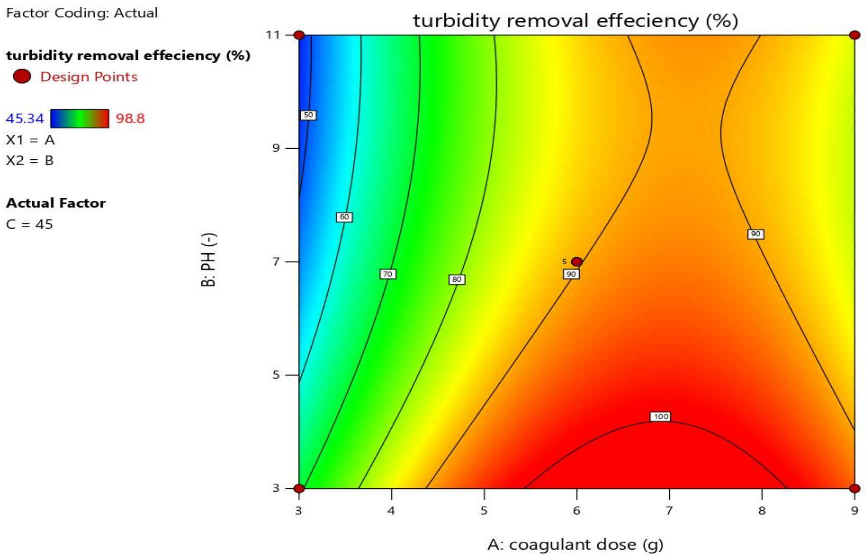


Figure 4-10: Contour plot of the interaction effect of dose and pH on turbidity removal.

4.6.Optimization of Operating Parameters for Produced Ferrous Sulphate

In order to define the optimum conditions for coagulation, numerical optimization of the experimental parameters was carried out through the Design expert software (Design expert 13.0.5.0). Process optimization is the discipline for adjusting a process so as to optimize some specified set of parameters without violating other constraints. The most common goals are minimizing the cost and maximizing the output and/or efficiency. Depending on the parameters, by compromising the percentage removal, economy and energy carrying, the best solution was selected and summarized below:

Table 4.9: Goal of the optimization and its range

Name	Goal (purpose)	units	Lower Limit	Upper Limit

A:coagulant dose	is in range	g/l	3	9
B:PH	is in range	-	3	11
C:Settling time	is in range	Min	35	55
turbidity removal efficiency	maximize	%	45.34	98.8

Solution

Table 4.10: Optimum points with its desirability for the combined responses

Number	coagulant dose	PH	Settling time	turbidity removal efficiency	Desirability	
1	5.834	3.617	48.310	99.417	1.000	Selected

The highest turbidity removal obtained in this optimization process is 99.417% at a coagulant dose of 5.834gram, pH of surface turbid water= 3.617 and settling time of 48 min. The validity of the results predicted by the regression model was confirmed by carrying out experiments using these optimal conditions. The validity of the results predicted by the regression model was confirmed by carrying out experiments using these optimal conditions.

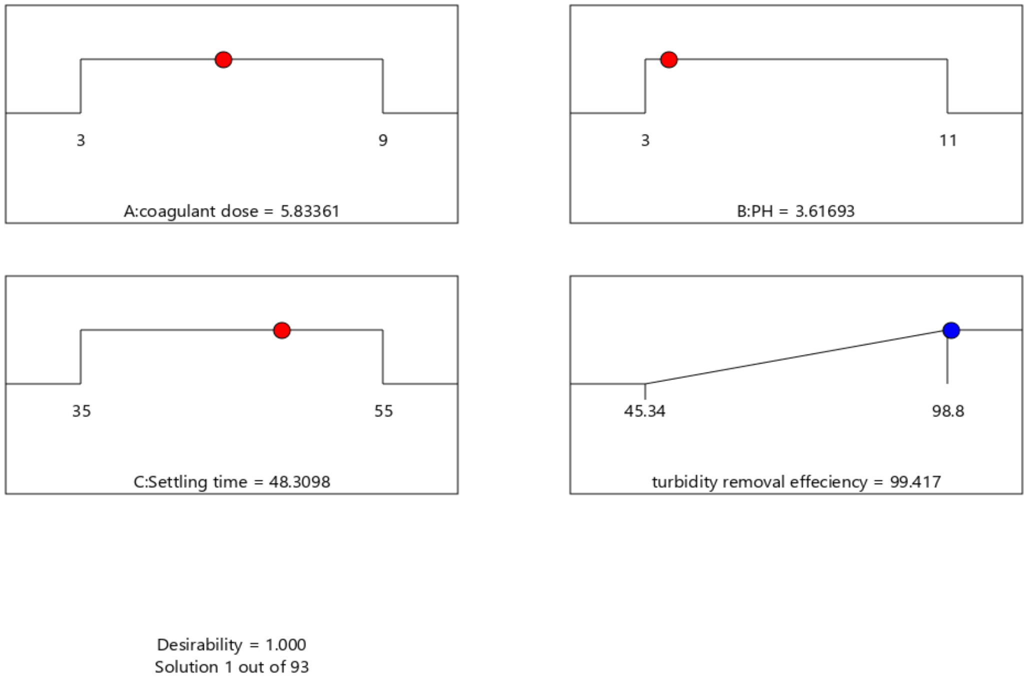


Figure 4-11: Numerical Optimization desirability of 1.000

The practical optimum turbidity removal efficiency of dry season and optimum parameters are shown in Table 4-11. The turbid water efficiencies in dry season were 445NTU. The turbidity removal efficiency in dry season of real surface turbid water was 99%.

Table 4-11: Optimum parameters (Dose, pH, and settling time) and Optimum Experimental turbidity removal efficiency.

Sample	Dose	pH	Settling time	Initial turbidity dry season	Final turbidity	Turbidity removal efficiency
Real turbid surface water	5.834	3.617	48.310	445	4.30	99%

(a) (b)

Figure 4-12: Photographic images of (a) before and (b) after treatment at the optimum operating parameters.

4.7.Comparison of Produced Ferrous Sulphate with Conventional Coagulant Alum and Ferric Chloride

A comparison of ferrous sulfate ($FeSO_4$) with conventional coagulants such as alum and $FeCl_3$ in water treatment focuses on several key factors although; the choice between these coagulants depends on water quality, treatment goals, and cost considerations. Table 4-12 shows the experimental results done using the jar test experiment for turbidity removal using three coagulants at the dose =5.834g/l, PH= 3.61, settling time =48min with rapid mixing 130rpm for 2min, and slow mixing 30rpm for 20min.

Table 4-12: Experimental turbidity removal efficiency of ferrous sulphate, ferric chloride and alum Optimum Dose, pH, and settling time

Type of coagulant	Initial turbidity of sample surface water	Final turbidity of sample surface water	Removal efficiency (%)	Final pH of decanted water

ferrous sulphate (FeSO$_4$)	445 NTU	4.3 NTU	99.03	4.12
ferric chloride (FeCl$_3$)	445 NTU	3.39 NTU	99.24	3.31
alum	445 NTU	1.75 NTU	99.61	3.84

To compare and suggest the best coagulant for turbidity removal based on the results provided, ferric chloride demonstrates excellent turbidity removal, achieving almost 99.24%. This suggests that ferric chloride effectively neutralizes and aggregates the particles in the water, allowing them to settle out. Ferrous sulfate also exhibits a significant turbidity removal (around 99.03%), although slightly less efficient than ferric chloride (by about 0.2%). This could be due to the differences in floc formation and settling rates between the two coagulants. Alum shows the highest turbidity removal efficiency (99.61%). This suggests that alum may form larger, denser flocs, which settle faster, leading to better turbidity reduction in this specific water sample. Previously reported study suggests that ferrous sulphate is effective in certain types of waters particularly those with moderate turbidity (khan et al., 2012).

The pH of water treated with ferric chloride drops significantly (from approximately neutral to 3.31), which is highly acidic. This is because ferric chloride dissociates in water to produce ferric ions and hydrochloric acid, lowering the pH of the solution. The low pH can potentially affect the stability of the floc and could also require neutralization before the water is safe for consumption. The pH of water treated with ferrous sulfate remains more neutral (4.12). The slight acidity can still have an impact but is less extreme compared to ferric chloride. However, the pH would still need to be adjusted before consumption. The pH of water treated with alum is 3.84, which is still acidic but closer to neutral than ferric chloride. The acidity of alum can affect aquatic life if the treated water is not further treated to neutralize the pH. Generally, ferrous sulphate requires less pH adjustment compared to ferric chloride and alum, but excessive dosage may still lower the pH.

Because the ferrous sulphate used in this study is produced from locally available material (from iron ore) it is less expensive than ferric chloride and alum. In addition, ferrous sulfate is generally less toxic and less hazardous to handle compared to ferric and alum-based coagulants but still requires care due to its acidic nature. Ferric chloride is corrosive and can lead to iron accumulation in water, causing discoloration and other aesthetic issues. Alum generates large volumes of aluminum hydroxide sludge, which may pose disposal challenges. However, ferrous sulphate and alum are less toxic to aquatic life than ferric chloride (sengupta et al., 2018).

When ferrous sulfate is used to treat water, the treated water shows no color changes. Water that has been treated stays colorless or slightly yellow, because the light-colored flocs formed by the ferrous ions (Fe^{2+}) settle out quite effectively, they are visually attractive and less likely to cause color-related issues. Because ferric chloride hydrolyzes in water to generate ferric hydroxide, it is known to give treated water a golden yellow color. Such color shifts are undesirable in treated water, particularly for drinking water, as the yellow color may not be aesthetically pleasing to users. However, its effectiveness in eliminating turbidity is unaffected by this. Similar to ferric chloride, alum at large dosages can make water appear a little cloudy or milky after treatment. In general, alum does not give the water a strong color; instead, it creates large, white flocs that settle easily. Its color shift is typically less noticeable than that of ferric chloride.

Table 4-13: color change observed when using Ferrous Sulfate, Ferric Chloride and Alum as coagulant

Coagulant	Water color observed after treatment
Ferrous Sulfate	Minimal color change (clear to light yellow).
Ferric Chloride	Golden-yellow color in treated water due to ferric hydroxide
Alum	no significant color change

Figure 4-13: The observed color observed before settlement and immediately after coagulation flocculation using (a) Alum, (b) Ferric chloride and (c) ferrous sulfate.

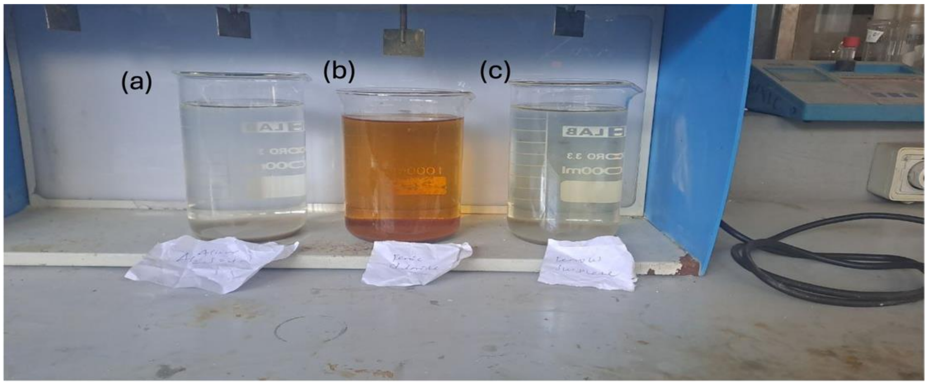


Figure 4-14: The observed color change of the treated water after treatment using (a) alum, (b) ferric chloride and (c) ferrous sulfate.

5. CONCLUSION AND RECOMMENDATION

5.1.Conclusion

The Physico-chemical characterization of the raw material and produced iron sulfate provides crucial information on their properties and proper use. The paper reveals that the efficiency of ferrous sulphate in removing turbidity is significantly influenced by coagulant dose, pH, and settling time. The optimal dosage is 6g, with the highest removal occurring under acidic conditions. Settling time improves turbidity removal up to 45 minutes.

This study further optimized these parameters using the Design Expert software and arrived at optimum conditions of 5.834 g dose of coagulant, pH 3.617, and 48 min of settling time that gave turbidity removal as high as 99.417%. This optimization was proved experimentally and reduced the turbidity to 4.3 NTU from an initial of 445 NTU in real surface water.

It was found that, compared to traditional coagulants like ferric chloride and alum, ferrous sulfate achieved a turbidity removal efficiency of 99.03%, only slightly different from ferric chloride and alum, at 99.24% and 99.61%, respectively. Ferrous sulfate produced treated water with a relatively neutral pH of 4.12 compared to the highly acidic pH of ferric chloride and alum, thereby reducing further neutralization.

Ferrous sulfate is also significantly cheaper and less harmful to the environment, as it is a product of easily accessible iron ore. It also tends to produce less discoloration in the treated water than other reagents such as ferric chloride, which imparts a golden-yellow color. By comparison, alum has somewhat higher efficiency but produces greater volumes of sludge.

Overall, ferrous sulfate presents a nontoxic, inexpensive, and effective alternative to conventional coagulants, with similar turbidity removal performance, which is a promising solution in water treatment.

5.2.Recommendation

Iron sulfate can be derived from both iron metal and iron ore; however, iron metal is very expensive and mostly imported. In contrast, various mineral exploratory studies undertaken in Ethiopia led to the discovery of rich deposits of iron ores where detail surveys reported iron rocks in different iron oxide forms. Thus, it will be both logical and reasonable to get locally sourced iron ore for the production of iron sulfate.

Based on the positive findings of this study, ferrous sulfate is thus strongly recommended as an efficient coagulant for use among conventional coagulants such as ferric chloride and alum in practical water treatment applications. Its application is especially suggested for regions interested in cost-effectiveness with minimum environmental impact.

Besides this, further studies should be conducted in relation to the economic viability of ferrous sulfate on the basis of both long-term cost-effectiveness and its environmental impact. The research would therefore complement its sustainability as a coagulant for water treatment.

Since ferrous sulfate is locally available, inexpensive, and has minor color variation with less pH alteration, it should be a better alternative coagulant particularly for drinking water treatment systems where aesthetic and environmental implication issues are highly critical.

Further studies on performance of produced ferrous sulphate on industrial and municipal waste water should be done.

In the long term, future research needs to establish efficiency and sustainability to make the ferrous sulfate viable for continued use as an effective coagulant compared to other alternatives.

This study will be more attractive to researchers and decision-makers since it provides a clear path into the future.

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7. APPENDIX

Appendix A: Laboratory Result Figure and Tables

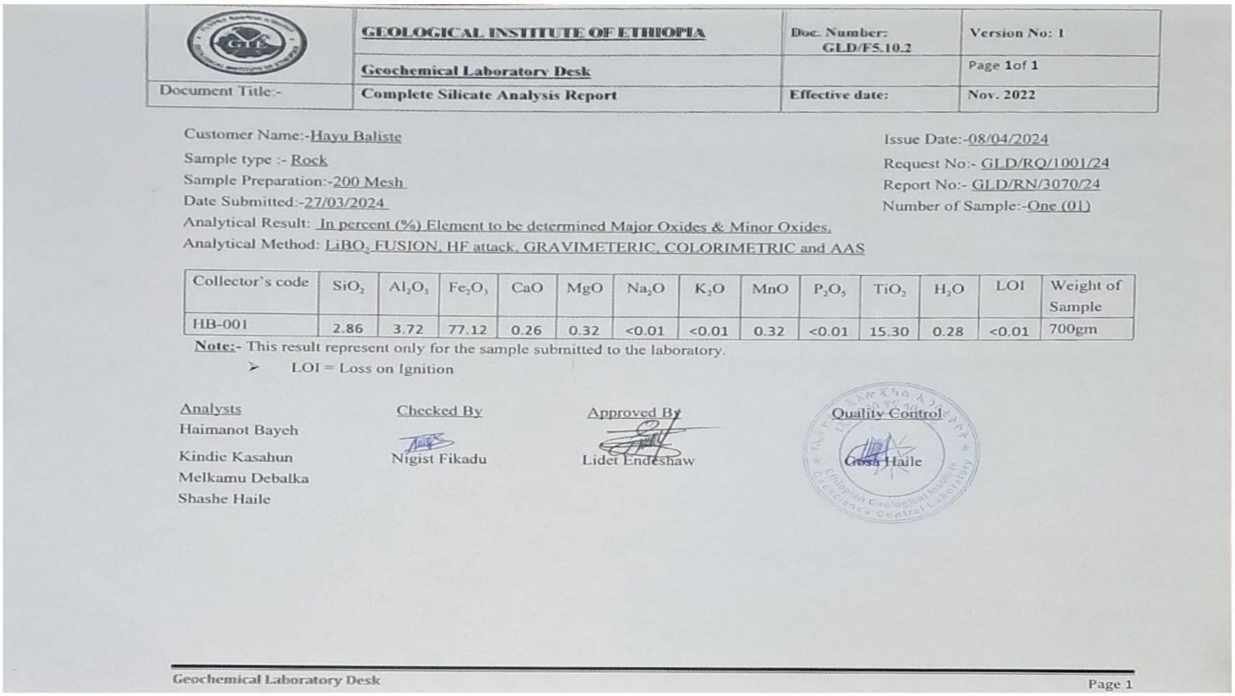
Table A1: Report of Actual and Predicted Results

Run Order	Actual Value	Predicted Value	Residual	Leverage	Internally Studentized Residuals	Externally Studentized Residuals	Cook's Distance	Influence on Fitted Value DFFITS	Standard Order
1	85.66	84.11	1.55	0.750	1.315	1.403	0.519	2.430(1)	12
2	90.40	89.69	0.7140	0.200	0.339	0.316	0.003	0.158	13
3	87.20	89.69	-2.49	0.200	-1.179	-1.219	0.035	-0.610	15
4	90.68	89.69	0.9940	0.200	0.471	0.443	0.006	0.222	14
5	47.80	47.38	0.4238	0.750	0.359	0.336	0.039	0.582	7
6	91.23	89.69	1.54	0.200	0.732	0.705	0.013	0.353	16
7	51.76	51.94	-0.1787	0.750	-0.152	-0.141	0.007	-0.244	5
8	77.14	77.56	-0.4237	0.750	-0.359	-0.336	0.039	-0.582	6
9	98.80	100.95	-2.15	0.750	-1.826	-2.336	1.000(1)	-4.046(1)	11
10	88.92	89.69	-0.7660	0.200	-0.363	-0.340	0.003	-0.170	17
11	95.70	93.73	1.97	0.750	1.674	2.002	0.841	3.467(1)	2
12	70.80	69.07	1.73	0.750	1.466	1.631	0.645	2.825(1)	1
13	83.25	83.07	0.1788	0.750	0.152	0.141	0.007	0.244	8

14	86.88	84.73	2.15	0.750	1.826	2.336	1.000(1)	4.046(1)	10
15	97.84	99.39	-1.55	0.750	-1.315	-1.403	0.519	-2.430(1)	9
16	45.34	47.31	-1.97	0.750	-1.674	-2.002	0.841	-3.467(1)	3
17	82.25	83.98	-1.73	0.750	-1.466	-1.631	0.645	-2.825(1)	4

1. (1) Exceeds limits.

Table A2: Complete silicate Analysis Report



	GEOLOGICAL INSTITUTE OF ETHIOPIA	**Doc. Number:** GLD/F5.10.2	**Version No: 1**
	Geochemical Laboratory Desk		Page 1of 1
Document Title:-	**Complete Silicate Analysis Report**	**Effective date:**	**Nov. 2022**

Customer Name:-Hayu Baliste
Sample type :- Rock
Sample Preparation:-200 Mesh
Date Submitted:-27/03/2024
Analytical Result: In percent (%) Element to be determined Major Oxides & Minor Oxides.
Analytical Method: $LiBO_2$ FUSION, HF attack, GRAVIMETERIC, COLORIMETRIC and AAS

Issue Date:-08/04/2024
Request No:- GLD/RQ/1001/24
Report No:- GLD/RN/3070/24
Number of Sample:-One (01)

Collector's code	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	Na_2O	K_2O	MnO	P_2O_5	TiO_2	H_2O	LOI	Weight of Sample
HB-001	2.86	3.72	77.12	0.26	0.32	<0.01	<0.01	0.32	<0.01	15.30	0.28	<0.01	700gm

Note:- This result represent only for the sample submitted to the laboratory.
- LOI = Loss on Ignition

Analysts	Checked By	Approved By	Quality Control
Haimanot Bayeh Kindie Kasahun Melkamu Debalka Shashe Haile	Nigist Fikadu	Lidet Endeshaw	Gosa Haile

Geochemical Laboratory Desk
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Appendix B: Coagulant preparation procedures and Coagulation steps


BOROSILICATE GLASS
2000ml
MAGNETIC STIRRER


200
300
400
500