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A Study of the Effects of Aluminum Sulfate (Alum) and Poly Aluminum Chloride (PAC) on the Coagulation Process of Dug Well Water

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Abstract

The local population of Pal IX Village in West Kalimantan heavily depends on dug wells as their main source of obtaining clean water. The prolonged consumption of elevated concentrations of manganese (Mn) and iron (Fe) in water sourced from dug wells have neurotoxic effects on both adults and children. Therefore, it is imperative to employ alum and PAC coagulants for the treatment of dug well water in order to comply with the established national quality standard. However, the utilization of both coagulants resulted in elevation in the levels of iron (Fe), hence restricting the capacity to satisfy the quality standards. An augmentation in the mass of the coagulant is associated with a decline in the reduction efficiency. It is indicated that utilizing a mass of 0.5 grams of alum coagulant is the most favorable choice, resulting in a reduced of 50.14% for total dissolved solids (TDS), 86.25% for color, 97.70% for turbidity, and 94.48% for the concentration of Mn metal. By PAC coagulant, it has been determined that an ideal coagulant mass of 0.5 gram produces favorable outcomes with a TDS reduction of 45.08%, a color reduction of 97.71%, a turbidity reduction of 97.22%, and a Mn reduction of 95.04%.

Keywords: Alum; PAC; coagulant; coagulation; dug well water

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Abstrak (Indonesian)

Penduduk Desa Pal IX di Kalimantan Barat sangat bergantung pada sumur sebagai sumber utama untuk mendapatkan air bersih. Pemanfaatan terus-menerus air sumur gali yang mengandung mangan (Mn) dan besi (Fe) konsentrasi tinggi memiliki efek neurotoksik pada orang dewasa dan anak-anak. Oleh karena itu, perlu dilakukan pengolahan air tersebut menggunakan koagulan tawas dan PAC agar dapat memenuhi standar kualitas nasional yang ditetapkan. Namun, penggunaan kedua koagulan tersebut mengakibatkan peningkatan kadar besi (Fe), sehingga tidak dapat memenuhi standar kualitas air bersih. Peningkatan massa koagulan dikaitkan dengan penurunan efisiensi. Dari penelitian, diperoleh hasil bahwa 0,5 gram koagulan tawas merupakan massa optimum dengan menghasilkan penurunan 50,14% untuk total padatan terlarut (TDS), 86,25% untuk warna, 97,70% untuk kekeruhan, dan 94,48% untuk konsentrasi logam Mn. Dengan koagulan PAC, telah diketahui bahwa massa koagulan ideal 0,5 gram memberikan hasil yang sangat baik dengan pengurangan TDS sebesar 45,08%, pengurangan warna sebesar 97,71%, penurunan kekeruhan sebesar 97,22%, dan pengurangan Mn sebesar 95,04%.

Kata Kunci: Tawas, PAC, koagulan, koagulasi, air sumur gali

INTRODUCTION

The issue of water quality is a major concern driven by limited supply to clean water. On account of the divergence in public perceptions of water quality, there is currently a usage of inappropriate water treatment for consumption. Consequently, the daily water needs of the region are fulfilled by the utilization of wells that have been excavated and the storage of rainwater. However, the water collected from the dug well exhibits substandard quality, characterized by a distinct fish-like odor a turbid appearance, and the propensity to leave yellow blemishes on fabrics when employed for laundering purposes. The cloudy look of water can be attributed to its elevated concentration of iron (Fe).

In Pal IX Village, located in the Sungai Kakap District of the Kubu Raya Regency in West Kalimantan, the local population relies on dug wells as a primary means of accessing sanitary water. The neighboring settlements primarily use water supplied from dug wells and rainwater tanks to cover their daily water demands, as the facilities provided by the Regional Drinking Water Company (PDAM) have not yet reached to these districts. Water serves multiple purposes such as laundering garments, preparing meals, and maintaining the hygiene of communal bathroom facilities.

Nevertheless, the prolonged consumption of elevated concentrations of manganese (Mn) and iron (Fe) contained in water supplied from dug wells can have neurotoxic effects on both adults and children [1]. Hence, it is indispensable that the water source employed by the Pal IX community conforms to the national water quality standard, as established in Regulation of the Minister of Health of the Republic of Indonesia Number 32 of 2017. The accomplishment of the aforementioned goal can be achieved through the usage of a chemical substance commonly regarded as a coagulant, such as alum ($Al_2(SO_4)_3$) and PAC (poly aluminum chloride).

The destabilization of colloids, which are present in aqueous environments and exhibit inability to settling and challenging in physical treatment, can be accomplished with the usage of alum and PAC. These substances behave as coagulants, encouraging the aggregation of colloidal particles. The presence of alum and PAC coagulants diminishes the stability of colloidal substances, leading to an accumulation of minuscule flocs. These flocs subsequently merge together through the act of flocculation, culminating in the production of larger aggregates. The destabilization of colloidal particles occurs when electrolytes are provided and subsequently absorbed by the particles, resulting in the neutralization of their charge. When the floc extends to a greater size and acquires more weight, it will undergo precipitation and settle at the bottom, resulting in the formation of two separate layers. The uppermost layer of the water is handled by treatment and is characterized by its cleanliness, while the bottom layer consists of a buildup of contaminants within the water. Karbito and Slamet [2] provides a comprehensive account of the reactions which generally occur during the coagulation process employing alum.

Poly Aluminum Chloride (PAC) is an additive that is frequently utilized in the manufacturing process of aluminum chloride. It possesses the ability to induce coagulation and flocculation. A study conducted by [3], the addition of PAC contributes to the liberation of cations required for the neutralization of the Van der Waals forces associated with the negatively charged colloids. The existence of cations within the water will arise in the neutralization of the negative charge supplied by colloidal particles, ultimately causing the formation of flocs that subsequently settle at the bottom. The probability of coagulation-active chemicals encountering and engaging with colloidal particles is enhanced when the duration of contact time is prolonged. Based on research by Karbito and Slamet [2], colloidal instability arises due to a reduced number of contacts resulting from the neutralization of charges and the generation of micro flocs prior to precipitation.

Therefore, this research performed a comparative analysis of the coagulation technique employing alum ($Al_2(SO_3)_4$) and PAC (poly aluminum chloride) coagulants in relation to the treatment process of dug well water. The ultimate goal of this study is to figure out the coagulant that exhibits the most significant influence on pH elevation, total dissolved solids (TDS) reduction, color reduction, turbidity reduction, as well as manganese (Mn) and iron (Fe) metal removal. In order to ensure that the water quality meets the sanitary standards provided for in Regulation of the Minister of Health of the Republic of Indonesia Number 32 of 2017, it is necessary to apply appropriate measures

MATERIALS AND METHODS

Materials

In this study, the chemicals utilized comprised distilled water (H_2O), aluminum sulphate (alum), poly aluminum chloride (PAC), and dug well water as the sample

Coagulation of dug well water

The experimental methodology required the utilization of a batch reactor, wherein a glass beaker was employed as the container for the process. For the main objective of this experiment, 1000 mL of water sourced from a dug well was utilized and subsequently transferred into a beaker. A quantity of 0.5 g of coagulant was introduced into a beaker containing the sample, followed by stirring for a duration of 15 minutes at a rotational speed of 200 revolutions per minute. The sample was allowed to undergo a 30-minute resting period as part of the deposition phase, during which it was subjected to slow stirring at a rate of 100 revolutions per minute before being separated from the layers of precipitation.

Analysis data

The coagulated samples were subjected to analysis in order to determine their pH levels, total dissolved solids (TDS), color intensity, turbidity, and the concentration of iron (Fe) and manganese (Mn) elements.

RESULTS AND DISCUSSION

Initial Characterization

To assess the appropriateness of the excavated well water for treatment, a preliminary analysis was performed on a water sample to evaluate various parameters involving pH, total dissolved solids (TDS), color, turbidity, and the presence of manganese (Mn) and iron (Fe) metals. **Table 1** displays the information obtained through the analysis conducted to characterize the water sourced from the excavated wells.

Table 1. Initial characterization of dug well water

Parameters	Units	Quality standards*	Results
Turbidity	NTU	< 25	252
Color	TCU	< 50	96.4
TDS	mg/L	< 1000	1.681
Fe	mg/L	< 1	5.05
Mn	mg/L	0,5	6.48
pH		6.5-8.5	5.4

*Source: Regulation of the Minister of Health of the Republic of Indonesia Number 32 of 2017

Based on the data summarized in **Table 1**, it can be noticed that the pH levels, total dissolved solids (TDS), color, turbidity, and iron (Fe) and manganese (Mn) metal concentrations of the excavated well water fail to meet the established criteria for clean water quality as stipulated in Regulation of the Minister of Health of the Republic of Indonesia Number 32 of 2017. This non-compliance is attributed to sanitary concerns. Prior to its safe utilization by the community, the water sourced from dug wells require the treatment. The point of this initial assessment was to conduct a comparative analysis of the outcomes achieved through coagulation with alum and PAC.

The impact of coagulation on pH

The outcomes from the experiment summarized in **Table 1** indicate that variations in the pH value were detected in correlation with the amounts of alum coagulant and PAC employed. Consequently, after the process of water coagulation from a manually excavated well, with variation in the amounts of alum and PAC coagulants, a decrease in the pH parameter occurred as displayed in **Figure** 1.

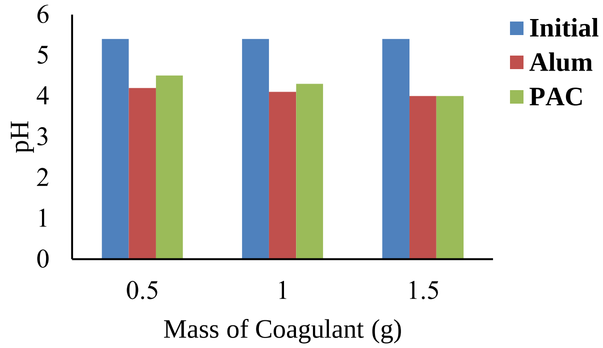

Figure 1. The impact of process on pH

The utilization of alum and PAC coagulants in the treatment of water has a detrimental impact on the resultant quality of water due to a further decrease in its pH level, as described by the data presented in **Figure 1**. The data provided cannot be utilized for the determination of the mass variation of alum and PAC coagulants, which is recognized for their pH-raising properties. Based on the observed correlation between the quantities of alum and PAC coagulants and the effect on pH parameters, it can be assumed that an increase in the concentration of coagulants in treated dug well water might result in a decrease in the pH value.

Alum is categorized as a weak acid. Consequently, when it is dissolved in water, it undergoes a process of dissociation, resulting in the formation of the aluminum ion (Al^{3+}) and the sulfate oxide ion (SO^{2-}). These ions subsequently react with two hydrogen ions (H^+) to produce the acidic compound recognized as sulfuric acid (H_2SO_4). This reaction ultimately leads to a decrease in the pH of the water [4]. The formation of $Al(OH)_3$ occurs in an aqueous environment by the combination of Al^{3+} and OH^- ions, resulting in the production of a coagulant that facilitates the binding of impurities. Hence, an increase in the usage of alum contributes to the generation of a greater quantity of sulfuric acid molecules. This, in turn, drives an elevation in the pH of water, resulting in a progressively more acidic nature after the final stage of processing. Upon the addition of alum coagulant to water, a chemical reaction occurs, resulting in the following transformation:

$$Al_2(SO_4)_{3(s)} \rightarrow 2Al^{3+}_{(aq)} + 3SO_4^{2-}_{(aq)}$$

$$Al_2(SO_4)_{3(s)} + 6H_2O_{(l)} \rightarrow 2Al(OH)_{3(s)} + 3H_2SO_{4(aq)}$$

Following the coagulation process, the addition of poly aluminum chloride (PAC), a water-soluble salt that dissociates into Al^{3+} metal ions and chloride (Cl^-) ions, allows the capture of H^+ ions to yield the acidic compound HCl. This ultimately brings to a decrease in the pH level of the water [4]. An increase in the consumption of PAC leads to a corresponding increase in the production of hydrochloric acid compounds, resulting in a decrease in the pH level of the processed water, thus turning it more acidic. The Al^{3+} ions encounter a chemical reaction with OH^- ions present in an aqueous medium, resulting in the formation of $Al(OH)_3$. This compound exhibits coagulant properties, enhancing the aggregation and binding of various contaminants present in the water. The reaction mechanism occurring during the addition of PAC coagulant to water has been referred to by [5] below:

$$2Al(OH)_{3(s)} + nHCl_{(aq)} \rightarrow Al_2(OH)_{6-n}Cl_{n(s)} + nH_2O_{(l)}$$
$$2Al(OH)Cl_{2(s)} + 4H_2O_{(l)} \rightarrow 2Al(OH)_{3(s)} + 4HCl_{(aq)}$$
$$[Al_2(OH)_5]^+_{(aq)} + H_2O_{(l)} \rightarrow 2Al(OH)_{3(s)} + H^+_{(aq)}$$

In contrast to the utilization of an alum coagulant, the decrease in pH levels witnessed in water supplied from drilled wells treated with PAC exhibited a rather minor decreasing. The distinction responses of alum and PAC coagulation factors can be observed by comparing their behaviours, as demonstrated in the study conducted by [6]:

$$\text{Alum:} Al_2(SO_4)_{3(s)} + 6H_2O_{(l)} \rightarrow 2Al(OH)_{3(s)} + 3H_2SO_{4(aq)}$$
$$3H_2SO_{4(aq)} \rightarrow 6H^+_{(aq)} + 3SO_4^{2-}{}_{(aq)}$$
$$\text{PAC: } Al_2(OH)_3Cl_{3(s)} \rightarrow 2Al(OH)_3^{3+}{}_{(s)} + 3H^+_{(aq)} + 3Cl^-_{(aq)}$$

Based on the aforementioned process, it is obvious that the PAC hydrolysis reaction results in the release of merely three H^+ ions, in contrast to the hydrolysis reaction of aluminum sulfate or alum in water, which yields six H^+ ions. According to [3], water treated with aluminum sulfate exhibits a lower pH level compared to water treated with PAC coagulants.

The impact of coagulation on TDS

The effectiveness of the coagulation process comprises the extent to which it removes dissolved solids (TDS) from water. Thus, the measurement of total dissolved solids (TDS) reduction was conducted subsequent to the coagulation process of water obtained from the dug well, with variations in the amounts of alum and PAC coagulants, as demonstrated in **Figure 2**.

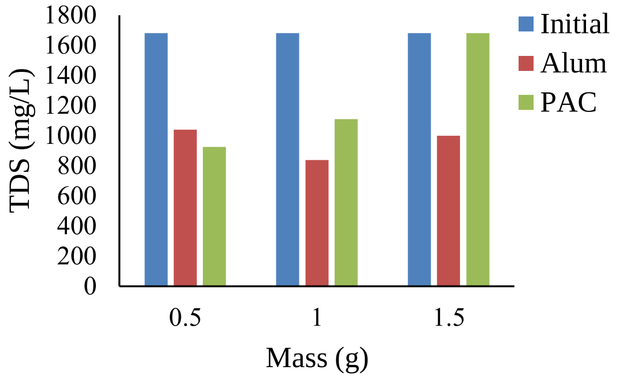

Figure 2. The impact of process on TDS

According to the data described in **Figure 2**, the application of coagulants, specifically alum and PAC, results in a significant reduction in total dissolved solids (TDS) levels. Specifically, the addition of 1 g of alum and 0.5 g of PAC successfully decreases TDS values. When colloidal particles are dispersed in an aqueous medium and exposed to the coagulation process utilizing alum and PAC coagulants, a chemical reaction occurs wherein the positively charged ions from the coagulant counterbalance the negatively charged repulsive forces surrounding the colloidal particles. This results in the attraction between the colloidal particles, leading to their aggregation and subsequent formation of larger particles. The flocs will undergo sedimentation, resulting in the formation of two distinct layers within the reservoir: an upper layer consisting of transparent water and a lower layer comprising sedimentary floc deposits resembling sludge.

The utilization of 1.5 g of alum leads to an elevation in the total dissolved solids (TDS) value. The total dissolved solids (TDS) value will decrease as the mass of alum rises until it approaches the allowable limits for alum mass. The occurrence of deflocculation arises when an excessive quantity of alum is introduced, above the permissible limit. This results in the transformation of alum into an impurity, which then leads to the reformation of colloidal particles within the water and a subsequent elevation in the total dissolved solids (TDS) value [3]. The utilization of 0.5 g of alum coagulant results in a TDS value that does not comply with the quality standards set by the Minister of Health of the Republic of Indonesia, as outlined in Regulation Number 32 of 2017. This discrepancy can be attributed to the limited coagulating capabilities of alum, which leads to the formation of insufficient floc. Consequently, the alum coagulant is unable to effectively precipitate all colloids and suspended dissolved solids, except for those that are not neutralized by the coagulant.

The utilization of PAC coagulants in the coagulation process has been observed to effectively decrease total dissolved solids (TDS) levels, hence achieving outcomes that align with established quality benchmarks. The decrease in total dissolved solids (TDS) can be attributed to the hydrolysis of poly aluminum chloride (PAC) in water, resulting in the formation of positively charged aluminate groups ($Al_2(OH)_3$) and chloride ions (Cl^-). The aluminate group plays a crucial role in the process of binding the component ions present in excavated well water, resulting in the formation of floc nuclei [7]. The introduction of poly aluminum chloride (PAC) into the well water resulted in a modest reduction in total dissolved solids (TDS), which can be attributed to the presence of many chloride compounds. The anion absorber is capable of absorbing chloride ions (Cl^-) and other anions present in excavated well water. Nevertheless, it has been shown that the anions with high absorbency tend to reach a saturation point, leading to an elevated total dissolved solids (TDS) value [7].

When poly aluminum chloride (PAC) is introduced into water, the cations present in PAC will undergo reactions with negatively charged entities that exhibit mutual repulsion in the vicinity of colloidal-sized dissolved particles inside the water. The interaction between the charge instability caused by positive ions from the coagulant and the colloidal particles leads to the attraction and agglomeration of the particles, resulting in the formation of bigger flocs that subsequently precipitate [8]. The utilization of poly aluminum chloride (PAC) coagulants, namely those with masses of 1 and 1.5 g, leads to a reduction in the effectiveness of total dissolved solids (TDS) removal. This decline in efficiency can be attributed to the fact that the outcomes obtained surpass the established quality criteria.

The addition of 1 g of PAC coagulant results in a total dissolved solids (TDS) concentration of 1,110 mg/L, whereas the addition of 1.5 g of PAC coagulant leads to a TDS concentration of 1,680 mg/L. The excessive quantity of coagulant leads to an over-release of cations by poly aluminum chloride (PAC) compared to the demand of negatively charged colloidal particles in the water, resulting in an excessive absorption of cations. The phenomenon of repulsion, characterized by the repulsive interactions between particles, has been observed by Audina [7]. Consequently, the formation of flocs is suboptimal.

The impact of coagulation on color

The efficacy of the coagulation process, as assessed by changes in color, demonstrates a reduction in the color value of the water resulting from the coagulation process. The measurement of color content was conducted using the test technique outlined in SNI 6989.80:2011 [9]. Thus, the reduction efficiency of the color parameters was achieved after the coagulation process of dug well water with variations in the mass of alum and PAC coagulants which can be revealed in **Figure 3**.

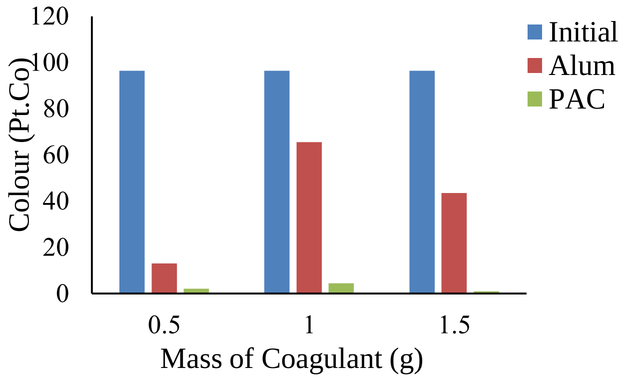

Figure 3. The impact of process on colour

Based on the information published in **Figure 3**, it can be discovered that the utilization of alum and PAC coagulants in the treatment of water yields a favorable impact on the resultant water quality. Based on the provided data, it is evident that altering the mass of alum and PAC coagulants yields a significant reduction in color. Based on the findings of this study, it can be concluded that the application of alum and PAC coagulants results in a significant reduction in color value, with a decrease of 0.5 g indicated for alum and 1.5 g for PAC. In the coagulation process employing a quantity of 1 g of alum, it has been determined that the intensity of color tends to exhibit a 31% increase, resulting in a value of 65.5 Pt-Co. The outcome demonstrated a negative correlation between the dosage of coagulant used and the extent of color intensity reduction in dug well water. This can be attributed to the surplus coagulant leading to the re-stabilization of destabilized colloids, as the lack of interparticle space hinders the process of destabilization [10].

The presence of negatively charged colloidal particles is commonly associated with the coloration of water. Consequently, the elimination of color in water is achieved through the introduction of positively charged coagulants. The introduction of alum coagulant into the colored drilled well water induces the decomposition of its constituents, resulting in the formation of suspended components that subsequently aggregate to form flocs. These flocs contribute to the enhancement of water clarity [11]. When employing a quantity of 1.5 g of alum, an excess of alum is present, afterwards resulting in its presence as an impurity within the water. As the quantity of alum is increased, it will surpass the capacity limit, leading to a deflocculation phenomenon in the water. The presence of alum in water can lead to the formation of impurities, resulting in the reformation of colloidal particles and subsequently causing a rise in the color intensity of the water.

The addition of varying masses resulted in nearly complete color removal, with the highest percentage achieved when 1.5 g of coagulant mass was added, yielding a removal efficiency of 98.85%. The reduction in the value of this color parameter can be attributed to the dissociation of PAC in water, resulting in the release of Al^{3+} ions. These ions have the ability to diminish the zeta potential value of the particles. Due to the inherently positive nature of this ion, it is expected to disrupt the charge stability of the water sample. Consequently, the repulsive force among the dye charges will diminish, leading to the emergence of an attractive force between the charge of the coagulant and the dye charge. The introduction of mechanical forces via a slow mixing process might enhance particle-particle interactions, hence promoting the grouping of bigger particles and facilitating their subsequent settling. Poly aluminum chloride (PAC) has demonstrated remarkable efficacy in mitigating color parameters in dug well water. Notably, all changes in mass have led to near-perfect elimination of color, with the most optimal outcome achieved by introducing 1.5 g of coagulant mass, resulting in a remarkable 98.85% color removal efficiency.

The impact of coagulation on turbidity

The performance of the coagulation process, as determined by the turbidity parameter, demonstrates a reduction in the turbidity level of the water due to the coagulation process. The measurement of turbidity level was conducted using the test technique specified in SNI 06-6989.25-2005 [12]. The efficiency of decreasing the turbidity parameter in drilled well water using different masses of alum and PAC coagulants is illustrated in **Figure 4**.

The examination of **Figure 4** reveals that the most efficient mass variations of alum and PAC coagulants in lowering turbidity were 1.5 and 1 g, respectively. The determination of the appropriate dosage of coagulant for water treatment cannot be reliably determined solely by considering turbidity levels, as it necessitates empirical experimentation. Not all instances of turbidity necessitate a high dosage. The presence of fine or coarse mud particles in water leads to turbidity, necessitating a relatively low dosage of coagulant. Conversely, water turbidity primarily driven by colloidal particles demands a significantly higher dosage of coagulant.

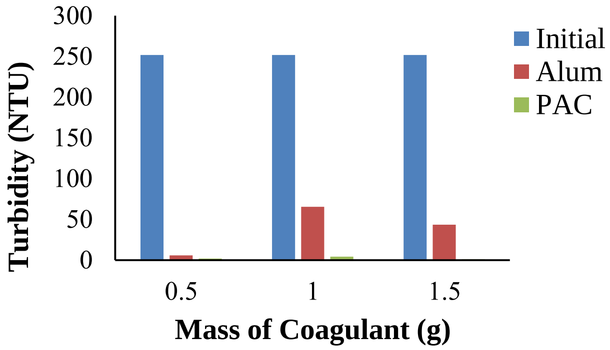

Figure 4. The impact of process on turbidity

The reduction in turbidity achieved by the application of alum can be attributed to the neutralization of the negatively charged humin group (a hydrophilic colloid) in the solution by Al^{3+} ions. The utilization of alum as the primary coagulant in the treatment of turbidity in dug well water produces the formation of substantial flocs or aggregates. Consequently, the accumulated floc exhibits increased weight, facilitating its rapid settling. This settling process is attributed to the sweep floc coagulation mechanism, wherein suspended particles are absorbed into the formed floc, effectively binding humic acid colloidal particles present in the dug well water [2] . The existence of Al^{3+} cations within the coagulant induces the formation of many macro flocs. The presence of several flocs induces a decrease in turbidity measurements. According to Kristijarti [13] the addition of a small quantity of alum leads to the decomposition of alum into Al^{3+} colloidal dispersion, which carries a positive charge. This dispersion is insufficient to effectively bind all the negatively charged colloidal particles present in dug well water. Consequently, the resulting floc is smaller in size and exhibits reduced settling ability, resulting in higher turbidity values.

A turbidity value of 5.78 NTU was achieved with a removal effectiveness of 97.70% when employing a coagulant dosage of 0.5 g. The efficacy of utilizing 0.5 g of alum in the coagulation process has proven insufficient to achieve complete removal of turbidity. This can be attributed to the incomplete binding of contaminants present in the dug well water by $Al(OH)_3$, which serves the purpose of binding such contaminants. Consequently, a lower value of removal efficiency is attained. A turbidity value of 3.44 NTU was observed at a mass of 1.5 g of alum, leading to a turbidity removal efficiency of 98.63%. In comparison, when the coagulant mass was reduced to 0.5 g, a lower amount of Al^{3+} ions was generated. Consequently, this led to the formation of fewer $Al(OH)_3$ flocs, resulting in a reduced ability to bind turbidity-causing contaminants and a lower percentage of removal.

The dosage of coagulant will exhibit an upward trend in response to an increase in turbidity; however, it should be highlighted that this dosage increase does not follow a strictly proportional relationship with the corresponding increase in turbidity. In the event of elevated turbidity levels, a reduced quantity of coagulant will be required due to the heightened frequency of collisions among the coagulated colloidal particles. Nevertheless, when the turbidity levels are low, the likelihood of collisions becomes more controllable, hence posing challenges in the coagulation process. The presence of diverse particle sizes in a suspension facilitates the process of coagulation in comparison to suspensions composed solely of particles of a single size. The process of floc generation is accomplished through hydrolysis reactions upon the adding of coagulants into water [14].

In the context of poly aluminum chloride (PAC) coagulants, the formation of dissolved aluminum species occurs in the form of monomers. The presence of positively charged ions allows for the neutralization of negatively charged colloidal particles, facilitating the process of coagulation. The aluminum hydrolysis reaction results in the formation of four distinct aluminum species, specifically Al^{3+}, $Al(OH)_2^{+}$, $Al(OH)^{2+}$, and $Al_2(OH)_2^{4+}$. In addition to its role in the formation of cationic monomers, poly aluminum chloride (PAC) also contributes to the formation of polymers that are primarily composed of $Al_{13}O_4(OH)_{24}^{7+}$ ions [15]. During the coagulation process, the instability of colloids and particles in water is induced by the introduction of a coagulant, followed by vigorous and gentle agitation for a duration of 10 minutes. The process of destabilization transpires as a result of the decomposition of PAC, leading to the formation of particles carrying positive and negative charges. The breakdown process of the coagulant also leads to the generation of positive and negative ions, which subsequently counteract the colloidal charge and facilitate the aggregation of particles into a floc [16].

The phenomenon of particle destabilization arises when the resulting compound from the hydrolysis process gathers with negatively charged particles present in the aqueous medium [17]. Haines [18] proposes that the process of charge neutralization has the potential to induce destabilization in these particles. As stated in the analysis of [15], charge neutralization refers to the direct contact occurring between positively charged hydrolysis products of aluminum (III), namely Al^{3+} and Al, and negatively charged colloidal particles. The process of charge neutralization is facilitated by the application of vigorous agitation while introducing the coagulant. The process of particle removal, recognized as sweep coagulation, involves the physical entrapment of colloidal particles within precipitates of aluminum hydroxide [2].

The abundance of Al^{3+} cations in the coagulant induces the formation of many macro flocs. The presence of numerous flocs leads to a reduction in turbidity measurements. According to Kristijarti [13], the addition of a limited quantity of PAC leads to the decomposition of PAC into colloidal dispersions with a positive charge. Consequently, the presence of negatively charged colloidal particles in dug well water prevents the binding of Al^{3+} ions. As a result, the formed flocs are small in size and exhibit poor settling characteristics, leading to an increase in turbidity levels. The addition of a coagulant with a mass of 1.5 gram resulted in an observed increase in turbidity in the water. This phenomenon can be attributed to the significant quantity of coagulants introduced into the water, leading to the formation of a colloid that subsequently stabilizes. The lack of available space for particle connection within the colloid implies the accumulation of impurities, thereby causing an elevation in turbidity levels [11].

The impact of coagulation on Fe metal ion

The evaluation of the coagulation process's efficiency, as determined by the Fe metal content, is quantified by the percentage of iron metal eliminated from water by the coagulation process. The levels of iron (Fe) were assessed using the test technique outlined in the SNI 6989-4:2009 [19]. The decrease effectiveness of the Fe metal parameter was determined following the coagulation process of drilled well water, with varying masses of alum and PAC coagulants. This information is provided in **Figure 5**.

Based on the information provided in **Figure 5**, it can be discovered that the utilization of alum and PAC coagulants in the treatment of water yields a detrimental impact on the resultant water quality. Consequently, the observed mass fluctuation of the alum coagulant can be considered as an effective means of reducing the concentration of Fe in the treated water.

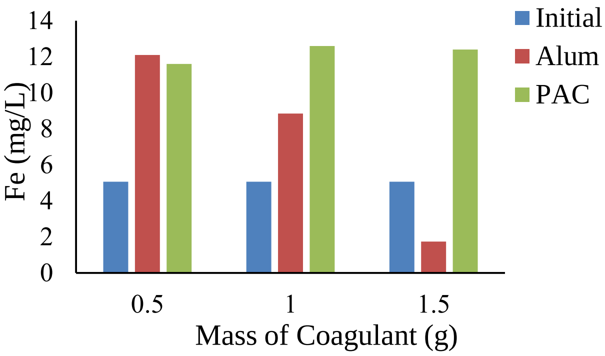

Figure 5. The impact of process on Fe metal ion

The introduction of alum coagulant into the treated water led to the neutralization of particle charges, facilitating particle collision and agglomeration, resulting in the formation of larger particles that subsequently settled. Aluminium-based coagulants, such as alum, have the ability to decrease iron (Fe) concentrations in water by effectively binding to suspended particles in the water, triggering the formation of aggregates or flocs that subsequently undergo precipitation. The chemical reactions that take place when alum is immersed in water can be described as follows, as documented by Kartini [20]:

$Al_2(SO)_{4(s)} \rightarrow 2Al^{3+}_{(aq)} + 3(SO_4)^{2-}_{(aq)}$
$2Al^{3+}_{(aq)} + 6OH^-_{(aq)} \rightarrow 2Al(OH)_{3(s)}$
$2Fe^{2+}_{(aq)} + 2Al(OH)_{3(s)} \rightarrow Fe(OH)_{3(s)} + 2Al^{3+}_{(aq)}$
$2Al^{3+}_{(aq)} + 3H_2O_{(l)} \rightarrow 2Al(OH)_{3(s)} + 3H^+$
$2Fe^{3+}_{(aq)} + 3(SO_4)^{2-}_{(aq)} \rightarrow Fe_2(SO_4)_{3(aq)}$

The observed chemical process is a hydrolysis reaction of Al^{3+}, resulting in the formation of $Al(OH)_3$. Subsequently, the aluminium hydroxide ($Al(OH)_3$) will form chemical bonds with iron (Fe) in an aqueous environment, resulting in the formation of aggregates composed of ferric hydroxide compounds ($Fe(OH)_3$). The reaction under consideration involves ion exchange, wherein the alum present in the dug well water forms bonds with metal particles during the coagulation phase. These bonds result in the formation of flocs, which then combine and agglomerate during the flocculation process [21]. Furthermore, the aforementioned reaction yields the molecule $Fe_2(SO_4)_3$, which exhibits coagulant properties and possesses a positive charge of Fe^{3+} [10]. The occurrence of Fe^{3+} ions in groundwater extracted from excavated wells leads to the facile adsorption of Fe^{3+} ions onto colloidal particles possessing negative charges, hence inducing charge neutralization. Subsequently, the formation of particle agglomerates occurs, which exhibit an increase in size and exhibit rapid sedimentation. Furthermore, based on the comparative analysis of the ionic radius of Al^{3+} and Fe^{3+} ions, it can be observed that Fe^{3+} ions possess a greater radius in comparison to Al^{3+} ions. Consequently, this disparity in radius facilitates a higher propensity for Fe^{3+} ions to engage in binding interactions with other particles, resulting in the formation of $Fe(OH)_3$ [22].

The application of PAC coagulant in dug well water has a detrimental impact on the water quality. Based on the available data, it is inconclusive whether the mass variation of PAC coagulant successfully reduces the Fe metal content. This uncertainty arises from the fact that the pH value is excessively low, resulting in a negligible decrease in Fe metal concentration. The pH value exerts a significant impact on the process of heavy metal removal due to its influence on the solubility of metals in excavated well water and the efficacy of PAC coagulants. The solubility of Fe metal in excavated well water is influenced by variations in pH. Consequently, in the coagulation process including the utilization of PAC coagulants, it becomes imperative to employ the ideal pH level specific to each heavy metal type. Furthermore, the choice of compounds employed also has an influence on the removal of Fe metal. For instance, the utilization of a NaOH solution, known for its ability to elevate the pH level, can effectively facilitate the dissolution of Fe metal, rendering it a favourable precipitating agent [23]. Syarifuddin [24] conducted study which indicates that a highly alkaline pH of 12 is ideal for the reduction of Fe metal. In the given circumstances, it can be observed that PAC exhibits the ability to form associations with various compounds, including both metals and non-metals. This phenomenon occurs due to the release of ions by PAC under these specific conditions, leading to the subsequent binding of cations, including both metals and non-metals, found in the water gained from the excavated well. The process of Fe metal removal by PAC coagulants can be observed as outlined by Syarifuddin [24].

$Al_2(OH)_3Cl_{3(s)} \rightarrow 2Al(OH)_3^{3-}{}_{(aq)} + 3H^+ + 3Cl^-_{(aq)}$
$2Al(OH)_3^{3-}{}_{(aq)} + 2Fe^{3+}_{(aq)} \rightarrow 2Al(OH)Fe_{(s)}$
$2Fe^{3+}_{(aq)} + 6OH^-_{(aq)} \rightarrow 2Fe(OH)_{3(s)}$

According to the observed reaction, an increase in the mass of the coagulant will result in a corresponding increase in the formation of $Fe(OH)_3$ precipitate, while simultaneously causing a drop in the content of Fe metal. The presence of iron in well water can lead to a reaction with hydroxide ions, resulting in the

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precipitation of iron in the sample and the formation of iron (III) hydroxide ($Fe(OH)_3$). The $Fe(OH)_3$ precipitate has the ability to serve as a floc core, possessing electropositive properties that facilitate the attraction of OH^- ions in the surrounding solution. This attraction leads to the formation of $Fe(OH)_4^-$ floc. Additionally, the $Fe(OH)_3$ precipitate can also attract cations originating from Al metal present in dug well water, resulting in the creation of 2Al(OH)Fe. The formation of dark brown flocs occurs during the coagulation process due to the binding of cations/anions, specifically metals and their compounds, in dug well water [24].

The impact of coagulation on Mn metal ion

The evaluation of the coagulation process's effectiveness, as influenced by the concentration of Mn metal, is quantified by the percentage of manganese metal removed from water as a result of the coagulation process. Manganese levels were quantified using the SNI 6989-5:2009 [25] testing procedure. The decrease efficiency of Mn metal characteristics was determined following the coagulation process of untreated potable water using different concentrations of alum and PAC coagulants, depicted in **Figure 6**.

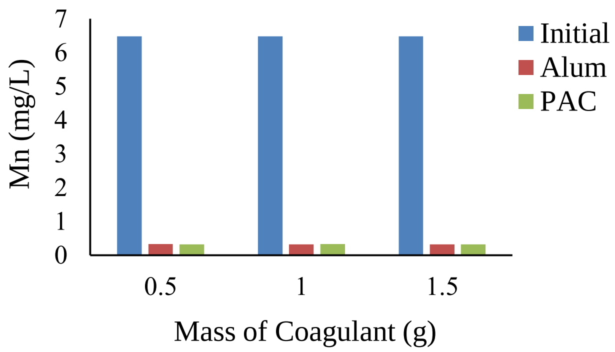

Figure 6. The Impact of Process on Mn Metal Ion

Based on the data gathered depicted in **Figure 6**, it can be inferred that variations in the mass of alum coagulant and PAC have an impact on the Mn parameter. Particularly, the group of alum coagulant with the greatest influence in reducing Mn values lies within the range of 1 to 0.5 g. Aluminium-based coagulants, such as alum, have the ability to mitigate manganese (Mn) concentrations in water due to their capacity to bind with suspended particles in the water, resulting in the formation of aggregated masses or flocs that subsequently precipitate. The chemical reactions that take place when alum is immersed in water can be described as follows, as reported by [20]:

$Al_2(SO)_{4(s)} \rightarrow 2Al^{3+}_{(aq)} + 3(SO_4)^{2-}_{(aq)}$
$2Al^{3+}_{(aq)} + 6OH^-_{(aq)} \rightarrow 2Al(OH)_{3(s)}$
$3Mn^{2+}_{(aq)} + 3(SO_4)^{2-}_{(aq)} \rightarrow 3MnSO_{4(aq)}$
$2Mn^{2+}_{(aq)} + 2Al(OH)_{3(s)} \rightarrow Mn(OH)_{2(aq)} + 2Al^{3+}_{(aq)}$
$2Al^{3+}_{(aq)} + 3H_2O_{(l)} \rightarrow 2Al(OH)_{3(s)} + 3H^+_{(aq)}$

According to the observed reaction, an increase in the mass of the coagulant leads to a more efficient formation of $Mn(OH)_3$ precipitate, resulting in a decrease in the Mn metal concentration. The presence of manganese in well water can lead to a reaction with hydroxide ions, resulting in the precipitation of Mn^{2+} in the sample and the formation of $Mn(OH)_2$. The $Mn(OH)_2$ precipitate has the potential to serve as a floc core due to its electropositive nature. This core can attract OH^- ions present in the solution, resulting in the formation of $Mn(OH)_3^-$ floc. Additionally, it can also attract cations originating from Al metal found in drilled well water, leading to the creation of $2Al(OH)Mn_3$. The formation of dark brown flocs occurs during the coagulation process due to the binding of cations/anions (metals and their compounds) in excavated well water by various coagulants [26].

CONCLUSION

Based on the aforementioned data and further analysis, it can be concluded that both coagulant alum and PAC effectively reduced the levels of pollutants in the water sourced from dug wells. Nevertheless, the levels of iron (Fe) exhibited an increase subsequent to the use of both processing procedures, hence restricting the ability to meet the required quality criteria. Based on the preceding explanation, it is evident that an increase in the mass of coagulant leads to a decrease in the resulting reduction efficiency. Consequently, a mass of 0.5 g of alum coagulant emerges as the optimum option, yielding a TDS reduction efficiency of 50.14%, color reduction efficiency of 86.25%, turbidity reduction efficiency of 97.70%, and a 94.48% efficiency in reducing the concentration of Mn metal. In the context of treating dug well water with PAC coagulant, it has been determined that an optimal coagulant mass of 0.5 g yields favorable results. This mass is associated with a TDS reduction efficiency of 45.08%, a color reduction efficiency of 97.71%, a turbidity reduction efficiency of 97.22%, and a Mn metal reduction efficiency of 95.04%.

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