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The potential of *Hibiscus sabdariffa* seed extract and rice straw as coagulants-adsorbents for processing batik liquid waste

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Abstract. *Rahmani AS, Masykuri M, Setyono P. 2025. The potential of* Hibiscus sabdariffa *seed extract and rice straw as coagulants-adsorbents for processing batik liquid waste. Nusantara Bioscience 17: 118-128.* One of the efforts to reduce the content of heavy metals in this batik liquid waste is by applying the process of a combination of coagulation and adsorption. This process involves the use of the coagulant of Rosella Seeds Extracts (RSE) to neutralize the charge of the heavy metal ions, making them more likely to bind to the adsorbents from rice straw biomass. The adsorption then occurs, where the neutralized heavy metal ions are physically or chemically bound to the surface of the adsorbents, effectively removing them from the liquid waste. This study aims to determine the decrease in chromium metal levels (Cr^{6+}) in artificial batik liquid waste using this coagulation-adsorption process with biocoagulants of rosella seed extracts combined with straw rice adsorbents. $K_2Cr_2O_7$ solution was used as an artificial solution for batik liquid waste. The coagulation process was repeated 3 times to determine the optimum RSE biocoagulant, both doses, pH, and contact time. The first coagulation was carried out by mixing biocoagulant RSE into a 10 ppm $K_2Cr_2O_7$ solution. The coagulation process was carried out in the same way at pH 2, 4, 5, 6, 8, and 10 using the optimal dose of biocoagulant. The result showed that the optimum dose of biocoagulant RSE was 30 × 103 ppm, with an absorbance value, and the percentage of chromium metal (Cr6+) was, respectively, 0.623 and 68.69%. Meanwhile, the optimum pH for RSE biocoagulant was at pH 2 (acid condition), with absorbance and the percentage of chromium metal (Cr6+) values being, respectively, 0.617 and 69.02%. These findings have potential applications in the field of environmental science and waste management, particularly in the development of effective and sustainable methods for treating industrial waste.

Keywords: Adsorben, batik liquid waste, biocoagulant, chromium, rice straw, rosella

INTRODUCTION

Waste from the batik business, dyes, are often non-degradable organic chemicals that pollute the environment. Only about 5% of this coloring material is used, with the remaining 95% being discharged into the atmosphere. Dyes such as CrCl3 (chromium chloride), $K_2Cr_2O_7$ (potassium dichromate), and mordants (dye binders) such as $Cr(NO_3)_2$ (chromium nitrate) are sources of the dangerous heavy metal chromium (Cr^{6+}) (Hastuti et al. 2016; Pirkarami and Olya 2017; Koosdaryani et al. 2019). Chromium metal (Cr^{6+}) is difficult to decompose in the environment and can ultimately accumulate in the human body through the food chain. Continuous exposure to high doses of chromium metal causes cancer of the human lungs and digestive organs (Saputro et al. 2016; Zarkasi et al. 2018). The Indonesian batik business has grown significantly. According to data from the Ministry of Industry of the Republic of Indonesia, 47,755 Small and Medium Batik Companies (SMEs) were established in Indonesia in 2015 (Pinasti and Adawiyah 2016). However, problems such as environmental degradation caused by batik waste are losses that must be minimized. According to Amutha (2017) and Budiyanto et al. (2018), waste disposal into the rivers and land is the primary source of water pollution and soil contamination. Diniyati (2012) reported that the quality and quantity of Pete River Water in the Masaran Sub-district, Sragen District, Central Java, had the levels of color, odor, pH, nitrate, nitrite, phosphate, COD, and COD levels, highlighting the severity of contamination. One promising method to address these issues is coagulation-adsorption.

Environmental pollution caused by the disposal of liquid batik waste requires wastewater treatment. One method of wastewater treatment is coagulation-adsorption. Coagulation is the process of mixing coagulants (chemicals) or precipitants into raw liquid waste at a high rotation speed in a short time. One of the coagulants that can be used to process liquid waste is the seeds of the roselle seed extract biocoagulant. The high glutamic acid and arginine content in seed extract biocoagulant protein can coagulate (Tounkara et al. 2013). These amino acids will provide the overall charge to the protein, depending on its isoelectric point. This cationic protein can neutralize the negative charge of dye particles in liquid waste (Yong and Ismail 2016).

Adsorption is the accumulation of several molecules, ions, or atoms at the boundary between two phases. The phenomenon occurs due to unbalanced forces at the boundary between the surfaces of two phases, which causes changes in the concentration of molecules, ions, or atoms between the phases (Santoso et al. 2014). The goal is to absorb the targeted substance in liquid, solid, or semisolid form. The absorbed substance is called an adsorbate/solute, and the adsorbent is called an adsorbent. Agricultural waste in the form of rice straw can be used as an adsorbent in waste processing (Liu et al. 2013). Chemically, the content of rice straw consists of lignin (22%), cellulose (38%), hemicellulose (35%), and several other nutrients (5%) (Gummert et al. 2019; Taufik et al. 2021). In addition, rice straw can remove heavy metal pollution, dyes, and phenolic compounds (Mahamad et al. 2015; Li et al. 2017).

This research combined these two methods using natural ingredients, namely roselle (*Hibiscus sabdariffa* L.) seeds as a coagulant and rice straw as an adsorbent. This study aimed to test the effectiveness of the combination of *H. sabdariffa* seed coagulant with rice straw adsorbent in processing liquid waste from the batik industry and determine the perception of batik business actors regarding innovations in processing batik liquid waste.

MATERIALS AND METHODS

Equipment and materials

Equipment used in this study included UV-Vis spectrophotometry, measuring cups, beakers, ovens, magnetic stirrers, 100 mesh sieves, grinders, blenders, timers, scales, measuring flasks, pH meters, and measuring pipettes. Meanwhile, the materials utilized in this study were roselle seed extract (*H. sabdariffa*) or RSE, rice straw, distilled water, filter paper, synthetic $K_2Cr_2O_7$ solution, NaOH solution, and H_2SO_4 solution.

Preparation of biocoagulant

The method used to create a biocoagulant from Roselle Seed Extract (RSE) was adapted from Yong and Ismail (2016). The RSE was washed using distilled water and then dried in the oven for 120 minutes at 60°C to let it evaporate. The dried seeds were then processed through a 100 mesh screen to ensure that the size is consistent before being ground using a grinder to produce powder. To extract the coagulant, 5 g of RSE powder was combined with 100 mL of 0.5 M NaCl solvent. This extraction was completed in 2 minutes using a blender. The resulting mixture was then filtered using a filter paper to remove impurities, and the cationic proteins served as a biocoagulant. The biocoagulant was immediately used to prevent bacterial digestion of the organic components, allowing for more effective coagulation results.

Preparation of adsorbent

The adsorbent used in this research is rice straw waste obtained from agricultural land. The preparation of the rice straw adsorbent began with thorough washing to remove dirt and impurities, followed by drying in an oven at 105°C until a stable weight was achieved, ensuring the complete removal of moisture. The dried rice straw was then ground using a mechanical grinder, which was calibrated to produce a consistent particle size suitable for adsorption. To achieve uniformity, the coarse ground material was passed through a 100-mesh sieve, standardizing the particle size to approximately 150 µm. Any particles that did not conform to the desired size were reprocessed to ensure consistency. The resulting fine rice straw powder was then stored in a sealed, desiccated container to prevent contamination and preserve its adsorptive properties. This approach ensures a uniform adsorbent with optimal surface area, leading to consistent and reliable adsorption performance in subsequent experiments.

Preparation of batik liquid waste

The artificial batik liquid waste used for this study was an aqueous $K_2Cr_2O_7$ solution. It was a simplified model of real batik wastewater, focusing specifically on chromium (Cr6+) contamination, which is a significant concern in the actual batik effluents. The K2Cr2O7 in the artificial waste isolates Cr6+ as the primary contaminant, allowing targeted evaluation of the coagulation-adsorption treatment for chromium reduction (Birgani et al. 2016). Its production was based on the National Standardization Agency's process for producing $K_2Cr_2O_7$ 500 ppm. In a 100 mL volumetric flask, 141.4 mg of oven-dried $K_2Cr_2O_7$ was dissolved in distilled water. Then, a dilution of 10 ppm was performed.

FTIR (Fourier Transform Infra-Red) analysis method

The FTIR method used in this study aimed to identify organic compounds and analyze the functional groups present in the roselle seed coagulant and rice straw adsorbent. FTIR characterization was performed before and after interaction with the heavy metal chromium (CrVI), allowing observation of spectral changes that indicate interactions or bonding between roselle seed coagulant and rice straw adsorbent. The BTR and JP samples were dried and ground into fine powders. A small amount of each sample was then mixed with potassium bromide (KBr) in a ratio of approximately 1:100 (sample:KBr) to form pellets. These pellets were subjected to FTIR analysis using an FTIR spectrophotometer, within a scanning range of 4000-400 cm^{-1}. FTIR detects the infrared spectrum generated by the vibrational bonds within an organic compound, which provides information about the types of functional groups present in the material. By comparing the spectra before and after exposure to Cr(VI), changes in peak positions, intensities, or the disappearance of peaks were used to infer the involvement of certain functional groups in metal binding. The FTIR research results revealed that some functional groups remained present before and after contact with Cr(VI), whereas absorption changes or disappearances were also seen at specific wavenumber. This demonstrates the development of bonds between the tested materials and Cr(VI). For example, in roselle seeds, active groups such as alkyl isothiocyanate (N=C=S) shifted after reacting with Cr(VI). Meanwhile, the O-H, C-H, C-C, and C-O groups found in rice straw helped with heavy metal adsorption.

Determination of biocoagulant dose and optimal pH for lowering chromium metal levels (Cr^{6+})

Two coagulation processes were performed in this study. The first coagulation was performed to establish the optimal biocoagulant dosage, and the second was to establish the optimal biocoagulant pH. Biocoagulant dosages of 0, 10, 20, 30, 40, and 50 mL were added to 1000 mL of synthetic $K_2Cr_2O_7$ solution at 10 ppm, and agitated for 90 minutes. The solution mixture was then separated from the precipitates using filter paper before the absorbance value was determined using UV-Vis spectrophotometry at a wavelength of 540 nm by SNI 6989.71:2009. The ideal dosage of the biocoagulant was established based on the absorbance value; the standard outlines the spectrophotometric method for measuring hexavalent chromium (Cr-VI) concentrations in water and wastewater samples within the range of 0.1 to 1.0 mg L^{-1} at wavelengths of 530 or 540 nm (BSN 2009). The second coagulation followed the same procedure as the first one, creating several solutions with pH values of 2, 4, 5, 6, 8, and 10.

Determination of the optimal condition of the coagulation process

At this stage, the prepared coagulant and adsorbent were added to a 10 ppm sample solution. The mixture was stirred using the optimal contact time determined for the coagulation process. To evaluate the effect of contact time on the adsorption process, the mixture was tested with time variations of 30, 60, 90, 120, 150, and 180 minutes using the optimal coagulant-to-adsorbent composition ratio.

Determining the appropriate parameters for the coagulation process is an important step in determining the efficacy of a coagulation method in treating wastewater, particularly in terms of reducing the concentration of contaminants in the sample. The produced adsorbent and coagulant were combined with the sample solution at a 10-ppm concentration. In addition to determining the most efficient contact duration for the coagulation process, this mixing procedure seeks to ascertain the ideal composition ratio between the coagulant and adsorbent.

In order to determine the ideal duration for the coagulant and adsorbent to bind efficiently and precipitate particles in the sample solution, changes in contact time were applied, specifically at 30, 60, 90, 120, 150, and 180 minutes. Important variables like the degree of turbidity, the effectiveness of sedimentation, and the decrease in pollutant concentration were routinely tracked during this process. The outcomes of this phase offer important information on the best circumstances for increasing coagulation efficiency in wastewater treatment, which will ultimately result in safer effluent that satisfies environmental regulations.

RESULTS AND DISCUSSION

FTIR-based biocoagulant and adsorbent characterization

The results of FTIR analysis of roselle seeds before and after contact with (Cr6+), as shown in Table 1, revealed several shifts in the absorption bands. For instance, the C-H deformation of the aromatic ring shifted from 722.37 to 723.34 cm^{-1}. The interaction likely causes a redistribution of electron density within the aromatic system, altering the bond stiffness and, consequently, the vibrational frequency. The O-H stretching associated with alcohols, ethers, carboxylic acids, and esters shifted from 1,165.05 to 1,166.98 cm^{-1}. The shift indicates that Cr6+ forms bonds or interactions, such as electrostatic attraction or coordination, with hydroxyl groups. This interaction weakens the hydrogen bonding within the functional groups, causing a minor shift in the vibrational frequency. Similarly, the C-H bending of alkanes showed a slight shift from 1,462.11 to 1,464.03 cm^{-1}. These shifts indicate an interaction between the functional groups of roselle seeds and (Cr6+), suggesting that roselle seeds are effective in binding and reducing (Cr6+) through coagulation.

Similar shifts were observed for rice straw as summarized in Table 2. The C-H stretching of alkenes shifted from 789.88 to 792.78 cm^{-1} after contact with (Cr6+), and the NO_2 stretching showed shifts from 1,316.47 to 1,319.37 cm^{-1}, as well as from 1,509.36 to 1,511.29 cm^{-1}. These shifts indicate the interaction between the nitro compounds and (Cr6+), confirming that rice straw can also effectively adsorb (Cr6+). Additionally, changes in C=C stretching vibrations from 2,156.51 to 2,135.29 cm^{-1} further support the adsorption of (Cr6+) by rice straw.

Impact of doses on the coagulation process

Several doses of the RSE biocoagulant were used to generate the absorbance ratio and adsorption concentration of chromium metal in Table 3. The 10×10^3 ppm dosage group was found to have the highest absorbance value (0.708) and the lowest adsorbed concentration of chromium metal (Cr^{6+}) (1.902) among the tested dosages. The contact duration employed was 90 minutes. The lowest chromium metal (Cr^{6+}) absorbance value was created by a dosage of 30×10^3 ppm, in contrast, and the highest chromium metal (Cr^{6+}) adsorbed concentration was obtained by this dose (5.54). Adsorption concentration refers to the amount of a substance, Cr6+, that is adsorbed onto the surface of the adsorbent (roselle seeds) per unit weight or area. It is typically expressed in units such as milligrams of adsorbate (Cr6+) per gram of adsorbent.

The absorbance value decreases when RSE biocoagulant is applied up to 30 × 103 ppm and increases again at higher doses. However, while utilizing RSE, the adsorption concentration of chromium metal was limited to 30 × 103 ppm and will decrease when the dose is raised.

RSE biocoagulant has a pattern of increasing the percentage of adsorbed chromium metal (Cr6+) at doses up to 30×10^3 ppm. Still, it decreased if the dose was increased, which was due to the results of the adsorbed concentration of chromium metal (Cr6+) in Figure 1. According to these findings, 68.69% of the chromium metal (Cr6+) was adsorbed at the dosage of 30×10^3 ppm, which was the highest among the doses.

The pH effect on the coagulation process

Following that, a 90-minute contact duration with a dosage of 30×10^3 ppm was examined to identify the ideal pH for employing RSE biocoagulant. Table 4 shows the absorbance values that were obtained. The absorbance value for pH 2 was 0.617, the lowest absorption value among the pHs tested. When the pH went up to 4, the absorbance value climbed to 0.704, and the absorbance value continued to rise when the pH was raised, especially at pH 4, 5, 6, 8, and 10.

Table 1. IR spectrum variations between roselle seeds (biocoagulant) before and following contact with (Cr6+)

Seeds oselle	Roselle seeds+(Cr6+)	Range (cm^{-1})	Intensity	Functional group	Kind of vibration
722.37	723.34	690-900	Solid	C-H deformation	Aromatic ring
1165.05	1166.98	1050-1300	Solid	O-H stretching	Alcohol, ether, carboxylic acid, ester
1462.11	1464.03	1340-1470	Solid	C-H bending	Alkane
1662.71	1662.71	1610-1680	Inconsistent	C-H bending	Alkene
1744.69	1744.69	1690-1760	Solid	C=O stretching	Aldehyde, ketones, carboxylic acid, ester
2854.77	2854.77	2850-2970	Solid	C-H stretching	Alkane
2926.14	2925.17	2850-2970	Solid	C-H stretching	Alkane
3380.4	3380.4	3300-3500	Mid	O-H stretching	Amine, amide

Table 2. IR spectrum variations between rice straw (adsorbent) before and following contact with (Cr6+)

Rice straw	Rice straw+(Cr6+)	Range (cm^{-1})	Intensity	Functional group	Kind of vibration
789.88	792.78	675-995	Solid	C-H stretching	Alkene
1098.51	1097.54	1050-1300	Solid	C-O bending	Alcohol, eter, acid, carboxylate, ester
1316.47	1319.37	1300-1370	Solid	NO$_2$ stretching	Nitro compound
1371.45	1372.41	1300-1370	Solid	NO$_2$ stretching	Nitro compound
1509.36	1511.29	1500-1570	Solid	NO$_2$ stretching	Nitro compound
1623.17	1628.95	1610-1680	Inconsistent	C=C stretching	Alkene
2156.51	2135.29	2100-2260	Inconsistent	C=C stretching	Alkyne
2920.35	2902.03	2850-2970	Solid	C-H stretching	Alkane

Table3. Optimization of RSE biocoagulants depending on doses

Dosage (10^3 ppm)	The absorbance value on average	Adsorption concentration (ppm)
0 (control)	1.981	0
10	0.708	1.902
20	0.668	1.961
30	0.623	2.028
40	0.644	1.997
50	0.668	1.959

Table 4. pH-based RSE biocoagulant optimization (dosage = 30 × 10^3 ppm)

pH	The absorbance value on average	Adsorbed concentration (ppm)
2	0.617	2.038
4	0.704	1.907
5	0.675	1.950
6	0.678	1.947
8	0.671	1.956
10	0.664	1.967

Optimization of coagulant adsorbent combination

This optimization was carried out based on comparing the composition and contact time. Optimization results (Table 5) were obtained based on the composition of the RSE coagulants and rice straw adsorbent. The ratio of 1:0.5 has the lowest absorbance value compared to other comparisons, which is 0.565 mL L^{-1}. In addition, the comparison produces the highest concentration of chromium metal (Cr^{6+}) metal compared to other comparisons, which is 2.115 ppm. Based on Table 6, the concentration of adsorbed substances increased with increasing contact time from 1.552 ppm at the 30th minute to 1.632 ppm at the 150th minute. After the 150th minute, the adsorbed concentration did not increase anymore, even returning to the initial value at the 180th minute.

Figure 2 shows that the percentage of chromium metal (Cr6+) adsorption is dependent on the solution's pH conditions. pH 2 gives the highest adsorption rate (69.02%). Figure 3 revealed that the lowest adsorption percentage is at the extremes 1:0 = 68.70% and 0:1 = 67.49%, where only one component was used, either coagulant or adsorbent alone. This suggests that neither coagulant nor adsorbent alone is highly effective in adsorbing Cr^{6+}. The maximum adsorption percentage, 71.63%, occurs at the ratio 1:0.5, where the coagulant was mixed with half the proportion of adsorbent. This indicates that a balanced combination of coagulant and adsorbent significantly enhances Cr^{6+} adsorption efficiency.

Based on Figure 4, the optimal contact time for Cr^{6+} adsorption is 150 minutes, where the percentage reaches its peak at 55.30%. Beyond 150 minutes, the adsorption efficiency decreases due to Cr^{6+} ions are released back into the solution over time. This trend shows that the adsorption efficiency improves with longer contact time, as the coagulant and adsorbent have more time to interact with Cr^{6+} ions.

Table 5. Optimization of RSE biocoagulant and rice straw (RS) adsorbent combinations based on composition ratio (reference contact time = 90 minutes)

Comparison (RSE:RS)	Compositions of average absorbance values (mL L^{-1})	Adsorbed concentration (ppm)
1:0	0.623	2.029
1:0.25	0.599	2.065
1:0.5	0.565	2.115
1:0.75	0.588	2.081
1:1	0.594	2.072
0.75:1	0.576	2.099
0.5:1	0.584	2.087
0.25:1	0.588	2.081
0:1	0.647	1.993

Table 6. Optimization of coagulant and adsorbent combinations based on contact time

Contact time (minutes)	Average absorbance value (mL L^{-1})	Adsorbed concentration (ppm)
30	0.572	1.552
60	0.561	1.568
90	0.539	1.601
120	0.530	1.615
150	0.518	1.632
180	0.572	1.552

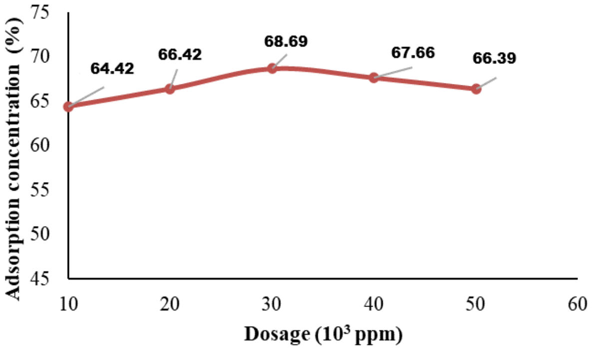

Figure 1. The chromium metal (Cr6+) adsorbed percentage depends on the doses of the RSE biocoagulant

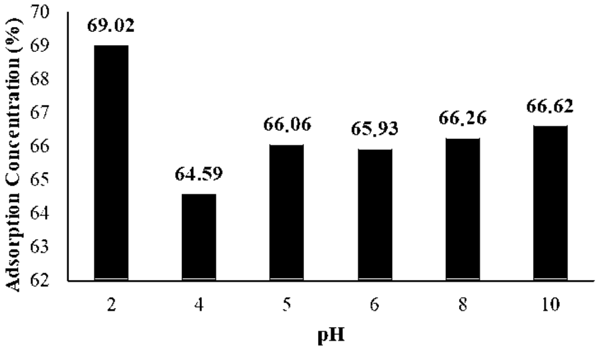

Figure 2. Adsorption of chromium metal (Cr) as a percentage of pH

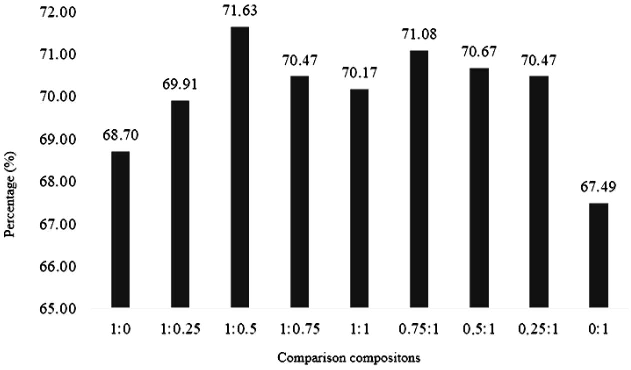

Figure 3. Percentage of chromium metal adsorption (Cr6+) based on the comparison of coagulant and adsorbent compositions

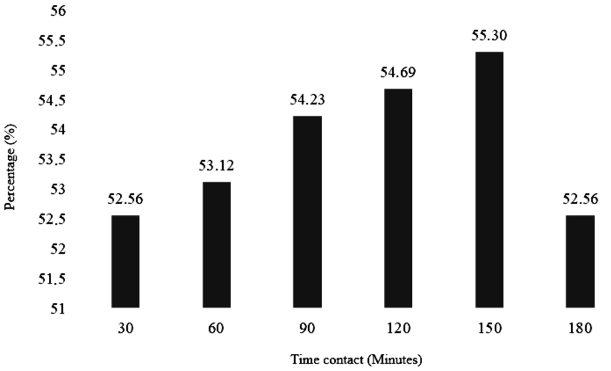

Figure 4. Percentage of chromium metal adsorption (Cr6+) based on contact time with coagulant composition and adsorbent 1: 0.5

Langmuir and Freundlich isotherm

Adsorption equilibrium can be interpreted as a mathematical translation of a particular isotherm in the adsorbent used. In general, overall adsorption predictions can be made by modeling isotherm data with linear analysis as a mathematical approach. The isotherm model is commonly used in determining the equilibrium model of adsorption in various studies, namely the Langmuir isotherm and the Freundlich isotherm.

Figure 5 shows the Langmuir isotherm pattern with a determinant coefficient of 0.998. The Langmuir isotherm accounts for the surface heterogeneity and multilayer adsorption, making it a more accurate representation of the adsorption process for rice straw. Thus, the Langmuir model effectively captures the adsorption mechanism of Cr^{6+} onto rice straw, highlighting its suitability for describing adsorption on natural heterogeneous adsorbents.

The resulting Freundlich isotherm graph (Figure 6) shows that the line formed is linear with intercept = log k and slope = 1/n. It can be seen that the (Cr^{6+}) adsorption research by rice straw follows the Freundlich isotherm pattern at a determinant coefficient of 0.9997. This behavior is attributed to the heterogeneous nature of the rice straw surface, which provides a variety of adsorption sites with differing affinities for Cr^{6+} ions. Rice straw, as a natural and porous material, contains cellulose, hemicellulose, lignin, and silica, which contribute functional groups such as hydroxyl and carboxyl.

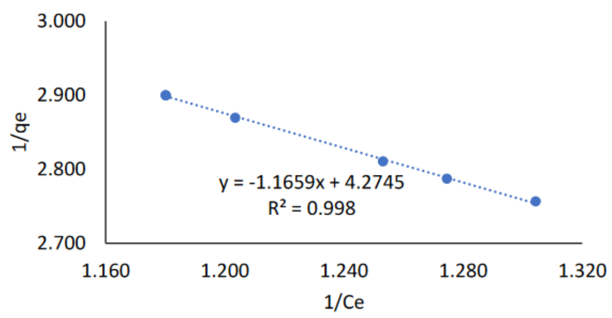

Figure 5. Graph of the Langmuir isotherm

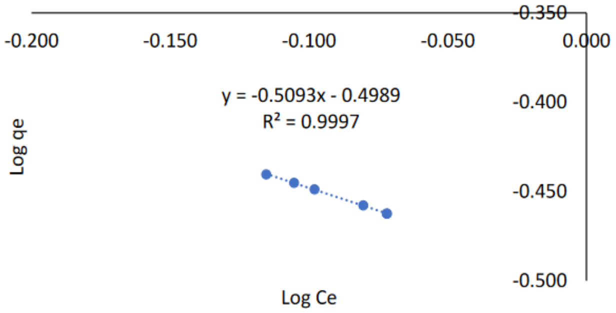

Figure 6. Graph of isotherm Freundlich

Discussion

The updated FTIR analysis, supported by the data from Table 1, shows a clear shift in the IR spectra of roselle seeds before and after contact with ($Cr6^+$). The absorption band for C-H deformation of the aromatic ring shifted slightly from 722.37 to 723.34 cm^{-1}. Similarly, the O-H stretching associated with alcohol, ether, carboxylic acid, and ester moved from 1,165.05 to 1,166.98 cm^{-1}, indicating interaction with (Cr6+). The C-H bending of alkane also showed a minor shift from 1,462.11 to 1,464.03 cm^{-1}, further supporting the occurrence of bonding between roselle seeds and (Cr6+). The shifts in wave numbers reflect chemical interactions, particularly with alkyl isothiocyanate, which is responsible for the coagulation process and leads to the reduction of (Cr6+).

In contrast, Table 2 shows the changes in the IR spectrum of rice straw. The absorption band for C-H stretching in alkenes shifted from 789.88 to 792.78 cm^{-1} after contact with (Cr6+), suggesting an interaction between the rice straw and (Cr6+) ions. A similar shift was observed in the NO_2 stretching, where wave numbers changed from 1,316.47 to 1,319.37 cm^{-1} and from 1,509.36 to 1,511.29 cm^{-1}. This interaction indicates that nitro compounds in the rice straw played a role in the adsorption process. The changes in the C=C stretching vibrations from 2,156.51 to 2,135.29 cm^{-1} further support the conclusion that multiple chemical bonds within the rice straw structure interact with (Cr6+), leading to higher adsorption capacity.

According to Table 1, most of the chemical compounds in roselle seeds before and after contact with (Cr^{6+}) are similar. However, the uptake in roselle seeds after interaction with (Cr^{6+}) shifted, and some has been lost because there was an interaction and bond between roselle seeds and (Cr^{6+}), such as a shift and loss of the wave number of the active chemical compounds of roselle seeds' alkyl isothiocyanate (N=C=S) after making contact with (Cr^{6+}). Based on measurements of the IR spectrum, it may be assumed that the active chemical particles, 4-alpha-4-rhamonsiloxy-benzyl-isothiocyanate, were responsible for the drop in (Cr^{6+}) levels. These chemically active substances mix with roselle seed particles to create bigger clumps that settle (adsorption between the positively charged roselle seed protein and oxo anions (HCrO4-). A study by Bahrodin et al. (2021) emphasizes the impact caused by chemical coagulants, which include chemical residues, toxic sludge, and health diseases, upon prolonged consumption. Thus, there is an emerging trend of transferring from chemical to natural coagulants. According to Hoong and Ismail (2018), rosella seeds can be chemical coagulants in processing industrial liquid waste since they are safer, biodegradable, and ecologically friendly. Zheng et al. (2021) argue that *H. sabdariffa* can be used as a natural coagulant because of the high protein content in its seeds. The protein content in *H. sabdariffa* is positively charged, while the dye waste is negatively charged. Coagulation occurs between the protein and dye waste, causing this mixture to become heavier and denser. This is what causes dyes to be removed from wastewater through sedimentation.

Table 2 shows that most of the functional groups found in rice straw adsorbents, before and after being interacted with (Cr^{6+}), tended to be the same; the difference is seen in absorption after being interacted with (Cr6+), which experiences a magnification, and some are missing. This is caused by the interaction and bond between rice straw and (Cr^{6+}), such as shifting. It is assumed that the formation of complexes between (Cr^{6+}) and certain functional groups in rice straw can cause a greater absorption shift, but does not always change the structure of the functional group permanently. (Cr^{6+}) can affect the saturation level of adsorption sites in rice straw and the interaction type. The type and structure of functional groups in rice straw influence the strength of interaction with (Cr^{6+}). Functional groups with a more complex structure and larger surface area have a higher adsorption capacity for (Cr^{6+}). Ponzoni et al. (2015) argue that high concentrations of (Cr^{6+}) can cause competition between functional groups to bind (Cr^{6+}) ions (Jahanmahin et al. 2016). This can induce an absorption shift, where (Cr^{6+}) binds to functional groups with higher affinity, although these functional groups do not always change their structure permanently. Hasan et al. (2009) stated that the interaction between (Cr^{6+}) and rice straw is not limited to electrostatic attraction. Other mechanisms, such as complexation, ion exchange, and physical adsorption, may also occur.

The absorbance esteem, adsorption fixation, and representation of the level of adsorbed chromium metal (Cr^{6+}) in Figure 1, the utilization of RSE biocoagulant at a concentration of up to 30 × 10^3 ppm, shows that the coagulation cycle is moving toward the balance point. In contrast, the equilibrium point happens at a concentration of more than 30×10^3 ppm, where there is an expansion in the absorbance value and a reduction in the adsorption capacity of chromium metal (Cr^{6+}). Meanwhile, the decrease in the percentage of adsorbed chromium metal (Cr^{6+}) was not excessive and tended to be consistent because a dense layer of biocoagulant particles surrounds the effluent particles. The surface of the effluent particles is saturated in this form, and therefore, the probability of the two interacting is relatively low. Apart from that, the precipitated chromium metal (Cr^{6+}) will dissolve again. As a result, there was no more coagulation process, which is no longer efficient (Yuniyarti and Isbandi 2018).

The formation of flocks (sediments) during the coagulation process is highly reliant on the coagulant dose utilized. The coagulant charge neutralizes liquid waste particles and encourages them to cling together. Because low-liquid-waste particles have low energy and form weak and tiny precipitates, a minimal dose quantity will neutralize them. Excessive dosing of liquid waste can potentially result in charge reversal, resulting in poor and inefficient coagulation activity (Patel and Vashi 2012). This biocoagulant may bind chromium metal (Cr6+) present in liquid batik waste colors due to its high amount of cationic peptides such as glutamate and arginine. Subsequently, coagulation between the protein and the color occurs, causing it to grow heavier and denser. Due to this, dyes are eliminated from wastewater through sedimentation (Alsukaibi 2022). Aside from that, pH is another aspect that affects the effective utilization of RSE in the coagulation process.

In Figure 2, we found the percentage of chromium metal (Cr6+) adsorption owing to the pH conditions of the solution. According to the results from the absorbance value, adsorption concentration, and visualization of the percentage of chromium metal (Cr6+) adsorption in Figure 2, pH is one of the affecting elements. Significantly impacts the stability of the proteins present in the seeds throughout the coagulation process (Jones 2016). Based on Figure 3, the optimal composition for removing Cr^{6+} using a coagulant and adsorbent mixture is at a ratio of 1:0.5. This balance ensures the best performance, leveraging the combined effects of both components. Using only one component or deviating too far from this ratio reduces the adsorption efficiency due to incomplete removal mechanisms. When the proportion of either coagulant or adsorbent dominates, the adsorption efficiency decreases, suggesting that both components are essential and work synergistically to maximize chromium removal. The slight decrease in efficiency beyond the 1:0.5 ratio indicates diminishing returns or saturation effects in the adsorption process.

Figure 4 shows that the optimal contact time for Cr^{6+} adsorption using a coagulant-to-adsorbent ratio of 1:0.5 is 150 minutes, achieving the highest efficiency of 55.30%. The adsorption efficiency decreases due to Cr^{6+} ions are released back into the solution over time. According to Yong and Ismail (2016), the coagulation process employing RSE is very pH-dependent. The negative charges in the artificial sample solution will attach to the cationic amino acids found in RSE, such as glutamic acid and aspartic acid (Jones 2016). Acidic circumstances enhance the density of positive charges (H+) surrounding the coagulant hydrolysate and improve the ability of cationic amino acid groups to behave as coagulants. Cationic coagulant proteins will neutralize dissociated organic components in liquid waste and promote particle adhesion (Cao et al. 2010). As a result, chromium metal adsorption effectiveness increases in acidic conditions, particularly at pH 2. The application of RSE effectively reduced turbidity and Chemical Oxygen Demand (COD) in liquid waste, supporting the findings obtained in this study. Consequently, RSE has the most excellent efficacy in eliminating turbidity and COD in acidic circumstances (pH 2) during coagulation, while its efficacy decreases in alkaline conditions (8-11). In acidic circumstances (pH 2), RSE removes turbidity and COD with 90.69 and 54.38% efficiency, respectively. Other research indicates that RSE works successfully in acidic circumstances during the coagulation process (Sibartie and Ismail 2018).

According to Yong and Ismail (2016), RSE can remove up to 95.1% of dyes. Furthermore, using RSE as a biocoagulant with other approaches, such as adsorption, would boost its efficiency. According to Hoong and Ismail (2018), the use of RSE as a biocoagulant and activated carbon as an adsorbent at coagulant and adsorbent dosages of 209 and 150 mg L^{-1}, respectively, at pH 2, was able to remove up to 96.67% of dyes.

The combination of RSE and rice straw adsorbent coagulants with a ratio of 1: 0.5 is the most optimal to reduce chromium metal levels (Cr^{6+}) in a sample solution. Thus, the most optimum combination of RSE and rice straw adsorbents was found in a ratio of 1: 0.5 (Table 5). In line with the results of the concentration of chromium metal (Cr^{6+}), the percentage of chromium metal (Cr^{6+}) is adsorbed in a sample solution using several comparisons of RSE coagulants and rice straw adsorbents showing that the ratio of 1: 0.5 produces the highest percentage, which is 71.63% (Figure 3). The lowest rate is produced by the coagulant RSE and rice straw adsorbent in a ratio of 0: 1, which is 67.49%. A ratio of 1:0.5 probably produces the optimal combination between the amount of RSE coagulant and the adsorption capacity of rice straw. At a ratio of 1:0.5, this interaction may reach an optimal balance, allowing efficient (Cr^{6+}) adsorption and minimal interference from other compounds. Other ratios may result in less optimal interactions, such as competition between compounds for adsorption sites or the formation of unstable complexes. According to Jian et al. (2016), rice straw has complex surface properties, with various functional groups that can bind (Cr^{6+}). According to Zhang et al. (2018), the dominant type of interaction influences the saturation level of adsorption sites and the stability of the (Cr^{6+}) rice straw complex. Mhlarhi et al. (2023) argue that (Cr^{6+}) binds to functional groups with higher affinity, although these functional groups do not always change its structure permanently.

The trend (Figure 4) is that the percentage increase in adsorbed by chromium metal (Cr^{6+}) occurs at contact times up to 150 minutes, but there is a decrease in percentage at a longer contact time of 180 minutes. The percentage is adsorbed by chromium metal (Cr^{6+}) due to the highest combination of RSE and Adsorbent rice straw coagulants occurring during contact for 150 minutes, which is 55.30%.

Thus, the optimal condition of the coagulant combination of RSE and rice straw adsorbents occurs in a ratio of 1:0.5 with a contact time of 150 minutes in the sample solution. At a contact time of 150 minutes, a balance was reached between the adsorption and desorption rates of (Cr^{6+}). At a contact time of 180 minutes, (Cr^{6+}) desorption began to dominate, causing a decrease in the percentage of (Cr^{6+}) adsorbed. Over time, the adsorption rate slows due to the reduction in available adsorption sites and the increase in the activation energy required to bind (Cr^{6+}). Cr($^{6+}$) is present in ionic form (CrO_4^{2-}), which has a negative charge (Tian et al. 2023). Rice straw contains functional groups such as carboxyl (COOH) and hydroxyl (OH), which have negative charges (Ahmed et al. 2023). Electrostatic attraction occurs between (Cr^{6+}) and negatively charged functional groups, causing (Cr^{6+}) to be adsorbed on the surface of rice straw.

Langmuir isotherm indicates (Figure 5) that the adsorption process is chemical, and a single layer of (Cr6+) is above the surface of the rice straw adsorbent at a constant temperature. The appropriate area variation and the porosity of the adsorbent can be tolerated with the Qm constant, which shows that the higher maximum adsorption capacity can be produced from the surface area and volume of large pores. The greater the Qm value in the Langmuir equation shows that the greater the adsorption capacity. It can be seen that the Cr6+ adsorption research by rice straw follows the Freundlich isotherm (Figure 5) pattern due to the porous structure of rice straw, which comprises micro- and mesopores, increasing the available surface area for adsorption and supporting multilayer adsorption, particularly at higher Cr^{6+} concentrations. Research conducted by Purnamasari et al. (2017) obtained an R2 value of 1 for the equation of Langmuir and Freundlich. However, the cost of b is lower than Kf; this means that this isotherm controller is a Langmuir rather than a Freundlich one because it is strengthened by results that refer to the price of b and Kf. At specific pressures, the level of adsorption is determined by the value of b, which depends on the temperature and adsorption enthalpy. The value of b is increased if there is a decrease in system temperature.

One of the considerations for a person who will adopt an innovation is whether the innovation benefits the adopter. Based on the results above, most batik businesses are optimistic that this innovation can provide benefits, even though a small portion of them judge that this is not the case (2%). This is inseparable from the costs incurred for this innovation, which is relatively cheaper than the conventional materials they used previously in the processing of batik liquid waste. This innovation offers a more cost-effective solution than traditional liquid waste processing methods. Cheaper raw material costs and more efficient processes can increase batik business profits. This is an essential consideration for batik entrepreneurs, especially for those who have limited capital. In addition, batik businesses assess this innovation by their conditions and habits in processing liquid waste (compatible). Business actors also realize that this innovation aligns with their expectations to preserve the environment. Batik entrepreneurs recognize the importance of protecting the environment. This innovation offers an environmentally friendly solution to reducing water pollution from liquid batik waste. This aligns with the expectations of batik entrepreneurs to run their business sustainably and responsibly.

The complexity of applying innovation also has an effect. The majority of business actors assess positive, which shows that the innovation of the combination of RSE coagulants and rice straw adsorbents has a low level of complexity, so it can be easily applied in processing batik liquid waste. This means that most business people assess this innovation as having a low level of complexity. The wastewater treatment process using a combination of RSE coagulant and rice straw adsorbent is easy to implement and understand. This convenience allows businesses to adopt innovations without making significant changes to existing infrastructure or expertise. Another critical factor that determines whether an innovation can be adopted which can be trialability and observability. They judge very positive (90%) and positive (10%) that this innovation can be tried first in a limited manner, and they judge very positively (89%) and positive (11%) can be directly observed in the processing of batik liquid waste. By offering a low-risk approach and clear visibility of benefits, trialability and observability play a significant role in why batik businesses show such positive sentiment towards this wastewater treatment innovation.

This study demonstrated the potential of *H. sabdariffa* seed extract and rice straw as effective natural coagulant-adsorbents for reducing chromium (Cr^{6+}) levels in artificial batik liquid waste. The optimal coagulation condition using RSE was achieved at a dosage of 30 × 10^3 ppm and pH 2, resulting in a Cr^{6+} reduction of 68.69 and 61.02%, respectively. The efficiency of RSE is influenced by its protein content, with both underdosing and overdosing leading to reduced coagulation performance due to insufficient charge neutralization or charge reversal effects. Additionally, RSE showed greater coagulation efficiency under acidic conditions, with performance declining at higher pH values.

The positive response from batik business actors toward the innovation of combining RSE and rice straw suggests practical potential for its application in small-scale industries. However, further research is recommended to evaluate floc volume, sedimentation time, and its performance under actual batik wastewater conditions, considering the complexity and variability of real waste characteristics.

Based on the FTIR analysis and data presented in Table 1, significant shifts in the IR spectrum of roselle seeds before and after contact with Cr^{6+} were observed. The absorption band for C-H deformation in the aromatic ring slightly shifted from 722.37 to 723.34 cm^{-1}. Similarly, the O-H stretching associated with alcohols, ethers, carboxylic acids, and esters shifted from 1,165.05 to 1,166.98 cm^{-1}, indicating an interaction with Cr^{6+}. The C-H bending in alkanes also experienced a minor shift from 1,462.11 to 1,464.03 cm^{-1}, further supporting the formation of bonds between roselle seeds and Cr^{6+}. These wavenumber shifts reflect chemical interactions, particularly with alkyl isothiocyanates, which play a role in the coagulation process and lead to Cr^{6+} reduction. The chemical compounds interacting with roselle seeds before and after contact with Cr^{6+} remained relatively consistent. However, after interaction with Cr^{6+}, certain shifts and the disappearance of specific compounds were observed due to bond formation between roselle seeds and Cr^{6+}, such as the shift and disappearance of the active alkyl isothiocyanate (N=C=S) wavenumber in roselle seeds. Based on IR spectrum measurements, it can be assumed that the active chemical particle, 4-alpha-4-rhamnosyloxy-benzyl-isothiocyanate, is responsible for Cr^{6+} reduction. This active compound interacts with roselle seed particles to form larger flocs, which settle through an adsorption process between the positively charged roselle seed proteins and the oxide anion ($HCrO_4^-$).

Analysis of Table 2, shows changes in the IR spectrum of rice straw, where the absorption band for C-H stretching in alkenes shifted from 789.88 to 792.78 cm^{-1} after contact with Cr^{6+}, indicating an interaction between rice straw and Cr^{6+} ions. A similar shift was observed in NO_2 stretching, where the wave numbers changed from 1,316.47 to 1,319.37 cm^{-1} and from 1,509.36 to 1,511.29 cm^{-1}. This interaction suggests that nitro compounds in rice straw play a role in the adsorption process. Changes in C=C stretching vibrations from 2,156.51 to 2,135.29 cm^{-1} further support the conclusion that some chemical bonds in the rice straw structure interact with Cr^{6+}, leading to increased adsorption capacity. The measurements presented in Table 2 indicate that most functional groups in rice straw remained unchanged before and after interaction with Cr^{6+}. However, after interacting with Cr^{6+}, some absorption bands intensified while others disappeared. This phenomenon is attributed to interactions and bonding between rice straw and Cr^{6+}, such as spectral shifts. High Cr^{6+} concentrations also caused competition among ion-binding sites, leading to absorption shifts (Ponzoni et al. 2015). The interaction between Cr^{6+} and rice straw can result in complexation, ion exchange, and physical adsorption, rather than solely electrostatic attraction (Hasan et al. 2009).

Absorbance values, adsorption concentration, and the percentage of adsorbed chromium (Cr^{6+}) can be observed in Figure 1. The use of RSE bio-coagulant at doses up to 30 × 10^3 ppm showed that the coagulation process approached equilibrium. However, at doses exceeding 30 × 10^3 ppm, absorbance values increased while Cr^{6+} adsorption concentration decreased. This decline in adsorption percentage occurs because a dense bio-coagulant layer surrounds the waste particles, reducing interaction and allowing previously precipitated chromium to redissolve, making coagulation ineffective (Yuniyarti and Isbandi 2018). Positively charged coagulants neutralize liquid waste particles, enabling them to aggregate. However, excessive coagulant doses may cause charge reversal, reducing coagulation efficiency (Patel and Vashi 2012).

Roselle seeds function as a bio-coagulant by binding Cr^{6+} in batik wastewater due to their high content of cationic peptides, such as glutamate and arginine. The coagulation process between proteins and dye compounds increases the weight and density of the mixture, facilitating the removal of dyes from wastewater via sedimentation (Alsukaibi 2022). Additionally, pH influences the effectiveness of roselle seeds in coagulation. A previous study by Sibartie and Ismail (2018) demonstrated that using roselle seeds as a bio-coagulant in wastewater treatment was successful. According to Yong and Ismail (2016), RSE can remove up to 95.1% of dyes. Furthermore, using RSE as a bio-coagulant in combination with other methods, such as adsorption, can enhance its efficiency. Hoong and Ismail (2018) reported that a combination of RSE as a bio-coagulant and activated carbon as an adsorbent, at doses of 209 and 150 mg L^{-1}, respectively, at pH 2, could remove up to 96.67% of dyes. The optimal combination of roselle seed coagulant and rice straw adsorbent was found at a 1:0.5 ratio, which was most effective in reducing Cr^{6+} concentrations in the sample solution. Consistent with the Cr^{6+} concentration results, the percentage of Cr^{6+} adsorbed in the solution using various RSE-to-rice-straw ratios showed that a 1:0.5 ratio achieved the highest adsorption percentage of 71.63%. This ratio allows for optimal equilibrium, facilitating efficient Cr^{6+} adsorption with minimal interference from other compounds. Other ratios may result in less effective interactions, such as competition for adsorption sites or the formation of unstable complexes. According to Jian et al. (2016), rice straw has a complex surface with various functional groups capable of binding Cr^{6+}. Zhang et al. (2018) stated that the dominant type of interaction influences the saturation level of adsorption sites and the stability of the Cr^{6+} rice straw complex. Mhlarhi et al. (2023) suggested that Cr^{6+} binds to functional groups with higher affinity, though these functional groups do not always undergo permanent structural changes.

One of the factors influencing innovation adoption is the perceived benefits. Based on the findings, most batik entrepreneurs positively assessed the innovation, with only a small percentage (2%) expressing reservations. The lower cost compared to conventional materials made this innovation more attractive. Additionally, its eco-friendliness aligns with batik entrepreneurs' aspirations for sustainable and responsible business practices. The complexity of implementation also plays a role. Most entrepreneurs found that the combination of RSE coagulant and rice straw absorbent had low complexity, making it easy to apply in batik wastewater treatment. With a low-risk approach and clear benefits, this innovation has been well-received by batik entrepreneurs.

This study demonstrates the effectiveness and cost-effectiveness of the combination of Roselle Seed Extract (RSE) and rice straw effectively reduces hexavalent chromium (Cr^{6+}) levels in synthetic batik wastewater. The optimization results indicate that the optimal dose of RSE bio-coagulant is 30 × 10^3 ppm, with a Cr^{6+} adsorption efficiency of 68.69%. Coagulation was most effective at pH 2, achieving a Cr^{6+} reduction efficiency of 69.02%. The optimal combination of RSE coagulant and rice straw adsorbent was a 1:0.5 ratio, yielding the highest adsorption efficiency of 71.63%. Additionally, the optimal contact time for maximum efficiency was 150 minutes, beyond which Cr^{6+} ions began to desorb back into the solution. The combination of RSE and rice straw as a coagulant-adsorbent offers an environmentally friendly and cost-effective alternative to conventional chemical coagulants. This study confirms the potential of RSE as a natural, biodegradable, and effective coagulant for batik wastewater treatment. Implementing this method can help mitigate the environmental impact of the batik industry while providing a sustainable wastewater treatment alternative for small and medium enterprises. Further research is recommended to explore the efficiency of this method under various wastewater parameters and its impact on floc volume and sedimentation time.

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REFERENCES

Ahmed W, Mehmood S, Mahmood M, Ali S, Shakoor A, Núñez-Delgado A, Asghar RMA, Zhao H, Liu W, Li W. 2023. Adsorption of Pb (II) from wastewater using a red mud modified rice-straw biochar: Influencing factors and reusability. Environ Pollut 326: 121405. DOI: 10.1016/j.envpol.2023.121405.

Alsukaibi AK. 2022. Various approaches for the detoxification of toxic dyes in wastewater. Processes 10 (10): 1968. DOI: 10.3390/pr10101968.

Amutha K. 2017. Sustainable Chemical Management and Zero Discharges. In: Sustainable Fibres and Textiles. Woodhead Publishing, United Kingdom. DOI: 10.1016/B978-0-08-102041-8.00012-3.

Bahrodin MB, Zaidi NS, Hussein N, Sillanpää M, Prasetyo DD, Syafiuddin A. 2021. Recent Advances on coagulation-based treatment of wastewater: Transition from chemical to natural coagulant. Curr Pollut Rep 7: 379-391. DOI: 10.1007/s40726-021-00191-7.

Birgani PM, Ranjbar N, Abdullah RC, Wong KT, Lee G, Ibrahim S, Park C, Yoon Y, Jang M. 2016. An efficient and economical treatment for batik textile wastewater containing high levels of silicate and organic pollutants using a sequential process of acidification, magnesium oxide, and palm shell-based activated carbon application. J Environ Manag 184 (Pt 2): 229-239. DOI: 10.1016/j.jenvman.2016.09.066.

BSN. 2009. Water and Wastewater - Part 71: Test Method for Hexavalent Chromium (Cr-VI) in Test Samples by Spectrophotometry. 114/KEP/BSN/12/2009.

Budiyanto S, Anies, Purnaweni H, Sunoko HR. 2018. Invironmental analysis of the impacts of batik wastewater polution on the quality of dug well water in the batik industrial center of jenggot Pekalongan City. E3S Web Conf 31: 09008. DOI: 10.1051/e3sconf/20183109008.

Cao BC, Gao BY, Xu CH, Fu Y, Liu X. 2010. Effects of pH on coagulation behavior and floc properties in Yellow River Water treatment using ferric based coagulants. Chinese Sci Bull 55: 1382-1387. DOI: 10.1007/s11434-010-0087-5.

Diniyati W. 2012. Characteristics of well water around the liquid waste flow of the batik craft industry in Kliwonan Village, Masaran Sub-district, Sragen District. [Thesis]. Universitas Muhammadiyah Surakarta, Sukoharjo. [Indonesian]

Gummert M, Hung NV, Chivenge P, Douthwaite B. 2019. Sustainable Rice Straw Management. Springer Nature, Cham. DOI: 10.1007/978-3-030-32373-8.

Hasan MA, Selim YT, Mohamed KM. 2009. Removal of chromium from aqueous waste solution using liquid emulsion membrane. J Hazard Mater 168 (2-3): 1537-1541. DOI: 10.1016/j.jhazmat.2009.03.030.

Hastuti B, Masykur A, Hadi S. 2016. Modification of chitosan by swelling and crosslinking using epichlorohydrin as heavy metal Cr (VI) adsorbent in batik industry wastes. Mater Sci Eng 107: 012020. DOI: 10.1088/1757-899X/107/1/012020.

Hoong HNJ, Ismail N. 2018. Removal of dye in liquid waste by adsorption-coagulation combined system with *Hibiscus sabdariffa* as the coagulant. MATEC Web Conf 152: 01008. DOI: 10.1051/matecconf/201815201008.

Jahanmahin O, Montazer Rahmawati MM, Mohammadi T, Babaee J, Khosravi A. 2016. Cr (VI) ion removal from artificial waste water using supported liquid membrane. Chem Pap 70: 913-925. DOI: 10.1515/chempap-2016-0027.

Jian-Gang H, Di-Wu F, Xiu-Zhi L, Yong-li Z, Sajjad A. 2016. Mechanism of Cr^{6+}, Mn2+, Cu2+ and Cd2+ adsorption by a low-cost rice husk-derived biochar in aqueous solutions. Fresenius Environ Bull 25 (8): 2736-2744.

Jones AN. 2016. Investigating the potential of *Hibiscus* seed species as alternative water treatment material to the traditional chemicals. [Thesis]. The University of Birmingham, Birmingham.

Koosdaryani, Masykuri M, Purwanto E, Suranto. 2019. Batik industry liquid waste treatment using fito remidiation of water hyacinth with adsorbent consist of organic waste bagasse, rice husks and bamboo charcoal. IOP Conf Ser Mater Sci Eng 508: 012111. DOI: 10.1088/1757-899X/508/1/012111.

Li WC, Law FY, Chan YHM. 2017. Biosorption studies on copper (II) and cadmium (II) using pretreated rice straw and rice husk. Environ Sci Pollut Res 24 (10): 8903-8915. DOI: 10.1007/s11356-015-5081-7.

Liu Z, Zhou X, Chen X, Dai C, Zhang J, Zhang Y. 2013. Biosorption of clofibric acid and carbamazepine in aqueous solution by agricultural waste rice straw. J Environ Sci 25 (12): 2384-2395. DOI: 10.1016/S1001-0742(12)60324-6.

Mahamad MN, Zaini MAA, Zakaria ZA. 2015. Preparation and characterization of activated carbon from pineapple waste biomass for dye removal. Intl Biodeterior Biodegrad 102: 274-280. DOI: 10.1016/j.ibiod.2015.03.009.

Mhlarhi N, Gitari WM, Ayinde WB, Tavengwa NT, Mudzielwana R, Izevbekhai OU. 2023. Biosorption of toxic metal ions (Cr+ 6, Cd2+) and nutrients (PO43-) from aqueous solution by diatom biomass. J Environ Sci Health A Tox Hazard Subst Environ Eng 58 (5): 483-497. DOI: 10.1080/10934529.2023.2196929.

Patel H, Vashi RT. 2012. Removal of Congo red dye from its aqueous solution using natural coagulants. J Saudi Chem Soc 16 (2): 131-136. DOI: 10.1016/j.jscs.2010.12.003.

Pinasti M, Adawiyah WR. 2016. Co-opetition to promote growth of batik small and medium enterprises. Intl J Bus Soc 17 (3): 401-412. DOI: 10.33736/ijbs.532.2016.

Pirkarami A, Olya ME. 2017. Removal of dye from industrial liquid waste with an emphasis on improving economic efficiency and degradation mechanism. J Saudi Chem Soc 21: S179-S186. DOI: 10.1016/j.jscs.2013.12.008.

Ponzoni C, Lancellotti I, Barbieri L, Spinella A, Saladino ML, Martino DC, Caponetti E, Armetta F, Leonelli C. 2015. Chromium liquid waste inertization in an inorganic alkali activated matrix: Leaching and NMR multinuclear approach. J Hazard Mater 286: 474-483. DOI: 10.1016/j.jhazmat.2014.12.054.

Purnamasari I, Trisnaliani L, Fatria. 2017. The effect of pH and adsorption time in Fe and Mn concentration decreasing using zeolite in Enim River at Desa Darmo Tanjung Enim. KINETIKA 8 (3): 34-39. [Indonesian]

Saputro S, Masykuri M, Mahardiani L, Mulyani B, Qorina I, Yoshimura K, Takehara K, Matsuoka S. 2016. The usage of activated carbon from teak sawdust (*Tectona grandis* l.f.) and zeolite for the adsorption of Cr(VI) and its analysis using solid-phase spectrophotometry (sps). IOP Conf: Mater Sci Eng 176: 012019. DOI: 10.1088/1757-899X/176/1/012019.

Sibartie S, Ismail N. 2018. Potential of *Hibiscus sabdariffa* and *Jatropha curcas* as natural coagulants in the treatment of pharmaceutical wastewater. MATEC Web Conf 152: 01009. DOI: 10.1051/matecconf/201815201009.

Taufik SH, Ahmad SA, Zakaria NN, Shaharuddin NA, Azmi AA, Khalid FE, Merican F, Convey P, Zulkharnain A, Abdul KK. 2021. Rice straw as a natural sorbent in a filter system as an approach to bioremediate diesel pollution. Water 13 (23): 3317. DOI: 10.3390/w13233317.

Tian H, Wang L, Xu Y, Du Y, Ma Y, Chen Y, Ye H, Chen S, Zhang TC. 2023. Efficient reduction of Cr (VI) and recovery of Fe from chromite ore processing residue by waste biomass. Environ Technol Innov 30: 103046. DOI: 10.1016/j.eti.2023.103046.

Tounkara F, Amza T, Lagnika C, Le GW, Shi YH. 2013. Extraction, characterization, nutritional and functional properties of roselle (*Hibiscus sabdariffa* Linn) seed proteins. Songklanakarin J Sci Technol 35 (2): 159-166.

Yong MY, Ismail N. 2016. Optimisation of *Hibiscus sabdariffa* as a natural coagulant to treat Congo red in liquid waste. J Eng Sci Technol 11: 153-165.

Yuniyarti S, Isbandi T. 2018. Degradation of chrome waste and recycling for leather tanning process materials using quicklime coagulant. Jurnal Rekayasa Lingkungan 18 (1): 10-25. DOI: 10.37412/jrl.v18i1.18. [Indonesian]

Zarkasi K, Moelyaningrum AD, Ningrum PT. 2018. The use of activated charcoal from durian skin (*Durio zibethinus* Murr) on the adsorption level of chromium (Cr 6+) in batik waste. Efektor 5 (2): 67-73. DOI: 10.29407/e.v5i2.12069. [Indonesian]

Zhang S, Wang Z, Chen H, Kai C, Jiang M, Wang Q, Zhou Z. 2018. Polyethylenimine functionalized Fe3O4/steam-exploded rice straw composite as an efficient adsorbent for Cr (VI) removal. Appl Surf Sci 440: 1277-1285. DOI: 10.1016/j.apsusc.2018.01.191.

Zheng WC, Ismail N, Boboi CO, Lin CB. 2021. Life cycle analysis for *Hibiscus sabdariffa* powder manufactured by freeze drying for wastewater application. EDP Sciences 335: 1002. DOI: 10.1051/matecconf/202133501002.