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Optimizing Anionic Polyacrylamide as Precipitating Agent for Effective Copper Ion Removal in Educational Laboratory Wastewater Treatment

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Abstract: This research highlights the potential of anionic polyacrylamide as a main treatment agent for liquid waste from educational laboratories, particularly in the removal of copper ions. This study using experiment with varies the concentration of anionic polyacrylamide with 3, 5, and 7% weight per weight. The initial concentration of copper in liquid waste was very high ranging between 600 mg/L. The findings indicate that the application of anionic polyacrylamide in wastewater treatment significantly reduces the concentration of copper ions, especially in wastewater from educational laboratories. Specifically, anionic polyacrylamide, at a concentration of 3% w/w, effectively removed almost all copper ions from the wastewater found in analytical chemistry laboratory and also achieved the quality standard of treated wastewater for copper parameter. The pH of the treated wastewater is critical in determining the overall effectiveness of the treatment, with a higher pH resulting in more effective coagulation of copper ions. The effectiveness of the treatment is influenced by the pH of the wastewater and the concentration of the polyacrylamide used. Further studies are needed on other types of heavy metals that can be coagulated using this method in order to gain a more comprehensive understanding.

Keywords: Anionic polyacrylamide; Coagulation; Educational laboratories; Wastewater

Introduction

Education involves more than just teaching and learning within the classroom; it includes various activities such as practical work, research, and laboratory experiments in educational laboratories. These experiences are crucial for giving students hands-on learning opportunities while also encouraging critical thinking and problem-solving skills (Mohzana et al., 2023). However, it is important to manage these activities responsibly for improving education (Asmarany et al., 2024), as they can potentially lead to environmental pollution if not handled correctly.

Laboratories play a significant role in producing wastewater, particularly chemical waste, which is considered hazardous compared to regular domestic waste. Waste generated from educational laboratories comes from a variety of activities, including research, teaching practices, product development in industrial and agricultural settings, as well as analysis and media testing. Generally, laboratory waste contains chemical substances that are often the result of unnecessary or excessive use of chemicals or chemical compounds. If released into the air, water, or soil, these substances can pose risks to human health and the environment (Dong et al., 2014; Putra et al., 2017).

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Educational laboratory activities typically generate both solid and liquid waste. This liquid waste is generally categorized as hazardous and toxic waste, including organic liquid waste such as organic dyes, indicators, and solvents, as well as inorganic liquid waste such as heavy metal waste (Dhenkula et al., 2024; Magriotis et al., 2021; Saifuddin et al., 2023).

Heavy metal waste generated from laboratory activities can originate from several sources. For example, the leftover heavy metal reagents that remains after chemical reactions during experiments. Additionally, the washing of laboratory equipment, such as glassware and instruments, can lead to the accumulation of heavy metal residues, especially if the equipment was used to handle or contain such substances. Furthermore, various research activities, ranging from analytical tests to synthesis procedures, can produce heavy metal waste as byproducts. Heavy metal waste is a significant environmental pollutant mostly found in aquatic environments that has a negative impact on aquatic biota and is characterized by its toxic properties and its propensity to bio-accumulate in living organisms (Bashir et al., 2022; Fitri et al., 2024). Certain heavy metals, including manganese, copper, chromium, cobalt, zinc, iron, and nickel, are essential for living organisms. Although those heavy metals are needed, it is only up to a certain threshold. In contrast, other heavy metals such as cadmium, arsenic, mercury, and lead are non-essential and can be toxic even in small amounts and could be carcinogenic, causing effects that range from acute to chronic health issues (Amalia et al., 2023; Bibi et al., 2023; Qasem et al., 2021; Zou et al., 2016).

All of heavy metals are persistent pollutants which do not biodegrade and can accumulate in the environment over time (Yusrizal et al., 2024). Their thermal stability allows them to resist high temperatures without breaking down, contributing to their longevity in ecosystems. Furthermore, these heavy metals have long biological half-lives, which mean they remain in living organisms for extended periods, posing risks to human health and wildlife (Al-Massaedh & Khalili, 2021; Asiminicesei et al., 2024).

Copper is a significant contributor to heavy metal liquid waste generated during various laboratory activities and it common found in the wastewater (Hamid et al., 2022). The use of copper, especially in higher education institutions and universities during chemistry practical activities, has become a concern due to its significant quantity discharged (Rai, 2023). This poses serious risks to ecosystem health and human safety if discharged without any treatment to the body of water. The influx of pollutants or contaminants that exceeds the environmental carrying capacity also leads to pollution and contributes to environmental degradation (Briffa et al., 2020; Shetty et al., 2023). To ensure that wastewater from educational laboratories does not surpass the environmental carrying capacity when discharged into water bodies, appropriate wastewater treatment is essential. Wastewater treatment is a process designed to eliminate the majority of contaminants present in wastewater, thereby safeguarding environmental and public health (Amoatey & Bani, 2011; Liu et al., 2023). This may involve physical, chemical, or biological methods to neutralize or remove pollutants, ensuring that the treated water meets regulatory standards for safety (Englande et al., 2015; Saravanathamizhan & Perarasu, 2021). Based on ministerial regulation of ministry of environment and forestry, the Republic of Indonesia number 6 of the year 2021, the quality standards for treated copper contain of wastewater is limited to 2 mg/L. According to the World Health Organization (WHO) and the United States Environmental Protection Agency (USEPA), the standard limit for copper concentration in wastewater is established at 1.3 mg/L (Sabok-khiz et al., 2024).

One of the chemical methods for the removal of copper ions from laboratory waste is the coagulation process, which involves the aggregation of suspended particles through the addition of coagulants, facilitating the subsequent separation of copper from the aqueous solution. The coagulation process is one of the easiest methods to treat heavy metal waste, especially for application in educational laboratories. In the coagulation process, particularly in the context of water treatment, a precipitation reaction can indeed occur as part of the mechanism by which suspended solids and colloidal particles are removed from the aqueous phase (Tahraoui et al., 2024). Precipitation is a chemical process that transforming metals ions into solid particles by adjusting the pH level of substances. Precipitation occurs when the concentration of a solid exceeds the solubility limit of its parent compound. This process typically requires a precursor. At higher pH levels, dissolved metal ions react with precipitating agents, resulting in their conversion into metal hydroxides, carbonates, or sulfides or simply it is depend on the precipitant (Mazur et al., 2018; Sk et al., 2016).

One of the precipitating agents that can help stabilize heavy metal ion waste is from polymer compound. Polyacrylamide, a water-soluble polymer with a high molecular weight, is synthesized from the reaction of acrylamide or combination of acrylamide and acrylic acid. It is a highly versatile synthetic polymer that has gained significant prominence across various industries due to its unique properties and functionalities. The negative charge of polyacrylamide, known as anionic polyacrylamide because it contains carboxylic group, is commonly used in wastewater treatment as a flocculent or precipitating agent. The molecular weight of this polymer varies from 10^3 to 20 x 10^6 gr/mol (Doble & Kumar, 2005; Fijałkowska et al., 2020; Gelardi et al., 2016; Wiśniewska et al., 2022).

Anionic polyacrylamide is widely available in the market, making it accessible for both industrial and research applications. One of the significant advantages of anionic polyacrylamide for treating heavy metal wastewater is its low cost compared to other chemical agents (Cheng et al., 2024). This affordability makes it an attractive option for large-scale applications, particularly in educational laboratories for treating their laboratory waste especially containing copper waste. The use of polyacrylamide in the treatment of educational laboratory waste containing copper is chosen due to its biocompatible properties and its ability to bind metal ions (Erizal, 2010). The efficacy of APAM in wastewater containing heavy metal ions is attributed to its high molecular weight and anionic charge density, which facilitate the aggregation of metal ions and improve coagulation processes (Wiśniewska et al., 2022). Furthermore, anionic polyacrylamide is a water-soluble polymer, which facilitates its application in binding heavy metal ions. Its high solubility allows for uniform dispersion in aqueous environments, enhancing its effectiveness in forming complexes with cationic heavy metal ions (Wu et al., 2020).

When anionic polyacrylamide used in conjunction with coagulants such as alum (aluminum sulfate) and caustic soda (sodium hydroxide), anionic polyacrylamide enhances the coagulation and flocculation processes. Alum acts as a primary coagulant, neutralizing the charges of suspended particles and heavy metal ions, while caustic soda adjusts the pH of the solution, promoting optimal conditions for metal ion precipitation (Mehrpour et al., 2023; Tahraoui et al., 2024). The combination of anionic polyacrylamide with alum and caustic soda not only simplifies the application process but also significantly improves the efficiency of heavy metal removal in wastewater especially from laboratory waste and also meet wastewater quality standards.

This study aims to determine the effectiveness of anionic polyacrylamide as valuable precipitating agent for treating wastewater from educational laboratories that contains copper as the primary source of heavy metal ions. The goal was to achieve the concentration of copper ions in treated wastewater meets the quality standards and assess how well anionic polyacrylamide could remove these contaminants from the wastewater, thereby determining its potential for improving waste management practices in educational settings.

Method

To determine the effectiveness of anionic polyacrylamide in treating liquid waste containing copper ions produced by educational laboratories, a comprehensive data collection effort was initiated. This process utilized purposive sampling techniques specifically designed to target and gather samples of wastewater containing heavy metal ions generated from chemistry laboratory activities. The samples were gathered from one of the educational laboratories in state universities located in West Sumatra, Indonesia, on October 2024. During that time, the total approximate volume of wastewater generated from the laboratory was 360 dm^3. Wastewater generated from analytical chemistry laboratory and chemistry research laboratory were the samples for this study. Two containers, each with a capacity of 5 liters, were used to collect wastewater. For a thorough analysis of the contaminants present, one liter of liquid was extracted from each container. The samples were labeled for identification purposes: the sample collected from the first container, which is generated from analytical chemistry laboratory, is designated as Sample A, while the sample from the second container is labeled as Sample B generated from chemistry research laboratory.

To optimize the coagulation process, a selection of high-quality technical-grade chemicals has been carefully sourced from various local markets. The cornerstone of this procedure is anionic polyacrylamide, which serves as the primary precipitating agent, effectively facilitating the aggregation of particles. In addition to this, caustic soda is used to adjust pH levels and enhance the efficiency of the reaction, while alum acts as a coagulant to further assist in particle removal. To ensure the highest purity of the solution and optimal reactions, deionized water is used as the solvent for all these chemicals, ensuring they dissolve completely and contribute effectively to the coagulation process.

Various concentrations of anionic polyacrylamide were prepared. Weighing 6 grams, 10 grams and 14 grams of anionic polyacrylamide and dissolved in 200 ml of deionized water to make solutions with concentrations of 3, 5, and 7% by weight per weight, respectively. Each concentration was carefully mixed to ensure complete dissolution of the polymer. Caustic soda and alum solutions were prepared to achieve a concentration of 2% weight by weight by dissolving 4 grams of caustic soda and 4 grams of alum in each 200 mL of deionized water. This process also involved accurately measuring the required each amounts of caustic soda and alum powders and mixing them thoroughly with the appropriate volume of deionized water until fully dissolved. All solutions and reagents were stored in labeled reagent flasks to store and avoid contamination. Proper storage conditions were observed to ensure the quality of the solutions for future use.

The chemical apparatus used in this research includes beakers, funnels, volumetric flasks, and measuring pipettes. Additional equipment consists of a waterproof pocket pH meter (Hanna HI98107) is used for measuring the acidity or alkalinity of the wastewater solutions. An analytical balance (Osuka model FA2004E) provides high-precision measurements of substances, and a hand blender (Conifer) for homogenizing samples during the experiments. The procedure for treating wastewater using anionic polyacrylamide that containing copper ions from educational laboratories liquid waste was carried out using various concentrations of anionic polyacrylamide that, followed by the addition of caustic soda and alum treatment in stages. Each concentration of anionic polyacrylamide was tested on the wastewater samples to determine the optimal dosage for maximum copper ion removal.

The preliminary identification was measuring the pH of samples by using a waterproof pocket pH meter (Hanna HI98107). Each of 100 mL of the samples was heated using 10 mL of concentrated nitric acid at 185°C until the volume was reduced by half. After that, the samples were filtered and diluted with deionized water into 100 mL of volumetric flask. The preparation of the samples was used for characterizing the wastewater samples. 10 mL of samples were measuring by using X-ray fluorescence (XRF) using the PANalytical Epsilon 3 XLE X-ray fluorescence spectroscopy to identify the presence of copper in the samples. After that, the atomic absorption spectroscopy (AAS) with the Shimadzu AA-6300 AAS Atomic Absorption Spectrophotometer was carried out to quantify the copper concentrations in the samples, and it was also used for measuring the concentrations of copper in the final treated wastewater stage with each measurement conducted in duplicate to ensure accuracy and reliability of the results.

In the first stage of wastewater treatment, a liter of each sample treated with anionic polyacrylamide with various concentrations (3, 5, and 7%). Each of the samples was mixed using a hand blender for 5 minutes to combine the anionic polyacrylamide solution with the liquid waste. The use of a hand blender is due to the viscosity of the polymer that cannot be homogenized by using a normal stirrer. This blending technique ensured an even distribution of the polymer throughout the wastewater, facilitating optimal interaction between the polymer and suspended particles. After 5 minutes, the solid waste separated from the treated wastewater and it was dried at room temperature. In the next stage, the treated liquid waste with the anionic polyacrylamide was further processed by adding 2% alum and 2% caustic soda. The settling time was 5 minutes for each step. The aggregate that formed was also separated from the treated wastewater and dried at the room temperature.

Result and Discussion

The optimization of anionic polyacrylamide as a precipitating agent in the coagulation process for the removal of copper ions from educational laboratory wastewater commences with a comprehensive identification and characterization of the waste generated. The wastewater produced by educational laboratories is predominantly acidic in nature. It is proven by the pH of both sample A and sample B with the pH range between 2 and 3.5, respectively. This acidity may arise from the nature of the chemicals used in the educational laboratory processes, which involve many acid-based reagents during the lab work. According to the Resource Conservation and Recovery Act (RCRA), liquid waste that is classified as hazardous waste is having the pH level below 2. This low pH indicates a highly acidic substance, which poses significant risks to health and the environment (USEPA, 2015).

Another characteristic of the wastewater produced by educational laboratories has a specific color, which indicates the presence of heavy metal. This color can originate from dissolved heavy metal ions, such as copper, iron, or nickel, which can cause a change in the color of the liquid waste. A visual example of this phenomenon can be seen in Figure 1, where the color of the wastewater reflects the presence of heavy metals contained within it.

A semi-quantitative analysis was carried out on wastewater to assess the presence of heavy metals especially copper in educational laboratories liquid waste samples. The results of the heavy metal concentrations in the wastewater samples that containing copper ions, analyzed using X-ray fluorescence (XRF), are presented in Table 1.

Figure 1. The color of liquid waste generated from educational laboratories (Source: image by researchers, 2025)

According to the data presented in Table 1, all the samples contain significant amounts of essential heavy metals includes copper (Cu), nickel (Ni), zinc (Zn), and iron (Fe). In contrast, cobalt (Co), cadmium (Cd), and lead (Pb) are only present in sample B which is the categorized as non-essential heavy metals. The percentage of copper oxide in sample A is higher compared to other heavy metals present in the same sample. Meanwhile, the percentage of copper oxide in sample B tends to be lower compared to the nickel oxide present in the same sample. This indicates that copper is one of the dominant heavy metals present in educational laboratory waste.

Table 1. The content of liquid waste containing heavy metals in educational laboratories liquid waste samples

Metal oxides	Sample A (%)	Sample B (%)
CuO	17.60	12.50
NiO	13.68	23.73
ZnO	12.53	8.52
Fe_2O_3	0.12	12.56
Co_3O_4	-	7.85
CdO	-	3.37
PbO	-	0.89

Source: Data processed by researchers, 2025.

The concentrations of copper ions in the samples were determined using atomic absorption spectroscopy (AAS). This method involves atomizing the sample and measuring the absorption of light at specific wavelengths corresponding to copper. By doing so, it can be accurately assess the concentration of copper ions present in the both of samples. The measurement of copper concentration was conducted using the duplicate method to ensure the accuracy and consistency of the results. The average amount of copper ions in sample A and sample B are 596.5 and 637.9 mg/L, respectively.

Based on the data, the concentration of wastewater containing copper ions in educational laboratories is very high, necessitating an effective treatment process for the waste. Based on this fact, this wastewater generated from educational laboratories goes through several stages treatment process, all of which are based on chemical methods. Each step involves a coagulation reaction to reduce copper ions in wastewater. The main precipitating agent in reducing the concentration of copper in educational laboratory wastewater is anionic polyacrylamide. Anionic polyacrylamide reacts through electrostatic interactions with cationic heavy metal ions such as copper (Cu^{2+}). This interactions result in the formation of stable metal-polymer complexes, which significantly enhance the adsorption and subsequent removal of heavy metals from aqueous solutions (Wiśniewska et al., 2022). In several studies, polyacrylamide has been used in conjunction with clay, as investigated by Ramadani & Efendi (2023) to reduce and bind heavy metals. In addition, anionic polyacrylamide contains negatively charged ions that are dispersed and interact with opposite charges, such as heavy metal ions. This interaction causes the heavy metal ions to adhere to the surface of the polyacrylamide and ultimately precipitate (Lailiani et al., 2023).

To optimize the using of anionic polyacrylamide, the solutions were prepared with several different concentration variations, includes 3, 5, and 7% based on weight per weight (w/w) ratios. Each concentration of anionic polyacrylamide was then used to perform coagulation process in the first stage. After that, the process continued with the sequential addition of caustic soda and alum, each at a concentration of 2% weight per weight. The addition of these two chemicals aimed to accelerate the coagulation process and assist in the separation of heavy metal particles from the wastewater.

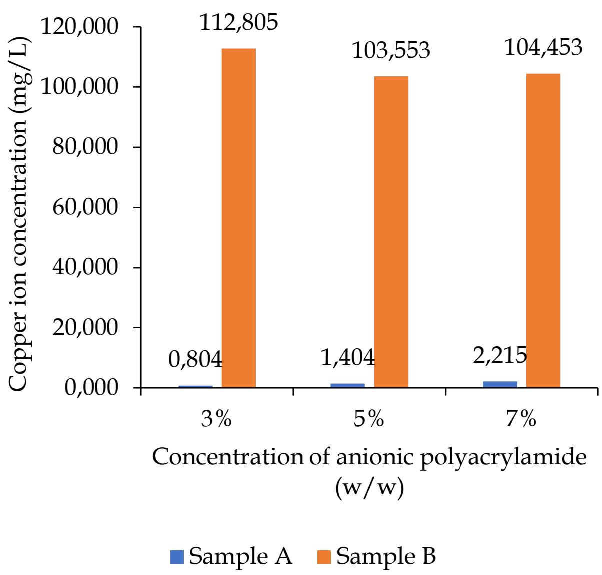

Figure 2. Concentration of copper ions after treatment (Source: Data processed by researchers, 2025).

Sample A and Sample B were treated to identical treatment conditions, and the resulting concentration of copper ions in each of the processed wastewater samples and the percent removal were measured. The results are showed in Figure 2 and 3, which provides a visual representation of the copper ion concentrations and percent removal for both samples after treatment.

Based on Figure 2, sample A, which contains copper as a heavy metal contaminant, shows the most optimal results after undergoing liquid waste treatment with the addition of anionic polyacrylamide at 3% weight per weight with the final concentrations was 0,804 mg/L. Furthermore, at all those concentrations, the sample also meets the wastewater quality standards. While the sample B, an optimal concentration of 5% anionic polyacrylamide was determined. Although the treatment conditions applied to sample B were identical to those used for sample A, the analytical results indicate that sample B does not meet the established wastewater treatment quality standards in terms of copper parameter. When considered in its entirety, the analysis reveals no significant differences in the reduction of copper concentration across the various dosages of anionic polyacrylamide applied.

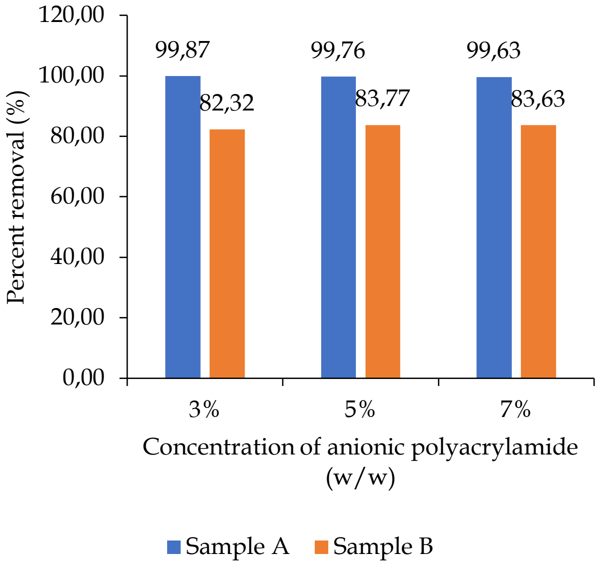

Figure 3. Percent removal of copper ion in wastewater (Source: Data processed by researchers, 2025).

This observation is further substantiated by the data presented in Figure 3, which shows the effectiveness of the treatment process in removing copper ions from the wastewater samples from percent removal of copper ion. In sample A, the percent removal of copper ions approaches nearly 100%, indicating that the treatment method employed was highly efficient in eliminating almost all of the copper present in the wastewater. In contrast, sample B shows a lower percent removal of approximately 83%. This indicates that while the treatment was still effective, there were likely factors that limited the complete removal of copper ions such as the pH level during the treatments and the dosage of anionic polyacrylamide used. This suggests that the addition of anionic polyacrylamide to sample B requires further investigation to achieve optimal treatment efficiency.

Although the copper concentrations in liquid waste samples A and B are nearly identical, the difference in pH between the two samples after the treatment prevents the wastewater treatment processes from being considered equivalent. The pH of sample A after the treatment was 9-10 while the pH of sample B was 4-5.

The pH factor has a significant influence on wastewater treatment processes, particularly in precipitation reactions (Heiderscheidt & Leiviskä, 2018; Yuanyuan, 2023). Heavy metals especially copper increased solubility in acidic conditions (Liu et al., 2023). This means that when the pH level of a solution decreases, these metals are more likely to remain in a dissolved state rather than precipitating out. The acidic environment can enhance the formation of soluble metal complexes (Czerwińska et al., 2024). Copper generally precipitates when the pH of the solution is elevated, indicating a basic or alkaline environment (Ali & Werner, 2024). In such conditions, the solubility of copper ions decreases, leading to the formation of insoluble copper compounds. This precipitation process is influenced by the presence of hydroxide ions in the solution, which can either promote the formation of the precipitation.

Slightly different from the pH principle, anionic polyacrylamide is a polymer that possesses a negative charge, which allows it to interact effectively with positively charged heavy metal ions in solution to form insoluble compound of heavy metals (Gupta et al., 2021; Xu et al., 2022). Although the pH of the environment is relatively acidic, the solubility of copper can decrease, leading to the formation of insoluble copper complexes. In this acidic condition, the anionic polyacrylamide can bind to this heavy metal ion, facilitating the aggregation and subsequent precipitation from the solution.

The use of anionic polyacrylamide for precipitation in the initial phase of wastewater treatment plays a crucial role in significantly lowering the concentration of copper in educational laboratory wastewater.

Conclusion

This study determined the effectiveness of anionic polyacrylamide in the treatment of wastewater generated from educational laboratories, particularly in the removal of copper ions. The percent removal of copper ions in sample A which generated from analytical chemistry laboratory is nearly 100% with the optimum dosage of anionic polyacrylamide was 3% and the concentration of copper in the treated wastewater was 0.804 mg/L after the treatment, demonstrating the high efficiency of the treatment method under optimal conditions. This indicates that the parameters and conditions applied during the treatment process were well-suited for achieving maximum precipitation of copper. Conversely, sample B exhibited a lower percent removal of approximately 83%, suggesting that certain factors may have hindered the complete removal of copper ions. The influential factor that effected this treatment was pH levels of wastewater during treatment. The use of anionic polyacrylamide for coagulation in the initial phase of wastewater treatment plays a crucial role in significantly lowering the concentration of copper in educational laboratory wastewater. Further studies are needed on other types of heavy metals that can be coagulated using this method in order to gain a more comprehensive understanding.

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Author Contributions
Investigation and conceptualization, data analysis, M.I., J.E., and I.D.; methodology, M.I., J.E., N.S., and E.B.; writing-original draft preparation, visualization, M.I.; writing-review and editing, M.I. and J.E.; supervision, M.I., J.E., I.D., N.S., and E.B. All authors have read and agreed to the published version of the manuscript.

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Conflicts of Interest
The authors declare no conflict of interest.

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