Moringa oleifera (MO) SEEDS AS A RENEWABLE DEWATERING AID IN ELECTRO-FORCED SEDIMENTATION (EFS)

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ABSTRACT: *Moringa oleifera* (MO), a readily available and sustainable plant, holds a promising alternative to traditional chemical coagulants. The bioactive compounds in the MO seeds such as cationic proteins and polysaccharides, can improve sludge settling efficiency and solid-liquid separation. Compared to chemical coagulants, MO-based coagulants are renewable, environmentally friendly alternatives with lower hazards due to their biodegradability and economic advantage due to local availability and lower cost. The potential of utilizing MO seed-based coagulant as a renewable dewatering agent in electro-forced sedimentation (EFS) process is investigated in this paper. The sedimentation rates between MO seed coagulant and the commonly employed chemical dewatering aid, polyacrylamide, PAC have been observed. The findings reveal that MO seed coagulant introduction into the slurry containing 7.5 mm and 9 mm initial solid concentration (expressed as total solid volume per unit cross-sectional area), results in a notably faster settling of sediment than PAC. This suggests that the effective application of MO seed coagulant as a dewatering aid in EFS depends on specific initial solid concentrations of the sludge under experiment.

KEY WORDS: *Electroforced sedimentation, Moringa oleifera, and Wastewater treatment.*

1. INTRODUCTION

Water management is a crucial aspect of various industries, including wastewater treatment, mining, and food processing [1]. The need for efficient dewatering techniques to separate solids from liquids has driven extensive research into developing sustainable, cost-effective solutions. Conventional methods often rely on extensive chemicals, which can be expensive and environmentally harmful. As a result, there is a growing interest in identifying natural alternatives for dewatering processes. One such promising alternative is the use of MO seed extract derived from MO seeds [2]. MO is recognized for its multifaceted applications in nutrition, medicine, and water treatment due to its abundant bioactive compounds. The coagulant and flocculant properties of MO extract have been extensively studied in the context of water purification, showcasing its potential as a natural dewatering aid [3–7].

In recent years, electrochemical dewatering has gained attention as an energy-efficient technique for solid-liquid separation [8–11]. Electro-forced dewatering involves applying electric fields to improve the separation process, reducing energy consumption compared to traditional mechanical dewatering methods. As sludge is made of all kinds of substances like organics, inorganics, metals, minerals, and water bound in cells or extracellular polymeric substances (EPS), or unbound water, conditioning it according to the desired characteristics can enable leveraging efficient dewatering with the least energy consumption. Variable properties of sludge with regard to pollutant type, rheology, and morphology require respective specific considerations in the sludge conditioning technologies [12]. Increasing current density enhanced the sedimentation rate of zinc oxide (ZnO) based sludge [13]. However, the scope of this study fixed the current applied to 0.01 A. A lower current minimizes electrode corrosion and allows a consistent electrostatic environment in which to observe the sedimentation process steadily. It also makes the small-scale experiment more energy-efficient and cost-effective [14].

Acid modification [15], thermal-acid modification [16], and application of peroxides [17], proved to be very effective chemical conditioners that could change the properties of sludge. However, these processes entail further research regarding complete production cost and long-term environmental impact. Furthermore, a greener approach uses natural sludge conditioners, attracting much research interest.

The application of natural coagulants in wastewater treatment yielded a very promising result in the effectiveness of pollutant removal in most studies, aside from the environmental issues contributed by the chemical conditioners [18]. Replacing the chemical sludge conditioners with renewable, naturally derived ones can help push the conventional sludge treatment processes in wastewater treatment plants to greener sustainability. Besides, the combination of both natural and chemical conditioners, like biochar and ferrate, respectively, caused a synergistic effect on improving sludge dewatering enhancement [13]. Hence, the approach of merging natural conditioners with chemical conditioners to initiate sludge dewatering proposes mitigating the environmental impacts of chemical conditioners while offsetting the enormous expenditure on natural conditioners. However, shorter shelf life, high dosage requirements, and variable efficacy of the natural coagulant on different wastewater, could stand as challenges in its commercialization.

In this regard, the search for natural dewatering aids represents a step toward greener sludge treatment technology. Though natural sludge conditioners offer environmentally friendly operation, there may be a lower rate of sludge dewatering than chemical conditioners. In addition, most of the bioactive compounds that can favor improved sludge dewaterability may have low extraction rates and thus require a large amount of starting substrates. Where available, agricultural wastes or plants like MO that exhibit high coagulation characteristics can potentially balance the drawbacks of chemically based conditioners while promoting green technology through recycling plant wastes to generate renewable dewatering aids. Seeds from MO contain high cationic protein content that can neutralize the negatively charged pollutants in the mixture, aiding floc formation and enhancing sedimentation.

This paper explores the feasibility and effectiveness of utilizing MO extract as a renewable dewatering aid in electro-forced sedimentation (EFS) processes. By investigating the coagulation and flocculation properties of MO extract under the influence of electric fields, this study seeks to shed light on the potential mechanisms behind its enhanced dewatering performance.

In pursuing sustainable and innovative solutions for solid-liquid separation, integrating MO extract and electro-forced dewatering holds promise for addressing both efficiency and environmental concerns. This research contributes to the expanding knowledge of renewable dewatering aids and their potential application in EFS.

2. EXPERIMENTAL METHODS AND MATERIALS

For coagulant extraction from readily available MO seed (MOS) powder, 1M NaCl solution was used as it has been demonstrated to be an excellent concentration for coagulant extraction from MO [6,19,20]. A slight variation of MOS concentration was noted in different studies for optimum coagulant activity, commonly ranging from 1 wt % to 3 wt%. The current applied was kept constant at 0.01 A for all the runs. Then, a number of runs were conducted, testing the best concentration of MOS for optimum dewatering efficiency. In 100 ml of 1M NaCl salt solution, MOS (1 g to 3 g) was added and mixed for 30 minutes using a magnetic stirrer, following the approaches of Noor et al. [4], Bouchareb et al. [19] and Dalvand et al. [20]. Then, 10 ml of 1 wt % of MOS coagulant solution was added to the slurry. The concentration of 1M NaCl is typically used for salt extraction as it provides an ideal environment for releasing coagulant proteins from the biomass. Next, the coagulant filtrate was obtained by passing the solution through a qualitative grade Whatman filter paper. The coagulant was prepared before every electrokinetic experiment, to maintain coagulant freshness.

An acryl tube, with height and internal diameter of 42 cm and 5.5 cm, respectively, was used as a sedimentation column for EFS. The electric field was applied by DC power supply (Twintex TP-2303K, Taiwan) in such a way that the bottom was cathode. The top was anode as ZnO particles have positive charges (shown in Fig.1). The experimental slurry was created by blending a specified amount of dry ZnO particles (ω= 5 to 10 mm), along with a 1M NaCl solution, and deionized water. This mixture resulted in a suspension with a known total solid volume per unit cross-sectional area, ω. Subsequently, the slurry was introduced into the sedimentation column, where it was allowed to settle undisturbed for two hours, reaching a state of equilibrium in terms of sedimentation height due to gravity. After that, EFS was carried out by allowing current flow up to 80 minutes to further reduce the sedimentation height by removing more water from the settled sediments. The rate of sediment height reduction in the column was recorded every five minutes. Three sets of EFS runs were carried out, with 10 ml of 1 wt % MOS coagulant solution, 1 wt % polyacrylamide (PAC) (chemical coagulant), and control (without any coagulant/dewatering aid).

The sedimentation rate was observed in terms of height change of the ZnO sludge sediment with time. The recorded height after two hours of gravitational sedimentation was taken to be the initial height for EFS. Every 5 minutes, a reduction in the sediment height was recorded. The sedimentation rate was modified from the initial consolidation ratio, Uc from the study by Alam et al. [21]. The differences in the sedimentation height with respect to time were shown in the graphs in Fig. 2. The results obtained were statistically analyzed and visualized with Python software version 3.12.6.

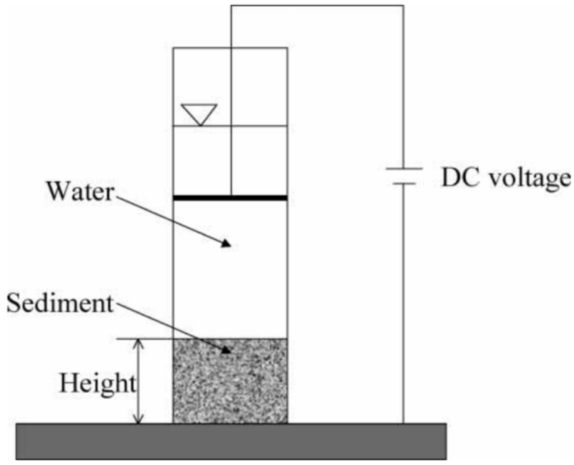

Fig. 1. Electro-forced sedimentation (EFS) schematic diagram [13]

3. RESULTS AND DISCUSSION

Gravitational sedimentation was assumed to be completed after two hours of settling. After that, EFS was conducted to dewater the sludge further with or without the addition of dewatering aids, that is, PAC and MO seed coagulant. The results in Fig. 2. show that the effectiveness of MO coagulant was notable in the slurry containing concentrations of 7.5 mm and 9 mm of ZnO, which could be attributed to the synergistic effects of MOS coagulant and ZnO in promoting coagulation and flocculation processes. The resulting coagulation and flocculation processes take place depending on the composition and rheological properties of the sludge and the coagulant. The combined action of the positive charges on ZnO and MOS coagulant helps in the charge neutralization of the pollutants in the mixture. Furthermore, the proteins in MOS coagulant further stabilize and enlarge flocs, forming aggregates that separate from the sludge mixture and enhance sedimentation.

While at 7.5 mm and 9 mm solid concentrations, the chemical interaction between ZnO and MOS coagulant effectively showed its dewatering effect. Besides, this increased contact of particle-particles promotes the formation of flocs, which become larger and denser. However, when increased to 10 mm initial solid concentration, the effect of MOS coagulant was much lower. The reason for such contrast can be the absence of surface area and accessibility of sludge particles with the dewatering aid because of a difference in rheological properties of the sludge and MOS coagulant [17]. If the initial solid concentration is too low (5 mm), the distance between solid particles will also be bigger, leading to the inability of effective floc formation. In 7.5 mm initial solid concentrations, MO seed coagulant seemed to exceed the sedimentation rate of that of PAC. MO seeds contain natural coagulants that can neutralize the charge on suspended particles and promote flocculation [23]. The coagulant components in MOS, such as proteins and polysaccharides, can bind to particles and promote their aggregation into larger flocs, aiding in their removal during sedimentation. The combination of MOS coagulant and ZnO particles resulted in larger and denser flocs, which settle more quickly [24]. At concentrations of 7.5 mm and 9 mm of ZnO, adding MOS coagulant likely intensified the coagulation and flocculation processes. This increased the effectiveness of particle aggregation and settling, ultimately leading to a higher sedimentation rate.

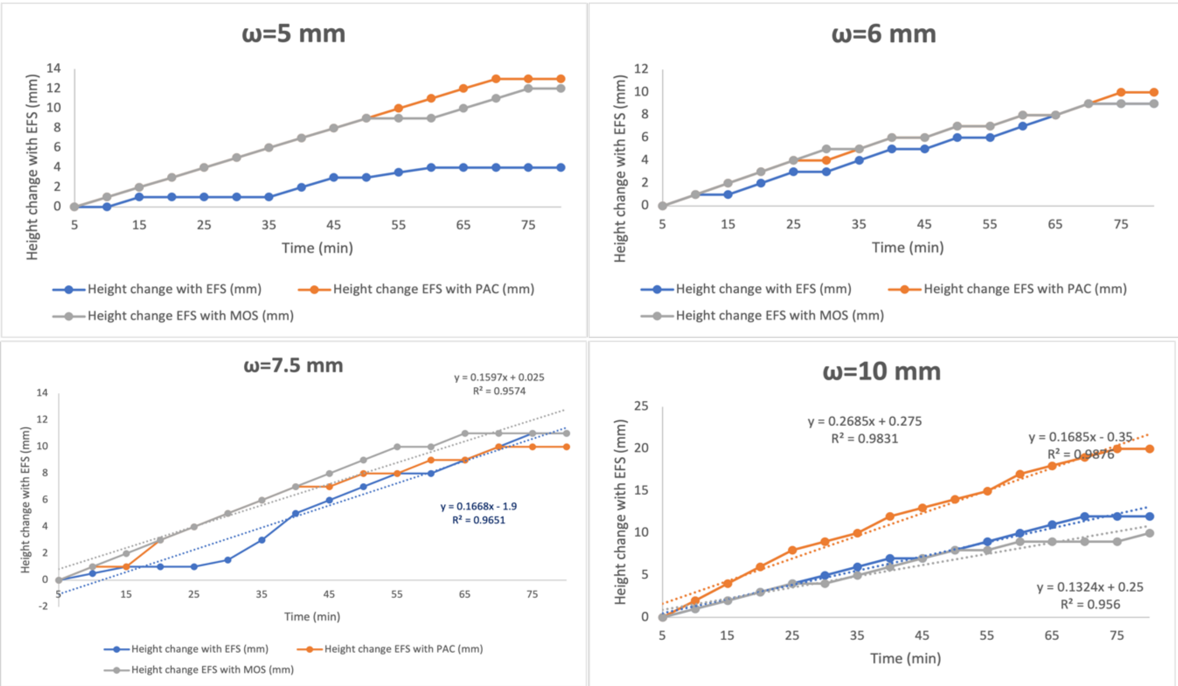

Fig. 2. Increase in sediment height difference after EFS at different initial solid concentrations (ω = 5 to 10 mm) with 10 ml of 1 wt. % *MOS* coagulant addition (green), 1 wt % PAC addition (red) and control (blue).

Factors, including the sludge particle characteristics, coagulant properties, and the specific conditions of the experiment, can influence coagulation. Therefore, the observed increase in sedimentation rate in the presence of MOS coagulant at these specific concentrations indicates the potential for synergistic effects between MOS and ZnO in promoting efficient particle removal through sedimentation at the initial solid concentration. To summarize, these insights suggest that while natural and chemical conditioners effectively alter sludge concentration, the chemical conditioner consistently outperforms the natural conditioner across all initial concentrations. The control condition shows the least change, highlighting the impact of the conditioners. The natural conditioner tends to outperform the chemical conditioner in the early stages of the experiment, especially at lower to moderate initial concentrations of sludge. Over time, however, the chemical conditioner generally shows a higher overall height change. This indicates that the natural conditioner can be more effective in the short term for moderate initial concentrations.

3.1. Model Fit and R-Squared

The regression analysis (Table 1) demonstrates a strong model fit, as indicated by the R-squared value of 0.902. This suggests that the independent variable (Initial Solid Concentration) explains 90.2% of the variance in the dependent variable (EFS). Such a high R-squared value implies that the model captures most of the variability in the data, which is a positive sign for the strength of the relationship between Initial Solid Concentration and EFS. The Adjusted R-squared of 0.853 is slightly lower, accounting for the number of predictors in the model. While there's a slight reduction from the R-squared value, this is expected in models with fewer predictors and indicates the model remains a good fit.

Table 1: OLS regression results on EFS with addition of PAC and *MOS*

OLS Regression Results						
Dependent variable	EFS height change		**R-squared**		0.902	
Model	OLS		**Adj. R-squared**		0.853	
Method	Least Squares		**F-statistic**		18.40	
Prob (F-statistic)	0.0503		**AIC**		9.842	
Log-Likelihood	-2.9209		**BIC**		8.614	
Df Residuals	2					
Df Model	1					
	coef	**Std error**	**t**	**P > |t|**	**[0.025**	**0.975]**
const	-1.1128	1.390	-0.801	0.507	-7.092	4.866
width	0.8088	0.189	4.289	0.050	-0.003	1.620
Omnibus	nan		**Durbin-Watson**		2.471	
Prob (Omnibus)	nan		**Jarque-Bera (JB)**		0.274	
Skew	0.359		**Prob (JB)**		0.872	
Kurtosis	1.938		**Cond. No.**		29.3	

3.2. Coefficient of Initial Solid Concentration

The coefficient for initial solid concentration is 0.8088, indicating that for every unit increase in initial solid concentration, the expected value of EFS increases by approximately 0.81 units. This positive relationship implies that higher levels of initial solid concentration led to higher values of sedimentation height change. However, the p-value for this coefficient is 0.050, which is right on the statistical significance threshold. While this suggests that initial solid concentration likely influences EFS, the borderline p-value raises some questions about the strength and reliability of the effect. This result could be considered marginally significant, meaning further investigation might be necessary to solidify the finding.

3.3. Model Diagnostics

Several diagnostic statistics suggest that the model is reliable. The Durbin-Watson statistic 2.471 indicates no significant autocorrelation in the residuals, an important check for regression models. The Jarque-Bera (JB) test has a p-value of 0.872, suggesting that the residuals are normally distributed, another positive indicator of model reliability. The skew and kurtosis values are also within reasonable ranges, meaning there are no significant deviations from normality. Additionally, Condition Number 29.3 suggests no major issues with multicollinearity, meaning that the independent variables are not highly correlated, which can otherwise distort the model estimates. The regression lines are drawn in Fig. 3.

Our analysis observed a Variance Inflation Factor (VIF) of 15 for the variable initial solid concentration. While this suggests potential multicollinearity, we applied regularization techniques, specifically Ridge and Lasso regression, to mitigate the impact of this collinearity. To address the issue of multicollinearity, as indicated by a high VIF of 15 for the initial solid concentration, we applied both Ridge and Lasso regression models Fig. 4.). Ridge regression, which uses an L2 penalty, resulted in a coefficient of 1.22 for initial solid concentration and a Mean Squared Error (MSE) of 0.3450. Applying an L1 penalty, Lasso regression yielded a slightly higher coefficient of 1.42 and a lower MSE of 0.2622, indicating a better model fit. These regularization techniques effectively stabilized the coefficients and reduced prediction error, allowing us to mitigate the impact of multicollinearity. Both models resulted in lower Mean Squared Errors (MSE) compared to traditional linear regression, demonstrating that the models could account for multicollinearity and provide robust predictions. Despite the limitations posed by our dataset, these models provided robust and reliable results, reinforcing the significance of the initial solid concentration variable in predicting height changes.

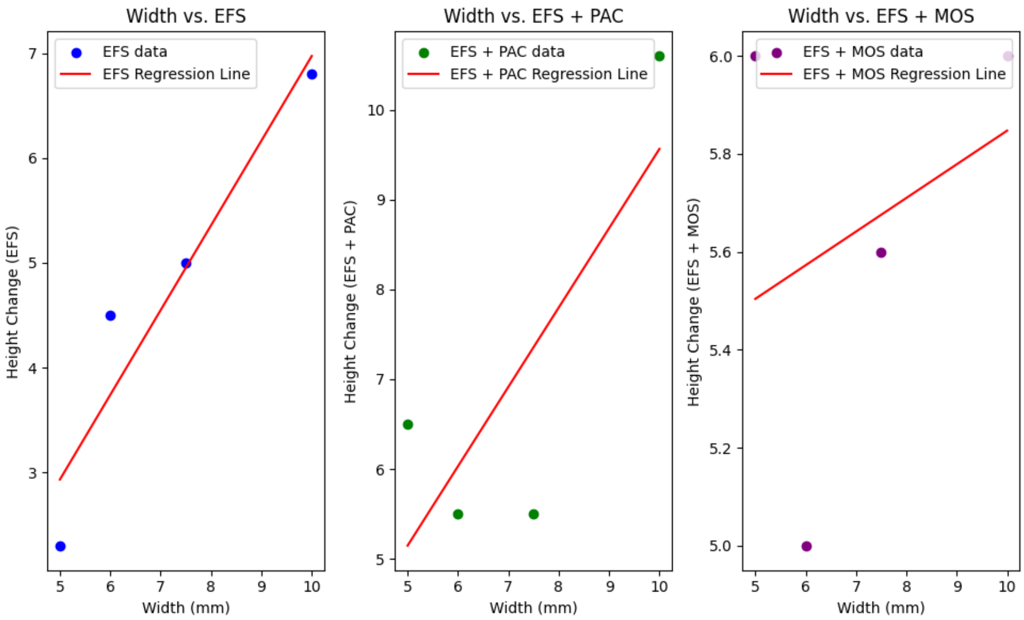

Fig. 3. Regression lines for sedimentation height change with and without PAC and MOS.

EFS alone showed the highest sensitivity (Fig. 5.). The EFS method alone is highly sensitive to width changes, meaning that in applications where this method is used, even small changes in width can lead to significant changes in height. EFS and PAC showed moderate sensitivity: EFS and PAC methods still demonstrate considerable sensitivity, but it is less than EFS alone. This could suggest that this method may have additional factors or complexities that moderate the width impact. EFS and MOS showed the least sensitivity in the sediment height change. It depicted stability in relation to changes in width, which could indicate that this method might be less responsive to variations in dimensions, making it potentially more robust under varying conditions. The lower sensitivity of EFS with MOS allows operators more flexibility in managing the process, as minor input changes are less likely to affect the outcome adversely. In practical scenarios, less sensitive processes are often more reliable and predictable, reducing the risk of operational failures if the process were too sensitive to variations. However, the coagulating effect can vary on different types of sludge, which can be further explored in future studies. In this study, the effects are limited to only ZnO, which is an artificial sludge.

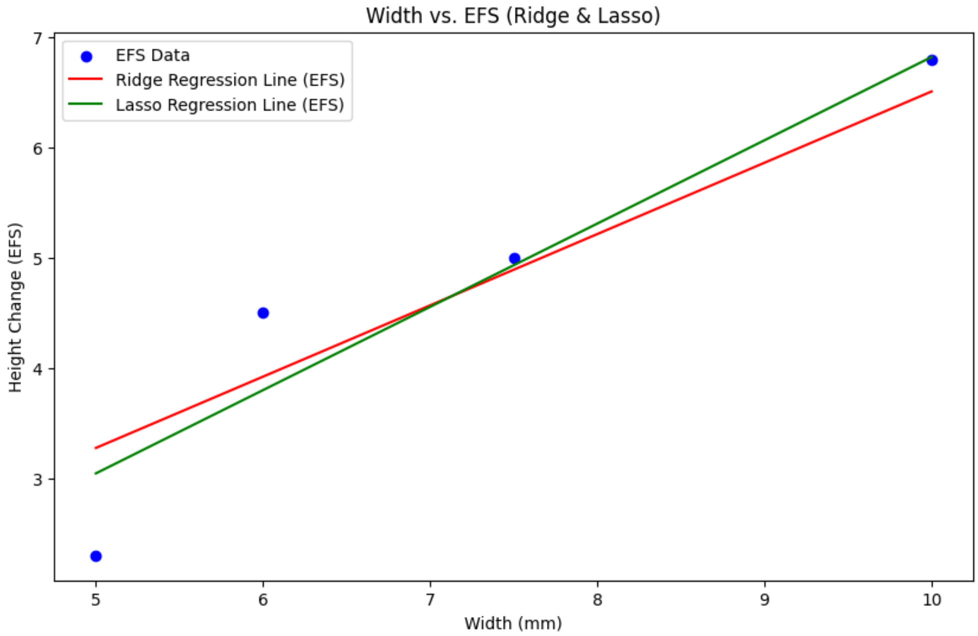

Fig. 4. Regression lines for sedimentation height change with and without PAC and MOS.

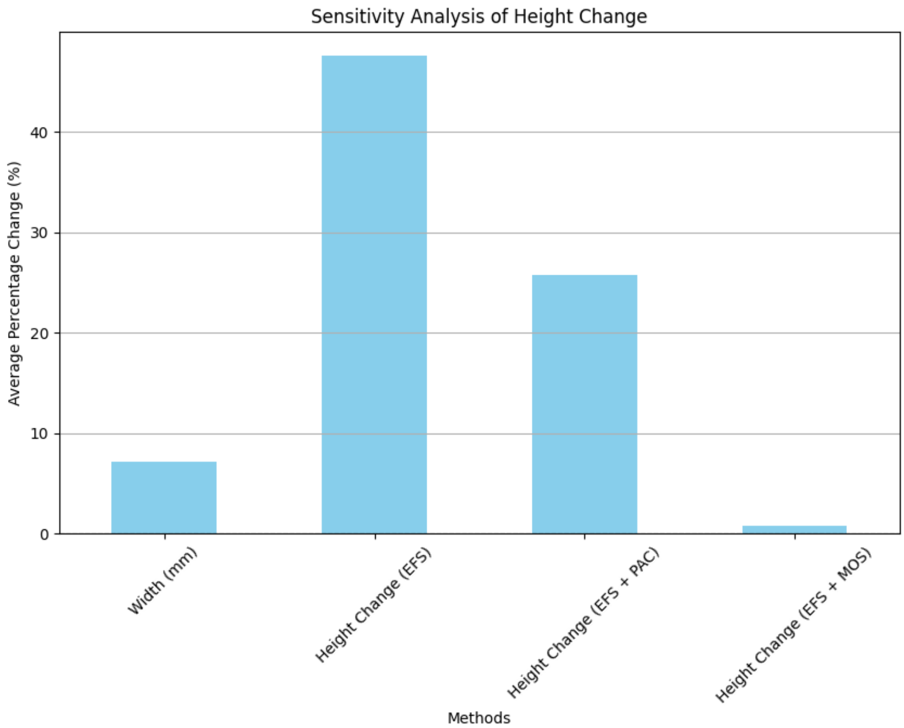

Fig. 5. Regression lines for sedimentation height change with and without PAC and MOS.

The adaptability of MOS in dewatering applications stems from its natural coagulation properties, broad pH tolerance, ability to interact with various particle types, minimal chemical residues, and lower sensitivity to dosage variations. These characteristics make it a versatile and effective option for sedimentation processes, particularly in dynamic operational conditions. The fact that EFS with MOS showed the least sensitivity suggests that this combination is stable and robust across different operational conditions. This makes it a favorable option in applications where consistent performance is essential, particularly in water treatment or sedimentation processes where variability can lead to significant operational challenges. Based on the sensitivity analysis, EFS with MOS is preferred over PAC for applications requiring stability and predictability in sedimentation processes. The robustness of MOS makes it a more reliable option, especially in scenarios where input conditions may not be controlled, thus providing better operational consistency and effectiveness in dewatering applications.

4. CONCLUSION

The potential of using MOS coagulant to be used in EFS as a renewable dewatering aid was explored in this study. Also, the sedimentation rate was compared with that of the commonly used chemical dewatering aid PAC. When MOS coagulant was added to water samples with 7.5 mm and 9 mm levels of ZnO, the slurry sediment settled faster than PAC. Hence, the effective application of MOS coagulant as a dewatering aid in EFS can be visualized depending on the specific initial solid concentration. This study can be further carried out by varying the effect of current density on the sedimentation rate for both MOS coagulant and PAC. Moreover, optimizing dosage systems in a wide range of sludge types, reactor simulation, and design can help further scale up MOS coagulants for industrial-scale application.

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