

Original Research

Performance of Chemical-Based vs Bio-Based Coagulants in Treating Aquaculture Wastewater and Cost-Benefit Analysis

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Abstract

Aquaculture sector plays important role for the economic development in Malaysia, but environmental concerns are arising due to the pollution caused by the discharge of untreated wastewater. Coagulation-flocculation-sedimentation is currently the best practice of aquaculture wastewater treatment. This research aims to compare the performance of chemical-based (alum) and bio-based (neem leaves) coagulants in treating aquaculture effluent while also studying the economic feasibility. Alum showed higher removal efficiencies of total suspended solid (99.7%), turbidity (98.8%), and color (97.3%), while neem coagulant showed a lower dosage needed to achieve the optimum performance. The total cost included capital and operational costs, while total benefit included the potential of water reuse and reclaimed valuable products from sludge. The net profit reveals negative values for both scenarios, while cost-benefit ratio showed 0 and 0.06 values for alum and neem coagulants, respectively. These values indicated that both scenarios are not feasible to gain economical profit, while the utilization of neem coagulant present benefit for water reuse and sludge utilization. A deeper analysis using Social Return on Investment (SROI) method is suggested to include the non-traditional calculation in cost-benefit analysis such as social and environmental values of the scenarios.

Keywords: circular economy, cleaner production, environmental pollution, fertilizer, green technology, recovery

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Introduction

Aquaculture sector plays an important role in the fulfillment of protein source for human beings [1, 2]. Aquaculture is one of the major sectors that contributes up to 0.9% to Malaysian national gross domestic products [3]. This sector had grown 10% annually for the past 5 years, with significant improvements from over 15 decades of establishment [4]. Along with the growth of this sector, some concerns related to the freshwater scarcity [5, 6] and surface water pollution had arisen [7, 8]. Freshwater aquaculture in Malaysia consumed around 20.15 m³ of water/kg production/year, as in-land pond system is currently the most dominant used and practiced method for culturing fish, shrimps, seaweed and others [3, 9]. It was also predicted that the amount of generated wastewater from the in-land aquaculture system in Malaysia will reach 7.519 km³ on the year of 2030 [3].

Wastewater treatment is an important unit in encircling the issue of freshwater scarcity and surface water pollution [9, 10]. Most aquaculture obtain water from rivers for their cultivation needs and releases back to the environment after using it. In general, majority of aquaculture in Malaysia are still not equipped with any form of wastewater treatment unit [3], while coagulation-flocculation and sedimentation treatment are the most frequently used technology for the equipped culture systems [11-13]. This technique was long known for its efficiency in removing such amount of solid in the wastewater and produce effluent that meets the quality standard. However, several concerns are raised due to the use of chemicals involved during the treatment [14-16]. Changing of environmental pH [17], potential residual metal exposure [18], and the biodegradability and toxicity of the produced sludge [19] accounting some of the emerging concerns.

The current trend of wastewater treatment has been shifted to the circular economy paradigm [14, 20, 21] in which the reuse of resource and reclamation of potential valuable product are the major watchlist and have become priority [22-24]. The most currently used technology for coagulation-flocculation process using chemicals fails to follow the new trend due to the decreasing water quality after treatment from the residual chemicals [25, 26] and limitation of sludge utilization due to the metal content [27, 28]. Overcoming these issues, bio-based coagulants are shown to be relevant to replace the most currently used chemicals of alum [29, 30]. The efficiency of bio-based coagulants was reported by Vu et al. [31] with no decreasing quality of water resource after treatment and more potential of sludge utilizations as fertilizer or soil conditioners.

The advantages of bio-based coagulants are no doubt to be a greener technology as compared to the metal-based coagulants. However, the current stress point in applying this green technology is related to

the cost efficiency. Limited study has been conducted to compare the current best practice *vis-a-vis* green technology in wastewater treatment, especially for aquaculture sector. This study is aimed to juxtapose the performance of chemical-based and bio-based coagulants in treating real aquaculture wastewater while also simply analyze the cost and benefit of aquaculture wastewater treatment using alum, as the most currently used chemicals, versus bio-based coagulants via scenarios implementation. The presented result is expected to give a clearer understanding of aquaculture wastewater treatment operation, especially related to the economic benefits for implementing an alternative greener technology for future approach as part of circular economy initiatives.

Materials and Methods

Initial Wastewater Characteristics

Characteristics of aquaculture wastewater used in this study was taken from a previous published article [11]. Freshwater catfish aquaculture wastewater was used as the basis for data calculation and a plant-based coagulant of neem (*Azadirachta indica*) was used during the study (Table 1).

Jar Test Experiment

The coagulation and flocculation were carried out using jar-test experiment (VELP, Malaysia). A total of 500 mL volume was used during the experiment. The operating condition of jar-test was fixed at 180 rpm for 3 mins for rapid mixing, 10 rpm for 20 mins for slow mixing, and 30 mins of settling time [11]. Parameter was focused on TSS, turbidity, and color for overall analysis. The obtained data was then compared using one way ANOVA and Tukey HSD with p -value \leq 0.05 showed significant differences [32, 33].

Table 1. Initial wastewater characteristics.

Parameter	Unit	Value
TSS	mg/L	427
Turbidity	NTU	307
Color	ADMI	1310.7
Ammoniacal nitrogen	mg/L	24.5
Nitrate nitrogen	mg/L	11.9
Phosphate	mg/L	0.07
COD	mg/L	120.3
pH	-	7.5

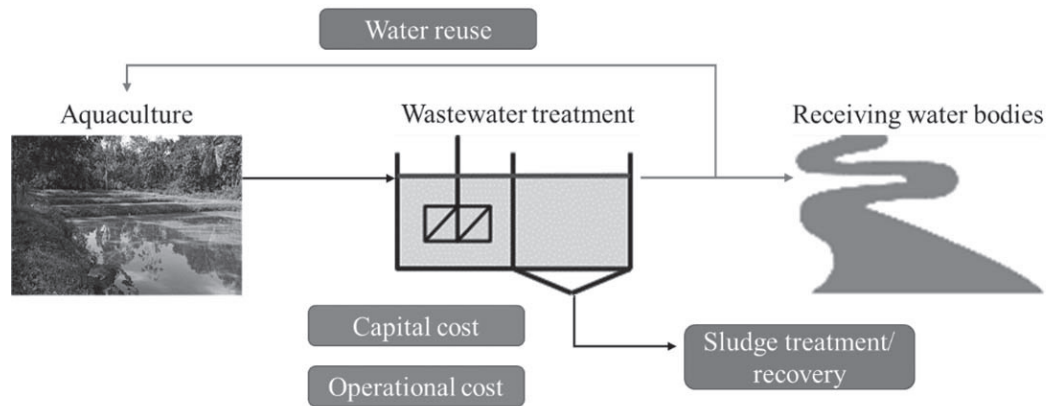


Fig. 1. Analyzed items for the cost-benefit analysis.

Data Source and Analysis Implementation

This study involves primary and secondary data in conducting cost and benefit analysis [34]. Primary data in this study are mentioned as wastewater characteristics, reagent characteristics, removal efficiencies, and sludge production. While secondary data involved in this study are used to determine the capital cost, operational cost, energy consumption, sludge handling cost, and value of recovered products as fertilizers. The removal efficiency was focused on the main parameter of total suspended solid (TSS) since it is most correlated with sludge production.

Scope and Limitations of Cost-Benefit Analysis

This study implemented the analysis inside the border of wastewater generation, wastewater treatment, and solid disposal/reclamation as depicted in Fig. 1. This study was designed to analyze the total wastewater treatment capacity of 1 m³ to be treated through coagulation-flocculation process in a modular unit system. While for the capital expenditure of the coagulation-flocculation process, it will be based on a capacity of 10 m³/day. Three (3) modular treatment units will be installed with justification of each treatment period operated for 1.5 h (coagulation, flocculation, sedimentation, and drainage). A total of 8 h working hour will result in 5 cycles of treatment. To achieve the 10 m³ of daily treatment capacity, 2 units will be operated continuously, and 1 unit will become a standby unit. Other factors such as fish productivity and environmental costs are not included in this study. Scenario comparison was used in this study to analyze different methods used for aquaculture wastewater treatment [35].

Applied Scenarios for Cost-Benefit Analysis

Two scenarios were comparatively analyzed in this study namely the utilization of conventional metal-based coagulant (alum) vs bio-based coagulant (Neem

leaves). These scenarios were applied to the mostly common condition in Malaysian aquaculture sector, in which no wastewater treatment unit is being used (direct discharge of wastewater to surface water) [3]. The used scenarios are illustrated in Fig. 2.

Cost-Benefit Analysis

The total cost for the aquaculture wastewater treatment was calculated by Eq. (1) [36].

$$\text{Total Cost} = \alpha \text{Capital Cost} + \text{Operational Cost} \quad (1)$$

where, α Capital Cost is annualized capital cost and α is the depreciation of the treatment unit [37]. The α is set to 8% with a salvage value of asset to be 10% and useful lifespan of 10 years [38]. The capital cost commonly consists of tank unit construction/establishment (40%), piping network (10%), operational modules (20%), installation and other necessities (30%) [39]. In this research, factors like engineering, procurement, and staff preparation are not deeply studied, with costs estimation are included in other necessities item.

The operational cost was estimated with energy consumption cost (max 40%) [40], chemicals/coagulants (max 30%) [41], sludge treatment (max 20%) [42], manpower and other operational costs (max 50%) [43]. Land cost is not included in this estimation due to the diversity of land price which make the bias of estimation becomes higher and normally the required space for treatment unit is within the available aquaculture area (land requirement is provided by calculating the surface area for treatment units). This study used 5 years of depreciation for modules.

The total benefit in this study was calculated as in Eq. (2) [36]:

$$\text{Total Benefit} = r\text{Benefit} + v\text{Benefit} \quad (2)$$

where, r Benefit is the value of reused water after treatment [44] and v Benefit is the potential gained profit from the valuable product recovery [45].

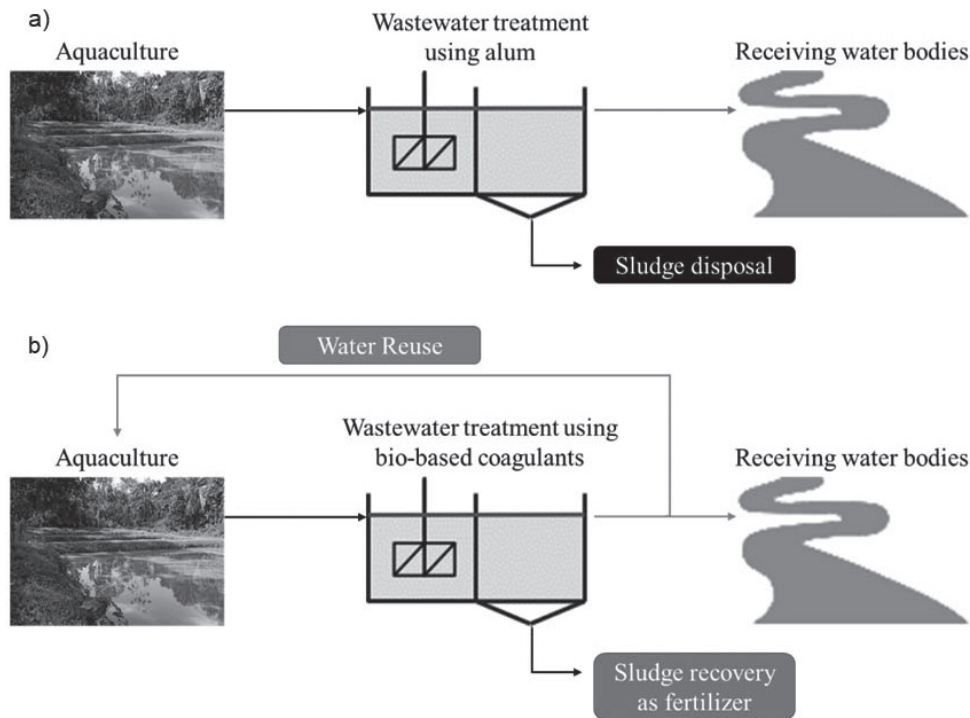


Fig. 2. Applied scenarios for cost-benefit analysis using a) alum and b) bio-based coagulant in aquaculture wastewater treatment.

The net profit and cost-benefit ratio for each used scenario are calculated based on Eq. (3) [46] and Eq. (4) [35]. The profitable scenario is indicated by positive net profit value [45] and cost-benefit ratio greater than 1 [35].

$$\text{Net Profit} = \text{Total Benefit} - \text{Total Cost} \quad (3)$$

$$\text{Cost - Benefit Ratio} = \frac{\text{Total Benefit}}{\text{Total Cost}} \quad (4)$$

Results and Discussion

Removal Performance

The juxtaposition of alum vs neem coagulant performances in treating aquaculture wastewater is depicted on Fig. 3. Based on the obtained results, the performance of neem coagulant was still significantly lower as compared to alum for the TSS, turbidity, and color removal. However, the potential of further optimization for neem coagulant is quite reliable. To obtain the showed performance, alum required a dosage of 0.4 mg/L while neem only 0.3 mg/L. Despite the lower coagulant dosage requirement, the utilization of bio-based coagulant may open to the potential of water reuse and sludge utilization which is currently cannot be applied by using chemical-based coagulant [13].

Estimated Land Requirement

Coagulation, flocculation, and sedimentation unit was designed in cylinder shape with a capacity of

1 m³ each. Three (3) modular system will be installed as detailed in Section 2.4. By applying design criteria of 1 m depth + 0.2 m freeboard, the surface area for each unit was 1.13 m² (∅ 1.2 m obtained using tube volumetric formula). Considering the void area of 25%, the minimum land area needed for all coagulation, flocculation, and sedimentation unit is 12.72 m². For the sludge treatment, sludge drying bed will be used to remove the water content from sludge. Sludge drying commonly take 10 days to fully produce dried sludge, thus 11 drying beds will be installed on site (considering the harvesting on Bed 1 on day 10). The volume of sludge per day to be dried in one bed is calculated on the basis of density. Suspended solid (SS) sludge commonly consisted of 99% water. With the removal efficiency displayed in Table 1, the maximum SS removal per day is 4.25 kg. Assuming the density of SS is 1400 kg/m³ and density of water is 1000 kg/m³, total volume of sludge to be dried is 0.3 m³ per day [47]. By applying the design criteria of 0.3 m depth of drying bed with rectangular shape, the required surface area per bed is 1 m². By applying 25% of void area, the total land needed for sludge drying beds are 13.75 m², resulting in 26.47 m² of total land needed for installing this system.

Cost Analysis

Capital Costs

The capital costs include the purchase of modular tanks, sludge drying bed modular tanks, piping network, operational modules (including pumps, dosing pumps,

Table 2. Detailed capital costs.

Item	Material	Requirement (unit)	Cost (RM)	Total cost (RM)	Source
Coagulation tank (1 m ³)	Plastic	3	2,900	8,700	[65]
Coagulant dosing tank (10 L)	Plastic	3	415	1,245	[66]
Flocculation tank (1 m ³)	Plastic	3	2,900	8,700	[66]
Sedimentation tank (1 m ³) with sludge chamber	Plastic	3	7,000	21,000	[67]
Paddles	Stainless	6	2,160	12,960	[68]
Piping network	PVC			13,151	10%
Operational modules				26,302	20%
Installation and other				39,454	30%
Total				131,512	

Note: [1 RM = 0.24 USD]

automation units), installation and other equipment as detailed in Table 2. The capital cost of alum- and plant-based.

Operational Costs

The operational costs include the consumption of energy, regular purchase of chemicals/reagent, sludge treatment, manpower and other operational costs. For chemical-based treatment, alum will be used in the calculation. With the mentioned optimum dosage (Table 1), a total of 4 kg alum is needed per day to achieve the desired treatment capacity. Varied energy consumption has been mentioned by several researchers which listed in Table 3.

With details mentioned in Table 1, the total sludge to be treated from chemical-based treatment per day is 8.257 kg/d (considering the addition of used alum). Produced sludge is estimated to be disposed into landfill monthly, thus 30 day of storage cost is applied for sludge storage cost. In this study, sludge treatment (drying) cost is made to zero (0) due to the variables

of energy consumption and manpower costs are already listed as separated item. With this justification, sludge treatment costs only consist of storage and disposal. Detailed operational costs for treatment with alum is presented in Table 4.

According to Table 1, neem plant had 81.37% of TSS removal thus resulting in 3.475 kg/d of the produced sludge. With the mentioned optimum dosage, 3 kg of neem coagulant is needed for the treatment. Referring to Thirugnanasambandham and Karri [48], the cost for producing plant-based coagulant from neem plant was 0.2 USD/kg. Not like alum, the organic coagulant can be decomposed and volatilized during the drying process. The total mass reduction reached >80%, leaving only minerals and reducing the total dried sludge [49]. With this basic understanding, 80% mass of the used plant-based coagulant will be removed. The dried sludge produced from treatment with plant-based coagulant will not undergo disposal process but will be sold as fertilizer, thus reducing the sludge treatment cost. The detailed operational costs for treatment with neem plant is presented in Table 5.

Table 3. Literature studies for operational cost in coagulation, flocculation, and sedimentation processes.

Variable	Unit	Costs (RM)				Average
		[69]	[42]	[70]	[71]	
Energy consumption	kW-h/m ³	1.61	2.21	1.67	1.78	1.81
Chemicals/reagent	1/kg	0.71	0.58	2.92	0.83	1.25
Sludge processing (drying)	1/kg	1.79*	-	-	-	1.79
Sludge storage	1/kg	-	0.42	-	-	0.42
Sludge disposal	1/kg	-	0.46	-	-	0.46

Note: [1 RM = 0.24 USD]

*Divided into energy consumption and manpower costs.

Table 4. Detailed operational costs for chemical-based treatment.

Item	Unit	Requirement/year	Cost (RM)/unit	Total cost (RM)
Energy consumption	kW-h	1,569.6	0.92*	1,444.03
Alum	Kg	1,440	1.25	1,800
Sludge treatment (storage and disposal)	Kg	2,972.52	0.88	2,615.82
Manpower and other**				5,869.69
Total				11,729.54

Note: [1 RM = 0.24 USD]

*https://www.globalpetrolprices.com/Malaysia/electricity_prices/

**Based on 50% estimation from the total operational cost

Table 5. Detailed operational costs for plant-based treatment.

Item	Unit	Requirement/year	Cost (RM)/unit	Total cost (RM)
Energy consumption	kW-h	1,569.6	0.92*	1,444.03
Neem	Kg	1,080	0.83	896.4
Sludge treatment (storage)	Kg	1,467	0.42	616.14
Manpower and other**				5,869.69
Total				8,826.26

Note: [1 RM = 0.24 USD]

*https://www.globalpetrolprices.com/Malaysia/electricity_prices/

**Made same with Table 4

Analysis of Benefit

Sludge produced from treatment with alum is categorized as non-biodegradable, since it contains such amount of metal residue [50]. The produced sludge is also not suitable for further bioprocessing or utilization as growth medium for plant, thus commonly ended up in landfill. The treated water from this method also considered toxic for aquatic life, including the cultured species. Rossi et al. [28] showed that recycled water from the treatment with Al- and Fe-based coagulants showed toxicity to cultured algae species. With this reason, no considered benefit is gained from the utilization of chemical-based coagulant. By utilizing plant-based coagulant, the generated sludge is safe to be used as fertilizer due to the organic characteristics of the coagulant-itself and nutrient-rich characteristics of the aquaculture wastewater [51, 52]. Treated water using plant-based coagulant also showed no/minimum harm to aquatic environment. Vu et al. [53] utilize recycled aquaculture water treated by chitosan which showed no negative effect to the cultured species. With this insight, water recycling and sludge conversion into fertilizer are the benefits of this bio-coagulant method.

The amount of water reuse after treatment is estimated to be 50% from the treatment capacity, considering the water loss during wet sludge disposal, losses, and evaporation [54]. The gained benefit of water reuse was calculated based on the reducing

freshwater used with a cost of 0.5 RM per m³. The treated wastewater contains high concentration of nitrogen which may result in high nitrogen content in sludge. For comparison, certain studies mention the characteristics of aquaculture sludge which is rich of nitrogen, organic carbon, and micronutrients which is suitable for crop plants [55, 56]. For selling price, it was mentioned that sludge from wastewater treatment are considered as low quality fertilizer with price ranging from 1/8 to 1/3 of the commercial fertilizer [57]. With a price of commercially available NPK fertilizer ranging from 4-10 RM/kg (<https://agrobridge.com.my/products/imported-compound-fertiliser/agrobridge-mop-based/#>), the gained benefit from sludge recovery is set to be RM 4/kg (taking the lowest available price). The total benefit is listed in Table 6.

Net Profit and Cost-Benefit Analysis

Distribution of the cost and the gained benefit per scenario is summarized in Fig. 4. According to Fig. 3, treatment using neem results in lower operational cost due to the cheaper price of the neem (as compared to alum) and the reduction of sludge handling cost. It can also be seen that treatment using alum did not gain any visible benefit inside the applied scope of the study. From this data, Eq. (1) to (4) was applied to calculate the net profit and cost-benefit ratio (Table 7).

Table 6. Total benefit for plant-based treatment.

Item	Value	Unit	Benefit (RM)	Total benefit (RM/year)
Water reuse	1,800	m ³ /year	0.5	900
Sludge as fertilizer	1,467	kg/year	4	5,868
Total				6,768

Note: [1 RM = 0.24 USD]

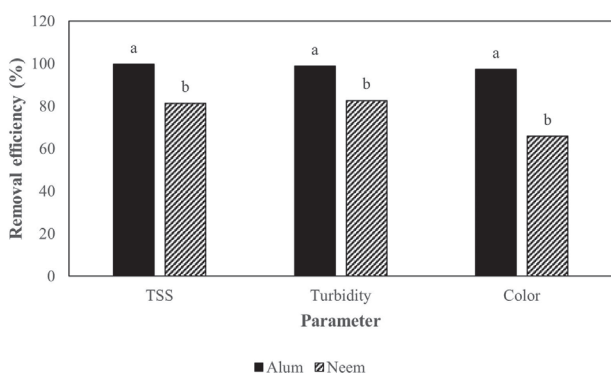


Fig. 3. Performance of alum and neem coagulant in treating aquaculture wastewater. Different letters (a-b) indicating significant differences of parameter removal between the used coagulants.

Table 7 showed that negative values are presented for both scenarios, indicating that both scenarios did not gain any benefit during the operation. Referring to the cost-benefit ratio, zero (0) value was obtained from alum, while 0.06 obtained for neem. These values also

Table 7. Net profit and cost benefit from scenarios.

Treatment	Net profit	Cost-benefit ratio
Chemical-based (alum)	-143241.54	0
Plant-based (neem)	-133570.26	0.06

indicated that applying these scenarios are not feasible to gain profit, which break-even point and return of interest will never be achieved [46]. Wastewater treatment is considered non-profit made unit, in which benefit gained from this facility is more to be indirect [58]. To enrich the discussion, inclusion of environmental benefit into the calculation is highly suggested to be conducted using Social Return on Investment (SROI) analysis [59] to present more understanding about the actual indirect benefit gained from wastewater treatment unit [36]. In addition to SROI analysis, further utilization of treated wastewater to grow microalgae or daphnids species may also be taken into benefit consideration, since the opportunity for this further utilization is proven to be feasible by previous researchers [60-64].

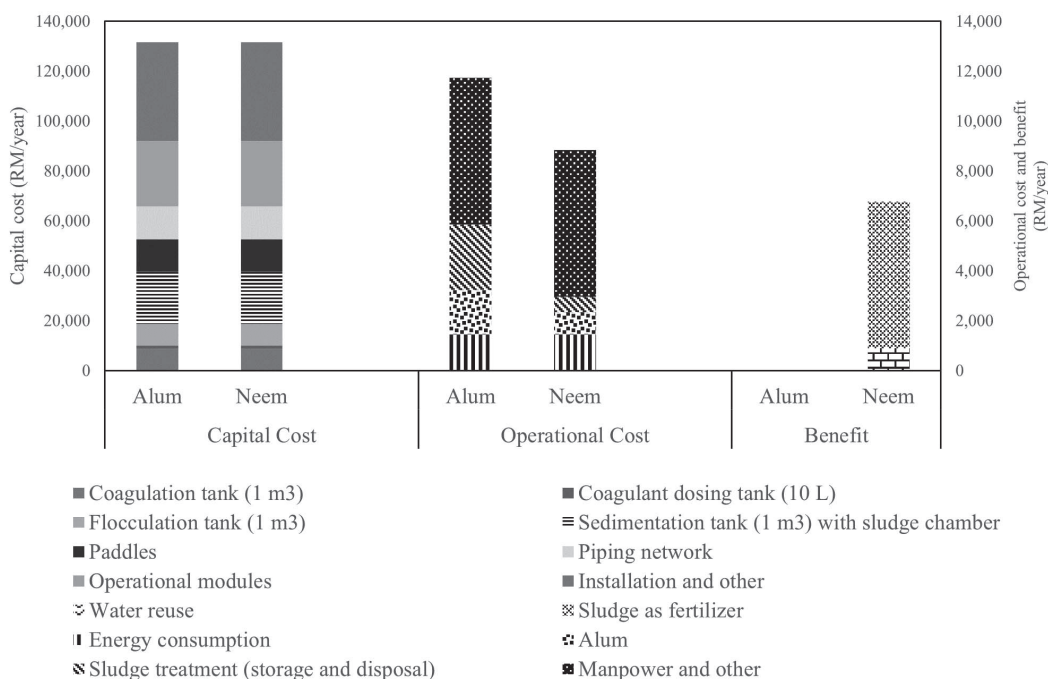


Fig. 4. Distribution of cost and benefit from scenarios.

Conclusions

The utilization of neem coagulant still showed a lower removal performance as compared to the alum. The highest removal obtained in this study was TSS 99.7%, turbidity 98.8%, and color 97.3% by using alum, while TSS 81.37%, turbidity 82.7%, and color 65.8% by using neem coagulant. Based on the comparative cost benefit analysis on the treatment unit comprising coagulation-flocculation-sedimentation units for respective alum and neem, both have resulted negative values for the net profit, and 0 and 0.06 for the cost-benefit ratio, respectively. These results are indicating that both approaches are not feasible to gain profit. Since wastewater treatment is considered as a non-profit made unit rather than as a resource recovery facility, cost-benefit analysis should be extended into Social Return on Investment (SROI) that considers all environmental and social benefits to clearly portray the actual indirect benefit gained from bio-based coagulant treatment. In addition to SROI analysis, further utilization of treated water as cultivation medium for daphnids or microalgae may add additional benefits to the aquaculture wastewater treatment using bio-based coagulant.

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Conflict of Interest

The authors declare no conflict of interest.

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