

Analysis of the Implementation of Bioaugmentation in the Remediation of Petroleum-Contaminated Soils in Oil and Gas Exploration Areas

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ABSTRACT

This study analyzes the impact of ecological remediation through bioaugmentation techniques to remediate crude oil-contaminated soil and its social and economic implications in Siak Regency, Riau Province. Oil contamination caused by leakage due to illegal tapping of oil pipelines has become a serious environmental issue requiring effective and sustainable remediation methods. This study aims to evaluate the effectiveness of bioaugmentation in reducing long-chain petroleum hydrocarbons (C10–C36) to meet environmental quality standards while also assessing the social and economic impacts of its implementation. A mixed-methods approach was applied, combining quantitative analysis of laboratory test results and environmental monitoring with qualitative surveys and interviews involving communities, government agencies, and companies. The results show that bioaugmentation using indigenous bacteria significantly reduced petroleum hydrocarbon concentrations from 8.4%–9.4% to below the environmental quality standard ($\leq 0.1\%$) within 5–6 weeks. The most efficient dosage was found to be 1 liter/m³ of contaminated soil, as it achieved degradation rates comparable to those of 2 liters/m³ but with lower operational costs. Environmental conditions during remediation remained optimal for microbial activity, with a pH of 6.0–6.9, a temperature of 26–36 °C, and humidity of around 70%. Socially and economically, the implementation received positive responses, although community satisfaction was slightly lower than that of government agencies and companies. Overall, bioaugmentation was proven to be an effective, economical, and environmentally friendly remediation technology for the sustainable recovery of crude oil-contaminated soil.

INTRODUCTION

Indonesia, as one of the largest oil and gas-producing countries in Southeast Asia, faces significant challenges in environmental management due to petroleum industry activities. Soil contamination by petroleum hydrocarbons constitutes a complex environmental issue that requires specialized treatment because of its adverse impacts on ecosystems and public health (Abbasian et al., 2015).

Oil and gas operational activities in Siak Regency have encountered several cases of oil theft along pipeline networks (illegal tapping) conducted by irresponsible parties (Rochmayanto, 2021; Sari, D. K., & Handayani, 2020). This has resulted in crude oil leakage from distribution pipelines, causing spills that spread into surrounding soil within operational areas and even affecting community land. According to regulations issued by the Ministry of Environment and Forestry (KLHK), crude oil that impacts the environment is classified as Hazardous and Toxic Waste (B3 Waste), hereafter referred to as crude oil-contaminated soil

(COCS). Consequently, the restoration of environmental functions is required in accordance with applicable government regulations.

From an ecological perspective, particularly within the framework of environmental management instruments outlined in Government Regulation No. 22 of 2021 concerning the implementation of environmental protection and management, various methods and technologies can be applied for environmental restoration. Each method presents distinct advantages and disadvantages, influencing the level of technical difficulty, economic feasibility, and time efficiency of remediation efforts (Bebbington et al., 2021; Gunningham et al., 2017). For instance, remediation of COCS can be conducted using conventional excavation followed by ex-situ treatment through licensed B3 waste management companies. While this approach entails significant costs, it ensures that treated materials meet environmental quality standards established by the Ministry of Environment. Alternatively, soil washing techniques enable on-site treatment, offering greater cost efficiency; however, they require intensive supervision and operational effort to achieve compliance with environmental standards (Dani & Fitri, 2022; Nurmalasari, 2018). On the other hand, bioremediation methods are considered more relevant, cost-effective, and operationally efficient while still capable of meeting regulatory quality standards (Atlas & Hazen, 2011; Zulkifliani, 2017).

Bioremediation of COCS consists of several techniques, including phytoremediation, biostimulation, and bioaugmentation (Arifudin et al., 2016; Nwankwegu et al., 2016). The bioaugmentation technique involves isolating microorganisms present in contaminated soil, cultivating them to increase their population density under controlled conditions, and subsequently reintroducing them into the remediation site through injection or spraying across treatment grids (Gong et al., 2018; Liu et al., 2011). This process enhances the degradation of petroleum hydrocarbons as the primary contaminants in COCS. The microorganisms utilized may include indigenous bacteria isolated from contaminated sites or genetically engineered strains (Hussain et al., 2018).

The advantages of bioaugmentation lie in its ability to degrade contaminants in situ, its relatively low operational costs, and the absence of hazardous secondary residues. Previous studies have demonstrated its effectiveness in degrading petroleum hydrocarbons. Research conducted by Prakash et al. (2016) showed that the application of hydrocarbon-degrading bacterial consortia reduced total petroleum hydrocarbon (TPH) concentrations by up to 85% within 120 days. Similarly, Azubuikwe et al. (2016) reported that combining bioaugmentation with biostimulation improved degradation efficiency to as high as 92%.

From an economic standpoint, conventional remediation of crude oil-contaminated soil through ex-situ treatment by third-party contractors is associated with very high costs, ranging from approximately USD 110 to USD 135 per cubic meter of contaminated soil. These costs arise from multiple operational requirements, including the construction of access infrastructure for heavy equipment, land acquisition over extensive areas to accommodate equipment maneuvering and safety, excavation and segregation processes, transportation logistics, and the procurement of large volumes of borrow soil for site restoration. Additionally, transportation to licensed treatment facilities may involve long-distance hauling to other regions.

From a social perspective, petroleum hydrocarbon contamination contributes to a decline in the quality of life among communities surrounding operational areas (Shofiandi & Ratni,

2021; Arifudin et al., 2016). Residents often experience health disturbances due to dust generated by heavy vehicles transporting contaminated soil, temporary loss of livelihoods in sectors such as agriculture and fisheries during remediation activities, limited community involvement due to inadequate skills, and degradation of environmental aesthetics. A study by Widodo et al. (2019) indicated that communities living near petroleum-contaminated areas exhibited higher incidences of respiratory and dermatological diseases compared to control areas.

The novelty of this research lies in its integrated multidimensional approach, combining ecological evaluation of bioaugmentation effectiveness with comprehensive social and economic impact assessments. Unlike previous studies that focused solely on technical parameters or were limited to laboratory scales, this study evaluates three different bioaugmentation dosages (0.5, 1.0, and 2.0 L/m³) at a field-scale remediation site in Siak Regency, Riau, while simultaneously assessing stakeholder perceptions across three clusters (community, government agencies, and companies) using statistical analysis, including ANOVA and Tukey's HSD test. This integrated approach provides a holistic understanding of bioaugmentation as a sustainable remediation technology, considering technical effectiveness, economic feasibility, and social acceptance—dimensions that remain largely underexplored in prior Indonesian studies.

From a government agency standpoint, the management of COCS remediation involves multiple stakeholders, including local governments, environmental agencies, the oil and gas industry, local communities, and regulatory and law enforcement bodies (Cox et al., 2019; Zikos, 2020). This government agency complexity necessitates clear delineation of roles, authorities, and responsibilities to ensure that environmental restoration efforts are implemented effectively, transparently, and accountably. Furthermore, the application of bioaugmentation techniques requires government agency adaptation to advancements in environmental science and technology. Agencies that lack adequate regulatory frameworks or operational readiness may encounter difficulties in integrating bioaugmentation into existing environmental policies. Such challenges include the absence of technical guidelines, standardized success criteria, and limited human resource capacity to properly understand and monitor bioremediation technologies. Therefore, government agency impact analysis is essential to evaluate the extent to which existing policies, organizational structures, and coordination mechanisms can support the sustainability of petroleum-contaminated soil remediation programs.

METHOD

Approach Study

This study used a mixed-method approach, combining quantitative and qualitative techniques. The quantitative component was used to analyze numerical data obtained from laboratory tests and questionnaires, while the qualitative component was applied to gain an in-depth understanding of contextual factors, particularly in the social and economic dimensions. The integration of both approaches was intended to provide a more comprehensive understanding of the research problem.

The quantitative data included measurements of long-chain petroleum hydrocarbons (C10–C36), Total Plate Count (TPC) for bacterial population assessment, and supporting

environmental variables such as temperature, moisture content, and soil pH. These parameters were measured at each stage of soil sampling and analysis to evaluate the effectiveness of petroleum-contaminated soil remediation.

The qualitative component used a survey approach to examine social and economic aspects. Data were collected through interviews with local farmers and workers whose land had been affected by petroleum contamination. The study also assessed community participation in remediation activities and the economic benefits gained from leasing land during the remediation period. In addition, questionnaires distributed to local communities captured perceptions of petroleum-contaminated soil conditions and remediation activities, as well as public views on bioaugmentation as an environmentally friendly remediation method compared to alternative techniques.

Data Types and Sources

The data collected and analyzed in this study consists of both primary and secondary data. Primary data refers to information obtained directly by the researcher through laboratory analysis, interviews, surveys, and observations. The primary data collected encompasses ecological, social, and economic aspects. Ecological primary data include measurements of long-chain petroleum hydrocarbons (C₁₀–C₃₆) and Total Plate Count (TPC), obtained through laboratory testing along with necessary monitoring analyses. Primary data for the social and economic aspect consist of multi-stakeholder participation, gathered through interview-based data collection.

Secondary data refer to information generated by external parties, either individuals or government agencies, other than the researcher. The secondary data collected in this study includes geographical conditions, land area, volume of treated soil, and remediation costs, including materials, labor services, and overhead expenses. These data are obtained through document review, observation of research reports, and analysis of relevant publications associated with the research topic, including scientific journals and other scholarly works.

Place and Time of Research

This study will be conducted at a remediation station located in Siak Regency, Riau. The research was scheduled to take place from December 2025 to March 2026.

Population, Sampling & Data Collection.

Population is defined as a generalization area consisting of objects or subjects that possess specific qualities and characteristics determined by the researcher to be studied and from which conclusions are subsequently drawn (Sugiyono, 2016). The population in this study comprises the dataset of soil sampling points, bacterial counts, fertilizer quantities, long-chain petroleum hydrocarbon values, Total Plate Count (TPC) values, environmental monitoring parameters such as temperature, moisture content, and soil pH, remediation costs, as well as interview respondents from the surrounding community, government agency and company.

The experimental treatments ecological aspect which applied in this study are as follows:

1. Control: No treatment is applied to the oil-contaminated soil.
2. Treatment A: Application of 0.5 liters of bacterial culture per 1 m³ of COCS.
3. Treatment B: Application of 1 liter of bacterial culture per 1 m³ of COCS.
4. Treatment C: Application of 2 liters of bacterial culture per 1 m³ of COCS

The data collection and analysis techniques required in this study are planned as follows:

Table 1. Data Collection Technique

Location	Grid	Ecology Analysis	Week 1	Week 2	Week 3	Week 4	Week 5	Week 6
Location	Grid 1 - Kontrol	PH C10-C36	...	...	...	...	...	...
		Total Plate Count (TPC)	■	...	■	...	■	...
		Temp, pH & Moisture Cont	...	...	...	...	...	...
	Grid 2 - Treatment A Replication 1	PH C10-C36	...	...	...	...	...	...
		Total Plate Count (TPC)	■	...	■	...	■	...
		Temp, pH & Moisture Cont	...	...	...	...	...	...
	Grid 3 - Treatment A Replication 2	PH C10-C36	...	...	...	...	...	...
		Total Plate Count (TPC)	■	...	■	...	■	...
		Temp, pH & Moisture Cont	...	...	...	...	...	...
	Grid 4 - Treatment A Replication 3	PH C10-C36	...	...	...	...	...	...
		Total Plate Count (TPC)	■	...	■	...	■	...
		Temp, pH & Moisture Cont	...	...	...	...	...	...
	Grid 5 - Treatment B Replication 1	PH C10-C36	...	...	...	...	...	...
		Total Plate Count (TPC)	■	...	■	...	■	...
		Temp, pH & Moisture Cont	...	...	...	...	...	...
	Grid 6 - Treatment B Replication 2	PH C10-C36	...	...	...	...	...	...
		Total Plate Count (TPC)	■	...	■	...	■	...
		Temp, pH & Moisture Cont	...	...	...	...	...	...
Grid 7 - Treatment B Replication 3	PH C10-C36	...	...	...	...	...	...
	Total Plate Count (TPC)	■	...	■	...	■	...	
	Temp, pH & Moisture Cont	...	...	...	...	...	...
Grid 8 - Treatment C Replication 1	PH C10-C36	...	...	...	...	...	...
	Total Plate Count (TPC)	■	...	■	...	■	...	
	Temp, pH & Moisture Cont	...	...	...	...	...	...
Grid 9 - Treatment C Replication 2	PH C10-C36	...	...	...	...	...	...
	Total Plate Count (TPC)	■	...	■	...	■	...	
	Temp, pH & Moisture Cont	...	...	...	...	...	...
Grid 10 - Treatment C Replication 3	PH C10-C36	...	...	...	...	...	...
	Total Plate Count (TPC)	■	...	■	...	■	...	
	Temp, pH & Moisture Cont	...	...	...	...	...	...

For the collection of social and economic data in this study, a purposive sampling technique will be employed. Data will be gathered through direct field observations at the research site, as well as through the administration of questionnaires and the conduct of interviews with local communities, relevant government agencies, and environmental remediation management personnel.

Data Analysis Techniques

For the ecological aspect, data analysis will be conducted using trend analysis. Trend analysis is the process of examining historical data over time to identify patterns, determine existing trends, and detect recurring patterns to understand the direction of change and project future conditions. This method assists researchers in making informed decisions by analyzing

the progression of petroleum hydrocarbon degradation values, specifically to assess whether they meet the established environmental quality standards. Consequently, trend-based graphical analysis can provide conclusions regarding the effectiveness of bioaugmentation as a remediation method for petroleum-contaminated soils.

For the analysis of social and economic aspects, the assessment of public perception in this study aims to examine the views of communities, government agencies, and company environmental remediation management entities regarding the implementation of the bioaugmentation method. The questionnaire is designed using positively framed statements, with responses scored on a five-point scale (5, 4, 3, 2, and 1). The Likert scale categories consist of strongly agree, agree, neutral, disagree, and strongly disagree as much as 90 respondents.

The evaluation is conducted by assigning the highest score to responses indicating the highest level of agreement (strongly agree) and the lowest score to responses indicating the lowest level of agreement (strongly disagree). The scores from each response are subsequently aggregated to determine the overall tendency of respondent's attitudes or perceptions toward the variables under study.

The target respondents include 30 individuals from local communities surrounding the remediation station, 30 respondents from relevant government agencies, and 30 respondents representing companies or environmental remediation management entities involved in the process. After all survey data have been collected, statistical interpretation will be performed using Analysis of Variance (ANOVA) and Tukey's Honestly Significant Difference (HSD) test for comparisons involving more than one group, whereas descriptive statistical analysis will be applied when only a single group of data is examined.

RESULTS AND DISCUSSION

Degradation Petroleum Hydrocarbon

The research findings related to the dynamics of long-chain petroleum hydrocarbon reduction in this study indicate variations in the rate of decrease across the different treatments applied. Observations were conducted periodically throughout the study period to obtain a clearer understanding of the patterns of change in the concentration of these compounds. The research data presented below provide a quantitative representation of the temporal changes in long-chain petroleum hydrocarbon concentrations for each treatment. The graph result showed average degradation PH C₁₀-C₃₆ over the time:

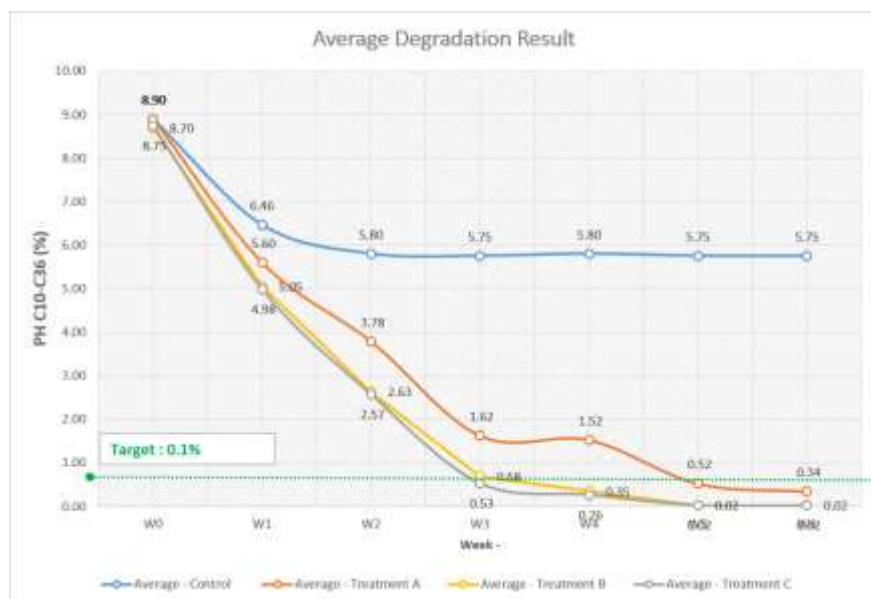


Figure 1. Average Degradation Result

The result shown on Figure 1 described average degradation result for all treatments. In the control plot, a relatively sharp decrease in long-chain petroleum hydrocarbons was observed during the first week, declining from approximately 8.9% to 6.46%. However, following this initial reduction, the rate of decline slowed significantly and tended to plateau. The concentration remained within the range of 5.75–5.80% until week 6, which is considerably above the environmental quality standard of 0.1%. This pattern suggests that natural attenuation processes do occur, but they are insufficient to significantly degrade heavy hydrocarbon fractions within the study period.

In contrast, the bioaugmentation treatment plots exhibited a substantially faster and more consistent reduction in long-chain petroleum hydrocarbons. Treatment A demonstrated a gradual decrease from approximately 8.7% to 0.34% at week 6. Although this represents a significant improvement compared to the control, the concentration still slightly exceeded the environmental quality standard. Treatment B showed superior performance, with hydrocarbon concentrations decreasing drastically from approximately 8.75% to 0.02% by week 5 and remaining stable through week 6. This indicates that the long-chain hydrocarbon concentration effectively met the established environmental standards. The most optimal reduction was observed in Treatment C, where concentrations decreased from approximately 8.8% to around 0.02% as early as week 4 and remained stable until the end of the observation period. These results demonstrate that the bioaugmentation strategy applied in Treatment C not only achieved faster degradation but also maintained consistent performance compared to other treatments. Previous studies by Nong et al. (2023) and Wang et al. (2025) have reported that bioaugmentation can enhance the degradation of heavy hydrocarbon fractions by more than 60–90% within a significantly shorter time frame compared to natural attenuation, primarily through increased microbial activity involving bacterial groups such as Proteobacteria and Actinobacteria.

Overall, when assessed from the perspective of cost efficiency and resource optimization, Treatment B is considered the most rational and practical scenario. Although

Treatment C exhibited a slightly faster rate of reduction, Treatment B was able to achieve and maintain hydrocarbon concentrations below the regulatory threshold without requiring maximum treatment intensity. This finding is consistent with the study by Koshlaf and Ball (2017), which suggests that increasing bioaugmentation intensity beyond an optimal threshold does not necessarily yield significant improvements in performance, but may lead to higher operational costs. Therefore, based on the findings of this study and supporting literature, Treatment B can be regarded as the most optimal bioaugmentation approach, as it effectively balances technical performance and cost efficiency in the remediation of petroleum-contaminated soils

Dynamic of Microbiological Growth

The research findings related to the dynamics of microorganism growth in this study indicate variations in the rate of increase and decrease across the different treatments applied. Observations were conducted periodically throughout the study period to obtain a clearer understanding of the patterns of change of Total Plate Count (TPC) in the concentration according to the table below:

Table 2. Microbiological Growth

Treatment	TPC W2 (CFU/gr)	TPC W4 (CFU/gr)	TPC W6 (CFU/gr)
Average - Treatment A	1,019,667	242,000	165,500
Average - Treatment B	2,082,667	784,500	19,000
Average - Treatment C	2,089,000	844,500	40,833

The Total Plate Count (TPC) values presented in Table 1 of the field study results demonstrate clear dynamics in bacterial population growth, which are directly associated with the reduction of long-chain petroleum hydrocarbons. At the initial stage of week 0 (W0) till week 1 (W1) of the study, bacterial populations measurement has not been sampled in reflecting the microbiological condition still growth or spread surrounding in the contaminated soil. Within the treatment grids, following the application of bioaugmentation, a significant increase in bacterial population was observed beginning at week two (W2), with TPC values rising to 10^6 – 10^7 CFU/g. This increase represents the adaptation and growth phase of hydrocarbon-degrading bacteria that utilize hydrocarbons as sources of carbon and energy. Entering week four to six (W4–W6), TPC values tended to stabilize or gradually decline, although they remained at relatively high levels. This decline does not indicate a failure of the bioaugmentation process; rather, it signifies the depletion of hydrocarbon substrates, resulting in a natural reduction in bacterial growth rates.

In contrast, the control grid exhibited significantly lower TPC values with limited fluctuation, indicating that indigenous microorganisms, in the absence of additional bacterial inoculation, are not sufficiently competitive to effectively degrade heavy hydrocarbon fractions. The temporal correlation between the increase in Total Plate Count (TPC) and the decrease in long-chain petroleum hydrocarbons serves as a fundamental basis for interpreting that the observed changes in soil chemistry are primarily driven by biological activity rather than purely physical processes. The significant reduction of long-chain petroleum hydrocarbons in the treatment grids indicates that bioaugmentation effectively accelerates the

biodegradation of heavy hydrocarbon fractions. Scientific literature suggests that the C₁₀–C₃₆ fraction possesses complex molecular structures and strong hydrophobic interactions with soil particles, thereby requiring microorganisms with specific enzymatic capabilities for effective degradation.

Changes in Total Plate Count (TPC) values are commonly used as a quantitative indicator to assess biological activity during the bioaugmentation process. Vidonish et al. (2018) reported that an initial increase in TPC reflects the exponential growth phase of hydrocarbon-degrading microorganisms utilizing hydrocarbons as a carbon source. Subsequently, the decline in TPC observed in later stages does not indicate reduced remediation effectiveness; rather, it signifies the depletion of hydrocarbon substrates due to intensive degradation processes.

The temporal relationship between decreasing hydrocarbon concentrations and microbial population dynamics is a characteristic feature of active biodegradation. Coulon et al. (2005) stated that hydrocarbon degradation accompanied by an increase in microbial biomass can be interpreted as evidence of the predominance of biological mechanisms over physical processes such as volatilization or leaching. This principle is further reinforced by Ron and Rosenberg (2014), who emphasized that microbial metabolic activity is the primary controlling factor in the remediation of petroleum-contaminated soils.

Social & Economic Impacts

In terms of social and economic, a survey was conducted within 3 cluster where the Community within a 50 km radius, Government Agencies, and Company with a total of 90 respondents to assess the extent of the impact of implementing COCS restoration using bioaugmentation. Perception respondents in study use five-level Likert scale, where Score 1 - Strongly Disagree, score 2 - Disagree, score 3 - Neutral, score 4 - Agree and score 5 - Strongly Agree. This scale is used to determine the level of assessment, attitude, or perception of respondents towards the variables studied. The values obtained are then analyzed using the mean value (average) to describe the general tendency of the assessment of each -respondent cluster.

The distribution of survey results in each cluster and the level of satisfaction can be seen in the table and graph below.

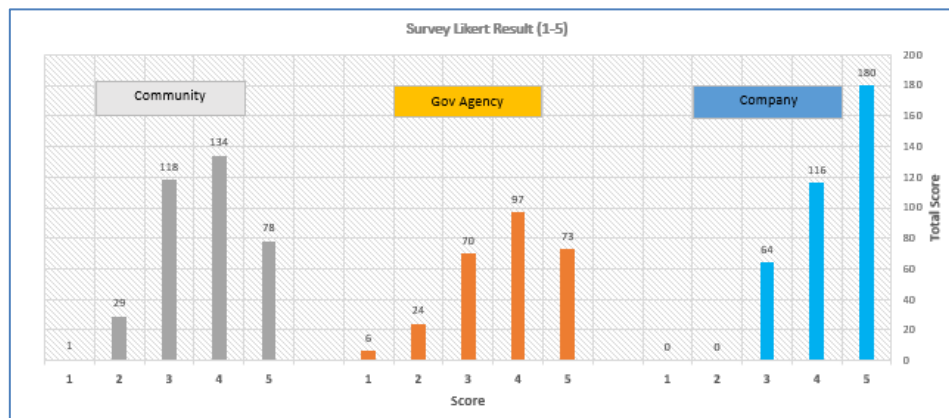


Figure 2. Total Likert Scale Score (1-5)

Table 3. Mean Likert Scale

Cluster	Mean	General Meaning
Community	3.72	Neutral until satisfied
Agency	3.77	Neutral until satisfied
Company	4.32	Satisfied to Very Satisfied

Table 4. ANOVA Analysis Results

Statistics	Mark
F count	4.11
Sig. (p -value)	0.0197
Criteria	p < 0.05
Decision	Significant

Table 5. Hasil Uji Tukey HSD

Perbandingan Klaster	Selisih Mean	Keputusan
Community – Gov Agency	0.05	Not Significant
Community – Company	0.6	Signifikan
Gov Agency – Company	0.05	Not Signifikan

The distribution pattern of survey results across clusters for the social and economic dimensions, as illustrated in Figure 2 and calculation analysis shown on tables 3, 4, and 5 which indicates differences in levels of acceptance and satisfaction among stakeholder groups. The community cluster recorded a mean score of 3.72, while the government agency cluster obtained a mean score of 3.77. Both values fall within the neutral-to-satisfied category, suggesting that bioaugmentation-based environmental remediation is generally perceived positively; however, its benefits have not yet been strongly or evenly realized by both communities and government agencies. In addition, the results of the One-Way ANOVA and Tukey's Honestly Significant Difference (HSD) tests reveal a statistically significant difference in the mean perception of environmental remediation impacts among respondent clusters ($F = 4.11$; $p < 0.05$), indicating that the company cluster exhibits a significantly different perception compared to the community and government agency clusters. Meanwhile, no statistically significant difference was found between the community and government agency clusters.

Within the community cluster, the neutral-to-satisfied rating reflects that social and ecological impacts—such as improved environmental comfort and reduced concern regarding pollution—have begun to be perceived. However, at the same time, economic benefits as well as the effectiveness and consistency of government agency roles are still perceived as suboptimal, resulting in a proportion of respondents maintaining a neutral stance. This suggests that environmental remediation has generated initial positive impacts but requires further strengthening to ensure that economic and government agency benefits are more tangibly experienced by local communities.

Similarly, the government agency cluster, which also falls within the neutral-to-satisfied category, demonstrates a comparable yet more cautious perspective. The mean value of 3.77 indicates that government agencies consider the implementation of environmental

remediation to be relatively satisfactory from technical and policy perspectives. Nevertheless, they continue to highlight challenges in the social and government agency domains, including the management of social dynamics and the effectiveness of monitoring and evaluation mechanisms. This stance reflects the role of government agencies as regulators and stabilizing agents, resulting in assessments that are not solely affirmative but also critically evaluative.

In contrast, the company cluster exhibits a higher mean score of 4.32, corresponding to a satisfied-to-highly satisfied category. This suggests that companies perceive the implementation of bioaugmentation as a successful approach that supports operational sustainability across social and economic dimensions. The higher level of satisfaction among the company cluster reflects the perception that stakeholder engagement activities have been effectively implemented, community disturbances have been relatively minimal, and government agency systems—such as regulatory compliance, documentation, and reporting—have functioned efficiently, thereby providing operational certainty.

These differences in perception reflect the distinct roles and interests of each stakeholder cluster. Communities and government agencies tend to remain in an evaluative phase, where the benefits of remediation have been recognized but still require further enhancement, particularly in economic aspects. In contrast, companies demonstrate a higher level of satisfaction, as the remediation process is perceived to support operational continuity, regulatory certainty, and stable social relations. In the context of bioaugmentation-based environmental remediation, the statistically significant ANOVA results indicate that remediation activities generate differing social and economic experiences among communities, government agencies, and companies. This finding is consistent with stakeholder perception theory, which posits that actors involved in an environmental intervention evaluate its impacts based on their respective interests, expectations, and levels of engagement.

The absence of a significant difference between the community and government agency clusters indicates that both groups occupy a similar evaluative zone, namely the neutral-to-satisfied category. Substantively, communities assess remediation impacts based on directly perceived benefits, such as improved environmental conditions and reduced concerns about contamination. However, medium-term economic benefits and government agency consistency have not yet been fully realized, preventing higher levels of satisfaction. Government agencies, on the other hand, evaluate remediation from the perspectives of policy, social stability, and governance. While technical and regulatory aspects are considered adequate, government agencies remain attentive to potential social dynamics, the need for continued monitoring, and government agency risks. Despite their different positions, both perspectives yield moderately positive yet cautious assessments, resulting in no statistically significant difference.

The significant difference observed between the company cluster and the other two clusters constitutes a key finding of the Tukey HSD test. Substantively, companies evaluate the success of remediation primarily in terms of operational continuity, regulatory certainty, and minimal social disruption. Bioaugmentation is perceived as an effective and relatively efficient method that can be integrated into company environmental management systems, thereby leading to higher satisfaction levels. Furthermore, companies tend to maintain a more positive perception as long as remediation activities proceed without significant conflict and do not disrupt operational processes.

Overall, these inter-cluster differences underscore that the impacts of environmental remediation are not perceived uniformly, but are shaped by the positions, roles, and interests of each stakeholder group. Communities and government agencies tend to remain in an evaluative phase, recognizing the benefits while still requiring further enhancement, whereas companies demonstrate higher levels of satisfaction as remediation aligns with operational sustainability and business certainty. These findings highlight the importance of adopting an inclusive and adaptive environmental remediation approach to ensure that social and economic benefits are more equitably distributed among all stakeholders.

CONCLUSION

Based on the results of this study and the discussion regarding the implementation of bioaugmentation techniques for the remediation of crude oil-contaminated soil, the effectiveness of the bioaugmentation method was demonstrated by its ability to significantly reduce long-chain petroleum hydrocarbon concentrations to meet environmental quality standards ($\leq 0.1\%$ or TK-C). The results indicated that the bioaugmentation treatment, particularly at a dosage of 1 liter of bacterial culture per m^3 (Treatment B), represented the optimal condition, as it achieved effective degradation performance while maintaining greater cost efficiency compared to other treatments.

Social perceptions of the implementation of bioaugmentation showed a generally positive trend across all respondent clusters. Communities experienced improved environmental conditions, reduced concerns regarding contamination, and sufficient access to information about remediation activities. From the perspectives of government agencies and companies, no significant social conflicts were identified, and activities were conducted in a relatively conducive manner. This indicates that the implementation of bioaugmentation generated positive social impacts.

The economic impact of bioaugmentation implementation showed positive outcomes, although with varying levels of benefit across stakeholder clusters. Communities experienced increased economic activity and potential enhancement of land-use value, while companies benefited from reduced remediation and monitoring costs compared to conventional methods, thereby supporting economic sustainability.

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