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Growth Response of Sea Kale (Ipomoea Pes-Caprae (L.) R. Br.) to Porong River Sediment Polluted by Lapindo Mud

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Abstract

Vegetative growth of sea kale (Ipomoea pes-caprae) can be affected by the condition of the growing medium, including sediments polluted by Lapindo mud. This study aimed to explore the effect of polluted sediments on the growth of stem cuttings of I. pes-caprae in the Porong River area. The study used an experimental approach with a completely randomized design (CRD), testing six growing media treatments: sediments of the Porong River not polluted by Lapindo mud (positive control), pure Lapindo mud (negative control), and sediments from four different locations located 0 km, 7 km, 14 km, and 21 km from the mud discharge point. Observation parameters included survival, number of shoots, shoot length, number of leaves, leaf size, root length, biomass, biomass efficiency, and root to crown ratio. Data were analyzed using one-way ANOVA with Tukey's further test at 95% confidence level. Results showed that 0 km media supported the highest growth consistently, while 7 km and 21 km media showed fluctuating results. These findings suggest that I. pes-caprae has tolerance to sediments with mild to moderate contamination, and has the potential to be used as a pioneer plant in passive revegetation and phytoremediation programs in the Porong River area affected by Lapindo mudflow.

Keywords: Ipomoea pes-caprae, lapindo mud, ecosystem rehabilitation, contaminated sediment, porong river.

1. Introduction

The Lapindo mud disaster that occurred on May 29, 2006 in Sidoarjo, East Java, has become one of the most significant environmental crises in Indonesia (Mazzini, 2018; Wulandari et al., 2022). The eruption released large quantities of hot mud (Masella & Purnomo, 2020; Mazzini, 2018). As the volume of Lapindo mud discharge into the Porong River increases, mud sediments cause siltation. These sediments contain high concentrations of heavy metals and their oxide forms such as iron (36.4%), silicon (31.1%), and other elements such as aluminum, manganese, and chromium (Ciptawati et al., 2022).

Figure 1: Lapindo mudflow disposal center in porong river
Source: Detik.com

Sedimentation and heavy metal contamination lead to decreased water quality, reduced biodiversity, and disruption of ecological services (Stephanus & Chairudin, 2013; Aziz & Budiyanto, 2022).

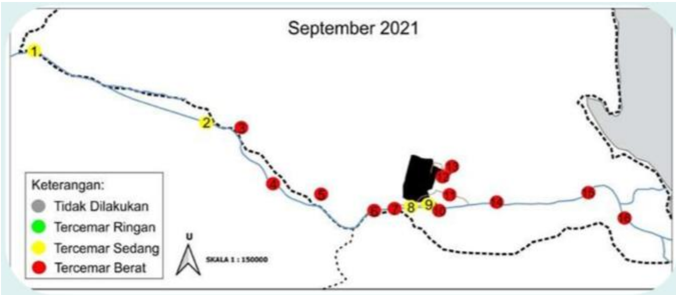

Figure 2: Map of pollution distribution in the porong river as of September 2021
Source: Mongabay.co.id

This study focuses on the growth and survival of sea kale (Ipomoea pes-caprae (L.) R. Br.) stem cuttings under conditions of heavy metal contamination from Lapindo mud. I. pes-caprae is an associated mangrove species widely found in coastal ecosystems (Basha & Amancharla, 2018; Brown & Frank, 2020; C. Silva & Bhat, 2011). This species has demonstrated the ability to thrive in harsh environments, including high salinity soils and areas exposed to heavy metals, making it a promising candidate for phytoremediation and ecological restoration of the Porong River (Acinas et al., 2019; Nizam et al., 2022). By examining the growth response of plant stem cuttings to contaminated sediments from different distances (0 km, 7 km, 14 km, and 21 km) from the source of Lapindo mud discharge in the Porong River, this study aimed to evaluate the growth potential through morphological and physiological observations.

The purpose of this study was to obtain data on the location of Lapindo mud contaminated sediment collection in Porong River that provides the least resistance to the growth of I. pes-caprae stem cuttings through morphological observations. The results of this study have the potential to support sustainable management strategies in mangrove ecosystem recovery through phytoremediation, by addressing heavy metal contamination and increasing ecosystem resilience. This study also provides information on the resilience of I. pes-caprae to polluted environmental conditions and its potential in Porong River sediment rehabilitation. Thus, it can be used as a basis in the management of I. pes-caprae to support the recovery of the Porong River ecosystem affected by human activities and Lapindo mud pollution.

2. Materials and Research Methods

This research was conducted in January-February 2025, at an artificial greenhouse in South Tangerang. Tools used included: stationery, basin, digital camera, oven, ruler with 0.1 cm accuracy, polybag, and analytical balance. The materials used in this study were Lapindo mud and sea kale plants (Ipomoea pes-caprae (L.) R.Br.). This research was conducted using an experimental approach with quantitative data analysis techniques. Experiments were conducted through the depiction of statistical analysis of the results of observations of the growth response of I. pes-caprae stem cuttings to the influence of Lapindo mud polluted sediments as a planting medium. The experimental design of this study used a completely randomized design (CRD) statistical model approach with six levels, resulting in six treatment groups (Porong River sediments taken at 0, 7, 14, and 21 km from the Lapindo mud discharge point, Porong River sediments at a distance of 7 km upstream (positive control) and Lapindo mud as a negative control.

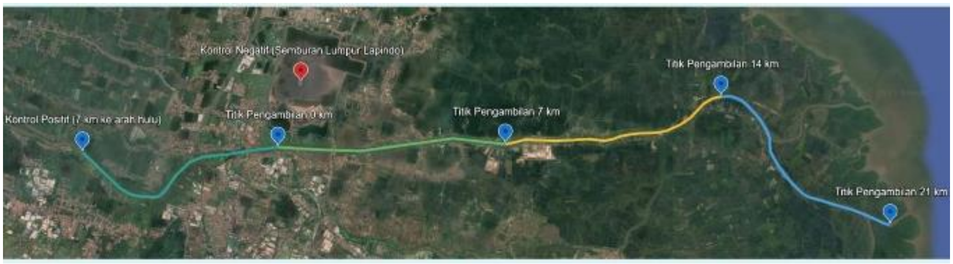

Figure 3: Map sediment sampling of the porong river

The growth parameters observed were: (1) survival rate, (2) shoot length increase, (3) number of leaves, (4) leaf length and width increase, (5) root length increase, (6) biomass, (7) biomass efficiency, and (8) root to shoot ratio. Growth observations were conducted at 0, 3, 6, 9, 12, 15, 18, 21, 24, 27, and 30 days after planting (DAP). Two-month-old I. pes-caprae plants with a minimum length of 30 cm were cut into 18 cm stem cuttings and ensured that there were 2 nodes per stem cutting for root and shoot growth. Then, I. pes-caprae stem cuttings were rinsed using distilled water and soaked in distilled water for seven days. After root growth, I. pes-caprae stem cuttings were planted in polybags containing Porong River sediment and grown in a greenhouse with a controlled environment. The stem cuttings received natural lighting and were exposed to direct sunlight with a photoperiod of ±12 hours per day. Watering was done regularly every 2 days using distilled water.

3. Results and Discussion

3.1. Survival Rate

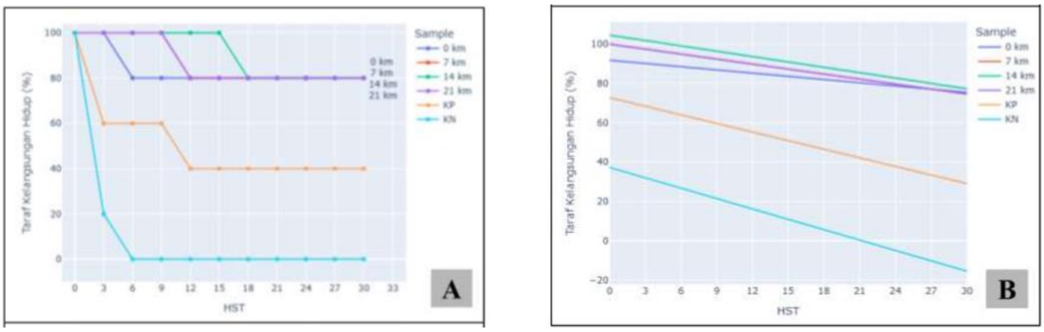

Figure 4: Survival rate of Ipomoea pes-caprae cuttings under various sediment treatments (A). Percentage survival rate during 30 DAP (B) Trends in survival rate changes during 30 DAP

The media treatment from the 14 km location showed the best performance with 100% survival rate until 18 DAP, then stabilized at 80% until 30 DAP. The 0 km, 7 km, and 21 km treatments were also quite good with an initial decline to 80%, but remained stable until the end. In contrast, the positive control (PC) showed a sharp decline to 40%, and the negative control (NC) experienced complete death from day 6. Linear regression analysis (Figure 4.B) showed that 0 km (gradient = -0.545) had the slowest rate of decline, while PC (gradient = -1.455) and NC (gradient = -1.758) experienced the fastest decline.

ANOVA and Tukey HSD tests confirmed significant differences between treatments, with NC as the worst medium and PC also less effective. There were no significant differences between the 0, 7, 14, and 21 km treatments, which showed similar relative effectiveness. Overall, media from 14 km was considered the most optimal for supporting cuttings survival in the early phase.

The results showed that the media from the 0 km and 14 km locations had outstanding performance in the early growth phase. This result indicates that both media have characteristics that still support the early adaptation of cuttings, despite coming from areas with exposure to Lapindo mud. In contrast, the negative control medium (NC), consisting of pure Lapindo mud, was unable to sustain plant life, confirming the presence of extreme toxic stress. This may have originated from heavy metal content, poor aeration, and nutrient imbalance (Chibuike & Obiora, 2014; Hallett & Bengough, 2013; Ovečka & Takáč, 2014).

3.2. Number of Buds

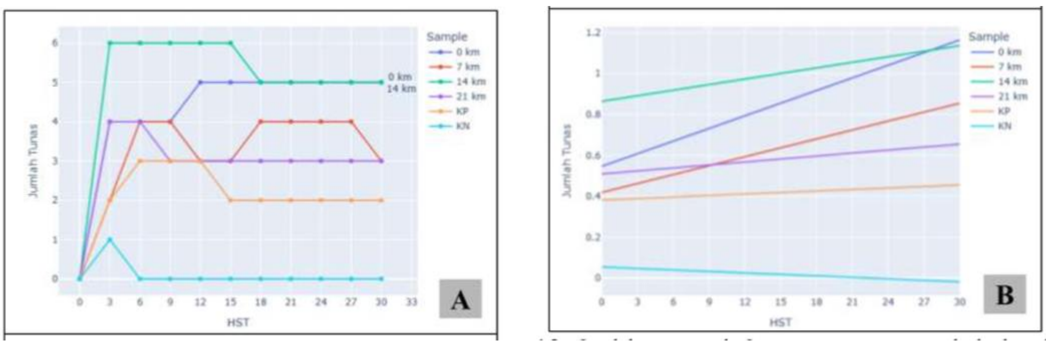

Figure 5: Number of Ipomoea pes-caprae cuttings under various sediment treatments (A) Development of the number of shoots during 30 DAP (B) Trends in survival rate during 30 DAP

Figure 5 shows that during 30 DAP, the growth of I. pes-caprae shoots differed between media. The 14 km media showed the fastest spike in shoots (6 shoots at 3 DAP), but decreased to 5 shoots by the end. The 0 km media showed stable and highest growth until 30 DAP. The 7 km and 21 km treatments fluctuated (3-4 buds), PC decreased from 3 to 2 buds, while NC only produced 1 bud at the beginning and zero thereafter.

Linear regression (Figure 5.B) showed the highest shoot growth rate at 0 km (gradient = 0.0206), followed by 14 km, 7 km, and 21 km. Positive Control (gradient = 0.0024) and Negative Control (gradient = -0.0024) showed the lowest growth rate. ANOVA and Tukey HSD results showed significant differences between treatments. 0 km and 14 km were statistically superior, while NC was the worst and PC was less effective. 7 km and 21 km showed intermediate and unstable performance. The 0 km medium was most optimal for shoot growth, while 14 km was also good although it decreased slightly. 7-21 km was less stable, PC declined after a good start, and NC failed to support growth from the beginning.

This reflects the physiologically favorable condition of the media for the regeneration process. The ability of cuttings to form early shoots indicates that the meristematic tissue is still active and not experiencing serious metabolic disturbances (Ovečka & Takáč, 2014). Meanwhile, 7 km and 21 km media showed more fluctuating results, and PC media did not stand out, which may be due to the incompatibility of the physical and chemical properties of these media with the natural habitat of I. pes-caprae in coastal environments (Brown & Frank, 2020; Neto et al., 2006).

3.3. Shoot Length Increase

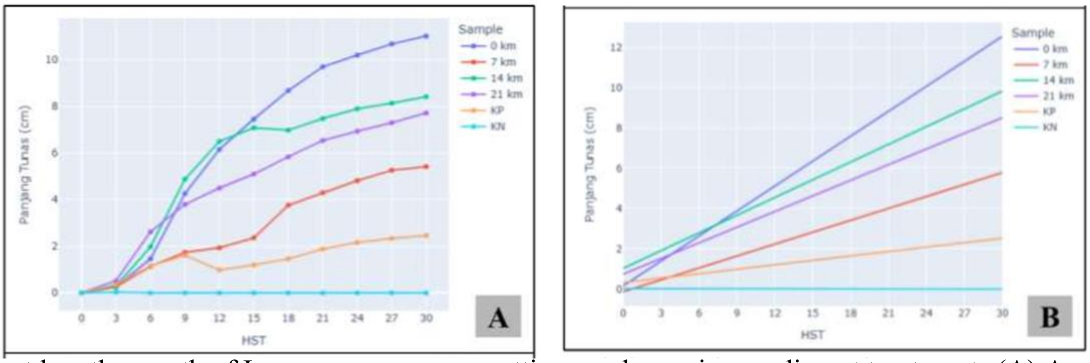

Figure 6: Shoot length growth of Ipomoea pes-caprae cuttings under various sediment treatments (A) Average shoot length during 30 DAP (B) Shoot length growth trend during 30 DAP

Based on Figure 6, sediment media from the Porong River at a distance of 0 km produced the highest and most consistent shoot length (average 11.02 cm), followed by 14 km (8.42 cm) and 21 km (7.72 cm). The 7 km treatment showed slower growth (5.42 cm), while the positive control (PC) was low and stagnant (2.46 cm), and the negative control (NC) showed no growth at all.

Linear regression analysis (Figure 6.B) showed the highest growth rate at 0 km (0.413 cm/day), followed by 14 km (0.294 cm/day), 21 km (0.259 cm/day), and 7 km (0.197 cm/day). The positive control had a very low rate (0.073 cm/day), while the negative control showed no shoot length increase during the observation time.

ANOVA and Tukey HSD tests showed significant differences between treatments. The 0 km and 14 km media proved to be the most effective, significantly different from PC and NC. The 21 km media had moderate performance, while 7 km and PC were low, and NC was the worst. Therefore, 0 km media was the most optimal for shoot length growth of I. pes-caprae, followed by 14 km and 21 km. PC and 7 km were less effective, while NC did not support growth at all.

Active shoot growth indicates that the plant is in sufficiently favorable environmental conditions to expand the photosynthetic surface and begin to form a crown system (Hartmann et al., 2014). This study found the highest shoot growth in the 0 km media, which despite coming from the Lapindo mud disposal area, still has physical and chemical qualities that support growth. This medium is thought to contain dissolved minerals and good pore structure, which can support cell development and early plant physiological processes (Hallett & Bengough, 2013; Landsberg & Sands, 2011). In contrast, the 7 km and 21 km media showed slow shoot growth, possibly due to poor drainage, high clay content, or the presence of toxic compounds, which caused the plants to prioritize survival over crown expansion, which was then reflected in the high root to crown ratio (Ai et al., 2015).

3.4. Number of Leaves

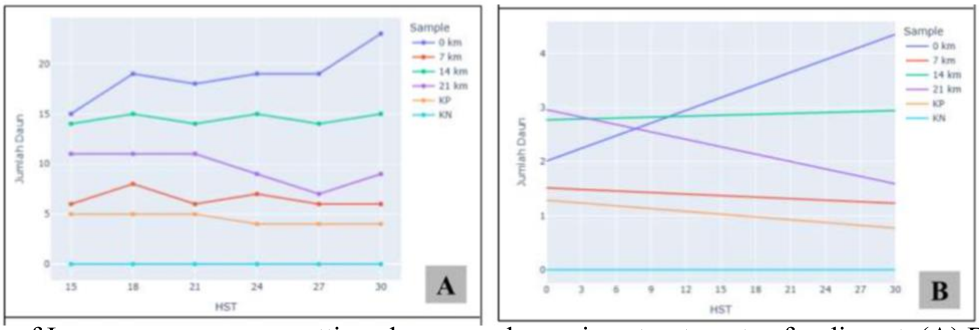

Figure 7: Number of Ipomoea pes-caprae cuttings leaves under various treatments of sediment. (A) Development of the number of leaves during 30 DAP. (B) Trend of increase in the number of leaves during 30 DAP

Based on Figure 7, during 30 DAP the number of leaves of I. pes-caprae cuttings differed between planting media. The 0 km treatment showed the best leaf growth, increasing from 15 strands (15 DAP) to 23 strands (30 DAP). The 14 km treatment was stable at 14-15 leaves, while 21 km had increased but decreased to 9 leaves at the end. The 7 km treatment and positive control (PC) showed a low and stagnant number of leaves, ranging from 6-8 strands and 4-5 strands, respectively. The negative control (NC) showed no leaf growth at all.

Regression analysis (Figure 7.B) showed that 0 km had the highest leaf growth rate (gradient = 0.0781), followed by 14 km. The 21 km medium was initially good constant = 2.96) but unstable (gradient = -0.0457), while (constant = 1.51; gradient = -0.0095) and the positive control (PC) (constant = 1.29; gradient = -0.0171) showed low growth and tended to tagnate. NC did not support growth at all.

ANOVA and Tukey HSD test results showed significant differences between treatments. The 0 km and 14 km media were statistically most effective in supporting leaf growth, while PC and NC showed low effectiveness. The 7 km and 21 km treatments were at a moderate level, not significantly different from the upper and lower groups. So that the Porong River sediment media from a distance of 0 km is most effective in supporting the formation of I. pes-caprae leaves, followed by 14 km. Media 7 km and 21 km are moderate, PC is less effective, and NC is the least supportive of growth.

The 14 km medium performed quite well, especially in the leaf length parameter, although the final results were not stable. The number of leaves was relatively high but showed variation between individuals, and the increase in leaf width decreased in the final phase. This instability suggests that although the media still supports growth, the nutrient availability or physical conditions are not consistent enough to support optimal tissue expansion over the full time period. In contrast, the 7 km and 21 km media showed a decline in all leaf development parameters. The number of leaves stagnated and even decreased towards the end of the observation, indicating a disruption in the formation of new leaves. Growth in leaf length and width was also restrained, indicating environmental stress that interferes with cell expansion. Hatamian et al. (2020) explained that heavy metal stress can inhibit leaf cell division and expansion, reduce leaf area, and disrupt photosynthesis through damage to mesophyll and stomatal structures. In addition, the predominantly clay-textured media at this location likely caused low aeration and excess water retention (Hallett and Bengough, 2013; Verhoef & Egea, 2013).

The number of leaves was high and continued to increase during the observation period, indicating the continued formation of new photosynthetic organs. The high increase in leaf length and width also indicates that the plant is also increasing the dimensions of each leaf blade, resulting in increased light capture efficiency (Leigh et al., 2017; Lusk et al., 2019). According to Yang et al. (2021), leaf size and area are strongly influenced by cell turgor, water supply, and the activity of growth hormones such as auxin and cytokinin. These factors are very sensitive to media quality. This suggests that 0 km media provide environmental conditions that do not inhibit these growth mechanisms.

3.5. Leaf Length Increase

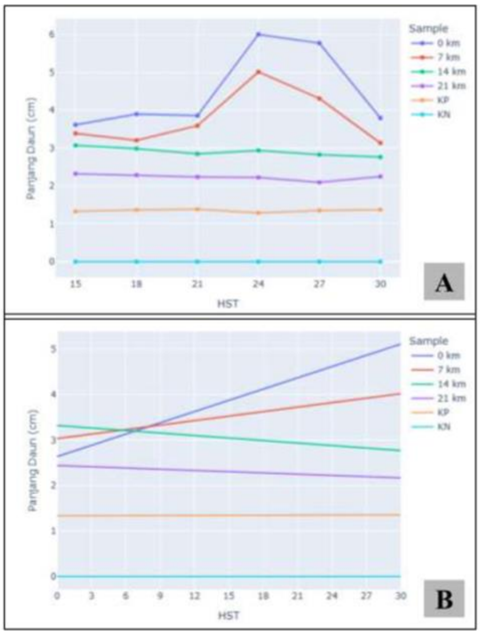

Figure 8: Leaf length growth of Ipomoea pes-caprae cuttings under various sediment treatments (A) Leaf length during 30 DAP (B) Leaf length growth trend during 30 DAP

Based on the observation until 30 DAP (Figure 8.A), the increase in leaf length of I. pes-caprae varied between treatments. The 0 km treatment showed the best results with the highest leaf length (max. 6.11 cm at 24 DAP, decreased to 3.84 cm at the end). The number of leaves was high and continued to increase during the observation period, indicating the continued formation of new photosynthetic organs. The high increase in leaf length and width also indicates that the plants also increased the dimensions of each leaf blade, resulting in increased light capture efficiency (Leigh et al., 2017; Lusk et al., 2019).

The 7 km treatment was also quite good although slower (max. 4.77 cm, decreased to 3.21 cm). The 14 km and 21 km treatments showed low growth and tended to decline. PC was stagnant, and NC showed no growth at all. Growth in leaf length and width was also restrained, indicating environmental stress that interferes with cell expansion. Hatamian et al. (2020) explained that heavy metal stress can inhibit leaf cell division and expansion, reduce leaf area, and disrupt photosynthesis through damage to mesophyll and stomatal structures.

Regression analysis (Figure 8.B) showed the highest growth rate at 0 km (gradient = 0.0825), followed by 7 km (0.0330). The 14 km (gradient = -0.0184; constant = 3.3) and 21 km (gradient = -0.0091; constant = 2.44) treatments showed negative rates, indicating media instability. PC was almost stagnant with a growth rate close to zero (gradient = 0.0006; constant = 1.34) and NC did not support growth (gradient = 0).

ANOVA results and Tukey test showed significant differences between treatments. The 0 km medium was most effective and significantly different from almost all treatments except 7 km. The 7 km treatment is high, while 14 km and 21 km are less stable. PC was low, and NC was not effective at all. Therefore, 0 km media was most optimal in supporting leaf elongation of I. pes-caprae cuttings, followed by 7 km. Media 14 km and 21 km were less stable, PC was almost stagnant, and NC did not support growth.

3.6. Leaf Width Increase

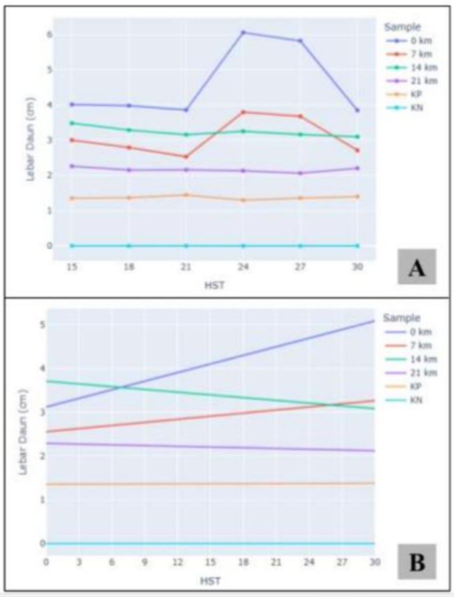

Figure 9: Increase in leaf width of Ipomoea pes-caprae cuttings under various sediment treatments (A) Leaf width during 30 DAP (B) Trend of leaf width increase during 30 DAP

Figure 9 shows that the increase in leaf width of I. pes-caprae varied between treatments. The 0 km medium showed the best results, with a peak growth of 6.00 cm at 24 DAP, then decreased to 3.84 cm at the end of the observation. The 7 km treatment grew slowly to 3.80 cm, then decreased to 2.71 cm. The 14 km treatment showed a relatively stagnant pattern with a slight gradual decrease from the beginning to the end of the observation, and a relatively high average value of leaf width (3.48-3.10 cm). The 21 km treatment also showed stability, but with leaf width values that tended to stagnate and fluctuate slightly between 2.07-2.27 cm, indicating media that did not actively encourage leaf expansion. The Positive Control (PC) stabilized in the very low range (1.28-1.43 cm), while the Negative Control (NC) showed no growth at all (0 cm). According to Yang et al. (2021), leaf size and area are strongly influenced by cell turgor, water supply, and the activity of growth hormones such as auxins and cytokinins. These factors are very sensitive to media quality. This suggests that 0 km media provide environmental conditions that do not inhibit these growth mechanisms.

Regression analysis (Figure 9.B) showed that 0 km had the highest growth rate of leaf width (gradient = 0.0655; constant = 3.12), followed by 7 km (0.0236; constant = 2.55). The 21 km treatment showed a slow decline in leaf width (gradient = 0.0057; constant = 2.29), while 14 km had the steepest decline (gradient = -0.0210; constant = 3.71), indicating that this medium although favorable for initial growth, became less effective over time. PC was almost stagnant (gradient = 0.0007; constant = 1.35), and NC did not support growth (gradient and constant = 0.0000).

The results of ANOVA test and Tukey test showed significant differences between treatments. The 0 km treatment was significantly different from all other treatments, showing the highest effectiveness. The 7 km and 14 km treatments were at the intermediate level. The 21 km treatment was as effective as PC (low effectiveness), while NC was the worst. Therefore, 0 km sediment medium was most effective in supporting leaf width increase of I. pes-caprae. 7 km medium still supported although slower, while 14 km and 21 km were less stable. PC and NC were not effective at all.

3.7. Root Length Increase

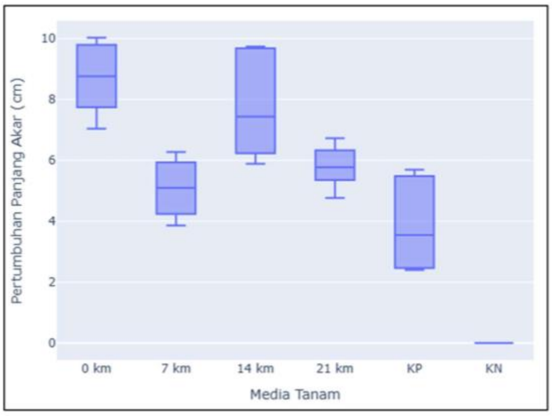

Figure 10: Distribution of root length increment of Ipomoea pes-caprae cuttings in various sediment treatments (30 DAP)

In Figure 10, the 0 km treatment showed the best root growth, with the highest median root length (8.76 cm), high minimum-maximum range (6.85-10.42 cm), and narrow inter-quartile spread (7.75-9.79 cm), indicating consistent growth. The data distribution is almost symmetrical with a slight positive skewness, so this medium is considered the most effective in supporting root growth.

The 14 km treatment also showed high root growth (median = 7.44 cm), but with large variation, reflecting inconsistency despite potential. The 21 km treatment had a lower median (5.77 cm) but with a narrow distribution and slightly skewed towards the lower quartile (q1 = 5.35 cm; q3 = 6.33 cm), indicating moderate but fairly uniform effectiveness. The 7 km treatment and the positive control (PC) showed low root growth with a homogeneous distribution, but within a small range. Meanwhile, the negative control (NC) showed no root growth at all (all values = 0), indicating that the media really did not support growth.

ANOVA and Tukey HSD tests showed significant differences between treatments. The 0 km treatment was most effective, NC was least effective, and the others were in intermediate positions with varying effectiveness. Media from location 0 km was the most optimal for root growth of I. pes-caprae cuttings, followed by 14 km (potential but inconsistent), 21 km (moderately effective), and 7 km and PC (less effective). NC did not support growth at all.

Optimal root growth is important for water and nutrient uptake, especially in cuttings (Hartmann et al., 2014). The 0 km medium supported good root growth as it had no physical or chemical barriers, allowing roots to grow and explore the soil efficiently. In contrast, the 7 km and 21 km media showed poor root growth, possibly due to too fine soil texture or heavy metal content that inhibited root development. This mismatch could stem from too fine a substrate texture or heavy metal content that interferes with root tissue growth (Hallett & Bengough, 2013; Ovečka & Takáč, 2014).

3.8. Biomass

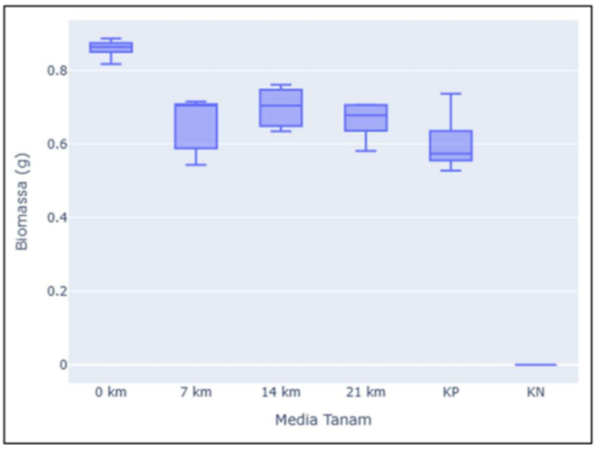

Figure 11: Distribution of biomass of Ipomoea pes-caprae cuttings in different sediment treatments (30 DAP)

Based on the distribution analysis (Figure 11), the 0 km treatment gave the best results with the highest median biomass (0.8631 g), narrow distribution, and very consistent growth, indicating high effectiveness and stability. The 14 km treatment had a high median (0.7042 g) and good growth potential, but with greater variation between individuals, making it less homogeneous than 0 km. The 7 km treatment had a similar median to 14 km (0.7043 g) but with higher variation and a lower maximum, indicating moderate effectiveness with low stability. The 21 km treatment showed a moderate median (0.6778 g) with a narrow and stable distribution, but less optimal than 0 km.

The positive control (PC) produced lower biomass (0.5734 g) with considerable variation, indicating limited effectiveness. The negative control (NC) did not support growth (all biomass = 0 g), proving that this medium does not support the physiological processes of plants.

ANOVA and Tukey HSD tests showed significant differences between treatments ($p < 0.05$). 0 km was significantly different from all other treatments (best). NC was significantly different (least effective). 7 km, 14 km, 21 km, and PC were in the medium effectiveness group. Media from the 0 km site was most optimal for biomass accumulation, followed by 14 km and 7 km which were moderately effective but inconsistent. 21 km was stable but suboptimal, PC was limited, and NC did not support growth at all.

Growing media from the 0 km site performed best in supporting I. pes-caprae biomass accumulation, with the highest median, narrow distribution, and uniform growth of individuals. The 14 km and 7 km media were also quite effective, but 14 km was more stable while 7 km showed greater variation in growth. The 21 km medium was classified as moderate, with fairly consistent but lower growth. The positive control (PC) had low effectiveness, characterized by low median biomass and high growth variation. The negative control (NC) did not support growth at all. Statistical test results (ANOVA and Tukey HSD) showed that the 0 km media was significantly different from all other treatments, making it the most effective media in supporting biomass growth.

This finding indicates that this medium not only supports optimal growth but also maintains stability between individuals. It is very likely that this medium has physical characteristics such as favorable aeration and porosity, as well as essential nutrient concentrations that are balanced enough to support plant tissue growth. This is in line with Kubota (2016) and Landsberg & Sands (2011) that dry biomass is closely related to photosynthetic productivity and tissue physiological quality.

The 14-km and 7-km media show almost equal median biomass, but with different stability. The 14 km medium tended to be more consistent, while the 7 km showed considerable variation between individuals. This indicates that although both media contain nutrients and textures that can still be utilized by plants, the heterogeneity of local conditions in the 7 km sediment could potentially trigger sharper growth differences. The positive control (PC), which was plain topsoil, produced lower biomass than the 0 km and 14 km treatments, and had a positive skewness of. These values reinforce the finding that conventional topsoil media are not necessarily suitable for coastal species such as I. pes-caprae, which naturally grows on sandy, nutrient-poor and high-salinity media (Brown & Frank, 2020; Neto et al., 2006). On the other hand, the negative control (NC) consisting of pure Lapindo sludge did not support growth at all, reflecting the extreme conditions of the medium, both in terms of heavy metal toxicity and dense, poorly drained soil structure (Hallett & Bengough, 2013; Ovečka & Takáč, 2014).

3.9. Biomass Efficiency

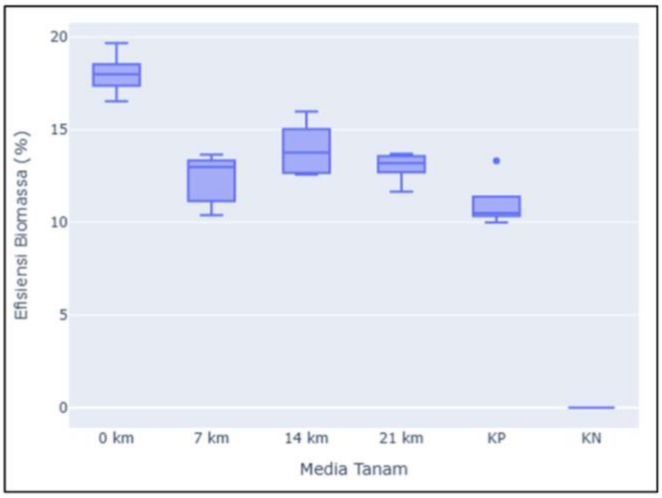

Figure 12: Distribution of biomass efficiency of Ipomoea pes-caprae cuttings in different sediment treatments (30 DAP)

Based on the distribution results (Figure 12), the 0 km treatment showed the highest efficiency (median: 17.99%) with narrow distribution and negative skewness, indicating high consistency and stability in fresh to dry biomass conversion. The 14 km treatment had a median efficiency of 13.76%, showing good potential, but more variable and less homogeneous than 0 km (positive skewness). The 21 km treatment showed moderate efficiency (13.20%), with good stability (narrow distribution and negative skewness), although performance was slightly below 14 km. The 7 km treatment had a median efficiency of 12.99%, but with high diversity and less consistent performance, although some individuals had high efficiency.

The positive control (PC) showed low efficiency (10.50%) with a narrow distribution and positive skewness, indicating that most individuals grew less efficiently. The negative control (NC) showed no growth at all (0% efficiency), confirming the total ineffectiveness of this medium.

ANOVA and Tukey HSD test results showed significant differences between treatments ($p < 0.05$). 0 km was significantly different from all other treatments (most optimal). NC was significantly different from all treatments (least effective). 14 km, 21 km, and 7 km were in the medium effectiveness group. PC was low, only not different from 7 km and 21 km. Media from the 0 km site was the most effective and stable in supporting biomass efficiency. 14 km also had high potential but was less stable. 21 km and 7 km were of medium effectiveness, while PC was low, and NC did not support growth at all.

In terms of biomass efficiency, the results showed that the 0 km treatment again showed superiority with the highest value and narrow distribution. This indicates an efficient and stable conversion of fresh biomass to dry biomass between individuals. High efficiency indicates that plants on this medium are able to maintain appropriate osmotic pressure and regulate metabolism to produce the maximum amount of functional tissue (Morales et al., 2020).

The 14 km and 21 km media showed intermediate efficiency values but were quite stable. In contrast, the 7 km and PC media had low efficiency and wide distribution, indicating irregularities in the growth process and possible environmental disturbances, such as ionic imbalance or oxygen availability in the root zone. The negative control (NC) again failed to show any accumulation of dry biomass. Overall, these results confirmed that the 0 km media was most optimal in supporting I. pes-caprae biomass production and efficiency. The second hypothesis was again not fully supported as there was no linear relationship between distance and reduced effectiveness. However, the distribution pattern and performance between media showed significant variation, strengthening the third hypothesis, possibly due to differences in the physical and chemical characteristics of each site.

3.10. Root to Shoot Ratio

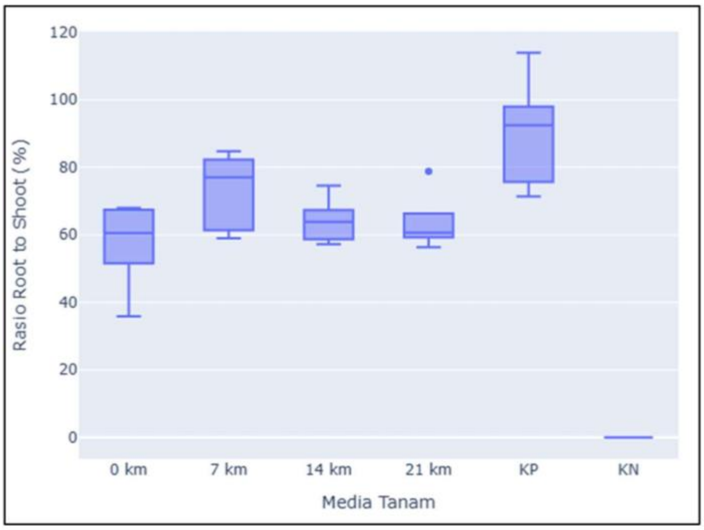

Figure 13: Distribution of root to shoot ratio of Ipomoea pes-caprae cuttings in various sediment treatments (30 DAP)

Based on the distribution analysis (Figure 13), the 21 km treatment showed the lowest root dominance (median: 60.63%) with a narrow distribution and positive skewness, indicating most individuals had a small and uniform allocation of biomass to roots. The 0 km treatment had the lowest median (60.52%), but with a wider distribution and mild negative skewness, indicating that although root allocation was generally low, there were still many individuals with high root dominance. The 14 km treatment showed a higher allocation of root biomass (median: 63.80%) with a narrow distribution and mild negative skewness, reflecting a consistent trend towards roots, but not extremes. The 7 km treatment had a very high root allocation (median: 77.01%) and strong negative skewness, indicating a dominance of biomass towards roots in most individuals, although there was variation.

The positive control (PC) showed the highest ratio (median: 92.49%) with sharp negative skewness, indicating extreme root dominance in almost all individuals. The negative control (NC) showed no growth (ratio = 0%), indicating the medium was completely unfavorable to root or crown development.

ANOVA and Tukey HSD test results showed significant differences between treatments ($p < 0.05$). NC was significantly different from all treatments (least effective). PC was only not significantly different from 7 km, but different from all other treatments (low effectiveness). 0 km, 7 km, 14 km, and 21 km were not significantly different from each other, belonging to the medium-good effectiveness category, with a tendency towards a more balanced ratio (less dominant to the root). The 21 km treatment was the most balanced (low and stable root dominance). 0 km also showed a low ratio, but was more variable. 14 km showed moderate root dominance, relatively consistent. 7 km and PC were very root dominant, especially extreme PC. NC completely failed to support growth.

The root-to-shoot ratio strengthens the picture of the plant's allocation strategy. The low and positively patterned ratio values in the 0 km media indicate the dominance of crown growth, which is an adaptive strategy under environmental conditions that do not force plants to explore roots intensively. In coastal ecosystems, such conditions are favorable because they accelerate the recovery of the photosynthetic surface and allow plants to respond quickly to environmental signals such as light and wind (Ali et al., 2013; Hartmann et al., 2014).

In contrast, the high and negatively patterned ratio values in the 7 km and 21 km media indicate environmental stresses that promote over-allocation to the roots. Although this strategy is useful for short-term survival, root dominance often goes hand in hand with slow crown growth, which will ultimately limit the photosynthetic ability and long-term productivity of the plant (Ali et al., 2013; Chibuike & Obiora, 2014).

3.11. Evaluation of Media Effectiveness in Supporting Growth

Evaluation of the effectiveness of the growing media is not only determined by the average growth results of each parameter, but also by the consistency between individuals within the same treatment. The results showed that 0 km media was the most superior in almost all parameters observed. This superiority was consistent in crown and root growth and development, as well as biomass accumulation and efficiency. The positive skewness of the root-to-shoot ratio and the narrow spread of the data indicate that these medium favors crown dominance and even growth (Ali et al., 2013; Landsberg & Sands, 2011). These results suggest that the media from the 0 km site is the most stable and productive, despite being geographically the closest location to the center of the Lapindo sludge disposal. These results suggest that the physical and chemical characteristics of the 0 km sediment, such as sandy texture, good drainage, and favorable pore structure, are well suited to the needs of I. pes- caprae, a coastal pioneer plant accustomed to living in open and extreme environments (Brown & Frank, 2020; Neto et al., 2006).

In contrast, the 14 km medium showed relatively good performance in the early phase, but experienced a decline or fluctuation towards the end of the observation. The spread of results between individuals was wider than at 0 km, and some parameters showed a decrease in effectiveness (e.g. leaf length and width). This indicates long-term instability that may be caused by media heterogeneity or inconsistent microenvironmental conditions. This means that this medium still has the potential to be utilized for revegetation, but requires a selective approach and additional management (Iskandar et al., 2024).

Table 1: XRF analysis of elemental and oxide content of lapindo mud

Element	Content (%)	Oxide	Content (%)
Al	9.90	Al_2O_3	13.00
Si	31.10	SiO_2	43.30
K	3.81	K_2O	2.64
Ca	7.99	CaO	6.30
Ti	2.20	TiO_2	2.01
V	0.087	V_2O_5	0.083
Cr	0.11	Cr_2O_3	0.20
Mn	0.35	MnO	0.35
Fe	36.40	Fe_2O_3	25.90
Ni	–	NiO	–
Cu	0.16	CuO	0.092
Zn	0.07	ZnO	0.04
Br	–	–	–
Sr	0.86	SrO	0.46
Mo	5.40	MoO_3	4.80
Eu	0.67	Eu_2O_3	0.40
Yb	–	Yb_2O_3	–
Re	0.30	Re_2O_7	0.20
P	0.44	P_2O_5	0.62

Source: Ciptawati et al. (2022)

The 7-km and 21-km media tended to show less prominent results, and were weak and volatile in some parameters. This instability is reflected in the wide distribution of data, uneven regression values, and negative skewness in some parameters, such as root-to-shoot ratio and biomass efficiency. These findings indicate that media conditions are not optimal in supporting the growth of I. pes-caprae, even though it comes from sediments that are farther from the source of pollution (Ali et al., 2013; Chibuike & Obiora, 2014).

The positive control (PC), which was sediment from the Porong River that was not polluted by Lapindo mud, also did not give the best results. Its clayey texture and low drainage ability most likely did not match the characteristics of I. pes-caprae, which is more adaptive to sandy soils with high drainage (Brown & Frank, 2020; Neto et al., 2006). Meanwhile, the negative control (NC), which is pure Lapindo mud, showed complete failure in all growth parameters. This failure indicates that the toxic and physical properties of the medium exceeded the physiological tolerance threshold of the plants. This is most likely related to the heavy metal content, extreme pH, and poor aeration (Hallett & Bengough, 2013; Landsberg & Sands, 2011; Ovečka & Takáč, 2014).

The extreme conditions of NC media can also be further explained by the chemical characteristics of Lapindo mud. Based on the results of X-Ray Fluorescence (XRF) analysis of pure Lapindo mud (see Table 5.1), it is known that this material contains potentially toxic levels of metal and metalloid elements to plants, such as iron (Fe), aluminum (Al), and other elements in high concentrations (Ciptawati et al., 2022). These elements are known to inhibit root cell expansion, disrupt enzyme activity, and reduce the efficiency of water and nutrient absorption (Hallett & Bengough, 2013; Landsberg & Sands, 2011). In addition, research by Tufo et al. (2021) showed that the presence of heavy metals, organic matter, and microbial activity markedly altered the physical characteristics of sediments, particularly through modification of clay aggregate size, porosity, and surface area. This contamination has an impact on sediment texture, mainly through increased interparticle associations that trigger the formation of aggregates.

Table 2: Evaluation of the effectiveness of planting media on the growth of ipomoea pes- caprae cuttings

Parameters	Treatment Rankings		
	Best	Medium	Worst
Survival rate	14 km	0, 7, 21 km	PC, NC
Number of shoots	0 km	14, 7 km	PC, NC
Shoot length	0 km	14, 7, 21 km	PC, NC
Number of leaves	0 km	7, 14 km	PC, NC
Leaf length	0 km	7, 14 km	PC, NC
Leaf width	0 km	7, 14, 21 km	PC, NC
Root length	0 km	7, 14, 21 km	PC, NC
Biomass	0 km	7, 14, 21 km, PC	NC
Biomass efficiency	0 km	7, 14, 21 km	PC, NC
Root to shoot ratio	0, 7, 14, 21 km	-	PC, NC

Based on the synthesis of results across parameters (Table 2), the planting media can be grouped into four zones of effectiveness. The 0 km medium falls into the highly favorable zone as it is high yielding, consistent, and adaptive, making it a prime candidate for revegetation and phytoremediation. The 14-km media is in the transition zone, still potentially usable with additional selection and management. The 7km and 21km media are classified as unstable zone, less viable for revegetation without intervention. NC media is classified in the failure zone, unable to be used directly as it completely inhibits growth.

Geographically, the Porong River area is an estuary that has undergone morphological and land use changes due to the disposal of large amounts of mud since 2006. The findings of this study are in line with those of Juniawan et al. (2013) who reported that Lapindo mud has a high moisture content (±70%) and a clayey loam texture (53% clay component). These characteristics cause the media to be anaerobic and potentially create ionic stress to plant tissues. The study of Hamzah et al. (2015) and Hermawan & Budiono (2013) reinforce these findings by showing that sediments on the banks of the Porong River are dominated by fine particles (<2.5µm). These physical characteristics make the media tend to be water-saturated, have low porosity, and do not support aeration needed for root growth (Hallett & Bengough, 2013; Landsberg & Sands, 2011). The findings in this study confirm that even though sites such as 0 km are very close to the discharge point, the local character of the sediment still supports vegetative growth. This indicates that revegetation strategies should not only rely on spatial data of distance from the point source, but also consider the texture, structure and local physico-chemical conditions of the media (Iskandar et al., 2024).

Thus, this finding supports the first hypothesis that not all polluted sediments are toxic, especially under certain conditions. These results also rejected the second hypothesis as growth performance did not decrease linearly with increasing proximity to the mud source. Instead, media from the closest location, 0 km, gave the best results. The third hypothesis was proven because variations in plant morphology were clearly influenced by the physical and chemical suitability of the media to the original habitat. Revegetation success depends on ecological suitability, not just geographical location or general nutrient content.

3.12. Ecological and Phytoremediation Implications of Ipomoea pes-caprae

The results of this study are ecologically important for the recovery of coastal areas in the Porong River Estuary, Sidoarjo. The successful growth of I. pes-caprae is strongly influenced by the suitability of the growing medium to its hot, salty, nutrient-poor and fast-draining natural habitat (Brown & Frank, 2020; Wardhani & Poedjirahajoe, 2020; Zheng et al., 2019). The 0 km medium reflects these conditions and supports optimal growth. In contrast, media such as PC, which is rich in organic matter but has a clay texture, inhibits growth even though it is not toxic.

Plant height performance in 0 km and 14 km media indicates that I. pes-caprae is tolerant of mild to moderate environmental stress. This confirms that ecological suitability of the media is more important than chemical fertility in revegetation success (Lestari et al., 2019; Li & Liber, 2018)). This finding supports a minimal intervention restoration approach, which utilizes local sediments without special treatment if they are still suitable for the plant's natural habitat.

As a coastal pioneer species, I. pes-caprae has an important role in stabilizing substrates, preventing erosion, and accelerating vegetative succession. Its creeping growth and rapid lateral roots make it highly effective in binding coarse to medium sediments (Brown & Frank, 2020; Neto et al., 2006; Wardhani & Poedjirahajoe, 2020; Zheng et al., 2019). Therefore, its successful growth on 0 km media not only reflects physiological tolerance, but also indicates potential as a natural revegetation agent for mud-polluted coastal areas.

Although I. pes-caprae is not a local endemic species of the Porong River Estuary, it has been widely distributed and grows naturally in coastal Indonesia (Akinniyi et al., 2022; Serosero et al., 2020). In addition, I. pes-caprae is recorded as one of the associated mangrove species growing in the coastal area of Jabon Subdistrict, Sidoarjo. A local species with ecological and morphological similarities, Ipomoea imperati, was also found in the area and occupies a similar habitat (Minata et al., 2023). However, to date there is no scientific documentation demonstrating the potential of I. imperati as a phytoremediation agent or pollution bioindicator. Therefore, I. pes-caprae remains relevant and scientifically superior to be used as a pioneer species in revegetation efforts of affected coastal areas, at least in initial stages or limited-scale field tests.

The utilization of I. pes-caprae is also relevant in the phytoremediation approach, especially in the passive phytoremediation category. This plant is proven to be able to absorb heavy metals such as Al, Fe, Zn, Pb, Ni, Cu, Cr, Cd and shows the ability to survive in polluted media without additional treatment (Abdullah et al., 2016; Acinas et al., 2019; Chowdhury et al., 2022; Cordova, 2021; Kozak et al., 2015; Nayak et al., 2016, 2017; Umoh et al., 2014). This approach is not only economical and easy to implement in the field, but also opens up opportunities for local community participation in rehabilitation efforts (Arifanti et al., 2022).

However, the success of this approach remains highly dependent on the character of the media. The findings of this study are in line with those of Juniawan et al. (2013) who reported that Lapindo mud has a high moisture content (±70%) and a clayey loam texture (53% clay component). These characteristics create severe physiological stress, especially on young roots that are sensitive to ionic stress and anaerobic conditions. This explains the complete failure on NC media and the yield instability on 7 km and 21 km media. Studies by Hamzah et al. (2015) and Hermawan & Budiono (2013) reinforce these findings by showing that sediments from the estuary and sides of the Porong River are dominated by silt and fine clay, which reduce porosity and inhibit drainage. Thus, although some media such as 7 km and 21 km do not support optimal growth, simple modifications such as sand mixing or pre-drying can improve their potential for revegetation (Iskandar et al., 2024). I. pes-caprae can also be used as an early indicator to assess the feasibility of media before they are widely applied in coastal area rehabilitation.

In addition, it should be noted that ecological pressures in the Porong estuary area do not only come from Lapindo mud pollution. A study by Prasenja (2018) shows that land conversion to ponds and illegal logging are also dominant factors in the degradation of the Porong River estuary ecosystem, especially the mangrove ecosystem. Therefore, revegetation and phytoremediation strategies are not technically sufficient, but must be supported by integrated spatial management policies and sustainable control of anthropogenic pressures (Gerona-Daga & Salmo, 2022; Iskandar et al., 2024; Szafranski & Granek, 2023).

Overall, the results of this study show that the sediments of the Porong River polluted by Lapindo mud still have ecological potential to support coastal revegetation. With an approach based on local adaptation and ecosystem management, I. pes-caprae can be optimized as a pioneer species in the recovery of affected areas, both as a phytoremediation agent and an early stabilizer in vegetation restoration.

4. Conclusion

Porong River sediment-based growing media polluted by Lapindo mud significantly affected the growth of sea kale (Ipomoea pes-caprae (L.) R. Br) stem cuttings. The medium from the 0 km location produced the highest performance in most parameters, such as survival rate, root length, number of leaves, and biomass accumulation and efficiency. These results indicate that despite being closest to the sludge disposal center, the 0 km media was more supportive of growth than other locations. This finding shows that the proximity of the location is not always directly proportional to the toxicity level of the media. Media from 7 km and 21 km locations showed a tendency to fluctuate. The variation in morphological responses between treatments supports that media characteristics determine the success of plant adaptation. With stable performance in 0 km and 14 km media, I. pes-caprae shows great potential as a pioneer plant in passive revegetation and phytoremediation programs in the Porong River area.

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