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Physiological responses of aloe vera to salt stress in coastal sandy soil: Morpho-physiological evaluation for sustainable cultivation

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ABSTRACT
This study aims to investigate the morphological and physiological responses of Aloe vera to various levels of salinity and seedling origins when cultivated in coastal sandy soils, which are considered marginal agricultural resources. A randomized factorial design was employed, testing four salinity levels (0, 5, 10, and 20 g/L NaCl) and seedlings sourced from three nurseries (Gunung Kidul, Bantul, Cilacap), resulting in a total of 36 treatment combinations evaluated over a 12-month nursery trial. The results showed that seedling origin had a significant influence on plant development. Seedlings from Gunung Kidul consistently demonstrated the best performance in fresh and dry biomass production as well as physiological stability under salinity stress. Moderate salinity (5–10 g/L NaCl) significantly improved parameters such as leaf length, leaf area, and net assimilation rate, indicating an optimal adaptive window for Aloe vera growth. Conversely, high salinity (20 g/L) reduced stomatal density and leaf number, signaling a physiological stress response. The combination of Gunung Kidul seedlings with 5 g/L NaCl (A1G1) resulted in the best overall plant performance, highlighting the importance of proper seedling selection and salinity management in maximizing productivity. These findings confirm the potential of Aloe vera as a sustainable crop for marginal lands, particularly coastal sandy soils. This study also provides a practical framework for improving yield and stress resilience through appropriate seedling selection and controlled saline irrigation practices. The study contributes to the development of adaptive agricultural systems in saline-prone areas.

Contribution/Originality: This study uniquely integrates seedling origin with salinity stress on coastal sandy soils, highlighting how nursery sources significantly influence Aloe vera's physiological resilience. This approach has not yet been explored in previous research.

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1. INTRODUCTION
Aloe vera (Aloe vera L.) could be a high-value financial plant broadly utilized within the well-being, corrective, and nourishment businesses (Baruah, Bordoloi, & Baruah, 2016; Pandey & Singh, 2016; Suprabowo, Winandi, & Jahroh, 2017). The worldwide demand for Aloe vera extract has significantly increased in recent years, driven by growing consumer awareness of its benefits. According to Information Bridge Market Research (2022), the global Aloe vera market was valued at USD 553.1 million in 2021 and is projected to reach USD 1,134.86 million by 2029, with a

compound annual growth rate (CAGR) of 9.40% (Martínez-Burgos et al., 2022). This rising request underscores the significant potential of Aloe vera for broader development, contributing to both neighborhood and worldwide economies (Fortune Business Insights, 2023).

Aloe vera shows solid flexibility in negligible situations, making it a promising product for development in coastal districts (Qanbari, Gandomkar, & Khodagholi, 2018; Solomou, Germani, & Georgakopoulou, 2020). This plant has a place in the Crassulacean Acid Metabolism (CAM) photosynthetic pathway, which permits higher water-use efficiency compared to other plants. As a result, Aloe vera can withstand dry season conditions and high salinity levels (Perron, Kirst, & Chen, 2024). In this manner, extending Aloe vera development in coastal sandy soils presents a viable approach for upgrading the efficiency of marginal lands, especially within the coastal locales of Central Java (Aprilia, Purwanto, Suryanti, & Rahayu, 2025; Cristiano, Murillo-Amador, & De Lucia, 2016). This province has a coastline of 971.52 km, spanning 17 locales, with sandy soils characterized by fast seepage, low water-holding capacity, and a high potential for salt accumulation due to seawater intrusion (Kartikawati, Kurniasih, Putra, & Hanudin, 2024; Oelviani et al., 2024; Primadipta, Saepuloh, Rachmayani, Ghazali, & Sahana, 2025; Triyatmo, Rustadi, & Priyono, 2018).

Despite Aloe vera's resistance to natural stress, inquiries about its physiological and morphological reactions to saltiness in coastal sandy soils remain limited. Most past studies, such as those by Murillo-Amador et al. (2015), have examined the impacts of saltiness on Aloe vera without considering sandy soil conditions Murillo-Amador et al. (2015). Other considerations have illustrated that expanded protein and proline substance, at the side PEP-case movement in Aloe vera, can upgrade its resilience to direct saltiness (Mirbakhsh & Sohrabi, 2022; Murillo-Amador et al., 2014; Nakhaie, Habibi, & Vaziri, 2022). Be that as it may, these studies utilized ordinary developing media and have yet to supply a comprehensive understanding of how Aloe vera adjusts to the particular challenges of coastal sandy soils.

This consideration presents a novel encompassing approach to assessing the morpho-physiological reactions of Aloe vera to salt stress in coastal sandy soils. Not at all like past considerations that were overwhelmingly centered on salt stress in conventional media, this investigation examines additional factors such as seedling roots from different nurseries within the Uncommon Locale of Yogyakarta and Central Java, as well as how different salt levels impact plant growth and development. The origin of seedlings may be a critical factor in successful growth, as differences in seedling quality may influence the plant's resistance to environmental stress.

This study considers points to evaluate the morphological and physiological reactions of Aloe vera to saltiness push in coastal sandy soils in Central Java, considering diverse saltiness levels and seedling beginnings. Moreover, the discoveries of this investigation are anticipated to contribute to the development of a more climate-adaptive and economical rural framework, improving resource-use efficiency and advancing natural preservation. Essentially, this inquiry is expected to provide suggestions for farmers and agribusiness partners on managing Aloe vera growth in limited lands to improve efficiency and create new financial opportunities for local communities through high-value crop expansion.

2. METHODS

This study was conducted in a nursery located in Tegalretno Town, Petanahan Locale, Kebumen District, from December 2023 to December 2024. The investigation utilized a randomized complete block design (RCBD) with two factors. The primary factor was saltiness levels, and the secondary factor was the beginning of Aloe vera seedlings. The saltiness levels consisted of four treatments: NaCl addition of 0 g/L (G0), 5 g/L (G1), 10 g/L (G2), and 20 g/L (G3). The selected saltiness levels were based on previous studies assessing Aloe vera's resistance to salinity, where moderate salt stress levels (5–10 g/L) appeared to enhance physiological adaptation, whereas higher concentrations (20 g/L) induced osmotic stress (Murillo-Amador et al., 2015). NaCl was connected by a water system and equitably conveyed inside the planting medium sometime recently transplanting. After each dangerous examination, NaCl was reapplied at a 20% lower concentration than the introductory dosage. This approach pointed to recreating the genuine conditions of coastal soils, which encounter variances in saltiness over time. The lower NaCl concentration in ensuing applications was aimed at avoiding intemperate salt aggregation within the polybags (Cheng & Milsch, 2020; Hamdani, Derridj, & Roger, 2017; Huang, Mi, Ito, & Kawagoshi, 2021; Zhang, Zuo, Wang, & Han, 2024). The moment calculated was the seedling root, comprising three diverse nurseries, Gunung Kidul (A1), Bantul (A2), and Cilacap (A3). There were 12 treatment combinations, each reproduced three times, resulting in 36 exploratory plots. Each plot contained eight plants: three test plants, three for destructive sampling, and two as reinforcement plants, totaling 288 plants. Dangerous inspecting was conducted every two months after planting. The collected information was analyzed utilizing ANOVA, and if noteworthy contrasts were found, a post hoc test utilizing DMRT at a 5% significance level was applied.

Planting was conducted with a division of 60 cm × 60 cm, with the same division connected between plots and replications. The planting gap profundity was set at 15 cm (Benhmimou et al., 2017; Dass, Chandra, Choudhary, Singh, & Sudhishri, 2016). The seedlings utilized were of the Chinensis Mill operator assortment, with an introductory seedling age of four months and a collection time of 12 months. The four-month-old seedlings had an average of five leaves and a height of 25.56 cm. The Chinensis Mill operator assortment is known for its high quality and adaptability in different environmental conditions. As a succulent species, Aloe vera stores water in its leaves, making it suitable for growth in dry climates or minimal lands, such as coastal sandy soils (Botanical Notes, 2009). The planting medium comprised coastal sand, goat manure compost, and rice husk charcoal in a 2:2:1 proportion, with up to 10 kg of developing medium per polybag (Nakhaie et al., 2022). At that point, carried out according to the treatment and planting schedule. Maintenance included pest and disease control, irrigation, earthing up, weeding, and supplemental fertilization every four weeks using goat manure compost at a rate of 250 g per plant (Aprilia et al., 2025; Sunaryo, Purnomo, Darini, & Cahyani, 2018).

Perceptions were conducted on abscisic acid, morphological, and physiological characteristics. Abscisic acid parameters, new leaf weight demonstrate the effectiveness of photosynthesis in takes off. Dry leaf weight measures the dry biomass substance without water and demonstrates the amassing of natural matter from photosynthesis (Farooq, Hussain, Ul-Allah, & Siddique, 2019; Huang et al., 2019; Khadka, Earl, Raizada, & Navabi, 2020). New root weight Assesses the volume of created root tissue and the plant's capacity to retain water and supplements. Dry root weight, Evaluates the commitment of roots to add up to plant biomass (Khosh, Ahmad, Alitabar, Mottaghi, & Pessarakli, 2012). New plant weight provides a general picture of plant efficiency in new conditions and assesses common physiological conditions. Dry plant weight is used to determine the plant's dry biomass and measures the productivity of biomass collection from photosynthesis. Several clear perceptions of surrender factors were conducted three times amid testing and once at collection. Testing was performed every 60 days after planting, with the final collection at 12 months (Buxbaum, Lieth, & Earles, 2022; De Souza Machado et al., 2019; Delaide et al., 2017).

Morphological perceptions point to portray the plant's physical characteristics, which can be straightforwardly observed. These parameters provide insights into plant development conditions, treatment responses, and adaptation potential. Leaf color indicates nutrient availability, especially nitrogen (N), iron (Fe), and magnesium (Mg). Plant height assesses vegetative growth. Leaf shape distinguishes genetic varieties or environmental impacts on the plant and evaluates treatment effects on leaf structure adjustments. Root perception, conducted on plants of the same age grown under different nursery sources and treatments, offers additional information on root development and health (Sattler & Rutishauser, 2022). Physiological perceptions pointed to get its metabolic forms and instruments of basic plant development, giving experiences into how plants react to medications and natural conditions. Relative Growth Rate (RGR), measures biomass increment per unit of time relative to initial biomass, assessing plant development effectiveness and the effect of medications on biomass accumulation speed. Net Absorption Rate (NAR), measures the rate of dry biomass generation per unit leaf zone per unit time, surveying photosynthesis effectiveness and analyzing the relationship between biomass generation and leaf area. Stomatal Thickness, the number of stomata per unit leaf surface area, is utilized to assess the plant's capacity for gas exchange (CO_2) and water loss, as well as its adjustment to environmental conditions (Akhtar et al., 2024; Carlson, Adams, & Holsinger, 2016; Peel, Mandujano Sánchez, López Portillo, & Golubov, 2017).

3. FINDINGS

The inquiry discoveries show that seed beginning and saltiness levels impact the abdicate of Aloe vera plants. Table 1 presents the results of the 5% DMRT post hoc test, analyzing new leaf weight, dry leaf weight, new root weight, dry root weight, and the number of takes off as key markers for evaluating plant reactions to salt stress.

Table 1. Results of the 5% DMRT analysis.

Treatment	Fresh leaf weight (g)	Dry leaf weight (g)	Fresh root weight (g)	Dry root weight (g)	Number of leaves
Nursery source					
Gunung kidul nursery	1337.53 a	42.73 b	49.25 b	17.24 a	12,799 a
Bantul nursery	910.36 a	26.24 a	28.11 a	10.32 a	11,653 a
Cilacap nursery	1909.81 a	34.64 ab	41.91 ab	15.65 a	12,419 a
NaCl addition (g/L)					
0	1102.56 a	34.03 a	38.04 a	13.56 a	12,233 a
10	1142.33 a	38.31 a	44.33 a	15.84 a	12,544 a
20	1091.96 a	33.61 a	39.15 a	15.01 a	12,288 a
30	2206.74 a	32.2 a	37.52 a	13.22 a	12,048 a

Note: Different letters in the same column indicate significant differences at $p < 0.05$ based on DMRT.

The DMRT investigation demonstrates that seed root significantly affected dry leaf weight and new root weight of Aloe vera (Table 1). Seeds from the Gunung Kidul nursery produced the highest dry leaf weight (42.73 g) and new root weight (49.25 g), which were significantly different from those from the Bantul nursery. Meanwhile, seeds from the Cilacap nursery produced the highest new leaf weight (1909.81 g), but the difference was not statistically significant compared to other sources. These findings suggest that genetic factors and initial seed quality influence the plant's ability to produce biomass and adapt to salt stress (Yuan et al., 2024).

The expansion of NaCl in water system water did not appear to have a noteworthy impact on any parameters based on ANOVA results. Be that as it may, new leaf weight showed an increasing trend at the highest saltiness level (30 g/L), reaching 2206.74 g, which was higher than other treatments. This suggests that at a certain level, salt stress may promote physiological adjustment, such as water accumulation in leaf tissues to preserve turgor weight (Hao et al., 2021). This impact is consistent with the physiological characteristics of CAM plants, which can maintain efficiency under osmotic stretch conditions (Males & Griffiths, 2017; Yang et al., 2021).

3.1. Effects of Salinity and Seedling Source on Leaf and Root Biomass

New and dry leaf weight are basic parameters in plant development, considered as they provide complementary data concerning efficiency, photosynthetic productivity, and plant adaptation to environmental conditions (Da Silva et al., 2020). Even though the contrasts were not measurably noteworthy, the most elevated normal values were observed, which might indicate the versatile capacity of Aloe vera. These discoveries are outlined in Figures 1 and 2 underneath.

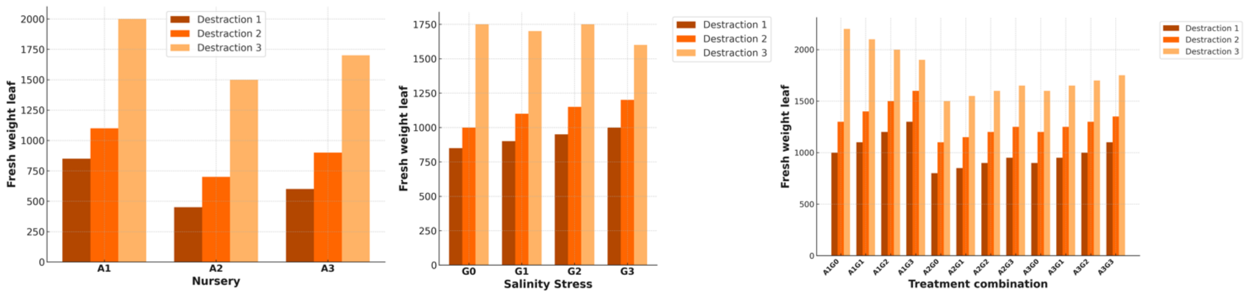
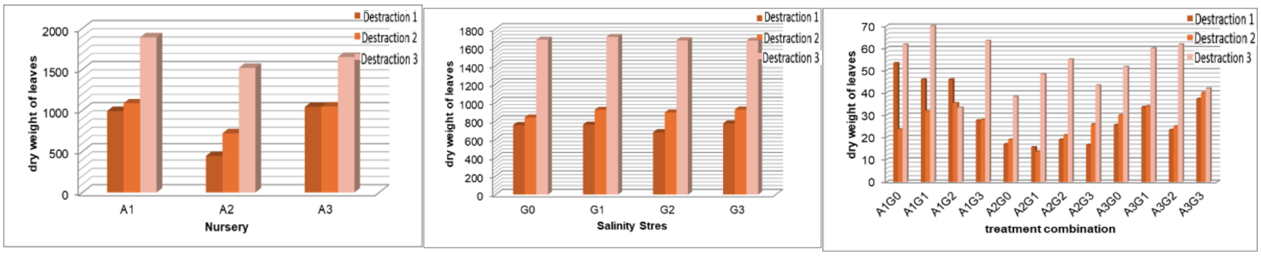


Figure 1. Bar chart of fresh leaf weight. (A) shows the relationship between fresh leaf weight at each nursery origin. (B) shows the relationship between fresh leaf weight and different salt doses. (C) shows the relationship between fresh leaf weight and the interaction between different breeder origins and salt stress.



(A) (B) (C)

Figure 2. Bar chart of leaf dry weight. (A) shows the relationship between dry leaf weight and the origin of the breeder. (B) shows the relationship between dry leaf weight and different salinity stresses. (C) shows the relationship between dry leaf weight and the interaction between different breeders and different salinity stresses.

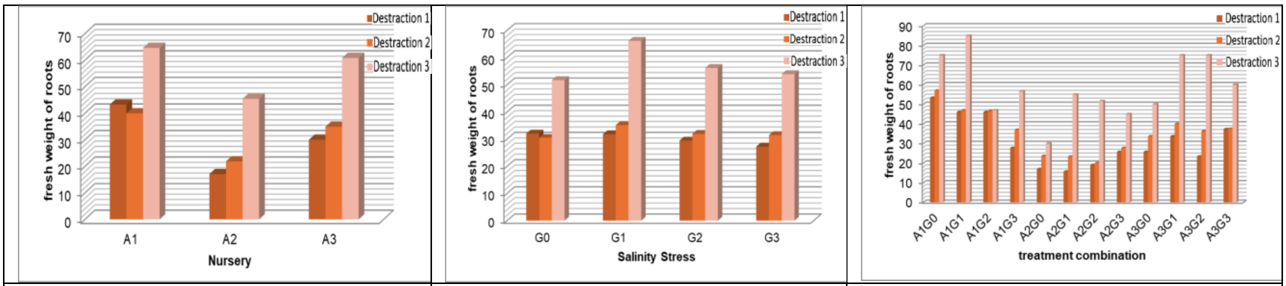
The beginning of the nursery treatment demonstrates that new leaf weight expanded dynamically from Dangerous Testing 1 to Damaging Testing 3 across all nursery sources. Plants from A1 (Gunung Kidul) showed the most noteworthy new leaf weight in all testing stages, followed by A2 (Bantul) and A3 (Cilacap). This trend is likely impacted by hereditary components, as seedlings from Gunung Kidul appear to be more adapted to natural conditions, driving higher biomass accumulation. Another possible explanation is the environmental differences in their native habitats, where plants originating from more extreme conditions may have developed greater resilience to environmental stress (Bechtold, 2018; Caro, Marques, Cunha, & Teixeira, 2020; Lambert et al., 2016).

The findings from saltiness treatment revealed that new leaf weight increased continuously from Damaging Inspecting 1 to Damaging Examining 3 across overall saltiness levels (G0–G3). There was no clear pattern indicating that high saltiness (G3) significantly decreased leaf biomass. This result suggests that Aloe vera exhibits a high level of salt resilience, as a CAM plant capable of water retention in its leaf tissues, thereby preventing severe biomass reduction under salt stress conditions (Habibi, 2018). Subsequently, at G3 (20 g/L NaCl), plants remained strong without showing an exceptional diminution in leaf weight, highlighting their acclimation potential.

The combination treatment of A1G0 (Gunung Kidul + g/L NaCl) resulted in the most significant increase in new leaf weight. In any case, combinations with higher saltiness levels (A1G3, A2G3, A3G3) still maintained moderately tall new leaf weights, with no noteworthy differences compared to non-saline treatments. No synergistic or antagonistic effects were observed between nursery root and saltiness levels, demonstrating that Aloe vera can grow under a wide range of conditions. This suggests that the initial biological adaptation plays a more dominant role than the salt concentration itself (Etesami & Beattie, 2017; Hossain et al., 2022; Sezhiyan et al., 2023).

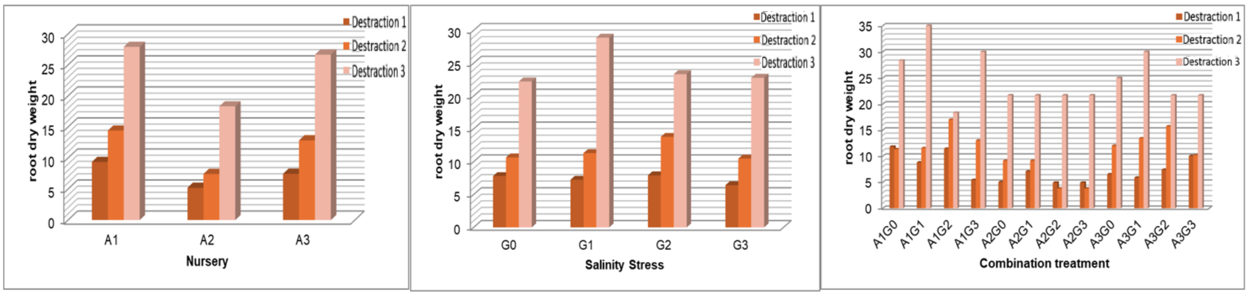
The consideration illustrates that new and dry leaf weight follow a similar pattern, where an increase in one is generally accompanied by an increase in the other. Overall treatments (nursery source, salinity, and their interactions), higher new leaf weight was typically associated with higher dry leaf weight. Based on the new and dry leaf weight outcomes, Gunung Kidul (A1) produced optimal yields for both parameters. Regarding salinity levels, moderate salinity levels (G1 – 5 g/L or G2 – 10 g/L NaCl) were ideal for consistent growth, although G3 (20 g/L) remained acceptable but resulted in higher water accumulation rather than dry biomass production. The best combination for new leaf weight was A1G3 (Gunung Kidul + 20 g/L NaCl), whereas the optimal combination for dry leaf weight was A1G0 or A1G1 (Gunung Kidul + 0–5 g/L NaCl). These findings suggest that G3 enhances new leaf weight primarily due to water retention rather than actual biomass accumulation. For overall plant growth (both new and dry weight), A1G1 (Gunung Kidul + 5 g/L NaCl) emerged as the most effective combination. The A1G3 interaction can also be considered, but it carries the risk of increased water content within the leaves.

New root weight and dry root weight are two basic parameters utilized to assess the improvement of the root framework, which plays a crucial part in water and supplement retention, resistance to natural push, and overall plant metabolic efficiency (Tajima, 2021). Figures 3 and 4 outline the new and dry root weights watched amid the ponder.



(A) (B) (C)

Figure 3. The fresh weight of roots. (A) shows the relationship between fresh root weight and different nursery origins. (B) shows the relationship between fresh root weight and different salinity (salt level) stresses. (C) shows the relationship between fresh root weight and the interaction between different nursery origins and different salinity (salt level) stress.

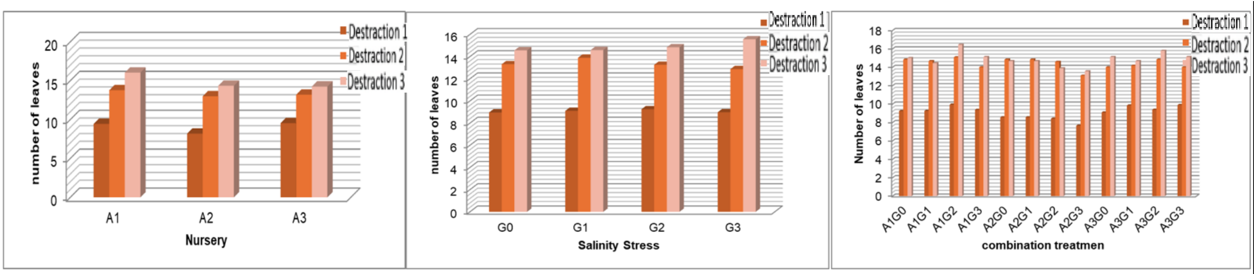


(A) (B) (C)

Figure 4. Dry weight of roots. (A) shows the relationship between dry root weight and different seedling origins. (B) shows the relationship between root dry weight and different salinity stresses. (C) shows the relationship between dry root weight, nursery origins, and different salinity stresses.

The discoveries revealed that plants from A1 (Gunung Kidul) had the highest dry root weight, followed by A3 (Cilacap) and A2 (Bantul). This suggests that seedlings from Gunung Kidul may possess a more developed root system, enabling more efficient water retention and greater resilience to environmental stress. In contrast, seedlings from Bantul (A2) likely originating from more fertile environments may rely more heavily on groundwater, resulting in a smaller root system. Generally, plants with larger root biomass tend to have a greater capacity for nutrient uptake, which supports overall plant growth. As noted by Delgado and Stefancic (2023), Aloe vera grown under extreme environmental conditions often develops larger root systems to enhance nutrient absorption and withstand abiotic stress (Delgado & Stefancic, 2023). An increasing trend in new root weight relative to a corresponding increase in dry root weight indicates consistency between these parameters. However, a slight anomaly was observed in A3, where the dry root weight was generally higher than the new root weight. This may suggest structural changes within the roots as a response to environmental stress, such as increased lignification (Chun et al., 2019; Dissanayake et al., 2024; Rui, Chen, Zhang, Shen, & Zhang, 2016).

In terms of saltiness levels, dry root weight did not appear to be critically decayed beneath G3 (20 g/L NaCl), comparable to the trend in new root weight. Interestingly, the most noteworthy dry root weight was observed beneath G1 (5 g/L NaCl), not G0, whereas new root weights were moderately comparable between G0 and G1. This may indicate that gentle osmotic pressure at G1 initiated biomass accumulation or lignification within the roots as part of a physiological adjustment process (Karlova, Boer, Hayes, & Testerink, 2021). The best-performing combination for dry root weight was A1G1 (Gunung Kidul + 5 g/L NaCl), whereas A1G0 also yielded generally tall new root weight. Medicines with tall saltiness (A1G3, A2G3, A3G3) still displayed generally tall dry root weights, proposing that Aloe vera is competent in maintaining root advancement beneath salt stress. This pattern was most clear in Dangerous Inspecting 3, demonstrating that long-term root development is more impacted by biomass allocation than transitory water content (Messier, Becker‐Scarpitta, Li, Violle, & Vellend, 2024). Whereas new and dry root weights are mostly taken after a steady drift, G1 appears to be more suitable for dry root biomass, likely due to differences in metabolic reactions to mellow saltiness compared to non-saline conditions (G0) (Paul et al., 2019; Tang, Zhou, Gao, & Li, 2022; F. Wang, Sun, & Shi, 2019). In G3, the new root weight remained generally tall, but the dry root weight stabilized, which may infer expanded water maintenance in roots as a stress-adaptive component (Lu, Zhang, Wang, & Li, 2023). The number of takes off is an imperative indicator of vegetative development, reflecting meristematic activity and the plant's adaptation to natural conditions (Czesnick & Lenhard, 2015). Figure 5 presents a bar chart outlining the comes about for leaf number.



(A) (B) (C)

Figure 5. Bar chart of several leaves. (A) shows the relationship between the number of leaves and the difference in the origin of the breeder. (B) shows the relationship between the number of leaves and the difference in salinity stress. (C) shows the relationship between the number of leaves and the interaction between different breeder origins and salinity stress.

The results indicated that medicines G1 and G2 produced a higher number of takes compared to G3. The reduction in leaf number at G3 (20 g/L NaCl) may be attributed to increased external osmotic weight, which inhibits cell division and elongation, thereby disrupting water balance within the tissues. Saadia, Shabir, Hassan, Jamil, and Bashir (2022), tall saltiness push can cause hormonal lopsided characteristics that stifle the arrangement of vegetative organs. In this manner, direct levels of NaCl application (e.g., 10 g/L) are still moderate for the plant, but higher concentrations start to show negative impacts on leaf development (Waadt et al., 2022).

Leaf color is one of the most perceptible morphological markers and serves as a visual signal for evaluating plant wellbeing and chlorophyll content. It reflects physiological reactions to environmental stressors, especially salinity and drought conditions (Brodribb, Bienaimé, & Marmottant, 2016; Sarker & Oba, 2018; Talebzadeh & Valeo, 2022). Leaf color moreover serves as a marker of metabolic movement, indicating the aggregation of auxiliary metabolites. In addition, it provides a reliable visual reference for seedling determination based on push resilience and vigor. Figure 6 presents a case of leaf color varieties watched amid the think about.

(A) (B) (C)

Figure 6. Example of Aloe vera leaf color grown on coastal sandy soil. (A) shows the color of the leaves at the Gunung Kidul breeder's origin. (B) shows the color of the leaves from the Bantul breeder. (C) shows the color of the leaves from the Cilacap breeder.

Leaf color may serve as a visual marker reflecting the physiological condition of the plant and is unequivocally impacted by supplement accessibility, chlorophyll concentration, and natural push (Moustaka & Moustakas, 2023). In this context, leaf color was analyzed employing an advanced color profiling approach based on the Munsell Book of Color. The results were presented in RGB, HSL, and CMYK color models to enhance objectivity and enable quantitative comparisons over different treatments. The RGB values recorded ranged from (112, 125, 72) to (103, 112, 33). Darker and more saturated green shades (e.g., RGB: 103, 112, 33 and HSL: 37, 54, 52%) were frequently observed in plants from treatments such as G1 or nursery A1, indicating higher chlorophyll content and steady photosynthetic activity. Conversely, lighter or paler green shades (e.g., RGB: 112, 125, 72 and HSL: 75, 27, 37%) showed early signs of chlorosis or physiological alterations due to salt stress, suggesting a decline in chlorophyll concentration and potential impairment of photosynthesis.

These varieties in color can be translated as a portion of the plant's acclimation mechanism to stretch. For illustration, darker green tones often demonstrate enhanced chlorophyll biosynthesis or thicker epidermal layers, which help decrease water loss through transpiration (Cai et al., 2023; Guo et al., 2023; Moustakas, Sperdouli, & Moustaka, 2022). In the meantime, pale or yellowish-green leaves may be related to supplement deficiencies (such as nitrogen or magnesium) or oxidative stress caused by saltiness. The consistency of leaf color in certain medicines may also reflect better hereditary resistance and physiological adjustment (Fukano et al., 2023). For instance, plants from the Gunung Kidul nursery (A1) tended to preserve a steady and darker green leaf color indeed beneath tall saltiness levels, proposing prevalent hereditary versatility. Total leaf color information is displayed in Table 2.

Table 2. Digital leaf color data of Aloe vera under different treatments.

	A1		A2		A3	
	leaf color data of *Munsell* book colour	**Note**	**leaf color data of Munsell book colour**	**Note**	**Leaf color data of Munsell book colour**	**Note**
S0	HEX #757F42 RGB (117,127,66) HSL (70,32,38) CMYK (8,0,48,50)	Indicates leaves with a slightly faded yellowish-green hue.	HEX #9D9959 RGB (160,156,93) HSL (56,26,50) CMYK (0,2,42,37)	depicts yellowish-green with a slight browning.	HEX #565E2D RGB (86,94,45) HSL (70,35,27) CMYK (9,0,52,63)	Dark dark olive green
S1	HEX #626B1C RGB (98,107,28) HSL (67,59,26) CMYK (8,0,74,58)	Displays a dark olive-green tone with a yellowish-green undertone.	HEX #677021 RGB (103,112,33) HSL (67,54,28) CMYK (8,0,71,56)	Dark dark olive green,	HEX #454D14 RGB (69,77,20) HSL (68,59,19) CMYK (10,0,74,70)	Very dark yellowish-green,
S2	HEX #A0A155 RGB (160,161,85) HSL (61,31,48) CMYK (1,0,47,37)	A bright yellowish-green color is commonly observed in young leaves or vigorously growing plants.	HEX #6A6F39 RGB (106,111,57) HSL (66,32,33) CMYK (5,0,49,56)	Dark olive green with yellowish and brownish tones,	HEX #707D48 RGB (112,125,72) HSL (75,27,39) CMYK (10,0,42,51)	Yellowish olive green with a medium degree of darkness.
S3	HEX #A2985A RGB (162,152,90) HSL (52,29,49) CMYK (0,6,44,36)	A soft, slightly faded yellowish-brown shade, indicative of leaf yellowing or a transitional phase under environmental stress.	HEX #6C7824 RGB (108,120,36) HSL (69,54,31) CMYK (10,0,70,53)	Dark yellowish green with a strong character and yellow dominance.	HEX #999650 RGB (153,150,80) HSL (58,31,46) CMYK (0,2,48,40)	Yellowish-green with medium brightness and low saturation.

Note: Color data were obtained using digital profiling based on the Munsell book of color.

Leaf color perceptions in Aloe vera were conducted employing a combination of advanced color values in HEX, RGB, HSL, and CMYK groups, referenced from the Munsell Book of Color. Perceptions were carried out at three information focuses (P1, P2, and P3) beneath four saltiness treatment levels (S0–S3). Moo Saltiness (S0): Pale Yellowish-Green. At g/L NaCl (S0), leaf color tended to seem pale yellowish-green (HEX #757F42, RGB 117,127,66), with direct brightness but moderately moo chlorophyll substance. This condition reflects constrained natural incitement (mellow push), coming about in problematic chlorophyll aggregation (Tan, Sha, Sun, & Li, 2023).

Direct Saltiness (S1–S2): More Steady Coloration. In S1, the leaf color moved to a darker olive green (HEX #626B1C and #677021), showing upgraded chlorophyll biosynthesis and conceivable dynamic adjustment to gentle osmotic push. The color became more profound (with lower HSL brightness values), proposing strides in photosynthetic effectiveness and a positive versatile reaction. In S2 (10 g/L NaCl), the tones showed a shining yellowish-green hue (HEX #A0A155 and #6A8F39), commonly related to effectively developing plants. This proposes that direct saltiness may invigorate optimal development, backed by adjusted RGB values and chlorophyll action (Heidari, 2012; Rouphael, Petropoulos, Cardarelli, & Colla, 2018; Zörb, Geilfus, & Dietz, 2019).

Tall Saltiness (S3): Transitional Stretch Indications. At the most noteworthy saltiness level (S3), leaf color appeared as light yellowish-brown (HEX #A2985A) and dim yellowish-green (HEX #6C7824), indicating that the plant had entered a transitional stage or was showing early stretch indications. This may include chlorophyll degradation or the accumulation of non-photosynthetic shades (Tanaka & Ito, 2025). Leaf color at point P3 (HEX #999650, RGB 153,150,80) moreover appeared to decrease immersion, possibly reflecting diminished metabolic movement and early signs of chlorosis. Generally, leaf color changes methodically with increasing saltiness and can be utilized as a visual morphological indicator of plant responses to environmental stressors (Hossain et al., 2022). Medications S1 and S2 appeared the most favorable in coloration, related to physiological adjustment and optimal development potential. Beneath S3, color changes demonstrated early push reactions, although no extreme harm was yet apparent.

Leaf length is one of the essential morphological indicators used to evaluate the growth performance of Aloe vera. This parameter is closely related to meristematic activity, photosynthetic efficiency, and the plant's capacity for water retention and gel production within the leaf tissues (Delatorre-Castillo et al., 2022). In this consideration, leaf length was observed as a reflection of plant reactions to distinctive levels of salinity and seedling roots.

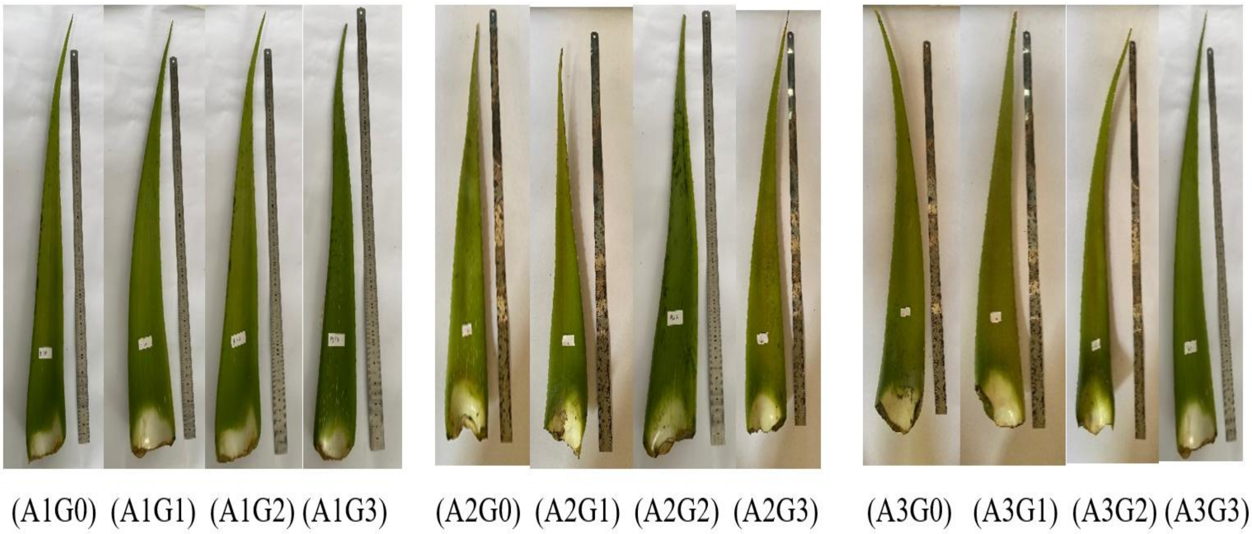


Figure 7. Leaf images and leaf length in research.

Figure 7 illustrates the visual morphology of Aloe vera leaves along with their respective lengths under different treatments. The figure shows that leaf length varies according to the breeder origin and salt dose, indicating a physiological response to salinity stress.

Leaf length is emphatically related to the leaf zone and a few physiological aspects of plant function (Schrader et al., 2021). As a key morphological characteristic, leaf length specifically impacts Relative Growth Rate (RGR). Longer leaves contribute to a larger leaf zone, which in turn enhances biomass accumulation over time (Ariani, Francini, Andreucci, & Sebastiani, 2016; Osone, Ishida, & Tateno, 2008; Singh, 2017). Net Absorption Rate (NAR), sound, and stretched clear out are regularly connected to higher photosynthetic productivity and dry matter generation per unit leaf zone (Sachan, Verma, Kumar, & Singh, 2022). Leaf region list (LAI), increments in leaf length and width upgrades add up to the canopy leaf range, moving forward light capture attempts and carbon absorption at the canopy level (Nomura et al., 2022).

Transpiration and stomatal conductance: A broader leaf surface zone permits more dynamic transpiration and gas exchange, which are essential for maintaining metabolic functions under stress (Hasanuzzaman & Fujita, 2023). In this manner, leaf length isn't merely a morphological characteristic but also a critical factor affecting key physiological capacities. These connections are further investigated within the physiological perception segment.

3.2. Physiological Perceptions

Physiological assessment provides a more comprehensive understanding of how Aloe vera reacts and adjusts to salt stress. Parameters such as relative growth rate (RGR), net assimilation rate (NAR), stomatal thickness, and transpiration rate serve as fundamental indicators for evaluating photosynthetic productivity, water-use efficiency, and metabolic changes under adverse environmental conditions (Moghbeli et al., 2012). Coordination of physiological information with morphological characteristics and surrender estimations improves the logical elucidation and bolsters the development of more versatile and resource-efficient procedures for Aloe vera, especially in coastal situations with minimal impact. The physiological parameters observed in this study provide insight into the plant's tolerance mechanisms under salt stress. Table 3 shows the mean values of physiological variables that were significantly affected by treatment, as determined by the DMRT 5% test.

Table 3. Physiological variable measurements analyzed using the 5% DMRT post hoc test.

Treatment	Leaf length	Leaf area	Net assimilation rate	Number of stomata	Relative growth rate	Transpiration rate
Breeder Origin						
The Southern Mountain Rancher	53.76b	256.8a	0.52a	22.36a	0.127a	111.2a
Bantul breeder	53.965b	246.3a	0.68a	22.54a	0.134a	104.6a
Cilacap Breeder	51.26ab	254.2a	0.6a	25.33ab	0.125a	104.9a
NaCl Addition (g/l)						
0	54.36	251.9a	0.71b	22.88a	0.127a	113.8ab
10	52.5ab	251.72a	0.58a	23.23a	0.124a	101.9ab
20	55.37b	279.2b	0.49a	22.36a	0.123a	115.7ab
30	48.66a	227.9a	0.62ab	21.89a	0.140a	96.1a

Note: Different letters in the same column indicate significant differences at $p < 0.05$ based on DMRT.

The application of 30 g/L NaCl essentially decreased leaf length, which can be attributed to high osmotic weight hindering cell stretching. Interestingly, the 20 g/L treatment resulted in the greatest normal leaf length, suggesting a dynamic adaptive response under moderate salt stress. The largest leaf area was recorded at G2 (20 g/L), indicating the plant's potential to enhance photosynthetic productivity under mild stress conditions. However, the difference was not statistically significant, suggesting that the response was not sufficiently robust to be considered conclusive over treatments.

Expanding saltiness levels driven to decay in Net Digestion Rate (NAR/LAB), affirming that salt stretch meddling with photosynthetic proficiency. This underpins past discoveries showing that photosynthesis is compromised beneath tall osmotic weight (Lu et al., 2023). Tall LAB values reflect the plant's capacity to deliver dry biomass productively per unit leaf region. The decrease in LAB beneath tall saltiness (e.g., 20 g/L – 0.49a) may result from disturbances in the photosynthetic digestion system (chemical action or photochemical forms) and diminished chlorophyll content.

Stomatal closure confines CO_2 take-up and limits photosynthesis. Stomatal thickness was most elevated in plants from the Cilacap nursery (25.33ab) and beneath 10 g/L saltiness (23.23a), whereas the least esteem was watched at G3 (21.89a). The diminish in stomatal number beneath tall saltiness likely reflects a versatile reaction pointed at lessening transpiration and water misfortune. Even though the contrast was not statistically significant, stomatal thickness remains a key marker of transpiration and gas trade control. Decreased stomatal numbers may speak to a long-term morphological adjustment to push (instead of as it were stomatal closure) (Bertolino, Caine, & Gray, 2019; Wang & Chang, 2024; Zahedi et al., 2025). In Aloe vera, a CAM plant, this diminishment helps preserve water. Be that as it may, excessively low stomatal thickness can impair CO_2 uptake and, consequently, photosynthetic performance.

An increase in Relative Growth Rate (RGR) at G3 suggests a compensatory metabolic response to tall stretch. Plants maintaining growth under high salinity may exhibit more efficient metabolic pathways or allocate biomass more selectively to specific organs (Wang & Chang, 2024). This lifted RGR may also be an artifact resulting from moo introductory biomass. Encouragement of investigation is required to obtain detailed biomass conveyance designs.

Transpiration rate declined altogether at higher saltiness levels, steady with stomatal closure and water preservation methodologies ordinary of CAM species such as Aloe vera. This decline reflects the plant's adjustment to salt-induced stress (González-Delgado et al., 2023; Pereira, Niechayev, Blair, & Cushman, 2021). Direct saltiness levels (10–20 g/L) showed up to advance positive physiological adaptation characterized by expanded leaf region, moderately steady LAB, and adequate stomatal thickness. Whereas tall saltiness (30 g/L) stifled a few parameters, it suddenly expanded RGR, justifying assist examination into potential elective development methodologies. The impact of seedling root was generally constrained; be that as it may, seedlings from Bantul displayed the most noteworthy LAB values, recommending higher beginning photosynthetic proficiency (Shipley, 2006).

4. CONCLUSION

This study illustrates that both saltiness levels and seedling origin collectively influence the development and physiological responses of Aloe vera cultivated on coastal sandy soils. Seedlings from Gunung Kidul (A1) demonstrated superior performance in terms of leaf and root biomass, both fresh and dry, as well as more stable physiological responses under salt stress. Direct saltiness levels (5–10 g/L NaCl) positively affected leaf length, leaf width, and photosynthetic efficiency, as evidenced by increased (LAB), relative growth rate (RGR), and optimal leaf coloration. The treatment combination A1G1 (Gunung Kidul + 5 g/L NaCl) consistently supported ideal growth and physiological function. These findings confirm that Aloe vera possesses significant adaptability to marginal conditions and can be cultivated sustainably in coastal regions, provided that seedling genetic background and salt management are appropriately considered. This research contributes to the development of resilient and resource-efficient agricultural systems for minimal coastal lands. Although these results are promising, long-term field trials are necessary to validate these findings under actual coastal farming conditions. Future research should explore the long-term effects of salinity on Aloe vera secondary metabolite profiles and investigate potential genetic markers associated with salt tolerance.

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