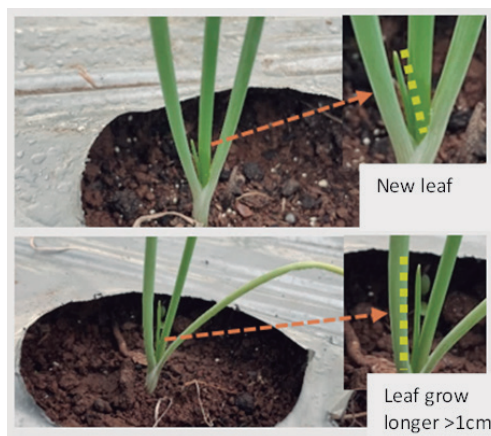


Relationship between seedling traits and recovery time after transplanting in shallot grown from true seed

Relación entre las características de las plántulas y el tiempo de recuperación después del trasplante en chalote cultivado a partir de semilla verdadera



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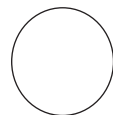
Visual recovery of shallot seedlings.

Photos: M. Faried

ABSTRACT

Shallot (*Allium ascalonicum* L.) seedlings frequently experience transplant shock, but the role of seedling traits in recovery dynamics remains unclear. This study investigated three seed-propagated varieties ('Lokananta', 'Merdeka F1', 'Sanren F1') under net-house conditions (June 2024, 5°S, 119°E) using ANOVA, regression, and correlation analyses. Results demonstrated that 'Merdeka F1' exhibited superior performance, with 28-42% greater biomass (2.36 g), enhanced root development (12.80 tips, 8.90 cm length), and faster recovery (5.77 days vs. 6.33-6.53 days) compared to other varieties. Pseudostem diameter emerged as the strongest predictor of recovery time (quadratic model: $R^2=0.77$; correlation: $r=-0.86$), with seedlings >4.5 mm diameter recovering ~1 day faster. Significant negative correlations were also observed between recovery day and biomass ($r=-0.66$) or leaf count ($r=-0.27$), while root traits showed minimal influence ($R^2<0.04$). These findings establish pseudostem diameter as a key selection criterion for transplant resilience and highlight 'Merdeka F1's genetic advantages. Future research should investigate optimal seedling age and biostimulant applications to enhance shallot transplant success.

Additional key words: *Allium ascalonicum* L.; transplant shock; seedling vigor; pseudostem diameter; leaf emergence; plant morphology; genotypes.



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RESUMEN

Las plántulas de chalote (*Allium ascalonicum* L.) frecuentemente experimentan estrés por trasplante, pero el papel de las características de las plántulas en la dinámica de recuperación sigue siendo poco claro. Este estudio investigó tres variedades propagadas por semilla ('Lokananta', 'Merdeka F1', 'Sanren F1') en condiciones de malla sombra (junio de 2024, 5°S, 119°E), utilizando análisis de ANOVA, regresión y correlación. Los resultados demostraron que 'Merdeka F1' presentó un desempeño superior, con un 28–42% más de biomasa (2.36 g), mejor desarrollo radicular (12.80 raíces, 8.90 cm de longitud) y recuperación más rápida (5.77 días frente a 6.33–6.53 días) en comparación con otras variedades. El diámetro del pseudotallo surgió como el predictor más fuerte del tiempo de recuperación (modelo cuadrático: $R^2 = 0.77$; correlación: $r = -0.86$), con plántulas de >4.5 mm de diámetro recuperándose aproximadamente un día antes. También se observaron correlaciones negativas significativas entre el día de recuperación y la biomasa ($r = -0.66$), el número de hojas ($r = -0.27$), mientras que las características de la raíz mostraron una influencia mínima ($R^2 < 0.04$). Estos hallazgos establecen el diámetro del pseudotallo como un criterio clave de selección para la resiliencia al trasplante y destacan las ventajas genéticas de 'Merdeka F1'. Las investigaciones futuras deben explorar la edad óptima de las plántulas y el uso de bioestimulantes para mejorar el éxito del trasplante de chalote.

Palabras clave adicionales: *Allium ascalonicum* L.; estrés por trasplante; vigor de plántula; diámetro del pseudotallo; emisión foliar; morfología de plantas; genotipos.

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INTRODUCTION

Transplant shock represents a critical bottleneck in modern horticultural systems, particularly for crops propagated from true seeds. In shallots (*Allium ascalonicum* L.), this phenomenon manifests as a 9–17% reduction in survival rates (Sumarno *et al.*, 2021), creating significant economic losses for growers. The physiological basis of transplant shock involves complex interactions between root architecture damage, water stress responses, and photosynthetic impairment (Close *et al.*, 2005; Arbona *et al.*, 2017). When seedlings are transplanted, root system disruption immediately compromises water uptake, triggering stomatal closure and reducing CO₂ assimilation. This cascade of events leads to the accumulation of reactive oxygen species (ROS) and temporary growth arrest (Wu *et al.*, 2022).

The challenges are particularly acute in seed-propagated shallots, which require a minimum 45-day nursery period before transplantation (Faried *et al.*, 2024). Unlike vegetative propagation, seed-based systems face additional hurdles including asynchronous growth patterns and variable seedling quality. Current research indicates that post-transplant survival depends on both intrinsic seedling characteristics and external management factors (Chiomento *et al.*, 2020). Key morphological traits such as pseudostem

diameter, root tip density, and biomass accumulation have been implicated in transplant resilience across various species (Grossnickle, 2012), but these relationships remain unexplored in shallots.

The recovery phase following transplant shock represents a critical knowledge gap in *Allium* physiology. While studies have documented the transient nature of transplant shock in other crops (Krinis *et al.*, 2023), the temporal dynamics of recovery in shallots - including the appearance of new leaves (>1 cm) or regrowth of existing foliage - have never been quantified. This oversight is particularly surprising given that recovery duration directly impacts field establishment timelines and ultimately, crop profitability.

We hypothesize that pseudostem diameter serves as a reliable predictor of recovery speed, as it reflects energy reserves available for regrowth. This study systematically evaluates: (1) varietal differences in key seedling traits (pseudostem diameter, root architecture, biomass), and (2) their correlation with post-transplant recovery time. Our findings provide both fundamental insights into stress physiology of *Allium* crops and practical metrics for nursery selection. By establishing quantitative relationships between easily measurable seedling characteristics and

field performance, this work enables growers to optimize transplant success through targeted seedling selection.

The research addresses three critical needs in contemporary shallot production: (1) developing science-based criteria for seedling quality assessment, (2) reducing transplant-related yield losses, and (3) improving the economic viability of seed-based propagation systems. Our trait-based approach bridges the gap between physiological understanding and practical crop management, offering actionable solutions for both researchers and commercial growers.

MATERIALS AND METHODS

Study location

The research was carried out in June 2024 at Experimental Farm, Hasanuddin University (5° 7' 40.07" S; 119° 28' 48.94" W; altitude of 9 m a.s.l.). Net house had 120 m², with a flat roof, installed in the west-south direction. The aluminum frame is covered at the top and sides with an anti-aphid screen (50 mesh).

Experimental design and procedures

The treatments consisted of three shallot materials ('Lokananta', 'Merdeka F1', and 'Sanren F1'). The experiment was designed in a randomized complete block design, with ten replications. Each plot, in each block, was composed of 27 plants. The three shallot varieties were sown in seedling tanks containing soil (the same soil as in the field) and chicken manure in a 1:1 ratio. The soil properties that we used in this research are shown in table 1. Seeds were sown as much as 0.5 g in each row. Then, it cared for 45 d, until it is ready to be moved.

Table. 1 Soil chemical characteristics

Parameter	Value	Unit
pH	6.58	–
Carbon (C)	3.52	%
Nitrogen (N)	0.28	%
C/N ratio	13	–
Phosphorus (P ₂ O ₅)	12.28	ppm
Potassium (K)	0.28	cmol kg ⁻¹
Cation exchange capacity (CEC)	19.65	cmol kg ⁻¹

Seedlings that had grown were selected in preparation for transplanting. The seedlings had young leaves not more than 1 cm long to facilitate the observation of plant recovery time, indicated by the increase in young leaf length or the appearance of new young leaves. After 45 d from sowing, seedlings were planted in beds covered with plastic mulch (0.5 μm thick) at a spacing of 10×15 cm, conducted at 17:00 to minimize heat stress. Plant care included watering twice a day, in the morning and evening, using a sprayer. Inside the net house, the average temperature during the study (Fig. 1).

Above-ground assessments

Traits were measured as follows: (1) pseudostem diameter 0.5 cm above soil with digital calipers (±0.01 mm), (2) seedling biomass as fresh weight post-soil removal, (3) root tips counted under 4× magnification, and (4) recovery day recorded when new leaves exceeded 1 cm. Edge effects were minimized by sampling ≥5 cm from bed borders. Root volume was measured via water displacement in a 10 mL graduated cylinder (±0.1 cm³). Leaf count included all leaves >2 cm in length. Pseudostem diameter was measured 0.5 cm above the base using a digital caliper (±0.01 mm precision). Seedling biomass (fresh weight) was recorded after uprooting and thorough soil removal using a digital scale (±0.01 g).

Below-ground assessment

Roots were gently washed before analysis. Root tips were manually counted under 4× magnification. The longest root was measured with a ruler (±0.1 cm). Root volume (cm³) was determined via water displacement in a graduated cylinder (±0.1 cm³ precision), calculated as:

Root volume = Final water level – Initial water level

Then, root density was calculated as:

$$Rootdensity = \frac{Rootvolume(cm^3)}{Rootlength(cm)}$$

Recovery time

Post-transplant recovery was recorded when: Pre-existing young leaves elongated by >1 cm, or new leaves (>1 cm) emerged. Observations were made daily at 17:00 for 14 d.

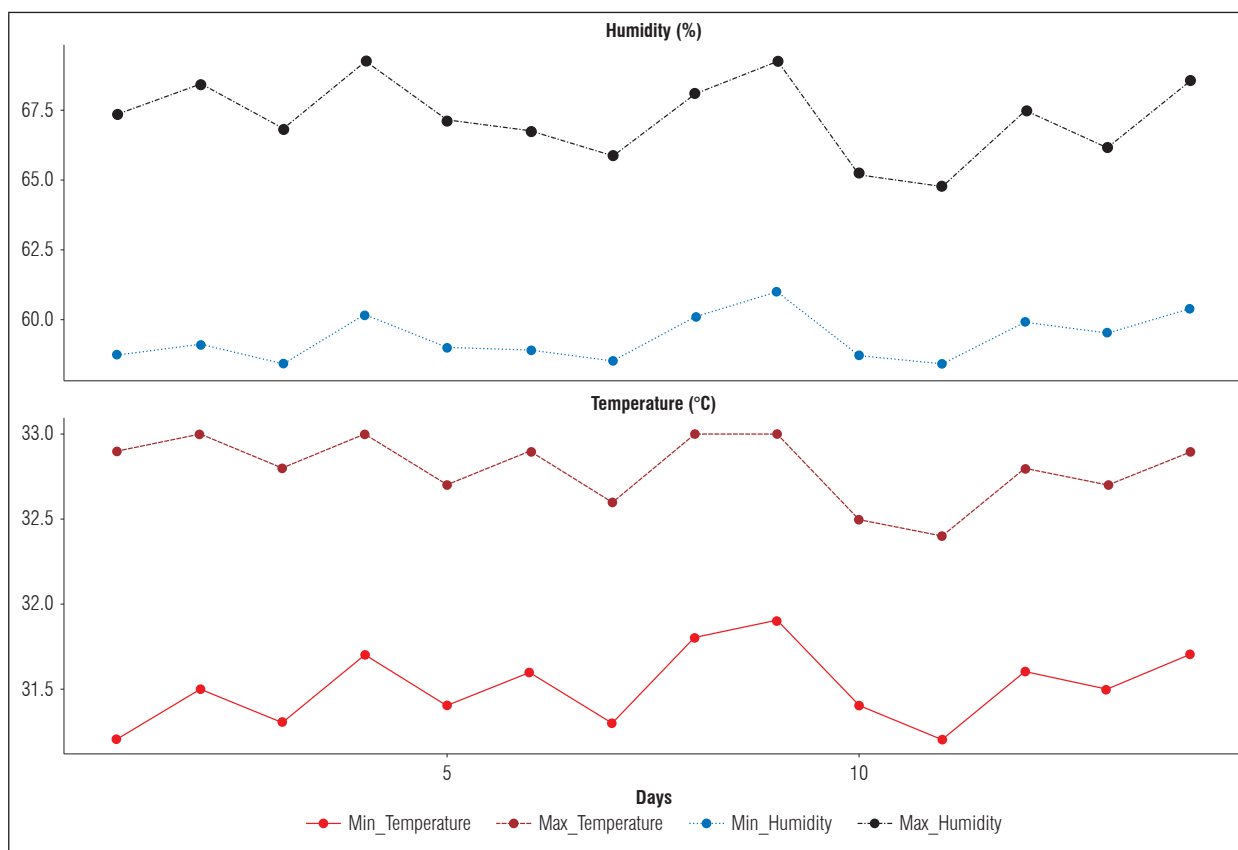


Figure 1. Daily average temperature (°C, bottom) and relative humidity (% top) under net-house conditions.

Data analysis

Varietal differences

Differences in seedling traits among the three shallot varieties were assessed using one-way analysis of variance (ANOVA). Post-hoc comparisons were performed with Duncan's multiple range test at $P < 0.05$ to identify significant pairwise differences. Assumptions of normality (Shapiro-Wilk test) and homogeneity of variance (Levene's test) were verified prior to analysis.

Regression modeling

The relationship between seedling traits (independent variables) and recovery time (dependent variable) was evaluated using three regression models:

Linear: $Y = \beta_0 + \beta_1 X$

Quadratic: $Y = \beta_0 + \beta_1 X + \beta_2 X^2$

Cubic: $Y = \beta_0 + \beta_1 X + \beta_2 X^2 + \beta_3 X^3$

Model selection was based on the Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC), with the lowest values indicating the best fit.

Correlation analysis

Pairwise associations among all measured traits were quantified using Pearson's correlation coefficient (r), interpreted as:

Table 2. Interpretation of correlation coefficient strength

Correlation coefficient (r)	Strength of association
0.00-0.10	Negligible
0.10-0.39	Weak
0.40-0.69	Moderate
0.70-0.89	Strong
0.90-1.00	Very Strong

Source: Schober *et al.* (2018).

Software implementation

All analyses were conducted in RStudio (version 4.4.1; R Core Team, 2024) using the following packages:

- agricolae: ANOVA and Duncan's test
- expdes: normality and homogeneity test
- ggpubr, ggpmisc, ggplot2: Regression visualization and equation annotation
- boot: aic and bic validation models
- corrplot, lavaan: Correlation matrix visualization

RESULTS

Analysis of statistics

The analysis of variance (ANOVA) results showed that all measured growth parameters, except for pseudostem diameter (PD), were significantly affected by the treatments ($P < 0.05$) (Tab. 3). The Shapiro-Wilk test confirmed that the residuals for all variables were normally distributed ($P > 0.05$), and the O'Neill-Mathews test indicated homogeneity of variances ($P > 0.05$), supporting the validity of the ANOVA assumptions. Highly significant differences ($P < 0.01$) we evaluated for leaf count (LC), biomass (B), number of roots (NORT), root length (RL), root volume (RV), root dry shoot (RDs), and root diameter (RD), demonstrating the strong influence of treatments on these traits. Although PD did not show a significant response ($P = 1.32$), all other traits responded positively to the treatments. The coefficients of variation

(CV) ranged from 11.1% to 28.51%, indicating acceptable experimental precision and reliability across the dataset.

Above-ground traits

Based on a comprehensive analysis of variance conducted on the collected data, it was determined that significant differences were present among the various plant varieties when evaluated across two out of the three measured parameters (Fig. 2).

Specifically, the variable concerning the leaf count exhibited notable discrepancies among the different varieties, with the Merdeka F1 variety demonstrating the highest average leaf count of 4.40 ± 0.21 , which was found to be 10.90% greater than that of the Sanren F1 variety (3.92 ± 0.13) and 22.72% superior when compared to 'Lokananta' (3.40 ± 0.11). Conversely, regarding the pseudostem diameter parameter, it was observed that no statistically significant difference existed among the three varieties that were measured; however, it is noteworthy that 'Merdeka F1' did record the largest diameter measurement of 4.81 ± 0.21 mm, followed by 'Sanren F1' (4.24 ± 0.26) and 'Lokananta' (4.12 ± 0.31). In a different aspect, the parameter measuring seedling biomass revealed significant variations among the different varieties; particularly, 'Merdeka F1' exhibited an impressive average seedling weight of 2.36 ± 0.21 g, which was 28.36% heavier than the weight of 'Sanren F1' (1.68 ± 0.11) and 41.52% heavier than that of 'Lokananta' (1.38 ± 0.11), thereby indicating a marked superiority in biomass accumulation in the Merdeka F1 variety.

Table 3. Analysis of variance, normality, and homogeneity.

Analysis	Traits ⁴							
	LC	PD	B	NORT	RL	RV	RDs	RD
Shapiro-wilk normality ¹	0.13	0.61	0.78	0.85	0.12	0.95	0.06	0.16
Homogeneity of variance ²	0.80	0.94	0.28	0.29	0.08	0.40	0.64	0.64
P-value ³	<0.01	1.32	<0.01	0.02	<0.01	<0.01	<0.01	<0.01
CV (%)	11.1	22.22	28.51	17.56	18.54	22.98	14.64	13.16

¹According to Shapiro-Wilk normality test at 5% of significance, residuals can be considered normal. ²According to the test of oneillmathews at 5% of significance, the variances can be considered homocedastic. ³According to ANOVA at 95% of significance. ⁴(LC: leaf count, PD: pseudostem diameter, B: biomass, NORT: number of root tips, RL: root length, RV: root volume, RDs: root density, RD: recovery day).

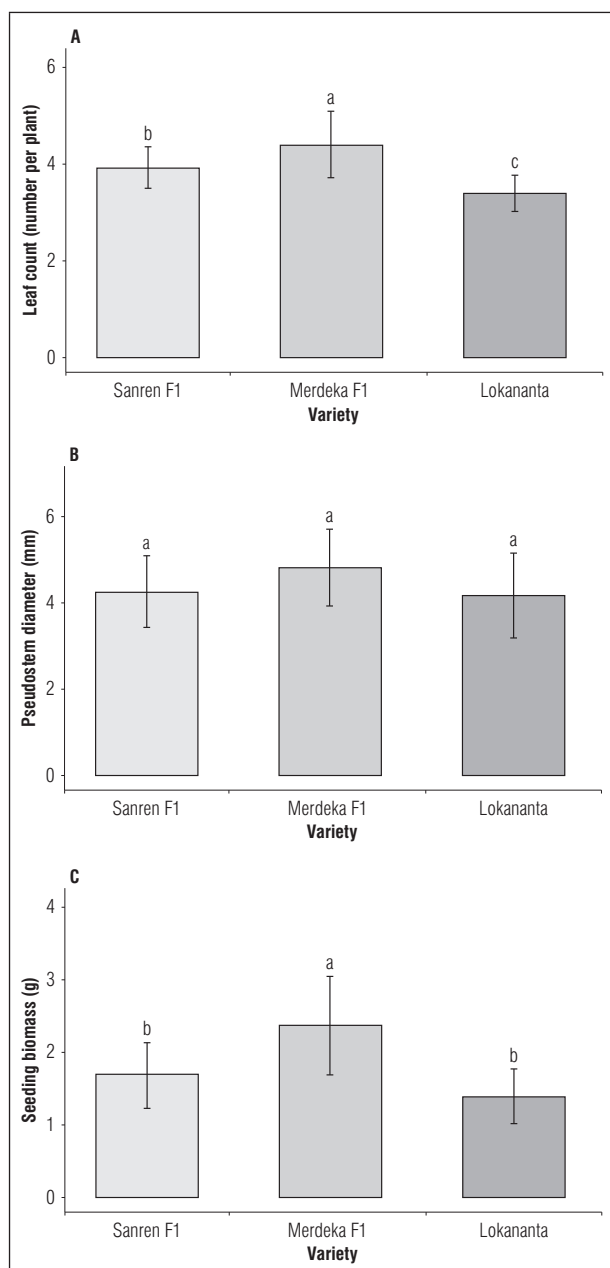


Figure 2. Aboveground seedling trait variation among three shallot cultivars (Merdeka F1, Sanren F1, Lokananta). Bars show mean $\pm$ standard error (SE) of: (A) Leaf count (number per plant, Y-axis range: 0-5), (B) Pseudostem diameter (mm, Y-axis range: 0-6), and (C) Fresh biomass (g, Y-axis range: 0-3). Different lowercase letters denote significant differences (Duncan's test, $P < 0.05$); NS = not significant.

Below-ground traits

Four distinct parameters related to the root characteristics of shallot seedlings namely the number of root tips (NORT), root length (RL), root volume (RV), and root density (RDs) showed statistically significant differences among the three observed varieties (Fig. 3).

The Merdeka F1 variety consistently exhibited the highest average values for all parameters, with 12.80 ± 0.49 root tips, 8.90 ± 0.40 cm root length, 2.51 ± 0.16 cm³ root volume, and 0.28 ± 0.01 cm³/cm root density. In comparison, the Lokananta variety recorded 10.53 ± 0.65 root tips, 6.89 ± 0.44 cm root length, 1.64 ± 0.08 cm³ root volume, and 0.24 ± 0.01 cm³/cm root density. The Sanren F1 variety showed the lowest values, with 10.47 ± 0.44 root tips, 6.53 ± 0.34 cm root length, 1.47 ± 0.13 cm³ root volume, and 0.22 ± 0.007 cm³/cm root density. These findings underscore the superior root development performance of the Merdeka F1 variety under the conditions studied.

Recovery day

In the rigorous examination and meticulous observation conducted on the designated recovery day, it became abundantly clear that the three distinct varieties exhibited notably divergent recovery times (Fig. 4). Specifically, the Merdeka F1 variety demonstrated a comparatively shorter recovery duration of 5.77 ± 0.16 d, a finding that, while not significantly distinct when contrasted with the Sanren F1 variety, which required 6.33 ± 0.19 d for recovery, was nonetheless markedly different from the Lokananta variety, which necessitated a longer recovery period of 6.53 ± 0.30 d after the transplanting process. The 13.2% faster recovery of 'Merdeka F1' over Lokananta suggests superior stress adaptation capacity.

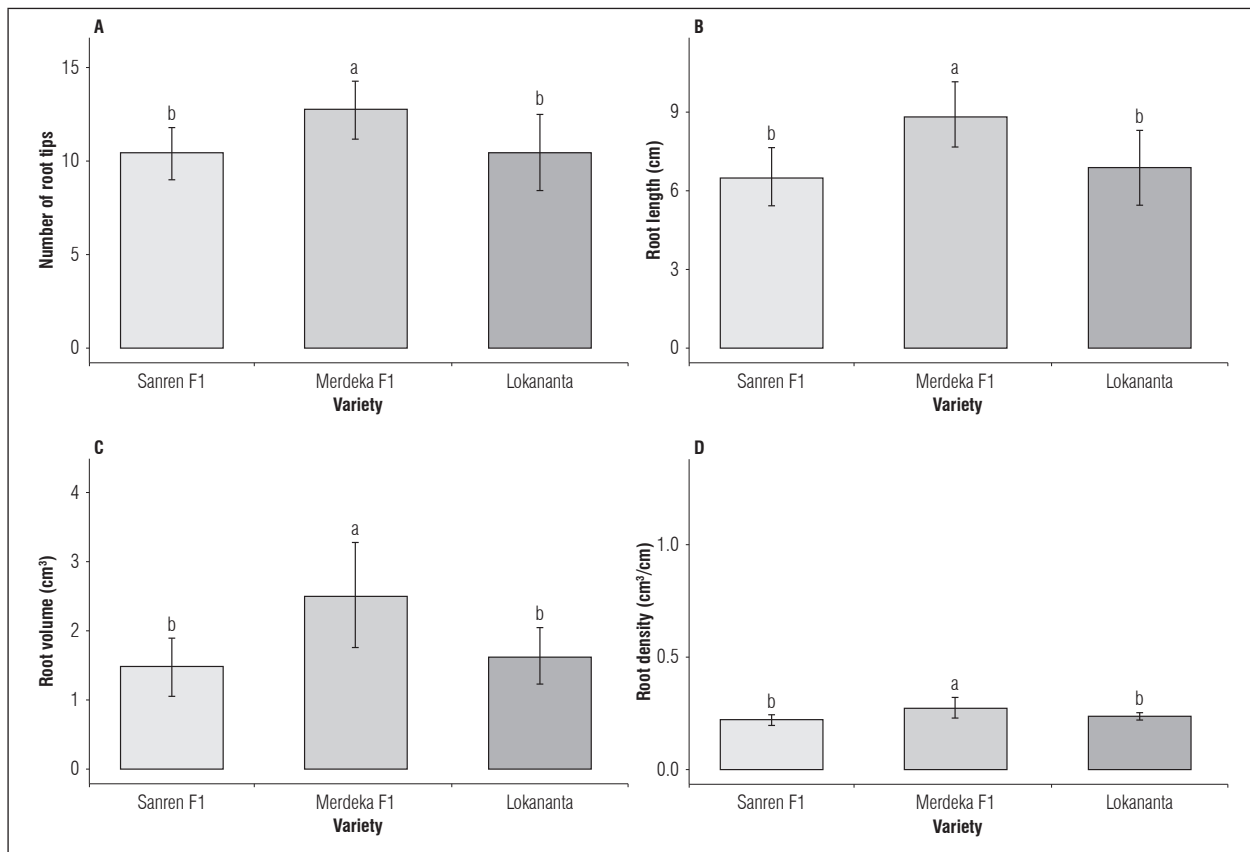


Figure 3. Below ground seedling trait variation among three shallot cultivars ('Merdeka F1', 'Sanren F1', 'Lokananta'). Bars show mean $\pm$ standard error (SE) of number of root tips per plant (A), root length (B), root volume (C), and root density (D). Different lowercase letters denote significant differences (Duncan's test, $P < 0.05$).

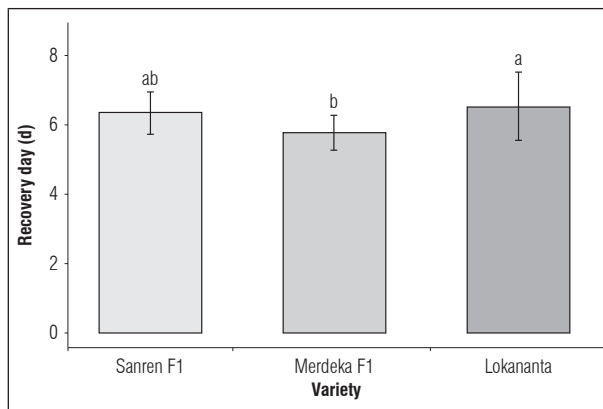


Figure 4. Recovery day variation among three shallot cultivars ('Merdeka F1', 'Sanren F1', 'Lokananta'). Bars show mean $\pm$ standard error (SE). Different lowercase letters denote significant differences (Duncan's test, $P < 0.05$).

Regression analysis

AIC and BIC analysis

The analysis of AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) was conducted to evaluate the most suitable regression model for predicting recovery day based on various seedling traits (Tab. 4). Lower AIC and BIC values indicate a better fit of the model, with a balance between goodness of fit and complexity. For the relationship between recovery day and the leaf count, the linear model yielded the lowest AIC (64.87) and BIC (69.07), suggesting that a simple linear approach was the most appropriate for this trait. Similarly, for seedling biomass, the linear model had the lowest AIC (57.53) and BIC (61.74), indicating that a simple linear model effectively captured the relationship

Table 4. Model selection statistics (AIC/BIC) for regression relationships between seedling traits and post-transplant recovery days.

Models	Recovery day (d)	
	AIC	BIC
vs. Leaf count		
Linear	64.87	69.07
Quadratic	65.13	70.74
Cubic	64.88	71.89
vs. Pseudostem diameter		
Linear	35.1	39.32
Quadratic	30.77	36.38
Cubic	32.35	39.36
vs. Seedling biomass		
Linear	57.53	61.74
Quadratic	58.28	63.88
Cubic	59.20	66.20
vs. Number of root tips		
Linear	74.08	78.28
Quadratic	72.41	78.01
Cubic	74.40	81.41
vs. Root length		
Linear	74.18	78.38
Quadratic	75.12	80.72
Cubic	76.78	83.79
vs. Root volume		
Linear	73.68	77.88
Quadratic	74.39	80.00
Cubic	76.35	83.36
vs. Root density		
Linear	73.65	77.85
Quadratic	73.79	79.40
Cubic	75.34	82.34

with recovery day. For root length, root volume, and root density, the linear model consistently showed the lowest values, further supporting its suitability for these traits.

In contrast, for pseudostem diameter, the quadratic model demonstrated the lowest AIC (30.77) and BIC (36.38), suggesting that a second-degree polynomial model was the best fit. Likewise, for the number of root tips, the quadratic model exhibited the lowest AIC (72.41) and BIC (78.01), making it the most

suitable model. Overall, the analysis indicates that the linear model was the most suitable for most seedling traits, except for pseudostem diameter and the number of root tips, where the quadratic model provided a better fit.

Figure 5 presents the regression analysis between recovery day and various seedling traits, including the leaf count, pseudostem diameter, seedling biomass, number of root tips, root length, root volume, and root density. The fitted regression lines are shown in

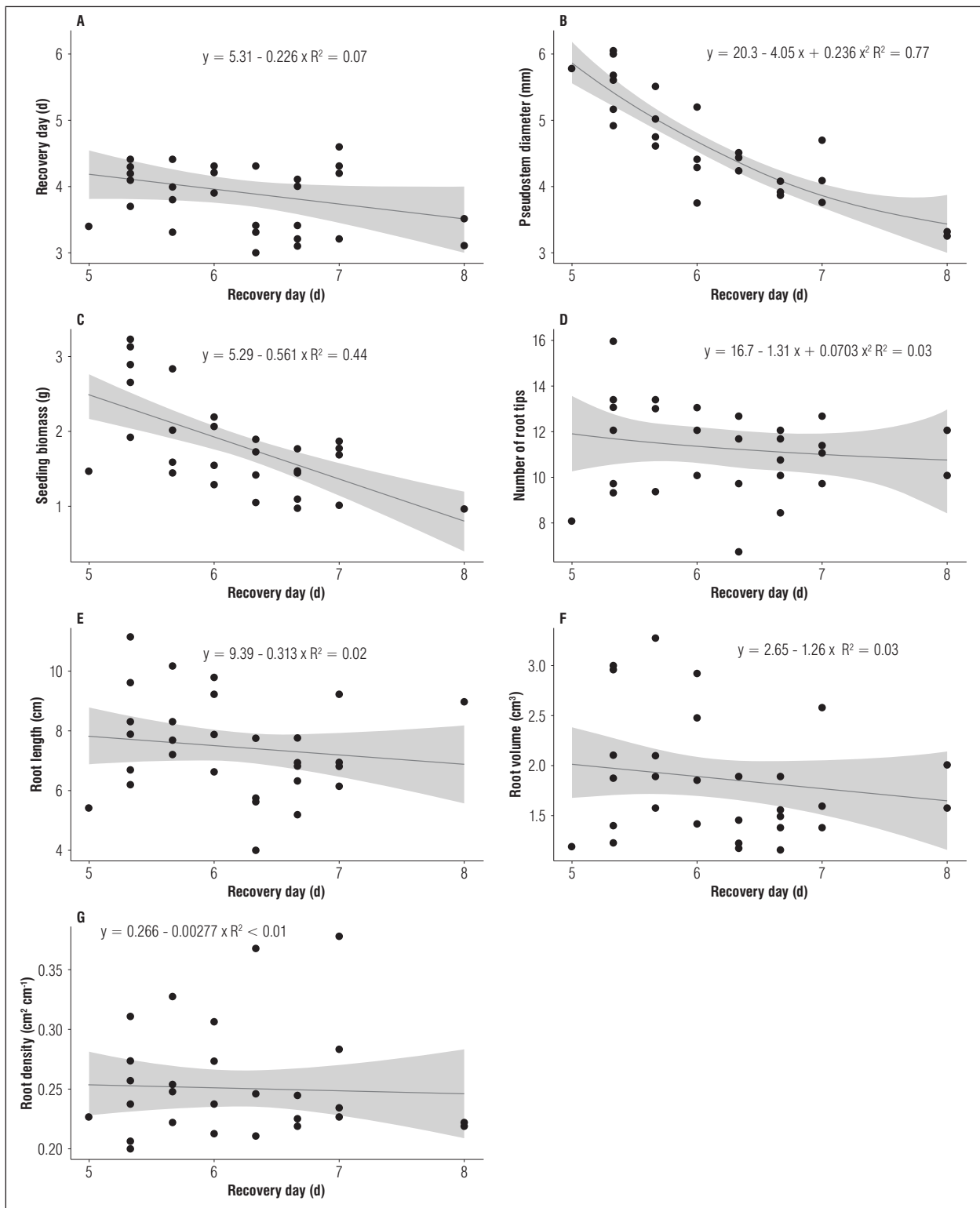


Figure 5. Regression relationships between post-transplant recovery days and seedling traits. Gray lines show fitted models with 95% confidence intervals (shaded).

gray, with shaded areas representing the 95% confidence intervals. In figure 5A, the linear regression for the leaf count indicates a negative relationship with recovery day ($y = 5.31 - 0.226x$), with an R^2 value of 0.07, suggesting a moderate fit. Figure 5B demonstrates a quadratic relationship for pseudostem diameter ($y = 20.3 - 4.05x + 0.236x^2$), with a high R^2 value of 0.77, indicating a strong fit. Figure 5C, seedling biomass exhibits a negative linear relationship with recovery day ($y = 5.29 - 0.561x$), supported by an R^2 value of 0.44, reflecting a moderate fit.

Figure 5D through (g) depict weaker relationships. The number of root tips ($y = 16.7 - 1.31x + 0.0703x^2$) (Fig. 5D) shows a very low R^2 of 0.03, indicating minimal explanatory power. Root length ($y = 9.39 - 0.313x$) (Fig. 5E) and root volume ($y = 2.99 - 0.18x$) (Fig. 5F) show similarly weak relationships, with R^2 values of 0.02 and 0.04, respectively. Lastly, root density ($y = 0.305 - 0.0096x$) (Fig. 5G) also shows a very weak negative relationship, with an R^2 value of <0.01 . Overall, the results highlight that pseudostem diameter and seedling biomass exhibit the strongest associations with recovery day, while the other traits display weaker correlations, suggesting that recovery day may influence certain traits more significantly than others.

Correlation analysis

Correlation matrix illustrating the relationships between seedling traits, including the leaf count (LC), pseudostem diameter (PD), biomass (B), number of root tips (NORT), root length (RL), root volume (RV), root density (RDs), and recovery day (RD) (Fig. 6). The results show strong positive correlations between root length and root volume ($r=0.96$), root density and root volume ($r=0.95$), and root length and root density ($r=0.83$). These findings suggest that as root length increases, both root volume and root density tend to increase as well. Additionally, biomass is positively correlated with pseudostem diameter ($r=0.73$) and the leaf count ($r=0.77$), indicating that seedling vigor is closely associated with these traits.

On the other hand, recovery day (RD) exhibits negative correlations with most traits, including pseudostem diameter ($r=-0.86$), biomass ($r=-0.66$), and the leaf count ($r=-0.53$). This negative relationship indicates that seedlings with more robust growth characteristics tend to recover more quickly

after transplanting. Overall, the correlation matrix highlights the interconnected nature of seedling traits and the influence of recovery day on seedling performance.

DISCUSSION

The three observed shallot varieties exhibited significantly different characteristics in terms of the average leaf count, seedling biomass, number of root tips, root length, root volume, root density, and recovery day. These seven parameters indicate that the Merdeka F1 variety is superior to the other two varieties, demonstrating a faster recovery after the transplanting process. This significant difference is undoubtedly due to the genetic influence of each variety. Genetic factors play a crucial role in influencing the success of transplanting in plants by determining attributes such as adaptability, yield potential, and resilience to environmental stressors. Various studies illustrate that genetic variability in plant germplasm enhances the adaptability of crops, facilitating better transplant success rates across diverse environments. For instance, research indicates that assessing genetic diversity is vital for breeding programs aimed at developing cultivars with improved traits, including tolerance to abiotic stresses like drought and salinity (Kamphorst *et al.*, 2021; Durge *et al.*, 2022; Rahmawati *et al.*, 2024).

Transplanting typically induces stress in shallot seedlings, temporarily affecting their physiological functions. In this study, the seedlings required approximately 5 d to recover, indicating a relatively extended adaptation period (Faried *et al.*, 2024a, 2024b). This delay is primarily caused by disruption of the root system, which impairs nutrient uptake and leads to early growth stagnation (Jehangir *et al.*, 2022; Mahalingam *et al.*, 2022). Transplant-induced stress also suppresses vital physiological processes, including photosynthesis and water absorption, both of which are crucial for seedling establishment (Muthoni and Shimelis, 2020). Although leaf water potential may return to its original state, the seedlings' photosynthetic capacity often remains limited during the recovery phase (Aloni *et al.*, 1991). Similarly, Lee *et al.* (2021) reported that delayed leaf development in rice seedlings following transplanting is linked to inhibitory effects occurring during early seedling growth. These findings highlight the complex physiological adjustments required for successful recovery after transplantation.

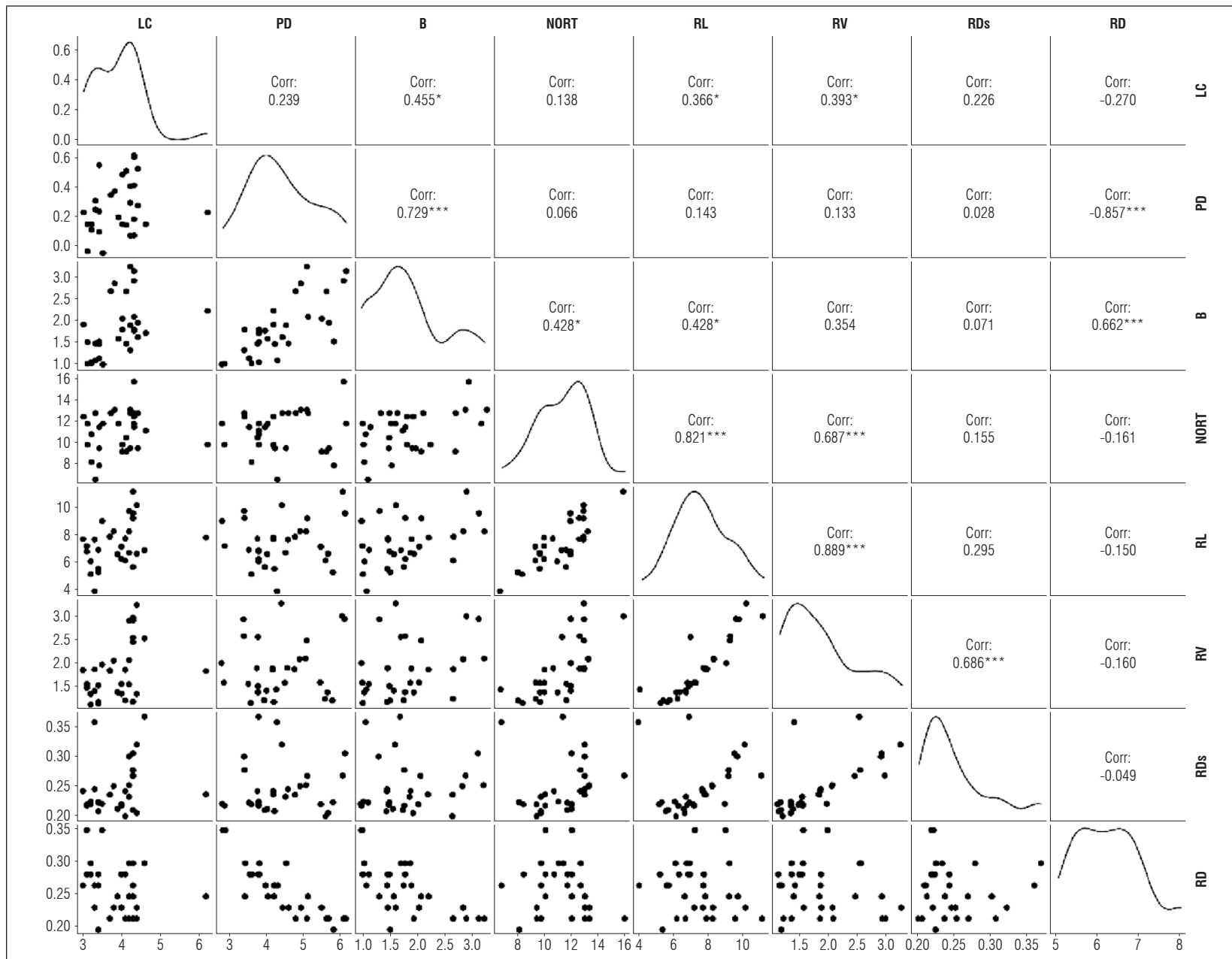


Figure 6. Correlation matrix of seedling traits: Leaf count per plant (LC), pseudostem diameter (PD), biomass (B), number of root tips (NORT), root length (RL), root volume (RV), root density (Rds), and recovery day (RD). Statistical significance is marked using asterisks: * $P < 0.05$ (significant), ** $P < 0.01$ (very significant), and *** $P < 0.001$ (highly significant).

Among the four measured seedling characteristics, pseudostem diameter had the strongest relationship with the speed of shallot seedling recovery from stress. The strong negative correlation ($r=-0.86$) between pseudostem diameter (PD) and recovery day (RD) aligns with Grossnickle (2012), confirming that larger PD (≥ 4.5 mm) enhances stress buffering via carbohydrate/water storage, reducing recovery time by ~ 1 day. PD explained 77% of RD variation ($R^2=0.77$), surpassing other traits (Fig. 5B). Additionally, the negative correlation between pseudostem diameter and recovery day suggests that larger diameters lead to faster recovery. The pseudostem diameter in shallots serves as an energy source during the recovery process. This indicates that the larger the pseudostem diameter, the quicker the seedlings recover from shock. This is likely because the pseudostem acts as a storage organ, providing energy reserves essential for overcoming transplant shock. In addition, thicker pseudostems can store more water, helping to buffer seedlings against dehydration during the recovery period (Skelton, 2020). Recent studies support this relationship between stem diameter and seedling performance. Arantes *et al.* (2021) demonstrated that seedlings with larger rootstock diameters exhibited greater vigor compared to those with smaller diameters, indicating that stem size plays a crucial role in post-transplant health and growth. Schöffel *et al.* (2023) also reported that stem diameter positively influences the number of buds, which can enhance subsequent plant development. Similarly, Kacheyo *et al.* (2024) emphasized that vigorous seedling traits, particularly stem size, are vital for successful transplanting in potato crops.

The leaf count shows a weak relationship with new leaf emergence. As we know, leaves are crucial organs for assimilate formation. However, in this study, it was observed that older leaves on the seedlings generally die off as a response to stress. This death is caused by cell damage, especially membrane failure (Guadagno *et al.*, 2017). The leaf count formed during the seedling stage does not affect the recovery time, as greater leaf area leads to increased transpiration. Yang *et al.* (2022) found that growth inhibition in plants is influenced by hormone signaling, which may hinder root growth and affect the plant's recovery after transplanting. Moreover, larger plant canopies experience greater transpiration compared to smaller ones. Therefore, before transplantation, shallot seedlings must be pruned to reduce their leaf area (Faried *et al.*, 2024a, 2024b).

The roots, as essential plant organs, have minimal impact on recovery day, as indicated by the low R^2 values for four root traits: number of root tips, root length, root volume, and root density. Weak root-RD relationships ($R^2 < 0.05$) suggest transplant-induced root damage (Zhu *et al.*, 2023). Mechanical root injury during transplanting may mask inherent root vigor effects. Root density (RDs) showed minimal correlation ($r=-0.12$), emphasizing careful handling to preserve root tips (Pryor and Watson, 2016). However, for optimal post-transplant growth, a low shoot-to-root ratio and strong root regeneration capacity marked by numerous root tip apices are desirable (Close *et al.*, 2005). Among root traits, total root length is a more reliable indicator of seedling vigor than the number of root tips (Chiantante *et al.*, 2002). After transplanting, root regeneration plays a crucial role in restoring the plant's ability to absorb water and nutrients, which is essential for resuming normal growth (Gao *et al.*, 2023).

The limited correlation between root traits and the recovery process is likely due to mechanical damage to the roots during transplanting. Therefore, the process of digging out the seedlings must be carried out with great care, also maintain moisture around the roots, thereby reducing the risk of damage during transplanting (Pryor and Watson, 2016). Roots, which are essential for water and nutrient absorption, experience significant damage during this process. However, recovery mechanisms are activated afterward, with various metabolic processes working to restore the plant's condition. Under transplant stress, seedlings often experience elevated glucose levels as part of their metabolic response to root injury and loss. This increase in glucose serves as an energy source to support defensive responses, including the activation of stress-related metabolic pathways. The metabolic shift often involves enhanced carbohydrate metabolism, where glucose is utilized to generate energy and facilitate the synthesis of protective compounds like antioxidants (Li *et al.*, 2016, He *et al.*, 2022). Despite the challenges, Sulistiono *et al.* (2024) demonstrated that healthier root development contributes to improved overall plant vigor. The root systems of freshly planted seedlings may be insufficient to expeditiously provide an adequate volume of water to the aerial parts, resulting in transplant shock (Leskovar and Othman, 2016a; Leskovar and Othman, 2016b). This suggests that while roots may not directly affect the recovery period, enhancing root development can support overall plant resilience and growth.

The quality of shallot seedlings, particularly the pseudostem diameter, plays a critical role in determining their condition after transplanting. An essential factor in seedling preparation is the production process leading up to transplant readiness. Moreover, optimal seedling age can minimize stress and accelerate the recovery period, as older seedlings tend to experience more severe transplant shock (Singh and Singh, 2014). Research by Kanton *et al.* (2022) demonstrated that younger onion transplants resumed vegetative growth more quickly than older ones. Merdeka F1 met these thresholds (PD = 4.81 mm, biomass = 2.36 g), explaining its 5.77-d RD (Fig. 4).

Additionally, the transplanting process has been shown to enhance crop yields. For instance, Gavric and Omerbegovic (2021) reported that sweet corn cultivated through a transplanting system yielded higher productivity compared to direct field planting. However, Ginigaddara and Ranamukhaarachchi (2011) found no significant difference between transplanted and directly planted rice seedlings regarding their response to transplant shock and recovery time.

Despite the stress associated with transplanting, this condition can be mitigated by carefully selecting the timing of transplanting to avoid harsh environmental conditions (Bantis and Koukounaras, 2023). Subsequently, administering interventions in the form of biostimulants and advantageous mycological agents, in conjunction with the careful selection of seeds that are devoid of pest and disease afflictions, may be implemented to mitigate seed mortality and expedite the recuperation of plant health (Upadhyaya *et al.*, 2016; Krinis *et al.*, 2023).

Environmental conditions during this experiment—net-house settings with an average temperature of 32.14 °C (Fig. 1)—may not fully replicate the intensity of stress typically experienced in the field. Therefore, field trials under drought or heat conditions are recommended to validate the robustness of the PD–RD relationship. Future studies should also explore biostimulant treatments, such as mycorrhizae (Krinis *et al.*, 2023), to further mitigate root shock. Additionally, extending this study to younger seedlings (<45 d) is suggested to assess potential trade-offs between seedling age and recovery duration (Kanton *et al.*, 2003).

CONCLUSION

This study reveals important information regarding the relationship between the characteristics of shallot seedlings and their ability to recover after transplanting. Pseudostem diameter (PD) is the strongest predictor of RD, with Merdeka F1's superior traits (PD, biomass) enabling rapid recovery. Optimal care for seedlings will produce good seedling characteristics, thereby increasing the likelihood of recovering quickly from stress and reducing the delay phase, including seedling death. Future studies should optimize seedling age and field performance, integrating biostimulants to enhance root resilience.

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