Australian Journal of Crop Science

Article | https://doi.org/10.21475/ajcs.26.20.11.pne370
Submitted: 04 July 2026 | Revised: 26 August 2026 | Accepted: 05 October 2026
Pages 1026–1037

Temporal growth and biomass partitioning of *Aloe vera* source batches in coastal sandy soil

Rennanti Lunnadiyah Aprilia[1], Edi Purwanto[2*], Venty Suryanti[3], Muji Rahayu[2]

[1]Doctoral Program in Agricultural Science, Faculty of Agriculture, Universitas Sebelas Maret, Indonesia
[2]Faculty of Agriculture, Universitas Sebelas Maret, Indonesia
[3]Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret, Indonesia

***Corresponding author: edipurwanto@staff.uns.ac.id**

Abstract: This study evaluated temporal growth, biomass accumulation, and biomass partitioning of five composite planting-material source batches of *Aloe vera* under a common coastal sandy-soil field environment in Tegalretno, Kebumen, Indonesia. The experiment used a randomized complete block design with five source batches and five blocks (25 plots; 35 plants per plot). Canopy traits were measured at 72, 163, 254, and 345 days after transplanting (DAT), whereas biomass, root traits, and sampled-leaf area were assessed by destructive sampling. Stage-specific RCBD ANOVA followed by Tukey HSD was complemented by linear mixed-effects models testing planting-material source, time, and their interaction. All five canopy traits showed significant source × time interactions ($P < 0.001$). Among destructively measured traits, source × sampling-time interactions were significant for whole-plant dry weight ($P = 0.027$), root fresh weight ($P < 0.001$), root dry weight ($P < 0.001$), and sampled-leaf area ($P = 0.047$), but not for whole-plant fresh weight, leaf fresh weight, leaf dry weight, or root length. At 345 DAT, leaf fresh weight did not differ significantly among source batches, whereas the plot-level root-to-leaf fresh-weight ratio did ($F(4,16) = 9.124$, $P < 0.001$), ranging from 0.0255 in Gunung Kidul to 0.0480 in Kebumen. No source batch was consistently highest across traits and stages. The results demonstrate dynamic source-batch variation under a shared field environment but do not establish geographic adaptation or genetic superiority because each location contributed one composite batch and the study was limited to a single site and cultivation cycle.

Keywords: destructive sampling; linear mixed-effects model; randomized complete block design; root-to-leaf ratio; vegetative offsets.

Abbreviations: ANOVA, analysis of variance; CAM, crassulacean acid metabolism; DAT, days after transplanting; HSD, honestly significant difference; RCBD, randomized complete block design.

Introduction

Aloe vera (L.) Burm.f. is a succulent medicinal and horticultural crop whose leaves are widely used as raw materials for pharmaceutical, cosmetic, food, and nutraceutical products (Martínez-Burgos et al., 2022). Because the leaf is the principal harvested organ, commercial production depends on sustained canopy development and biomass accumulation. As a crassulacean acid metabolism (CAM) plant with succulent water-storing tissues, *A. vera* also has physiological characteristics relevant to production under water-limited conditions (Davis et al., 2019; Silva et al., 2014). These attributes support interest in its cultivation on marginal land, including coastal sandy soils. Such soils commonly have rapid drainage and limited water- and nutrient-retention capacity, which can constrain crop establishment and sustained biomass production (Huang and Hartemink, 2020; Aprilia and Sukur, 2022). Field cultivation of *A. vera* on coastal sandy soil has nevertheless been demonstrated in Indonesia, where organic-mulch management affected leaf yield and quality (Darini, 2019).

Growth and biomass production in *A. vera* are responsive to cultivation conditions. Irrigation regime and microbial biofertilizers can alter plant height, leaf development, fresh biomass, dry biomass, and water productivity (Khajeeyan et al., 2019, 2022), while organic and inorganic fertilization can modify vegetative growth and leaf biomass yield (Chowdhury et al., 2020). Site and fertilization effects on morphological traits have also been reported (Boukour et al., 2024), and water availability can modify leaf morphology and biomass production (Silva et al., 2014). Salinity provides another example of trait-specific response: NaCl treatments have been shown to affect plant and leaf biomass, leaf length, root length, and root weight (Asghari and Ahmadvand, 2018), while more recent studies have reported changes in root biomass, leaf dimensions, and related growth traits under salinity and nutrient treatments (Ebrahimzadeh et al., 2022; Mota-Ituarte et al., 2023). Collectively, these studies establish that *A. vera* growth and biomass are sensitive to growing conditions, but they have primarily evaluated experimentally imposed irrigation, salinity, fertilization, or site-management treatments. Much less

attention has been given to whether planting-material batches from different production sources follow different growth trajectories when evaluated simultaneously under the same field environment.

Variation among planting materials is therefore a relevant practical consideration. Genetic and horticultural diversity among *A. vera* accessions has been documented under common growing conditions (Nejatzadeh-Barandozi et al., 2012), and AFLP analysis of 60 genotypes collected from different agroclimatic zones also revealed substantial within-species genetic variation (Kumar et al., 2022). These studies demonstrate that biological variation among *A. vera* materials can exist, but they do not justify treating geographical source as a genetic factor in the absence of direct characterization. In the present study, vegetative offsets were obtained as one composite planting-material batch from each of five locations in Java: Gunung Kidul, Bantul, Purbalingga, Cilacap, and Kebumen. Because each location contributed only one composite batch, source location is confounded with possible differences in mother-plant composition, nursery management history, pre-transplant condition, and genotype. The experimental factor is therefore defined as planting-material source batch, while landscape, elevation, and geographical coordinates are used only to describe the source locations. The design supports comparison among the five tested batches under a common field environment, but not inference of replicated geographical populations, genetic superiority, or adaptation to the original source environments.

Parts of the broader Tegalretno field experiment have been reported previously. Agustin and Aprilia (2025) presented selected yield and physiological measurements from the same five-source field experiment, whereas Jumanto and Aprilia (2025) reported shoot-growth observations from a restricted period of the same experimental population. These publications therefore overlap with selected observation periods and variables from the broader field dataset used in the present study. Separately, two publications arose from a related greenhouse salinity experiment within the same research programme (Aprilia et al., 2025a, 2025b). Both greenhouse publications evaluated planting materials from Gunung Kidul, Bantul, and Cilacap under four NaCl levels, but that greenhouse experiment used a different experimental design and dataset from the present open-field study. The earlier field reports did not integrate the verified plot-level observations across the complete 72–345 days after transplanting (DAT) period or explicitly test planting-material source × time responses. Accordingly, the present manuscript is framed as an extended full-season synthesis and statistical re-analysis of the verified Tegalretno field dataset rather than as an independent field experiment.

The present study therefore aimed to (i) characterize temporal variation in plant height, leaf number, leaf length, leaf thickness, and stem height among the five planting-material source batches; (ii) test planting-material source × time interactions for repeatedly observed canopy traits; (iii) evaluate source × sampling-time responses in whole-plant, leaf, and root biomass and sampled-leaf area using destructive sampling data; and (iv) compare final-harvest biomass partitioning using plot-level root-to-leaf fresh-weight ratios. The central question was whether the five source batches differed in their temporal growth, biomass accumulation, and biomass-partitioning patterns when cultivated under the same coastal sandy-soil environment. Because the experiment was conducted at a single site during one cultivation cycle and each geographical location contributed one composite batch, the findings are interpreted as source-batch responses within the tested environment rather than as evidence of geographical adaptation, population-level differences, or genetic superiority.

Results and discussion

Planting-material source characteristics and field conditions

The five *Aloe vera* planting-material source batches were obtained from locations spanning coastal lowlands, inland lowlands, low hills, and a karst upland setting in Java, Indonesia (Table 1; Fig. 1). These geographic characteristics are descriptive only. Each location contributed one composite planting-material batch; therefore, landscape and elevation were not independently replicated factors and were not used to attribute differences in plant performance to geographic origin.

Table 1. Geographic characteristics of the five *Aloe vera* planting-material sources.

Planting-material source	Specific location	Province	Geographic coordinates	Landscape setting	Approx. altitude
Gunung Kidul	Buyutan, Watusigar, Ngawen	Special Region of Yogyakarta	7.867122° S, 110.674066° E	Karst upland/dryland	±350 m a.s.l.
Bantul	Jojoran Wetan, Triwidadi, Pajangan	Special Region of Yogyakarta	7.851012° S, 110.289381° E	Low hills	±80–180 m a.s.l.
Purbalingga	Tumanggal, Pengadegan	Central Java	7.347278° S, 109.486220° E	Inland lowland to middle elevation	±113 m a.s.l.
Cilacap	Cilacap Selatan/coastal area	Central Java	7.723333° S, 109.020833° E	Coastal lowland	±5–6 m a.s.l.
Kebumen	Kutowinangun	Central Java	7.701389° S, 109.750556° E	Lowland	±13 m a.s.l.

Landscape setting and approximate altitude characterize the source locations only; they were not independently replicated treatment factors.

The experiment was conducted under open-field coastal sandy-soil conditions in Tegalretno, Petanahan, Kebumen. Baseline soil characterization is reported in the Materials and Methods. The measured permeability was consistent with the freely drained behavior of sandy soils, which generally have limited water- and nutrient-retention capacity because of rapid water movement through coarse-textured profiles (Aprilia and Sukur, 2022; Huang and Hartemink, 2020). These properties provide environmental context for the plant responses but were not experimental treatments.

Periodic microclimatic observations revealed pronounced within-day variation (Table 2). Mean air temperature increased from 26.89 °C in the morning to 38.75 °C at midday, while relative humidity declined from 84.95% to 49.47%; midday illuminance was 14,844.47 lux. The measurements were collected every three days and therefore characterize scheduled observation periods rather than a continuous meteorological record.

Table 2. Microclimatic conditions at the coastal sandy-soil experimental site during the field experiment.

Observation period	Measurement time	Air temperature (°C)	Relative humidity (%)	Illuminance (lux)
Morning	07:00–08:00	26.89	84.95	2,790.32
Midday	12:00–13:00	38.75	49.47	14,844.47
Afternoon	16:00–17:00	32.28	87.94	6,417.26
Overall mean	—	32.64	74.12	8,017.35

Values are means of periodic field observations recorded every three days at the indicated observation periods. Illuminance was measured using a lux meter and is expressed in lux.

Water availability and irrigation regime can alter *A. vera* growth, leaf development, and yield-related traits (Khajeeyan et al., 2019; Silva et al., 2014). Field cultivation on coastal sandy soil has likewise shown that surface-management practices can modify *A. vera* leaf yield and quality (Darini, 2019). However, rainfall, reference evapotranspiration, vapor-pressure deficit, and continuous soil-water status were not measured in the present experiment. The recorded field conditions are therefore used to describe the shared cultivation environment, not to infer a specific water-stress mechanism.

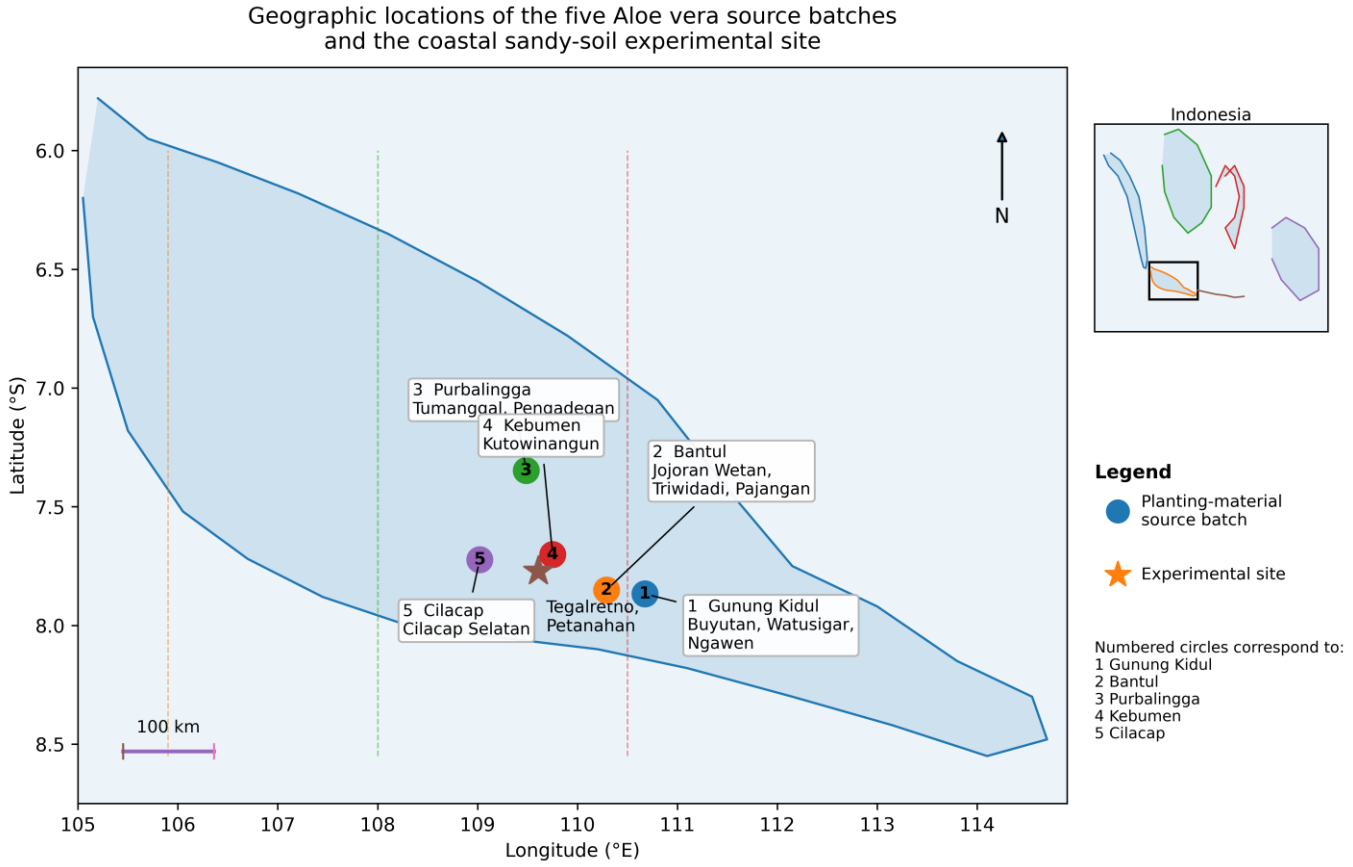


Fig. 1. Geographic locations of the five *Aloe vera* planting-material source batches and the open-field experimental site in Tegalretno, Petanahan, Kebumen, Central Java, Indonesia. Source-batch coordinates are listed in Table 1, while the experimental-site coordinates are reported in Materials and methods. The figure was generated in Python using Matplotlib as a vector map, with a simplified schematic outline of Java and an inset showing the position of Java within Indonesia. No external basemap was used.

Temporal growth and canopy responses

Growth and canopy responses were time dependent. Linear mixed-effects models detected significant planting-material source × time interactions for plant height, leaf number, leaf length, leaf thickness, and stem height ($P < 0.001$ for all traits; Table 4). Time significantly affected all five traits, whereas the source main effect was significant for all traits except stem height ($P = 0.077$). Accordingly, temporal inference is based on the interaction term rather than on differences in significance among separate observation dates.

Stage-specific RCBD analyses identified where individual source batches differed (Table 3). At 163 DAT, for example, plant height differed among batches ($F(4,16) = 3.335$, $P = 0.036$); Gunung Kidul (46.85 cm) exceeded Bantul (40.25 cm), while the remaining batches were intermediate. At 254 DAT, most canopy traits were not separated by Tukey HSD, although leaf number differed. At 345 DAT, differences remained for plant height, leaf number, and leaf length, whereas stem height did not differ. Leaf thickness had a significant overall ANOVA at 345 DAT, but Tukey-adjusted pairwise comparisons did not separate individual means.

Table 3. Growth and canopy traits of *Aloe vera* planting-material source batches at different observation times.

Observation time	Planting-material source	Plant height (cm)	Leaf number	Leaf length (cm)	Leaf thickness (mm)	Stem height (cm)
72 DAT	Gunung Kidul	41.36 ± 0.98^{a}	8.94 ± 0.30^{ab}	39.44 ± 0.89^{a}	10.86 ± 0.35^{a}	4.50 ± 0.62^{b}
	Bantul	31.16 ± 0.98^{b}	7.63 ± 0.30^{b}	29.76 ± 0.89^{c}	8.26 ± 0.35^{b}	4.30 ± 0.62^{b}
	Purbalingga	40.68 ± 0.98^{a}	9.60 ± 0.30^{a}	35.92 ± 0.89^{ab}	10.08 ± 0.35^{a}	5.20 ± 0.62^{ab}
	Cilacap	42.32 ± 0.98^{a}	9.45 ± 0.30^{a}	39.60 ± 0.89^{a}	10.88 ± 0.35^{a}	7.20 ± 0.62^{a}
	Kebumen	34.00 ± 0.98^{b}	8.02 ± 0.30^{b}	32.94 ± 0.89^{bc}	8.48 ± 0.35^{b}	3.22 ± 0.62^{b}
163 DAT	Gunung Kidul	46.85 ± 1.38^{a}	12.95 ± 0.31^{a}	43.80 ± 1.18^{a}	14.35 ± 0.43^{a}	2.30 ± 0.22^{ab}
	Bantul	40.25 ± 1.38^{b}	11.40 ± 0.31^{b}	38.30 ± 1.18^{b}	12.45 ± 0.43^{b}	1.80 ± 0.22^{b}
	Purbalingga	45.15 ± 1.38^{ab}	11.55 ± 0.31^{b}	41.45 ± 1.18^{ab}	13.95 ± 0.43^{ab}	2.10 ± 0.22^{b}
	Cilacap	42.95 ± 1.38^{ab}	13.10 ± 0.31^{a}	40.65 ± 1.18^{ab}	12.20 ± 0.43^{b}	3.10 ± 0.22^{a}
	Kebumen	42.75 ± 1.38^{ab}	11.80 ± 0.31^{ab}	39.80 ± 1.18^{ab}	13.40 ± 0.43^{ab}	2.40 ± 0.22^{ab}
254 DAT	Gunung Kidul	48.75 ± 1.47^{a}	15.10 ± 0.39^{ab}	43.65 ± 1.23^{a}	15.75 ± 0.47^{a}	1.80 ± 0.28^{a}
	Bantul	43.95 ± 1.47^{a}	13.90 ± 0.39^{ab}	40.05 ± 1.23^{a}	14.85 ± 0.47^{a}	1.10 ± 0.28^{a}
	Purbalingga	46.95 ± 1.47^{a}	13.55 ± 0.39^{b}	41.35 ± 1.23^{a}	14.60 ± 0.47^{a}	1.50 ± 0.28^{a}
	Cilacap	47.65 ± 1.47^{a}	15.50 ± 0.39^{a}	43.40 ± 1.23^{a}	14.40 ± 0.47^{a}	2.10 ± 0.28^{a}
	Kebumen	44.80 ± 1.47^{a}	13.95 ± 0.39^{ab}	39.90 ± 1.23^{a}	14.75 ± 0.47^{a}	1.40 ± 0.28^{a}
345 DAT	Gunung Kidul	49.18 ± 1.44^{a}	15.60 ± 0.42^{ab}	43.29 ± 1.13^{a}	16.73 ± 0.42^{a}	2.45 ± 0.19^{a}
	Bantul	43.87 ± 1.44^{ab}	13.87 ± 0.42^{b}	38.78 ± 1.13^{ab}	14.93 ± 0.42^{a}	2.52 ± 0.19^{a}
	Purbalingga	46.61 ± 1.44^{ab}	14.02 ± 0.42^{b}	39.43 ± 1.13^{ab}	15.27 ± 0.42^{a}	2.35 ± 0.19^{a}
	Cilacap	46.21 ± 1.44^{ab}	15.96 ± 0.42^{a}	41.71 ± 1.13^{ab}	15.02 ± 0.42^{a}	2.17 ± 0.19^{a}
	Kebumen	42.72 ± 1.44^{b}	14.11 ± 0.42^{b}	37.90 ± 1.13^{b}	14.98 ± 0.42^{a}	2.40 ± 0.19^{a}

Values are means ± standard errors of five experimental plots (n = 5). Within each trait and observation time, different superscript letters indicate significant differences by Tukey HSD at α = 0.05 following stage-specific RCBD ANOVA. DAT, days after transplanting.

Comparable morphological plasticity has been reported in *A. vera* under irrigation and organic-manure management, which altered plant height, leaf number, leaf length, leaf area, and leaf thickness (Gul et al., 2023), as well as under salinity, microbial inoculation, site, fertilization, and water-availability treatments (Silva et al., 2014; Asghari and Ahmadvand, 2018; Khajeeyan et al., 2022; Boukour et al., 2024; Majumder et al., 2026). Horticultural variation among *A. vera* accessions has also been documented under common growing conditions (Nejatzadeh-Barandozi et al., 2012). These studies support the responsiveness of canopy traits but do not identify the mechanism responsible for the present source-batch differences. Here, the significant interactions establish only that the five tested batches followed different temporal patterns under the same field environment.

Table 4. Effects of planting-material source, time, and their interaction on growth and canopy traits of *Aloe vera*.

Trait	Source Wald χ^2 (df = 4)	P	Time Wald χ^2 (df = 3)	P	Source × time Wald χ^2 (df = 12)	P
Plant height	20.504	<0.001	224.272	<0.001	78.128	<0.001
Leaf number	28.442	<0.001	545.740	<0.001	54.134	<0.001
Leaf thickness	27.210	<0.001	438.556	<0.001	83.179	<0.001
Stem height	8.423	0.077	52.067	<0.001	56.190	<0.001
Leaf length	18.629	<0.001	138.709	<0.001	54.098	<0.001

Linear mixed-effects models included planting-material source, time, and source × time as fixed effects and experimental plot as a random effect. Fixed effects were evaluated using Wald chi-square (χ^2) tests.

Biomass accumulation across destructive sampling times

Biomass responses varied with planting-material source and destructive sampling time (Tables 5 and 6). Both factors significantly affected whole-plant fresh weight, leaf fresh weight, whole-plant dry weight, and leaf dry weight. The source × sampling-time interaction was significant only for whole-plant dry weight (Wald $\chi^2(12) = 23.052$, $P = 0.027$); interactions for whole-plant fresh weight, leaf fresh weight, and leaf dry weight were not significant ($P = 0.088$, 0.099, and 0.250, respectively).

Stage-specific differences were concentrated at 72 and 163 DAT. At 72 DAT, whole-plant and leaf fresh weights differed among batches ($P < 0.001$ for both traits). At 163 DAT, these fresh-weight differences remained ($P = 0.008$ for both traits), and whole-plant dry weight also differed ($F(4,16) = 4.280$, $P = 0.015$), with Gunung Kidul exceeding Bantul. No source effect was detected for the four biomass traits at 254 DAT. At 345 DAT, whole-plant dry weight differed ($F(4,16) = 3.948$, $P = 0.020$), whereas whole-plant fresh weight, leaf fresh weight, and leaf dry weight did not.

Table 5. Biomass traits of *Aloe vera* planting-material source batches at different destructive sampling times.

Sampling time	Planting-material source	Whole-plant fresh weight (g)	Leaf fresh weight (g)	Whole-plant dry weight (g)	Leaf dry weight (g)
72 DAT	Gunung Kidul	659.00 ± 74.53^{a}	631.20 ± 71.74^{a}	34.70 ± 5.89^{a}	25.10 ± 5.05^{a}
	Bantul	234.80 ± 74.53^{b}	200.40 ± 71.74^{b}	21.30 ± 5.89^{a}	16.52 ± 5.05^{a}
	Purbalingga	599.20 ± 74.53^{a}	564.60 ± 71.74^{a}	30.26 ± 5.89^{a}	20.58 ± 5.05^{a}
	Cilacap	440.60 ± 74.53^{ab}	414.80 ± 71.74^{ab}	39.00 ± 5.89^{a}	28.68 ± 5.05^{a}
	Kebumen	166.80 ± 74.53^{b}	149.40 ± 71.74^{b}	18.96 ± 5.89^{a}	12.54 ± 5.05^{a}
163 DAT	Gunung Kidul	2028.60 ± 207.78^{a}	1968.00 ± 203.65^{a}	68.14 ± 6.56^{a}	47.08 ± 5.24^{a}
	Bantul	830.20 ± 207.78^{b}	805.30 ± 203.65^{b}	30.12 ± 6.56^{b}	22.84 ± 5.24^{a}
	Purbalingga	1316.80 ± 207.78^{ab}	1272.76 ± 203.65^{ab}	47.42 ± 6.56^{ab}	33.76 ± 5.24^{a}
	Cilacap	1047.40 ± 207.78^{b}	1001.40 ± 203.65^{b}	47.86 ± 6.56^{ab}	34.48 ± 5.24^{a}
	Kebumen	1025.20 ± 207.78^{b}	976.80 ± 203.65^{b}	44.64 ± 6.56^{ab}	30.26 ± 5.24^{a}
254 DAT	Gunung Kidul	1664.20 ± 167.33^{a}	1601.20 ± 164.77^{a}	62.60 ± 8.31^{a}	49.00 ± 6.81^{a}
	Bantul	1160.00 ± 167.33^{a}	1109.00 ± 164.77^{a}	61.00 ± 8.31^{a}	50.00 ± 6.81^{a}
	Purbalingga	1423.00 ± 167.33^{a}	1365.00 ± 164.77^{a}	65.00 ± 8.31^{a}	54.00 ± 6.81^{a}
	Cilacap	1359.00 ± 167.33^{a}	1288.00 ± 164.77^{a}	77.00 ± 8.31^{a}	64.00 ± 6.81^{a}
	Kebumen	1078.00 ± 167.33^{a}	1015.00 ± 164.77^{a}	58.00 ± 8.31^{a}	47.00 ± 6.81^{a}

Sampling time	Planting-material source	Whole-plant fresh weight (g)	Leaf fresh weight (g)	Whole-plant dry weight (g)	Leaf dry weight (g)
345 DAT	Gunung Kidul	2380.25 ± 182.98^{a}	2077.00 ± 166.96^{a}	67.70 ± 4.97^{ab}	39.00 ± 3.39^{a}
	Bantul	1663.00 ± 182.98^{a}	1431.00 ± 166.96^{a}	50.25 ± 4.97^{b}	27.50 ± 3.39^{a}
	Purbalingga	2050.25 ± 182.98^{a}	1768.25 ± 166.96^{a}	62.65 ± 4.97^{ab}	34.20 ± 3.39^{a}
	Cilacap	2081.75 ± 182.98^{a}	1775.75 ± 166.96^{a}	74.90 ± 4.97^{a}	39.20 ± 3.39^{a}
	Kebumen	1777.50 ± 182.98^{a}	1535.00 ± 166.96^{a}	73.05 ± 4.97^{a}	33.90 ± 3.39^{a}

Values are means ± standard errors of five experimental plots (n = 5). Within each trait and destructive sampling time, different superscript letters indicate significant differences by Tukey HSD at α = 0.05 following stage-specific RCBD ANOVA. Different designated plants were harvested at successive sampling times. DAT, days after transplanting.

The distinction between fresh and dry biomass is important in succulent *A. vera* leaves. Irrigation, microbial inoculation, organic or inorganic fertilization, and individual nutrient supply have all been reported to alter leaf fresh weight, dry matter, or biomass yield (Khajeeyan et al., 2019, 2022; Chowdhury et al., 2020; Sultana et al., 2021; Billah et al., 2022; Gul et al., 2023; Boukour et al., 2024; Majumder et al., 2026). Potassium fertilization, for example, significantly increased leaf biomass yield (Sultana et al., 2021), while integrated organic-inorganic nutrient management affected leaf biomass and canopy development (Majumder et al., 2026). In the present experiment, the significant interaction for whole-plant dry weight indicates that dry-matter differences among the tested batches changed across sampling times, whereas the non-significant interactions for the other three biomass traits do not support distinct temporal trajectories.

Because different designated plants were harvested at 72, 163, 254, and 345 DAT, an apparent decrease in a treatment mean between sampling dates does not represent biomass loss by the same plant. Temporal interpretation therefore relies on the source × sampling-time model, while stage-specific ANOVA describes differences only within each harvest.

Table 6. Effects of planting-material source, sampling time, and their interaction on biomass traits of *Aloe vera*.

Trait	Source Wald χ^2 (df = 4)	P	Sampling-time Wald χ^2 (df = 3)	P	Source × sampling-time Wald χ^2 (df = 12)	P
Whole-plant fresh weight	33.004	<0.001	436.833	<0.001	19.039	0.088
Leaf fresh weight	33.379	<0.001	338.662	<0.001	18.584	0.099
Whole-plant dry weight	22.953	<0.001	152.838	<0.001	23.052	0.027
Leaf dry weight	16.892	0.002	139.580	<0.001	14.849	0.250

Linear mixed-effects models included planting-material source, destructive sampling time, and their interaction as fixed effects and experimental plot as a random effect. Fixed effects were evaluated using Wald chi-square (χ^2) tests.

Root traits, sampled-leaf area, and biomass partitioning

Root biomass and sampled-leaf area displayed source-dependent temporal variation (Tables 7 and 8). Source × sampling-time interactions were significant for root fresh weight (Wald $\chi^2(12) = 33.275$, $P < 0.001$), root dry weight (Wald $\chi^2(12) = 47.665$, $P < 0.001$), and sampled-leaf area (Wald $\chi^2(12) = 21.222$, $P = 0.047$), but not for root length (Wald $\chi^2(12) = 13.834$, $P = 0.311$).

Stage-specific contrasts were most evident for root biomass. Gunung Kidul exceeded Bantul in root fresh weight at 72 and 163 DAT, whereas no source difference was detected at 254 DAT. At 345 DAT, Kebumen and Cilacap had greater root fresh weight than Bantul. Root dry weight differed at 163 DAT and more strongly at 345 DAT, when Kebumen had the highest mean (39.15 g) and Bantul the lowest (22.75 g). Root length showed no significant source × sampling-time interaction, and Tukey-adjusted pairwise comparisons did not establish persistent separation among batches. Sampled-leaf area differed at 72 DAT but not at later individual stages, despite the weaker significant temporal interaction.

Root responses of *A. vera* are also sensitive to imposed growing conditions. Soil or irrigation salinity has been reported to modify root biomass and root-related growth traits (Jin et al., 2007; Moghbeli et al., 2012; Asghari and Ahmadvand, 2018), and combined salinity and foliar nutrient treatments affected root dry weight (Ebrahimzadeh et al., 2022). Jin et al. (2007) also documented cultivar-dependent differences in root fresh weight under seawater irrigation, illustrating that belowground responses need not parallel leaf responses. Leaf dimensions likewise respond to water availability and salinity (Silva et al., 2014; Mota-Ituarte et al., 2023). These studies provide biological context but do not establish the mechanism behind differences among the present source batches.

Table 7. Root traits and sampled-leaf area of *Aloe vera* planting-material source batches at different destructive sampling times.

Sampling time	Planting-material source	Root fresh weight (g)	Root dry weight (g)	Root length (cm)	Sampled-leaf area (cm^2)
72 DAT	Gunung Kidul	38.00 ± 4.76^{a}	9.60 ± 1.70^{a}	16.20 ± 1.84^{a}	122.80 ± 10.44^{a}
	Bantul	15.20 ± 4.76^{b}	4.78 ± 1.70^{a}	14.50 ± 1.84^{a}	61.40 ± 10.44^{c}
	Purbalingga	34.60 ± 4.76^{ab}	9.68 ± 1.70^{a}	21.60 ± 1.84^{a}	115.40 ± 10.44^{a}
	Cilacap	25.80 ± 4.76^{ab}	10.32 ± 1.70^{a}	20.58 ± 1.84^{a}	108.60 ± 10.44^{ab}
	Kebumen	17.40 ± 4.76^{ab}	6.42 ± 1.70^{a}	14.58 ± 1.84^{a}	67.00 ± 10.44^{bc}
163 DAT	Gunung Kidul	51.60 ± 6.68^{a}	21.06 ± 2.21^{a}	22.80 ± 2.20^{a}	272.47 ± 50.26^{a}
	Bantul	18.90 ± 6.68^{b}	7.28 ± 2.21^{b}	18.30 ± 2.20^{a}	117.93 ± 50.26^{a}
	Purbalingga	36.04 ± 6.68^{ab}	13.66 ± 2.21^{ab}	23.90 ± 2.20^{a}	140.60 ± 50.26^{a}
	Cilacap	36.00 ± 6.68^{ab}	13.38 ± 2.21^{ab}	22.50 ± 2.20^{a}	112.00 ± 50.26^{a}
	Kebumen	40.40 ± 6.68^{ab}	14.38 ± 2.21^{ab}	20.70 ± 2.20^{a}	130.60 ± 50.26^{a}
254 DAT	Gunung Kidul	54.00 ± 8.30^{a}	13.60 ± 2.35^{a}	25.80 ± 2.82^{a}	163.80 ± 13.97^{a}
	Bantul	45.00 ± 8.30^{a}	11.00 ± 2.35^{a}	25.20 ± 2.82^{a}	160.60 ± 13.97^{a}
	Purbalingga	50.00 ± 8.30^{a}	11.00 ± 2.35^{a}	27.40 ± 2.82^{a}	170.40 ± 13.97^{a}
	Cilacap	61.00 ± 8.30^{a}	13.00 ± 2.35^{a}	32.00 ± 2.82^{a}	160.40 ± 13.97^{a}
	Kebumen	55.00 ± 8.30^{a}	11.00 ± 2.35^{a}	25.80 ± 2.82^{a}	155.20 ± 13.97^{a}
345 DAT	Gunung Kidul	52.75 ± 4.66^{ab}	28.70 ± 2.30^{bc}	22.05 ± 1.22^{a}	206.35 ± 32.36^{a}
	Bantul	43.00 ± 4.66^{b}	22.75 ± 2.30^{c}	21.95 ± 1.22^{a}	177.47 ± 32.36^{a}
	Purbalingga	56.50 ± 4.66^{ab}	28.45 ± 2.30^{bc}	22.30 ± 1.22^{a}	176.00 ± 32.36^{a}
	Cilacap	66.50 ± 4.66^{a}	35.70 ± 2.30^{ab}	24.20 ± 1.22^{a}	265.33 ± 32.36^{a}
	Kebumen	71.75 ± 4.66^{a}	39.15 ± 2.30^{a}	24.55 ± 1.22^{a}	170.07 ± 32.36^{a}

Values are means ± standard errors of five experimental plots (n = 5). Within each trait and destructive sampling time, different superscript letters indicate significant differences by Tukey HSD at α = 0.05 following stage-specific RCBD ANOVA. Sampled-leaf area refers to a representative leaf rather than total whole-plant leaf area. DAT, days after transplanting.

Table 8. Effects of planting-material source, sampling time, and their interaction on root traits and sampled-leaf area of *Aloe vera*.

Trait	Source Wald χ^2 (df = 4)	P	Sampling-time Wald χ^2 (df = 3)	P	Source × sampling-time Wald χ^2 (df = 12)	P
Root fresh weight	18.774	<0.001	147.683	<0.001	33.275	<0.001
Root dry weight	34.224	<0.001	448.554	<0.001	47.665	<0.001
Root length	10.888	0.028	80.265	<0.001	13.834	0.311
Sampled-leaf area	12.089	0.017	34.538	<0.001	21.222	0.047

Linear mixed-effects models included planting-material source, destructive sampling time, and their interaction as fixed effects and experimental plot as a random effect. Fixed effects were evaluated using Wald chi-square (χ^2) tests.

At final harvest, the plot-level root-to-leaf fresh-weight ratio differed among source batches ($F(4,16) = 9.124$, $P < 0.001$; Fig. 2). Mean ratios ranged from 0.0255 in Gunung Kidul to 0.0480 in Kebumen, with Tukey groups c and a, respectively; Bantul and Purbalingga were bc and Cilacap was ab. Log-transformed ratios produced the same overall conclusion ($F(4,16) = 9.621$, $P < 0.001$).

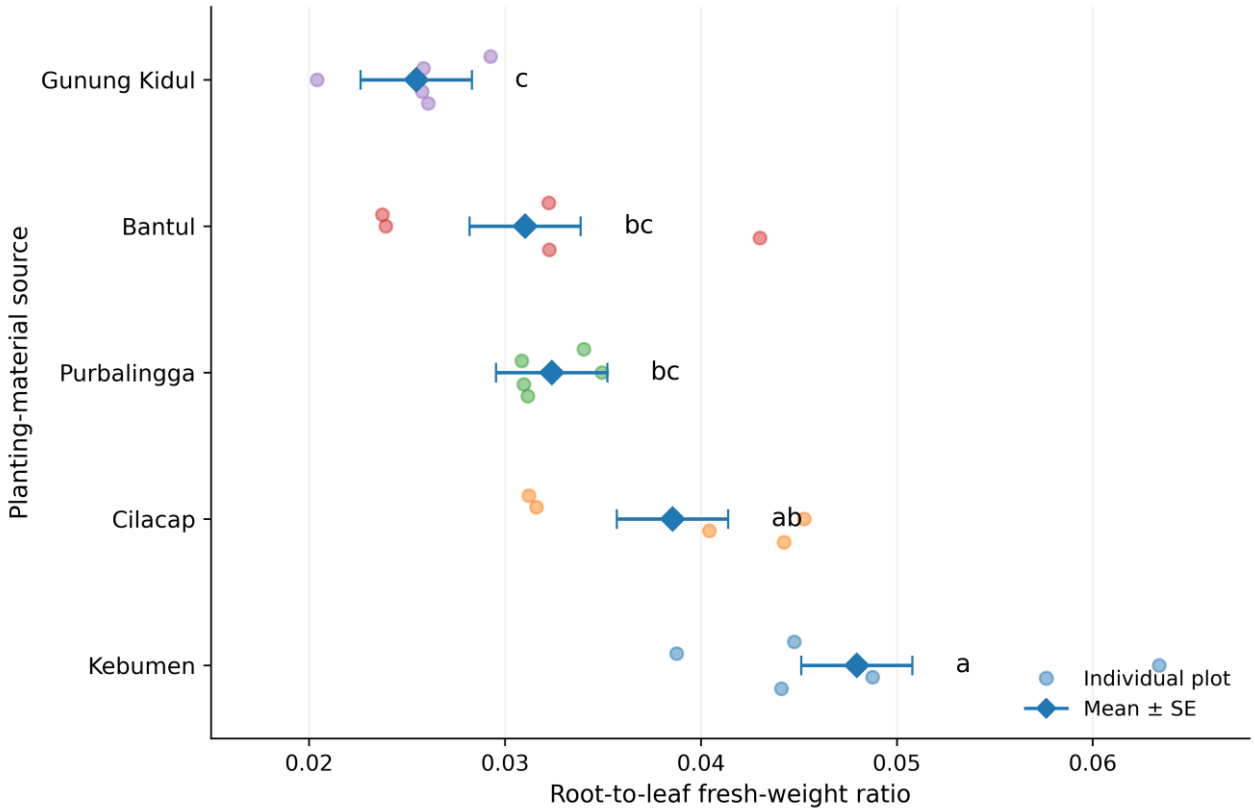


Fig. 2. Root-to-leaf fresh-weight ratio of *Aloe vera* planting-material source batches at final harvest (345 DAT). Small circles represent individual experimental plots; diamonds and horizontal error bars represent means ± model-based standard errors (n = 5 independent plots). Ratios were calculated independently for each plot as root fresh weight divided by leaf fresh weight from the same plot. Different letters indicate significant differences by Tukey HSD at α = 0.05.

The higher ratio in Kebumen therefore reflects a greater proportional contribution of root fresh biomass relative to leaf fresh biomass at 345 DAT; it is not, by itself, evidence of drought tolerance, adaptation, or a distinct resource-acquisition strategy. Likewise, absolute root biomass and proportional allocation should not be conflated: the two metrics describe different aspects of plant structure.

Integrated interpretation and practical implications

Across the full 72–345 DAT period, source-batch differences were trait- and time-dependent. All canopy traits had significant source × time interactions, while temporal interactions among destructive variables were significant for whole-plant dry weight, root fresh weight, root dry weight, and sampled-leaf area. No single batch ranked highest for all traits or stages. Gunung Kidul and Cilacap were frequently among the higher-ranking batches for canopy traits, whereas final root biomass and root-to-leaf allocation highlighted a different pattern, particularly for Kebumen. Final leaf fresh weight, however, did not differ significantly among source batches, so the present experiment does not justify designating one source as universally superior for commercial leaf yield.

The novelty of this manuscript lies in the full-season, plot-level re-analysis rather than in treating the field experiment as independent of earlier outputs. Selected observations from the same broader Tegalretno experiment were reported by Agustin and Aprilia (2025) and Jumanto and Aprilia (2025). The present analysis integrates verified observations across 72, 163, 254, and 345 DAT, includes final-harvest biomass partitioning, and explicitly tests source × time or source × sampling-time interactions. A separate greenhouse salinity experiment from the same research programme generated two related publications (Aprilia et al., 2025a, 2025b); that experiment used a distinct treatment structure and dataset and is therefore not treated as field evidence in the present analysis.

Interpretation is necessarily limited to the five composite source batches, one field site, one cultivation cycle, and the management regime used here. Geographic source is confounded with potential differences in genotype, mother-plant composition, nursery history, and pre-transplant condition, none of which was independently replicated or fully quantified. Future validation should therefore use multiple independent batches per source, quantitative pre-transplant characterization, and multi-location or multi-cycle trials; genetic or clonal characterization would further help separate planting-material composition from source-location effects. Commercial evaluation should also integrate marketable leaf biomass with relevant quality traits rather than relying on vegetative growth alone.

Materials and methods

Experimental site and study period

The field experiment was conducted from 23 February 2024 to 2 February 2025 in Tegalretno Village, Petanahan District, Kebumen Regency, Central Java, Indonesia (7.7711396° S, 109.6066985° E), near the southern coast of Java. The site represents an open-field coastal sandy-soil environment. Before transplanting, soil subsamples were collected from five points within the experimental area at a depth of 0–20 cm and combined to form one composite sample for baseline soil characterization. The composite sample had a pH of 6.5, total N, P, and K concentrations of 10, 8, and 120 ppm, respectively, a porosity of 42%, permeability of 15 cm h^{-1}, cation exchange capacity of 12 meq 100 g^{-1} soil, and an initial salinity of 2 ppt. Soil pH was determined using a glass electrode, total N by the Kjeldahl method, total P and K following HNO_3–$HClO_4$ digestion, porosity by the gravimetric method, permeability by the constant-head method, cation exchange capacity by the barium chloride method, and salinity using a refractometer.

Field microclimatic conditions were monitored every three days throughout the experimental period. Air temperature, relative humidity, and illuminance were recorded in the morning (07:00–08:00), at midday (12:00–13:00), and in the afternoon (16:00–17:00). Illuminance was measured in lux using a lux meter. The reported values therefore represent periodic field microclimatic observations collected at three-day intervals rather than continuous meteorological measurements.

Planting materials and source batches

The planting materials consisted of vegetative offsets of *Aloe vera* (L.) Burm.f., locally recognized by the supplying nurseries as the chinensis or jumbo type. Botanical identity was based on nursery records and the morphological characteristics of the planting materials. No herbarium voucher was prepared; therefore, *Aloe vera* (L.) Burm.f. is used throughout the manuscript, while "chinensis" or "jumbo type" refers only to the local horticultural designation of the planting material.

The offsets were approximately four months after separation from the mother plants and were obtained from five planting-material sources in Java, Indonesia: Gunung Kidul, Bantul, Purbalingga, Cilacap, and Kebumen. Each location supplied one composite batch of planting material and is therefore treated as a planting-material source batch rather than as a replicated geographical population. The exact number of mother plants contributing offsets to each source batch was not documented in the nursery records.

Before transplanting, offsets were selected for relative uniformity based on plant height and leaf number, healthy vegetative appearance, and absence of visible pest or disease symptoms. Selected offsets were approximately 20–25 cm tall and had about six leaves at transplanting.

Experimental design and crop management

The experiment was arranged in a randomized complete block design (RCBD) with five planting-material source treatments and five blocks, resulting in 25 experimental plots. Within each block, the five planting-material source treatments were randomly assigned to the experimental plots. The plot was the experimental unit, with five replicate plots per planting-material source (n = 5). Each plot consisted of five beds separated by 50 cm. Each bed was 70 cm wide and 490 cm long and contained seven plants, giving 35 plants per plot and a total experimental population of 875 plants. Plants were arranged at a spacing of 60 × 60 cm. The offsets were transplanted on 23 February 2024, and the experiment continued until the final harvest on 2 February 2025 (345 DAT).

Within each plot, plants designated for routine observations, destructive sampling, final harvest, and non-sampled positions were spatially separated rather than placed immediately adjacent to one another. Three plants were designated for routine non-destructive observations. Three different plants were allocated to destructive sampling, with one plant removed at each of 72, 163, and 254 days after transplanting (DAT). Destructively sampled plants were not replaced. A separate set of three plants per plot was retained for the final harvest at 345 DAT. The remaining plants maintained the plot stand and provided spatial separation among designated sampling positions.

Before transplanting, goat manure was incorporated as basal organic fertilizer at 15 t ha^{-1}. A liquid organic fertilizer (SIMURP Agro Purbo Tani, Kebumen, Indonesia) was applied every three months as a soil drench at 250 mL $plant^{-1}$. According to the product information, the formulation contained organic C (1.88–3.10%), total N (0.15–1.27%), P_2O_5 (0.06–1.42%), and K_2O (0.34–0.57%), with a reported pH of 5.6–6.4. The fertilizer also contained micronutrients and functional microorganisms associated with nutrient cycling. The same fertilizer regime was applied uniformly to all experimental plots.

Irrigation was generally applied every 3–5 days and adjusted according to field moisture and prevailing climatic conditions. Weed control and other routine crop-maintenance practices were applied uniformly across treatments.

Observation and destructive-sampling schedule

Observations covered three destructive sampling stages and one final harvest. One designated plant per plot was destructively sampled at each of 72 DAT (5 May 2024), 163 DAT (4 August 2024), and 254 DAT (3 November 2024). At the final harvest, three separate designated plants per plot were harvested at 345 DAT (2 February 2025). Destructively sampled plants were not replaced, and different plants were used at successive destructive sampling dates.

The three routine-observation plants were used for non-destructive canopy measurements across the observation schedule. For destructive variables, one designated plant per plot was harvested at 72, 163, and 254 DAT, whereas three separate designated plants per plot were used at the final harvest (345 DAT).

Growth and canopy measurements

Canopy-growth variables included plant height, leaf number, leaf length, leaf thickness, and stem height. Plant height was measured from the base of the plant to the tip of the highest leaf, and leaf number was recorded as the number of fully developed leaves per plant. For leaf-level measurements, three representative fully developed leaves were selected from each of the three designated observation plants per plot. Leaf length was measured from the base to the tip of each selected leaf, while leaf thickness was measured at the middle portion of each selected mature leaf using a vernier caliper. Stem height was measured from the base of the plant to the position of the highest leaf. Measurements from the three selected leaves per plant and the three designated observation plants were averaged to obtain one plot-level value for statistical analysis. Individual leaves and plants within a plot were not treated as independent biological replicates.

Biomass, root, and leaf-area measurements

Destructive measurements included whole-plant fresh weight, leaf fresh weight, root fresh weight, whole-plant dry weight, leaf dry weight, root dry weight, root length, and leaf area. Stem fresh weight was recorded at the sampling stages for which this component was available in the verified dataset. Fresh biomass was measured immediately after harvest. Whole-plant fresh weight was determined by weighing the entire harvested plant before separation into individual plant components. The plant was subsequently separated into its component organs, and the corresponding fresh weights were recorded. Root length was measured from the root base to the tip of the longest root.

For dry-mass determination, the separated plant components were first sun-dried under uniform conditions and subsequently oven-dried at 80 °C until a stable dry mass was reached. Stable dry mass was considered achieved when three consecutive weighings yielded the same mass, indicating no further detectable mass loss. Because the whole plant could not be accommodated in the oven as a single intact sample, plant components were dried separately. The dry masses of the separated components were then combined to obtain whole-plant dry weight, while leaf and root dry weights were recorded separately.

Leaf area was determined from representative leaves using the original field and laboratory procedure. The leaf outline was traced on millimeter-block paper, and the enclosed area was calculated. The resulting values represent the area of the sampled representative leaf rather than total whole-plant canopy area.

At 72, 163, and 254 DAT, one designated plant from each plot was used for destructive measurements and constituted the plot-level observation for that sampling stage. At the final harvest (345 DAT), measurements from the three designated harvest plants within each plot were averaged to obtain one plot-level value for statistical analysis. Thus, individual plants within a plot were not treated as independent biological replicates.

Root-to-leaf fresh-weight ratio

At final harvest, the root-to-leaf fresh-weight ratio was calculated independently for each experimental plot by dividing root fresh weight by leaf fresh weight obtained from the same plot. The plot-level ratio, rather than a ratio calculated from treatment means, was used as the response variable for statistical analysis. A logarithmic transformation was also examined as a sensitivity analysis because ratio data may deviate from normality.

Statistical analysis

The experimental plot was treated as the experimental unit in all inferential analyses. Individual plants, leaves, or measurements within a plot were not treated as independent biological replicates.

For stage-specific comparisons, data at each observation or sampling time were analysed separately according to the randomized complete block design (RCBD), with planting-material source as the treatment factor and block as the blocking factor. Analysis of variance (ANOVA) was performed using F-tests. When the planting-material source effect was significant at $\alpha = 0.05$, means were compared using Tukey's honestly significant difference (HSD) test. These stage-specific analyses were used to describe differences among source batches within individual observation or sampling times. The root-to-leaf fresh-weight ratio at final harvest was analysed using the same RCBD framework.

Temporal responses of canopy traits were analysed using linear mixed-effects models. Planting-material source, observation time, and the source × time interaction were included as fixed effects, and experimental plot was included as a random effect to account for observations obtained from the same plot over time. The significance of fixed effects was evaluated using Wald chi-square (χ^2) tests. The source × time interaction was used to determine whether temporal response patterns differed among planting-material source batches.

For biomass, root, leaf-area, and other destructively measured traits, sampling time was treated as a destructive sampling factor because different designated plants were harvested from the same experimental plots at successive sampling dates. These variables were analysed using linear mixed-effects models with planting-material source, sampling time, and the source × sampling-time interaction as fixed effects and experimental plot as a random effect. Fixed effects were evaluated using Wald chi-square (χ^2) tests. The source × sampling-time interaction was used to determine whether differences among planting-material source batches varied across destructive sampling times.

Stage-specific RCBD analyses and Tukey HSD comparisons were performed using IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA). Temporal mixed-model analyses were performed in Python 3.13.5 using statsmodels version 0.14.6, with supporting calculations performed using SciPy version 1.17.0. Statistical significance was assessed at $\alpha = 0.05$. Exact *P* values are reported where informative, whereas values below 0.001 are reported as $P < 0.001$.

Data provenance and scope of the revised analysis

Selected observation periods and variables from the present Tegalretno field experiment have been reported previously in two publications. Agustin and Aprilia (2025) reported selected yield and physiological variables from the same five-source, five-block field experiment, whereas Jumanto and Aprilia (2025) reported shoot-growth observations collected during August–November 2024 from the same experimental population. These publications therefore overlap with selected observation periods and/or variables from the broader field dataset used in the present study. The present manuscript is not treated as an independent field experiment, but as an extended full-season re-analysis of the verified plot-level dataset spanning 72, 163, 254, and 345 DAT, including the final harvest and temporal analyses of planting-material source × time responses. Previously reported observations, corrected values, and newly performed analyses are distinguished in a variable-by-variable data-provenance matrix provided as supplementary material.

A separate greenhouse salinity experiment from the same research programme generated two related publications (Aprilia et al., 2025a, 2025b). That experiment evaluated three planting-material sources (Gunung Kidul, Bantul, and Cilacap) under four controlled NaCl treatments using coastal sandy growing media. Although the two publications originated from the same broader greenhouse experiment, that experiment had a different design, treatment structure, and dataset from the present Tegalretno open-field study. Neither greenhouse publication is therefore treated as a source of field observations used in the present analysis.

Conclusion

The full-season re-analysis demonstrated trait- and time-dependent variation among the five *Aloe vera* planting-material source batches under a common coastal sandy-soil field environment. Significant source × time interactions were detected for all canopy traits, whereas source × sampling-time interactions were significant for whole-plant dry weight, root fresh weight, root dry weight, and sampled-leaf area. At final harvest, leaf fresh weight did not differ significantly among source batches, while whole-plant dry weight, root biomass, and the plot-level root-to-leaf fresh-weight ratio showed source-related differences. No single source batch consistently ranked highest across traits and sampling stages.

These findings characterize variation among the five tested source batches rather than geographical adaptation or genetic superiority. Because each location contributed one composite batch and the experiment was conducted at a single site during one cultivation cycle, broader recommendations require validation using multiple independent batches, locations, and cultivation cycles. Future planting-material selection should therefore combine marketable leaf biomass with relevant quality traits and, where feasible, quantitative pre-transplant and genetic or clonal characterization.

Acknowledgements

The authors thank Peny Agustin and Ari Jumanto for assistance with selected field observations and data collection during parts of the broader Tegalretno field experiment.

AI-generated content disclosure

OpenAI ChatGPT was used for English-language editing, manuscript organization, consistency checking, assistance with the statistical re-analysis workflow and code checking, table organization, and drafting/editing responses to reviewers. The AI tool did not generate or fabricate field or laboratory data. All numerical results, references, analyses, interpretations, and final manuscript text were checked and approved by the authors, who take full responsibility for the content.

Statement of contributions

RLA conceived the research idea, designed the study, conducted the field experiment, collected and analysed the data, interpreted the results, and prepared the original manuscript. EP contributed to finalizing the experimental design and research timeline and supervised the overall study. VS and MR contributed to the research design and manuscript refinement. All authors reviewed, edited, and approved the final version of the manuscript.

Ethical statement

Not applicable to human or animal research; the study involved cultivated plant material in an agronomic field experiment.

Conflict of interest

The authors declare no conflict of interest.

Data availability

The verified data supporting this study are available from the corresponding author upon reasonable request. A variable-by-variable publication-provenance matrix is provided as supplementary material.

References

Agustin P, Aprilia RL (2025) Pengaruh perbedaan asal bibit terhadap respon hasil dan fisiologi pada tanaman lidah buaya berumur 10 bulan pada lahan pasir pantai. Innofarm J Inov Pertan. 27(1):46–53. https://doi.org/10.33061/innofarm.v27i1.11817

Aprilia RL, Purwanto E, Suryanti V, Rahayu M (2025a) Impact of salinity stress on the response of *Aloe vera* from different breeders on coastal sand land. BIO Web Conf. 155:01023. https://doi.org/10.1051/bioconf/202515501023

Aprilia RL, Purwanto E, Suryanti V, Rahayu M (2025b) Physiological responses of *Aloe vera* to salt stress in coastal sandy soil: Morpho-physiological evaluation for sustainable cultivation. Asian J Agric Rural Dev. 15(3):406–418. https://doi.org/10.55493/5005.v15i3.5566

Aprilia RL, Sukur (2022) Kajian sifat fisik, kimia, dan biologi pada tanah berpasir di beberapa wilayah Indonesia. J Agroteknol (Agronu). 1(2):71–79. https://doi.org/10.53863/agronu.v1i02.475

Asghari R, Ahmadvand R (2018) Salinity stress and its impact on morpho-physiological characteristics of *Aloe vera*. Pertanika J Trop Agric Sci. 41(1):411–422.

Billah MM, Halder RK, Tuzzohura F, Nibir O, Islam SR, Rahman MK (2022) Growth and yield of *Aloe vera* (L.) Burm.f. as influenced by organic manures and chemical fertilizers. Dhaka Univ J Biol Sci. 31(2):203–212. https://doi.org/10.3329/dujbs.v31i2.60879

Boukour B, Florido MC, Lama-Muñoz A, Amallah L, Bouazza F, Sehlaoui H, Douaik A, El Mekkaoui A, El Faiz C, Hassikou R (2024) Effect of site conditions and fertilization treatments on morphological traits and mineral content of *Aloe vera* plants. J Appl Bot Food Qual. 97:36–44. https://doi.org/10.5073/JABFQ.2024.097.005

Chowdhury T, Chowdhury MAH, Rahman MA, Nahar K, Chowdhury MTI, Khan MSI (2020) Response of *Aloe vera* to inorganic and organic fertilization in relation to leaf biomass yield and post harvest fertility of soil. Bulg J Agric Sci. 26(2):346–354.

Darini MT (2019) Effects of different types and dosage of green mulch on yield and quality of *Aloe vera* L. on coastal sandy soil. Ilmu Pertan (Agric Sci). 4(3):103–109. https://doi.org/10.22146/ipas.37136

Davis SC, Simpson J, Gil-Vega KDC, Niechayev NA, van Tongerlo E, Hurtado Castaño N, Dever LV, Búrquez A (2019) Undervalued potential of crassulacean acid metabolism for current and future agricultural production. J Exp Bot. 70(22):6521–6537. https://doi.org/10.1093/jxb/erz223

Ebrahimzadeh A, Ghorbanzadeh S, Vojodi Mehrabani L, Sabella E, De Bellis L, Hassanpouraghdam MB (2022) KNO_3, nano-Zn, and Fe foliar application influence the growth and physiological responses of *Aloe vera* under salinity. Agronomy. 12(10):2360. https://doi.org/10.3390/agronomy12102360

Gul Z, Sajid M, Khan MN, Haq FU, Nawaz Z, Bakhtiar M, Siddique S, Aslam K, Irshad M (2023) Response of *Aloe vera* growth and gel production to organic manures and irrigation intervals. J Innov Sci. 9(1):144–153. https://doi.org/10.17582/journal.jis/2023/9.1.144.153

Huang J, Hartemink AE (2020) Soil and environmental issues in sandy soils. Earth Sci Rev. 208:103295. https://doi.org/10.1016/j.earscirev.2020.103295

Jin ZM, Wang CH, Liu ZP, Gong WJ (2007) Physiological and ecological characters studies on *Aloe vera* under soil salinity and seawater irrigation. Process Biochem. 42(4):710–714. https://doi.org/10.1016/j.procbio.2006.11.002

Jumanto A, Aprilia RL (2025) Analisis pertumbuhan tunas lidah buaya (*Aloe vera*) yang berasal dari berbagai penangkar pada lahan berpasir. Nusant Hasana J. 4(11):1–7. https://doi.org/10.59003/nhj.v4i11.1400

Khajeeyan R, Salehi A, Movahhedi Dehnavi M, Farajee H, Kohanmoo MA (2019) Physiological and yield responses of *Aloe vera* plant to biofertilizers under different irrigation regimes. Agric Water Manag. 225:105768. https://doi.org/10.1016/j.agwat.2019.105768

Khajeeyan R, Salehi A, Movahhedi Dehnavi M, Farajee H, Kohanmoo MA (2022) Growth parameters, water productivity and aloin content of *Aloe vera* affected by mycorrhiza and PGPR application under different irrigation regimes. S Afr J Bot. 147:1188–1198. https://doi.org/10.1016/j.sajb.2021.02.026

Kumar R, Salar RK, Naik PK, Yadav M, Kumar A, Kumar A, Yogi R, Kumar M, Chhokar V (2022) Elucidation of genetic diversity and population structure of sixty genotypes of *Aloe vera* using AFLP markers. S Afr J Bot. 147:1146–1155. https://doi.org/10.1016/j.sajb.2021.06.008

Majumder N, Chowdhury MAH, Rabbi RHM, Etu SY, Saha BK (2026) Synergistic effect of organic and inorganic fertilizers on *Aloe vera*: Enhancing leaf biomass, nutrient uptake, medicinal properties, and soil fertility. Agrosyst Geosci Environ. 9(1):e70306. https://doi.org/10.1002/agg2.70306

Martínez-Burgos WJ, Serra JL, Marsiglia Fuentes RM, Montoya P, Sarmiento-Vásquez Z, Marin O, Gallego-Cartagena E, Paternina-Arboleda CD (2022) *Aloe vera*: From ancient knowledge to the patent and innovation landscape - A review. S Afr J Bot. 147:993–1006. https://doi.org/10.1016/j.sajb.2022.02.034

Moghbeli E, Fathollahi S, Salari H, Ahmadi G, Saliqehdar F, Safari A, Hosseini Grouh MS (2012) Effects of salinity stress on growth and yield of *Aloe vera* L. J Med Plants Res. 6(16):3272–3277. https://doi.org/10.5897/JMPR11.1698

Mota-Ituarte M, Pedroza-Sandoval A, Minjares-Fuentes R, Trejo-Calzada R, Zegbe JA, Quezada-Rivera JJ (2023) Water deficit and salinity modify some morphometric, physiological, and productive attributes of *Aloe vera* (L.). Bot Sci. 101(2):463–475. https://doi.org/10.17129/botsci.3175

Nejatzadeh-Barandozi F, Naghavi MR, Enferadi ST, Mousavi A, Mostofi Y, Hassani ME (2012) Genetic diversity of accessions of Iranian *Aloe vera* based on horticultural traits and RAPD markers. Ind Crops Prod. 37(1):347–351. https://doi.org/10.1016/j.indcrop.2011.12.013

Silva H, Sagardia S, Ortiz M, Franck N, Opazo M, Quiroz M, Baginsky C, Tapia C (2014) Relationships between leaf anatomy, morphology, and water use efficiency in *Aloe vera* (L.) Burm.f. as a function of water availability. Rev Chil Hist Nat. 87:13. https://doi.org/10.1186/s40693-014-0013-3

Sultana T, Chowdhury AH, Saha BK, Rahman A, Chowdhury T, Sultana R (2021) Response of *Aloe vera* to potassium fertilization in relation to leaf biomass yield, its uptake and requirement, critical concentration and use efficiency. J Plant Nutr. 44(14):2081–2095. https://doi.org/10.1080/01904167.2021.1881546