



Integrated Evaluation of Morphological Traits and Seed Source Ripeness on the Growth and Yield Performance of Local *Capsicum frutescens* Genotypes from Gorontalo, Indonesia

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Abstract: This study aims to characterize four local chili genotypes from Gorontalo based on quantitative and qualitative traits. In addition, it seeks to determine the effects of genotype and fruit maturity on germination performance, plant growth, and yield. The research was conducted both in the laboratory and in the field. Characterization was carried out by selecting 10 plants per variety according to the applicable descriptors. Agronomic evaluation of chili plants was conducted under laboratory and field conditions. The experiment followed a randomized complete block design (RCBD) in a factorial arrangement with two treatment factors. The first factor was genotype, comprising four local varieties: Diti, Malita FM, Samia, and Siropu. The second factor was fruit maturity level, categorized as 50%, 75%, and 100% maturity. The characterization of four local chili genotypes from Gorontalo revealed significant morphological, germination, and growth-performance variations that underscore the importance of genotype and seed maturity in influencing overall plant performance. Samia and Siropu consistently demonstrated superior traits across all parameters. Malita FM showed potential for high performance but only when seeds were harvested at full maturity. In contrast, Diti displayed strong vegetative traits but poor reproductive output and low germination vigor.

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1. Introduction

Chili (*Capsicum* spp.) represents a horticultural crop of considerable agronomic and economic value, particularly in tropical and subtropical regions. It is also recognized as one of the earliest domesticated plant species in human agricultural history (Kraft et al., 2014). In Indonesia, specifically in Gorontalo Province, *Capsicum frutescens* is widely cultivated, with numerous landraces and local genotypes having evolved through farmer-mediated selection and adaptation over generations. Beyond its agronomic value, *Capsicum frutescens* offers significant functional and nutritional benefits for human health. The fruits are rich in bioactive compounds such as capsaicinoids, carotenoids, flavonoids, and ascorbic acid, which exhibit strong antioxidant, anti-inflammatory, antimicrobial, and metabolic

regulatory properties (Olufemi et al., 2020; Handayani et al., 2022; Chinnkar and Jadhav, 2023; Ordaz and Fernández, 2023).

Local genotypes such as Malita FM, Samia, Siropu, and Diti represent valuable genetic resources with unique morphological, physiological, and agronomic characteristics. Local genotypes are known to be well adapted to specific edaphic and climatic conditions (Canales et al., 2021; Ediwarman et al., 2023). Their continued cultivation contributes to the conservation of local biodiversity and enhances resilience in smallholder production systems. The utilization of local germplasm offers a strategic advantage in developing regionally adapted cultivars and promoting sustainable agricultural practices tailored to the local agroecological context (Arumingtyas et al., 2017; Shree et al., 2021).

Comprehensive characterization of local genotypes is fundamental for germplasm conservation and crop improvement programs (Fu, 2023). Morphological evaluation enables the identification of distinct phenotypic traits associated with genotype performance, while agronomic assessment provides insight into yield potential and adaptability. Such studies are essential for determining the suitability of genotypes for cultivation and for potential integration into breeding pipelines aimed at enhancing productivity and stress tolerance.

Seed quality remains a primary determinant of crop establishment and productivity, and it is significantly influenced by the physiological maturity of the fruit at harvest. The ripeness stage of fruits used for seed extraction affects seed development, dormancy status, viability, and subsequent vigor (Yildirim and Demir, 2020; Popović et al., 2022). Premature or overripe fruits may produce seeds with suboptimal physiological quality, leading to inconsistent germination and reduced seedling performance (Shivashankar and Sumathi, 2019; Jackson et al., 2022). Thus, the determination of an optimal fruit ripening stage for seed harvest is critical, particularly for underutilized species such as *C. frutescens* in localized production systems.

Despite the recognized importance of genotype selection and seed source maturity, there is limited data on their interactive effects on the growth and productivity of local chili genotypes. This study aims to evaluate the morphological traits, vegetative growth, and yield performance of four local *Capsicum frutescens* genotypes from Gorontalo, using seeds obtained from fruits harvested at varying stages of physiological ripeness. The findings are expected to offer critical insights for optimizing seed source parameters and harnessing local genetic resources to promote sustainable chili cultivation in Gorontalo and similar agroecosystems.

2. Materials and Methods

2.1. Research location

The study was conducted from March 2023 to May 2024 and comprised both laboratory and field experiments. Germination tests were carried out in the Seed Testing Laboratory at the Seed Testing and Certification Center, Gorontalo Province. Subsequently, the field experiment was conducted at the experimental field of the Agricultural Extension Center, Bulango Timur Subdistrict, Bone Bolango Regency, Gorontalo Province, from May 2023, to March 2024.

2.2. Morphological evaluation

2.2.1. Plant sampling and morphological characterization

Four local genotypes of *Capsicum frutescens*: Malita FM, Samia, Siropu, and Diti were selected from farmer-maintained populations in Gorontalo Province. Malita FM and Samia were collected from Bone Pantai Subdistrict, Bone Bolango Regency; Siropu from Kota Tengah Subdistrict, Gorontalo City; and Diti from Atinggola Subdistrict, North Gorontalo Regency. Morphological characterization was conducted using both quantitative and qualitative descriptors, following the standard guidelines provided by the International Plant Genetic Resources Institute (IPGRI, 1995). Observations were made at physiological maturity, with each genotype represented by 10 randomly selected plants. Mean values of morphological traits were calculated for further analysis.

2.2.2. Data analysis

To reduce scale-related bias among traits measured in different units, the data were standardized using Z-score normalization. This transformation ensures that all variables contribute equally to the

analysis, regardless of their original measurement scales (Gauch, 1982; Hair et al., 2010). A Euclidean distance matrix was computed from the standardized dataset to quantify morphological dissimilarity among genotypes. Hierarchical cluster analysis was then performed using the Ward's minimum variance method (*ward.D2*), which minimizes the total within-cluster variance and is considered robust for morphological data (Ward, 1963; Everitt et al., 2011).

The resulting hierarchical clusters were visualized using a dendrogram constructed in RStudio (version 4.3.1) using the `hclust()` function from the base R stats package. The number of clusters was determined by examining natural divisions in the dendrogram and using the `cutree()` function to define cluster boundaries. Graphical representation of the dendrogram was enhanced with `rect.hclust()` to highlight distinct genotype groups. All data processing and statistical analyses were conducted using R software (R Core Team, 2025).

2.3. Agronomic evaluation

2.3.1 Experimental design

The agronomic evaluation of chili plants was carried out under both laboratory and field conditions. The laboratory experiment employed a two-factor factorial design arranged in a completely randomized design, whereas the field experiment used a two-factor factorial design arranged in a randomized block design. The first factor was genotype, consisting of four local varieties: Diti, Malita FM, Samia, and Siropu. The second factor was fruit maturity level, categorized as 50%, 75%, and 100% maturity, based on the degree of red coloration on the fruit surface. These two factors resulted in 12 treatment combinations, each replicated three times, for a total of 36 experimental units with 180 plants in the field experiment.

2.3.2. Germination test

Seed germination tests were conducted under controlled laboratory conditions using the paper method in petri dishes. For each treatment combination, 25 seeds were randomly selected and placed in sterilized 9-cm diameter petri dishes lined with double-layered moistened filter paper. The filter paper was moistened with distilled water (15 mL each) and kept adequately moist throughout the germination period. The petri dishes were arranged in a completely randomized design and incubated at room temperature ($\pm 28^\circ\text{C}$) under ambient light conditions. Germination was monitored daily for 14 days. Seeds were considered germinated when the radicle had emerged to at least 2 mm in length.

2.3.3. Growth and productivity test

The seeds were pre-germinated in polybags containing a soil and compost mixture at a 1:1 (v/v) ratio. After five weeks of growth, the chili seedlings were ready for transplanting. Planting beds were constructed with dimensions of 1 × 2 meters and a height of 30 cm, and were covered with silver plastic mulch. The planting distance was set at 80 × 60 cm in a zig-zag pattern, accommodating five plants per plot. Plant maintenance included regular irrigation conducted twice daily, in the morning and afternoon. Pest and disease management was performed using appropriate fungicides and pesticides. Weed control was implemented manually using the hand weeding method.

2.3.4. Data collection and analysis

In the germination test, the evaluated parameters included final germination percentage (%), mean germination time (days), germination speed index, and the coefficient of variation of germination time. Meanwhile, in the open-field test, the observed growth and productivity parameters were plant height (cm), number of branches, canopy diameter (cm), number of fruits per plot, and fruit weight per plot (g). Plant height, number of branches, and canopy diameter were measured at 4 months after transplanting. The number of fruits and fruit weight per plot were calculated based on the cumulative yield from six harvests. Subsequently, an analysis of variance (ANOVA) was performed. Duncan's multiple range test was applied to determine treatment differences if significant effects were detected. The calculations for the germination parameters were performed using the Seedcalc package (Silva et al., 2019), while data analysis was conducted using the ggplot2 and AgroR packages in RStudio version 4.2.1 (Shimizu et al., 2023; R Core Team, 2025).

3. Results

3.1. Morphology characteristics

3.1.1. Qualitative and quantitative characteristics

The morphological characterization of the four chili genotypes Diti, Malita FM, Samia, and Siropu revealed a mixture of uniform and diverse traits across both qualitative and quantitative descriptors (Table 1). Qualitatively, all varieties exhibited similar characteristics in several traits such as branching habit (dense), flower position (erect), corolla shape (rotate), fruit shape (elongate), and absence of blossom end appendage. However, noticeable differences were observed in leaf shape and reproductive organ colors. For instance, Diti had ovate leaves while Malita FM had lanceolate, and Samia and Siropu had deltoid leaf shapes. Anther and filament colors also varied, with Samia displaying a distinctive yellow anther and blue filament, in contrast to the white and green or light purple observed in others.

Table 1. Qualitative and quantitative characteristics

Descriptor	Variety			
	Diti	Malita FM	Samia	Siropu
Qualitative				
Branching habit	Dense	Dense	Dense	Dense
Leaf shape	Ovate	Lanceolate	Deltoid	Deltoid
Flower position	Erect	Erect	Erect	Erect
Corolla shape	Rotate	Rotate	Rotate	Rotate
Corolla colour	Light yellow	Light yellow	Yellow	Yellow
Anther colour	White	White	Yellow	White
Filament color	Green	Light purple	Blue	Green
Fruit colour at intermediate stage	Green	Purple	Yellow	Yellow
Fruit colour at mature stage	Red	Red	Red	Red
Fruit shape	Elongate	Elongate	Elongate	Elongate
Fruit shape at pedicel attachment	Obtuse	Obtuse	Obtuse	Obtuse
Fruit shape at blossom end	Pointed	Pointed	Pointed	Pointed
Fruit blossom end appendage	Absent	Absent	Absent	Absent
Fruit cross-sectional corrugation	Slightly corrugate	Slightly corrugate	Slightly corrugate	Slightly corrugate
Fruit surface	Semi-wrinkled	Semi-wrinkled	Semi-wrinkled	Semi-wrinkled
Seed colour	Straw	Straw	Straw	Straw
Seed surface	Rough	Smooth	Smooth	Smooth
Quantitative				
Corolla length	5.12	5.23	8.5	5.32
Filament length	5.32	5.18	6.27	5.42
Anther length	7.87	3.53	8.65	6.53
Fruit length	3.16	3.24	4.15	3.48
Fruit pedicel length	2.33	3.73	3.86	2.79
Fruit width	4.85	4.90	4.65	11.30
Fruit weight	0.58	0.75	1.16	1.01
Number of seeds per fruit	15.9	24.8	27.3	36.9

Note: Quantitative traits were scored according to IPGRI (1995), while quantitative values are means of 10 plants per genotype.

Intermediate fruit coloration showed striking variation, serving as a key distinguishing trait among the genotypes. Diti was green, Malita FM was purple, while Samia and Siropu both turned yellow at the intermediate stage. At maturity, however, all fruits converged to a red color, indicating uniformity

in ripened fruit appearance. The seed traits were largely consistent across the genotypes, except for seed surface texture Diti had rough seeds while the others had smooth ones. These qualitative descriptors suggest that while some traits are stable and conserved, others, particularly related to coloration and leaf morphology, offer clear markers for genotype differentiation. Quantitative data further highlighted the distinctiveness of Samia and Siropu. Samia had the highest corolla (8.5 mm) and anther lengths (8.65 mm), while Siropu showed an exceptionally large fruit width (11.30 mm) and the highest seed count per fruit (36.9). Fruit weight also varied, with Samia producing the heaviest fruit (1.16 g) followed by Siropu (1.01 g), which may be related to its wider fruit size.

3.1.2. Dendrogram analysis

The dendrogram provides a visual representation of the morphological similarity and clustering patterns among four chili genotypes Diti, Malita FM, Samia, and Siropu based on both qualitative and quantitative descriptors (Figure 1). The horizontal dendrogram uses Euclidean distance as a metric for dissimilarity and groups the genotypes into two major clusters. The first cluster includes Diti and Malita FM, while the second cluster groups Samia and Siropu, indicating that members within each cluster share more morphological similarities with each other than with members of the other cluster.

The lower cluster (red) includes Diti and Malita FM, which exhibit closer similarity in features such as branching habit, flower and fruit shapes, and particularly in their fruit characteristics like weight, size, and seed count. Interestingly, while Malita FM has distinct purple intermediate fruit coloration, its other traits align closely with Diti, which may explain their clustering despite that visual difference. On the other hand, Samia and Siropu, forming the upper cluster (blue), are grouped together due to their shared characteristics like deltoid leaf shape, yellow intermediate fruit color, and similar values for floral organ measurements. However, Siropu shows an exceptionally wider fruit compared to Samia, which still keeps them in the same group but with a greater Euclidean distance between them, as indicated by the branching length.

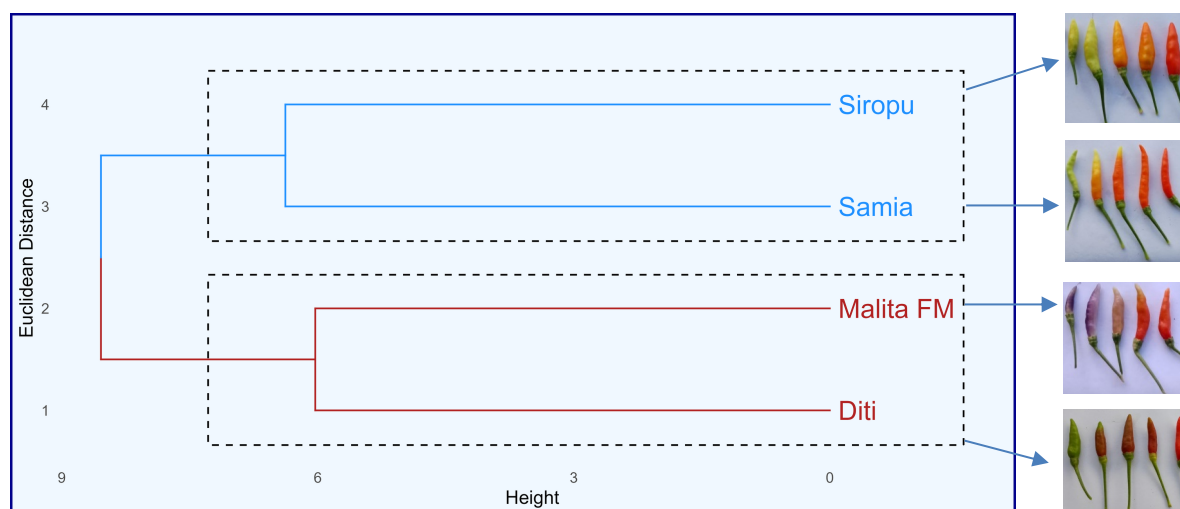


Figure 1. Dendrogram analysis.

3.2. Germination characteristics

3.2.1. Final germination percentage (%)

Samia and Siropu exhibited the highest germination rates across all ripeness levels, consistently achieving over 89%, with no significant differences between ripeness stages within each genotype (Figure 2). This suggests strong seed vigor and stability in these two varieties, making them promising candidates for consistent germination performance. Diti and Malita FM, in contrast, showed much lower germination percentages at 50% and 75% ripeness, ranging from 33% to 44%. However, at 100% ripeness, Malita FM significantly improved to 74%. Meanwhile, Diti showed no significant improvement with ripeness, maintaining a plateau around 44%.

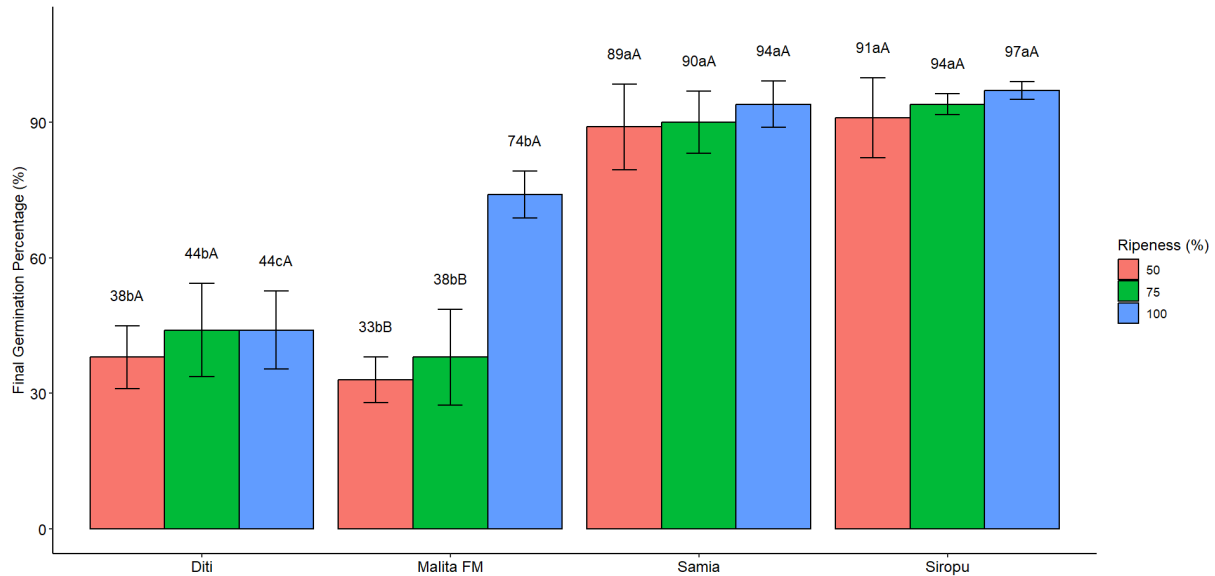


Figure 2. Final germination percentage.

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

3.2.2. Mean germination time (d)

Figure 3 presents the influence of fruit ripeness on the mean germination time of chili seeds, revealing differences in seed vigor across genotypes. Diti showed the slowest germination overall, with a significantly longer mean germination time of 8.38 days at 50% ripeness, decreasing slightly at 75% and 100% ripeness. However, the differences across ripeness levels were not statistically significant within Diti. Malita FM exhibited a more noticeable trend, where seeds from 50% ripe fruits germinated significantly faster (3.24 days) compared to those from 75% and 100% ripeness. Samia and Siropu, on the other hand, demonstrated relatively stable germination times across all ripeness levels, ranging between 3.3 and 4 days, without significant differences.

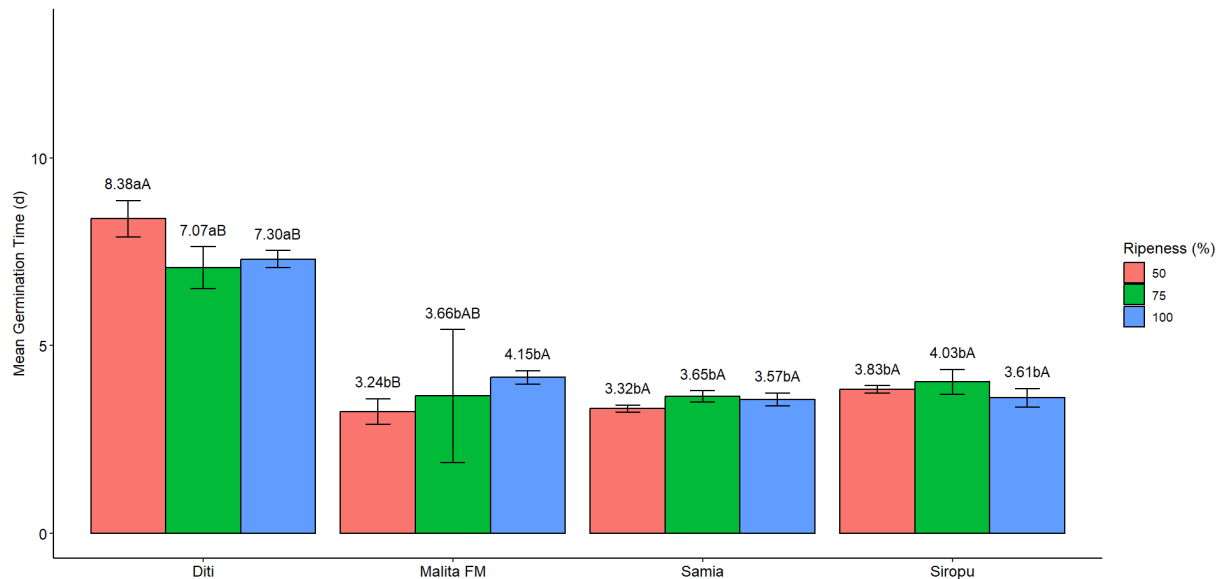


Figure 3. Mean germination time.

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

3.2.3. Coefficient of variation of germination time

Diti consistently displayed the lowest CV values across all ripeness levels (14.4–18.5%), indicating relatively uniform germination regardless of fruit maturity. In contrast, Malita FM showed

high variability at 50% and 75% ripeness, with CV values exceeding 50%, suggesting inconsistency in germination. Interestingly, the CV dropped significantly at 100% ripeness, implying that seeds from fully ripe fruits in Malita FM germinate more synchronously. Samia exhibited moderate variability (around 40–48%) that remained statistically similar across all ripeness levels, suggesting stable but less uniform germination compared to Diti. Siropu also had moderate CVs, fluctuating between 38% and 44%, but these differences were not statistically significant.

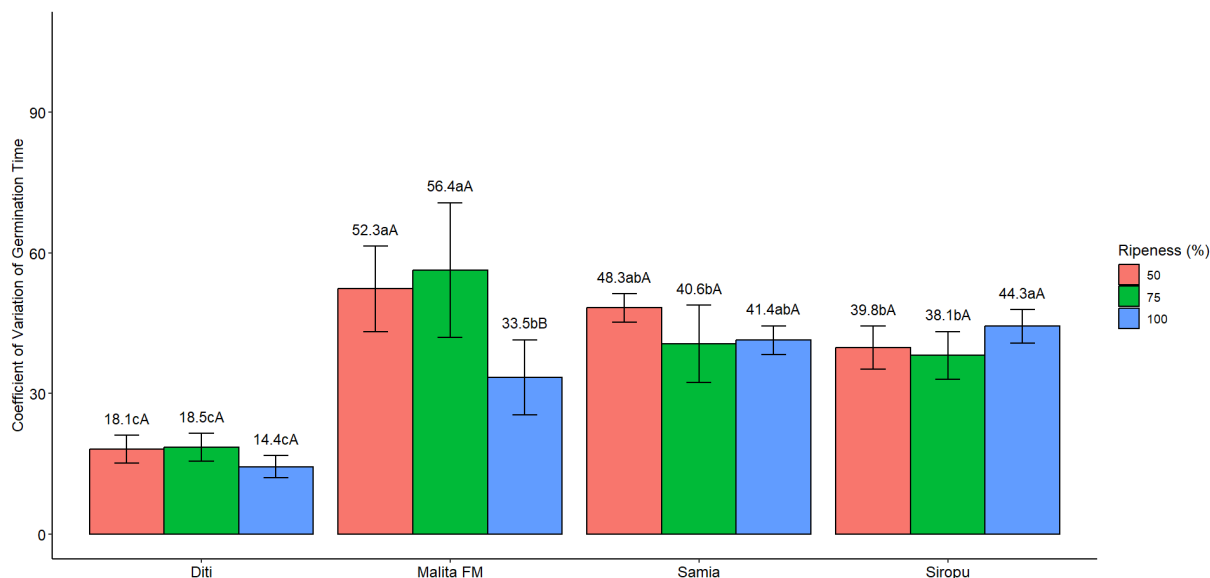


Figure 4. Coefficient of variation of germination time.

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

3.2.4. Germination speed index

Diti exhibited the lowest GSI across all ripeness stages (1.18–1.61), with no significant differences between them, indicating consistently slow germination. Malita FM showed a gradual increase in GSI with fruit ripeness, from 3.65 at 50% ripeness to 5.47 at 100%, suggesting enhanced vigor as seed maturity progresses. Samia and Siropu both demonstrated high GSI values, indicating rapid germination. Samia had the highest GSI at 50% ripeness (10.18), though the differences across ripeness levels were not statistically significant, reflecting stable and fast germination. Siropu followed a similar trend, maintaining strong germination speed with a slight increase at 100% ripeness.

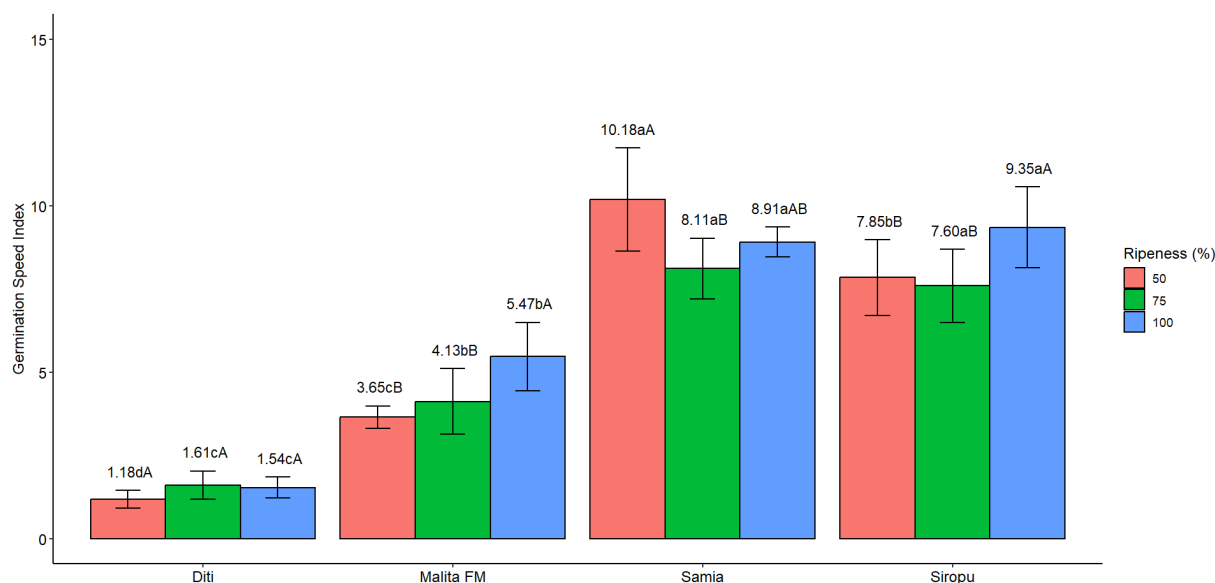


Figure 5. Germination speed index.

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

3.3. Growth and production characteristics

3.3.1 Vegetative traits

Among the four chili varieties, Samia exhibited the tallest plant height at 29.28 cm, followed closely by Siropu (28.65 cm) and Diti (28.55 cm), with Malita FM being the shortest at 26.50 cm (Table 2). In terms of branching, Diti produced the highest number of branches (8.3), indicating a bushier growth habit. Siropu followed with 7.13 branches, while Malita FM and Samia produced fewer branches, with 6.6 and 6.31, respectively. These results suggest that Diti is a promising genotype for producing compact, highly branched plants, while Samia combines height with a more upright, less branched architecture.

Table 2. Plant height and number of branches

Variety	Plant Height (cm)	Number of Branches
Diti	28.55	8.3
Malita FM	26.50	6.6
Samia	29.28	6.31
Siropu	28.65	7.13
Ripeness (%)	Plant Height (cm)	Number of Branches
50	23.65b	6.12
75	29.03a	7.8
100	32.05a	7.3

Note: Similar letters following the means indicate that there is no statistically significant difference according to the Duncan Multiple Range Test (DMRT) with $\alpha = 0.05$.

Seed ripeness had a significant effect on plant growth. Plants grown from seeds harvested at 50% ripeness had the shortest height (23.65 cm) and the fewest branches (6.12), indicating lower seed vigor at immature stages. As seed maturity increased, both plant height and branching improved. The 100% ripeness group achieved the tallest height (32.05 cm), significantly taller than 50%, while 75% ripeness produced the highest number of branches (7.8), though not significantly different from 100% (7.3). These findings suggest that seeds harvested at full maturity (100%) enhance plant height, while those at mid-maturity (75%) may promote better branching.

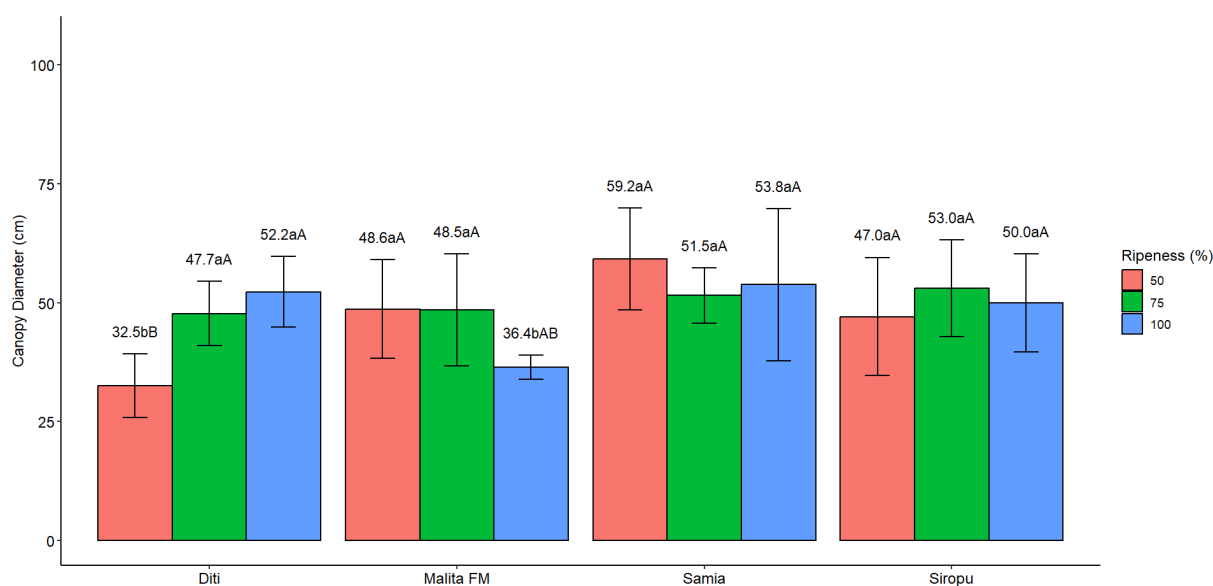


Figure 6. Canopy diameter.

Note: Means followed by the same letter are not significantly different according to Duncan's Multiple Range Test (DMRT) at $\alpha = 0.05$.

Diti showed a significant increase in canopy diameter with seed maturity, from 32.5 cm at 50% ripeness to over 50 cm at later stages, indicating that seed ripeness positively affects vegetative growth. Malita FM, however, had a relatively stable canopy diameter at 50% and 75% ripeness (~48.6 cm), but experienced a significant decrease at full ripeness (36.4 cm). Samia consistently exhibited the widest canopy diameter across ripeness levels, with the highest mean at 50% ripeness (59.2 cm), though the differences among ripeness levels were not statistically significant. Siropu displayed no significant differences in canopy diameter across maturity stages, maintaining values around 47–53 cm.

3.3.2. Generative traits

The research results show that the variety of plant significantly affects both the number of fruits per plot and the total fruit weight. Among the varieties tested, Siropu yielded the highest number of fruits (2136.75) and the heaviest fruit weight (1392.71 g), closely followed by Samia with 1838.33 fruits and 1366.52 g of fruit weight. These two varieties were notably more productive than Malita FM and Diti, with Malita FM producing fewer fruits (1378.08) and a moderate fruit weight (990.69 g), and Diti having the lowest yields in both fruit count (1288.25) and weight (421.20 g).

Table 3. Number of fruits and fruit weight per plot

Variety	Number of Fruits per Plot	Fruit Weight per Plot (g)
Diti	1288.25b	421.20c
Malita FM	1378.08b	990.69b
Samia	1838.33ab	1366.52a
Siropu	2136.75a	1392.71a
Ripeness (%)	Number of Fruits per Plot	Fruit Weight per Plot (g)
50	1345.37b	773.04b
75	1640.00ab	1089.54a
100	1995.25a	1265.76a

Note: Similar letters following the means indicate that there is no statistically significant difference according to the Duncan Multiple Range Test (DMRT) with $\alpha = 0.05$.

Additionally, the study revealed that the ripeness level at harvest plays a significant role in yield. 100% ripeness resulted in the highest yield, with 1995.25 fruits and 1265.76 g of fruit weight, significantly outperforming the other ripeness stages. 75% ripeness also showed a relatively high yield, though slightly lower than the 100% stage, with 1640 fruits and 1089.54 g of weight. However, 50% ripeness led to a considerable decrease in both fruit number (1345.37) and fruit weight (773.04 g).

4. Discussion

4.1. Morphology characterization

Qualitative and quantitative traits are essential for identifying and characterizing plant germplasm (Kheerti et al., 2016; Islam et al., 2019; Jha et al., 2024). Qualitative traits are generally more stable across different environments, making them reliable for initial plant identification and classification. While, quantitative traits provide detailed information on plant performance, such as growth rates and yield, which are crucial for breeding and agricultural productivity (Joshi et al., 2020; Hafsa and Rahmawati, 2021). The four local chili genotypes from Gorontalo exhibit diverse characteristics, although some specific traits show similarities. Diti and Malita FM demonstrate closer resemblance in several features, such as branching patterns, flower and fruit morphology, as well as fruit-related traits like weight, size, and seed count. Interestingly, although Malita FM displays a distinctive purple color at the intermediate fruit stage, this visual difference does not significantly affect its grouping with Diti. Several studies have also reported that varietal differences can lead to distinct morphological and performance traits under field conditions (Muradoğlu et al., 2022; Dermawan et al., 2025).

In contrast, Samia and Siropu, are grouped together due to shared characteristics such as deltoid leaf shape, yellow intermediate fruit coloration, and similar floral organ measurements. These shared features indicate strong phenotypic similarities, which justify their inclusion in the same cluster. However, Siropu shows a notably wider fruit compared to Samia. Despite this difference, both genotypes remain within the same group, although the greater Euclidean distance between them, represented by the longer branch length on the dendrogram, reflects a higher degree of variation within the cluster.

The observed grouping pattern highlights the complexity of morphological diversity among local chili genotypes. The clustering results can inform future selection and breeding programs by identifying genotypes with desirable traits that are both unique and complementary (Osawaru et al., 2015; Arief et al., 2017). For instance, Diti and Malita FM may serve as promising candidates for breeding programs focused on fruit quality traits, while Samia and Siropu may offer valuable traits related to leaf architecture and floral morphology. Furthermore, understanding the morphological divergence among these genotypes contributes to the conservation of local genetic resources, ensuring that the phenotypic diversity of Gorontalo's chili germplasm is preserved for future agricultural development.

4.2. Germination characteristics

Among the tested genotypes, Samia and Siropu consistently demonstrated superior germination performance across all ripeness stages, suggesting a high level of seed vigor and physiological stability. Their high final germination percentage (FGP), relatively short and stable Mean Germination Time (MGT), moderate coefficient of variation of germination time (CV), and elevated germination speed index (GSI) reflect genotypes that are well-suited for consistent seedling emergence, which is essential for uniform crop establishment.

In contrast, Diti showed suboptimal germination behavior characterized by low FGP (~44%), extended MGT (up to 8.38 days), and the lowest GSI values, regardless of ripeness level. Despite its low germination speed, Diti displayed remarkably low CV values, indicating a uniform but delayed germination pattern. This suggests a potential physiological dormancy or lower seed maturity that is not sufficiently overcome even at full fruit ripeness. Such traits may limit its applicability in commercial seed production or cropping systems where rapid and synchronous emergence is critical.

Malita FM exhibited a more dynamic germination response to fruit ripeness. At 50% and 75% ripeness, seeds had low FGP and high CV, indicating poor and inconsistent germination. However, at 100% ripeness, the FGP increased dramatically to 74%, CV decreased, and GSI improved notably. This pattern implies that seed physiological maturity in Malita FM is highly dependent on fruit ripeness, and that harvesting at full ripeness is essential to maximize germination performance. These findings are consistent with previous research indicating that seed quality improves with fruit maturity due to better accumulation of reserves and desiccation tolerance (Neto et al., 2016; Botey et al., 2022). Moreover, no signs of germination occurred in seeds extracted from immature fruits (Takac et al., 2015).

The relatively stable MGT and GSI values in Samia and Siropu suggest that these genotypes may achieve sufficient physiological maturity even at earlier stages of ripeness, a valuable trait for breeders and producers seeking to optimize harvest timing. Their performance also supports previous reports that seed germination characteristics are strongly influenced by genetic factors (Li et al., 2015; Waterworth et al., 2015). The variation in CV among genotypes highlights important considerations regarding germination uniformity (Sulaiman et al., 2023). While Diti exhibited low CV and thus uniform germination, its consistently low vigor limits its practical utility. Conversely, Malita FM showed high CV at early ripeness stages, indicating asynchronous germination, which can complicate crop management. Notably, its CV decreased significantly at 100% ripeness. High variability in germination time, reflected by a high CVt, may suggest issues with seed viability or vigor, potentially due to genetic or environmental factors (Pereira and Santana, 2013).

Overall, the interaction between genotype and fruit maturity plays a critical role in determining seed germination performance. Genotypes such as Samia and Siropu, which combine high germination percentage with stable vigor across different maturity stages, appear to be promising candidates for robust seedling establishment under varied conditions. Meanwhile, genotypes like Malita FM demonstrate the potential for high performance if harvested at optimal maturity, whereas Diti may require targeted interventions to improve seed quality, such as priming or selection for improved seed traits.

4.3. Growth and production characteristics

Among the genotypes, Samia and Siropu consistently exhibited superior vegetative and generative performance. Samia recorded the tallest plant height (29.28 cm), suggesting strong vertical growth potential, while Siropu had the highest fruit number (2136.75) and total fruit weight (1392.71 g), indicating its excellent reproductive capacity. The robust productivity of these two genotypes, particularly under varying seed maturity conditions, underscores their suitability for commercial cultivation and breeding programs targeting high-yielding traits.

Conversely, Diti showed a contrasting growth profile. While it produced the highest number of branches (8.3), indicative of a bushy architecture, its productivity was the lowest across both fruit number and weight. This suggests that although Diti may allocate resources toward vegetative branching, its reproductive efficiency is limited, potentially due to lower resource partitioning to fruit development. Some plant species also have a mechanism that allocates more assimilates to vegetative organs than to generative organs. Nevertheless, many factors contribute to the occurrence of this trade-off, one of which is environmental stress (Zhang et al., 2019; Zhu, 2023; Tian et al., 2024).

Seed ripeness significantly influenced vegetative development. Plants from seeds harvested at 100% ripeness reached the greatest height (32.05 cm), whereas seeds collected at 50% ripeness produced shorter plants (23.65 cm) and fewer branches (6.12). This observation is in line with reports that physiological maturity enhances seed vigor, resulting in improved early seedling growth and overall plant vigor (Patel et al., 2024). Interestingly, while full ripeness improved plant height, branching peaked at 75% ripeness (7.8 branches), suggesting a potential optimum between seed maturity and shoot proliferation.

Canopy diameter trends further revealed genotype-specific responses. Samia maintained a consistently wide canopy across ripeness levels, suggesting inherent architectural traits that support better light interception and possibly more reproductive sites. In contrast, Malita FM showed a decline in canopy diameter at 100% ripeness, possibly indicating that the physiological state of the seed affects early plant establishment in this genotype more strongly. These variations support the importance of genotype-specific management practices for optimizing plant architecture and productivity.

Generative traits further confirmed the advantage of harvesting seeds at full ripeness. Fruit number and weight were significantly higher at 100% ripeness (1995.25 fruits, 1265.76 g), consistent with improved seedling vigor translating into enhanced reproductive success. In contrast, 50% ripeness produced the lowest yield values, confirming that premature seed harvest compromises crop productivity. This is likely due to incomplete seed development, resulting in poor seed reserve accumulation and weak seedling establishment (Eskandari et al., 2012; Obura and Lamo, 2024), as described in earlier germination studies.

Conclusion

In summary, the characterization of four local chili genotypes from Gorontalo revealed significant morphological, germination, and growth-performance variations that underscore the importance of genotype and seed maturity in influencing overall plant performance. Samia and Siropu consistently demonstrated superior traits across all parameters, morphological uniformity, high germination vigor, and robust yield, making them ideal candidates for breeding and commercial cultivation. Malita FM showed potential for high performance but only when seeds were harvested at full maturity, highlighting the need for precise harvest timing. In contrast, Diti displayed strong vegetative traits but poor reproductive output and low germination vigor, indicating a possible trade-off in resource allocation and suggesting the need for further improvement. Collectively, these findings emphasize the value of integrating morphological and physiological assessments to guide genotype selection, seed harvest strategies, and crop improvement programs.

Ethical Statement

Ethical approval is not required for this study because it did not involve human participants, animals, or endangered plant species.

Conflict of Interest

The authors declare that there are no conflicts of interest.

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Author Contributions

Milawati Lalla contributed to data collection, experimental execution, and initial manuscript drafting. Elkawakib Syam'un supervised the research, contributed to the conceptual framework, and reviewed the final manuscript. Fachirah Ulfa assisted in data analysis and interpretation. Ifayanti Ridwan participated in experimental setup and data validation. All authors read and approved the final version of the manuscript.

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