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Altitude-Driven Differences in Thermal Units, Growth and Quality of Beetroot (*Beta vulgaris* L.)

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Abstract. *Beetroot is traditionally cultivated in highland areas; however, limited land availability and growing market demand have encouraged its expansion into mid-altitude regions. Thermal unit accumulation is an important factor in predicting crop phenology and harvest time. This study aimed to analyze the thermal unit requirements, growth performance, and tuber quality of beetroot cultivated at different altitudes in East Java, Indonesia. The experiment was conducted from August to December 2024 in greenhouses located in Jatimulyo, Malang (445 m a.s.l., midland) and Sumberejo, Batu (873 m a.s.l., highland) using 250 plants of the Boro variety with a single-plant observation method. Results showed that midland-grown plants reached harvest earlier (84 DAS; 1,527.3 °C·day) compared to highland-grown plants (104 DAS; 1,572.7 °C·day). Higher thermal accumulation had a strong positive correlation with soluble solids (r = 0.74) and a strong negative correlation with fresh tuber weight (r = –0.79), indicating that increased heat enhanced sugar synthesis but reduced biomass. Highland conditions produced larger tubers, while midland conditions improved betacyanin and sweetness levels, showed that altitude-driven temperature differences affect both yield and quality, suggesting that highland cultivation is suitable for fresh markets, whereas midland cultivation is more appropriate for industrial uses such as natural food colorants and processing industries.*

Keywords: *Agroclimatology, Altitude, Beetroot, Thermal unit, Tuber quality*

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INTRODUCTION

Beetroot (*Beta vulgaris* L.) is increasingly recognized as a functional food crop due to its high nutritional value and bioactive compounds such as betacyanin, antioxidants, and essential vitamins. These attributes make beetroot valuable for food, pharmaceutical, and cosmetic industries. In Indonesia, however, local production is still very limited while market demand continues to rise. Consequently, most domestic needs are met through imports. Traditionally, beetroot is cultivated in highland regions with cool climates, fertile soils, and sufficient moisture. Yet, land scarcity and competition with other horticultural crops such as potato, carrot, and cabbage constrain its expansion. Exploring beetroot cultivation in mid-altitude environments is therefore essential to diversify production areas and increase domestic supply.

Temperature and altitude strongly affect plant growth and development. One of the most widely used agroclimatic approaches to quantify plant phenology is thermal units or growing degree days (GDD), which represent the cumulative heat required for plants to complete each growth stage. Thermal unit analysis provides more accurate predictions of harvest time than calendar days, allowing better planning of planting schedules and improved production efficiency. Although this concept has been applied to cereals, legumes, and other horticultural crops, empirical studies on beetroot under tropical conditions remain scarce. Lower temperatures in high altitude areas often result in longer plant growth times due to delays in physiological maturity. Research shows that plants in higher altitude environments may require more heat units to reach maturity than those grown at lower altitudes. The results of research conducted by Sánchez-Mora et al. (2020) note that fruit crops grown at higher altitudes require longer days to develop from anthesis to harvest, as measured in GDDs. These findings highlight the importance of accurately calculating GDDs to effectively adjust harvesting strategies between different elevations. Consequently, understanding thermal requirements can significantly improve harvest timing, thereby optimizing market quality and yield (Parra-Coronado et al., 2016).

Previous studies on beetroot in Indonesia have largely focused on its nutritional potential, pigment extraction, and highland-based production systems (Lembong & Utama, 2021; Wirayuda, 2023; Yuangga, 2020). There is limited information on how thermal unit accumulation influences growth performance and tuber quality across altitudinal gradients. In addition, quality traits such as betacyanin content and soluble solids (°Brix) have not been systematically compared between highland and midland conditions. This lack of data limits the development of adaptive strategies for beetroot cultivation in diverse environments.

This study provides empirical evidence on thermal unit accumulation, growth response, and tuber quality of beetroot grown in two altitudinal environments in East Java, Indonesia. The research demonstrates that midland-grown plants reach harvest faster with higher betacyanin and sweetness, while highland-grown plants produce heavier tubers. These findings contribute to agroclimatology by linking thermal unit accumulation with phenology and quality attributes of beetroot under tropical conditions. Practically, the results offer a scientific basis for optimizing planting schedules, predicting harvest time, and diversifying beetroot cultivation into mid-altitude areas to reduce dependence on imports and align production with market demands. The research hypothesis is that the time to reach total thermal units during the beetroot growth phase is faster in midland than in highland.

LITERATURE REVIEW

Beetroot (*Beta vulgaris* L.) as a Functional Crop

Beetroot is a root vegetable widely valued for its high content of betacyanin pigments, nitrates, and antioxidants. These compounds provide multiple health benefits, such as antihypertensive and anti-inflammatory effects, and make beetroot useful for food, pharmaceutical, and cosmetic applications (Chen et al., 2021; Lembong & Utama, 2021). The tuber has a distinctive red-purple color, sweet earthy taste, and nutritional potential that supports its increasing demand in Indonesia. Despite this, domestic production remains low, creating opportunities for crop expansion.

Phenological Development of Beetroot

The growth of beetroot proceeds through several stages: germination, leaf development, vegetative growth, tuber formation, and harvest. Each stage is strongly influenced by environmental conditions, particularly temperature and light (Misra et al., 2022). Germination typically occurs within 4–6 days after sowing under optimal temperatures (18–30 °C), while tuber formation begins around 38–60 days and is followed by harvest at 2–3 months (Yuangga, 2020). Understanding phenology is critical to predict crop cycles and improve yield stability under diverse environments.

Concept of Thermal Units (Growing Degree Days, GDD)

Thermal units or growing degree days (GDD) represent the accumulated heat required for plants to complete their growth stages. The calculation is based on mean daily temperature relative to a base temperature, which for beetroot is 10.7 °C (Syukur, 2012). This approach has been widely applied to cereals, legumes, and horticultural crops to estimate harvest time more accurately than calendar days (Sattar et al., 2015; Pradiko et al., 2019). However, its application to beetroot under tropical conditions is still limited, creating a need for localized studies.

Influence of Altitude and Microclimate

Altitude significantly shapes microclimate by affecting air temperature, humidity, and radiation. Higher altitudes are generally cooler and favorable for temperate crops such as beetroot, while mid-altitude environments are warmer and may accelerate heat accumulation, leading to shorter crop duration (Sinaga et al., 2015; Harahap et al., 2021). These differences can also affect yield and quality, with highland crops producing larger tubers, while midland crops may express higher sweetness and pigment concentration.

Research Gap and Contribution

Most beetroot studies in Indonesia focus on nutritional properties, pigment extraction, and highland cultivation (Wirayuda, 2023; Yuangga, 2020). Empirical data linking thermal unit accumulation to phenology and tuber quality across different altitudes remain scarce. This study addresses the gap by evaluating thermal unit requirements and their effects on growth and quality traits of beetroot grown in midland and highland environments in East Java.

RESEARCH METHODS

Research Location and Time

The study was carried out from August to December 2024 in two greenhouse locations in East Java, Indonesia:

1. Midland site: Jatimulyo, Lowokwaru District, Malang (445 m a.s.l.; average temperature 21–28.6 °C; relative humidity 74–97%).
2. Highland site: Sumberejo Village, Batu (873 m a.s.l.; average temperature 21–24 °C; relative humidity 70–98%).

The location were selected to represent distinct altitudinal gradients with different microclimatic conditions.

Tools and Materials

The tools used included a RHS Color Chart, Temperature Data Logger, Thermohygrometer, Hand Refractometer, Spectrophotometer, and a digital camera. The materials consisted of beetroot (*Beta vulgaris* L.) cv. Boro seeds, polybags (35 × 35 cm), topsoil, farmyard manure (1:1), and distilled water.

Experimental Design and Procedure

The research was conducted in a greenhouse to obtain a more uniform growing environment, such as consistent solar radiation intensity, protection of plants from rain, and reduced risk of pest attacks. The growing medium used was soil and cow manure in a 1:1 ratio, and the planting containers were 25 cm diameter polybags.

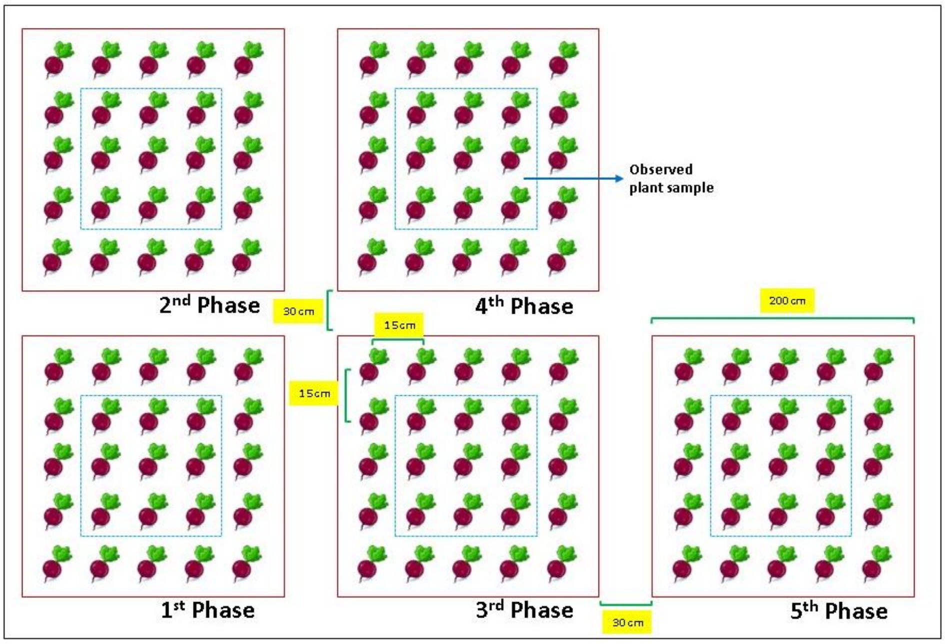

Figure 1. plant layout inside the greenhouse grouped according to plant growth phase

The experiment applied a single-plant observation method with a total of 250 plants (125 plants per site) (Figure 1) by conducting qualitative and quantitative measurements on beetroot plants. The study was conducted at two different altitudes, highlands and midlands. Observations were made at each stage of plant growth, including the germination phase, leaf formation, vegetative growth, tuber formation, and harvest. Twenty-five plants were provided at each growth phase, and nine sample plants were observed at each growth phase of beetroots planted at each research location. Each location was planted with 125 plants, bringing the total plant population to 250 plants. Plants were observed individually from germination to harvest. The procedure was as follows:

1. Soil preparation: a 1:1 mixture of soil and manure was filled into polybags.
2. Seedling preparation: seeds were germinated in trays and transplanted at the two-leaf stage.
3. Planting: seedlings were planted in polybags at 3–5 cm depth, one seedling per bag.
4. Crop management: irrigation was applied daily, weeding every two weeks, and pest control was conducted manually.
5. Harvesting: tubers were harvested when they appeared above the soil surface and leaves started to wilt.

Observed Variables

1. Agroclimatic conditions: air temperature (°C), relative humidity (%)
2. Phenological development: days to each growth stage (days after sowing, DAS).
3. Growth parameters: plant height (cm), number of leaves, tuber diameter (cm), and fresh tuber weight (g).
4. Quality parameters: soluble solids (°Brix, hand refractometer) and betacyanin content (mg/L, spectrophotometer λ = 536–600 nm).

Thermal Unit Calculation

Thermal units (TU) were calculated using the following formula:

$$TU = \sum (T - To)$$

where:

- TU = thermal unit (°C·day),
- T = daily mean air temperature (°C),
- T_0 = base temperature for beetroot(10.7 °C).

Accumulated TU values were calculated for each phenological stage and for the entire growth cycle.

Data Analysis

1. Descriptive analysis was used to describe the results of calculations of thermal units required by plants to achieve thermal units in each phase of plant growth at each

observation location. Correlation analysis was used to determine the relationship between differences in altitude and the time required to achieve thermal units, growth variables, and beetroot yieldsTesting

The testing conducted in this study consisted of physical quality tests (pH and color), organoleptic tests, and antioxidant activity tests.

2. Data Analysis

Data obtained from the results of color, pH, and organoleptic questionnaire tests were analyzed using the Analysis of Variance (ANOVA) method, consisting of five treatments with four replications. If significant differences were found, a Duncan's Multiple Range Test (DMRT) was performed.

RESULTS AND DISCUSSION

Agroclimatic observations during the study period showed clear differences between the two sites. The midland location (445 m a.s.l.) experienced higher daily mean temperatures of 21–28.6 °C with relative humidity ranging from 74–97%, while the highland location (873 m a.s.l.) was cooler at 21–24 °C and had a relative humidity of 70–98%. These variations in microclimate influenced the accumulation of thermal units and the phenological progression of beetroot. Similar findings were reported by Sinaga et al. (2015), who emphasized the role of altitude in shaping temperature and microclimate, thereby affecting crop development.

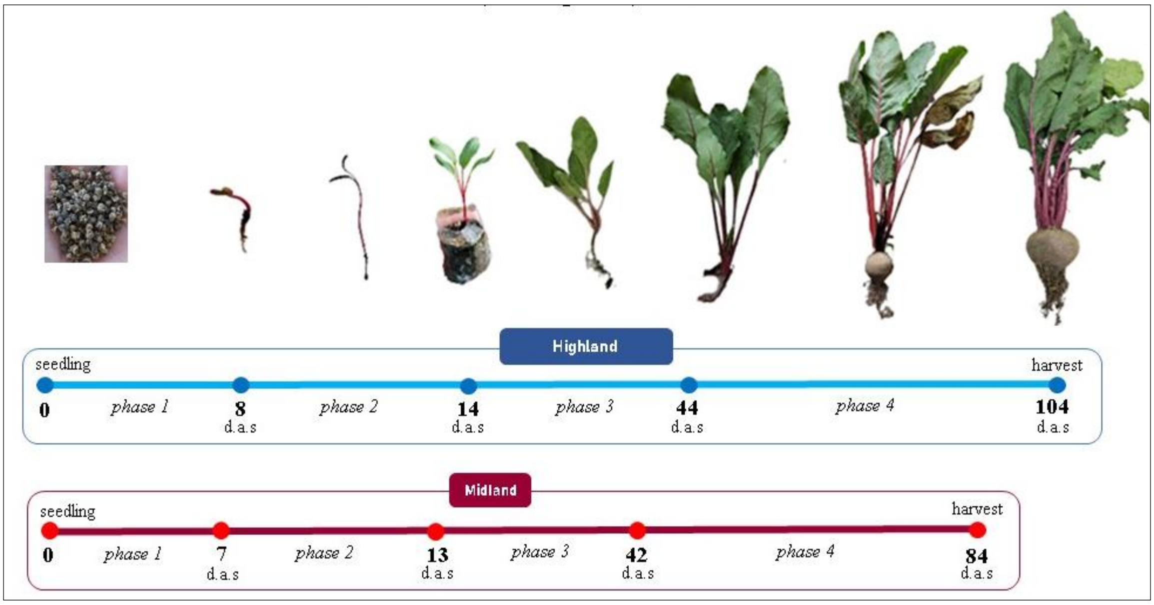

Figure 2. Growth phase of beetroot plants at two different altitudes

The accumulation of thermal units revealed distinct differences between the two environments (Table 1). Plants grown in the midland site reached harvest earlier, at 84 days after sowing (DAS), with a total of 1,527.3 °C·day. In contrast, plants cultivated in the highland site required 103 DAS to accumulate 1,572.7 °C·day (Figure 2). This indicates that the warmer conditions in the midland accelerated heat accumulation and shortened the growth duration. Sattar et al. (2015) reported that higher ambient temperatures can hasten the attainment of required growing degree days, leading to earlier crop maturity. Thus, thermal unit analysis provides a more reliable measure of growth duration than calendar days, particularly across altitudinal gradients.

Table 1. Phenological Stages and Thermal Unit Accumulation of beetroot (*Beta vulgaris* L.) at Different Altitudes

Phenological Stage (days after sowing, DAS)	Midland (445 m a.s.l.)	Highland (873 m a.s.l.)
	Thermal unit accumulation	
Germination	0-7 DAS (60.3 °C·day)	0-8 DAS (65.6 °C·day)
Leaf formation	8-13 DAS (214.7 °C·day)	9-14 DAS (209.8 °C·day)
Vegetative growth	14-42 DAS (846.2 °C·day)	15-44 DAS (731.6 °C·day)
Tuber initiation	43-83 DAS (1,273.6 °C·day)	45-103 DAS (1,089.6 °C·day)
Harvest	84 DAS (1,527.3 °C·day)	104 DAS (1,572.7 °C·day)

Growth performance also varied between sites. Highland-grown plants produced tubers with larger diameters and heavier fresh weights compared to those cultivated in the midland. This suggests that the cooler conditions at higher altitude supported greater biomass accumulation. Conversely, midland-grown plants exhibited faster phenological development but smaller tubers, highlighting a trade-off between growth rate and yield. These results are consistent with Pradiko et al. (2019), who found that variation in thermal unit accumulation across environments influenced growth performance and yield characteristics of tropical crops.

The differences in phenological stages and thermal unit accumulation of beetroot cultivated at two different altitudinal levels, observations showed that all growth phases, from germination to harvest, occurred more rapidly in plants grown in the midland compared to those in the highland (Table 1). This finding is associated with the higher ambient temperature in the midland area, which accelerated metabolic rates and the accumulation of thermal units required to complete each growth stage.

During the germination and leaf formation phases, beetroot in the midland reached these stages at 0–7 and 8–13 days after sowing (DAS), respectively, while those in the highland required slightly longer periods of 0–8 and 9–14 DAS. The accumulated thermal units in the germination and leaf of beetroot formation phases were also higher in the midland (60.3 °C·day and 214.7 °C·day) than in the highland (65.6 °C·day and 209.8 °C·day). This difference indicates that higher temperatures promote faster physiological processes in the early stages of growth, including germination and leaf organ formation.

The vegetative growth and tuber initiation phases exhibited similar trends. Beetroot plants in the midland completed the vegetative phase earlier (14–42 DAS; 846.2 °C·day) compared to those in the highland (15–44 DAS; 731.6 °C·day). Likewise, beetroot tuber initiation occurred at 43–83 DAS with 1,273.6 °C·day in the midland, while in the highland it extended to 45–103 DAS with 1,089.6 °C·day. The variation in thermal unit attainment suggests that higher temperatures accelerate tuber filling processes, even though the overall growth duration is shorter.

In the final phase, plants grown of beetroot in the midland reached harvest maturity at 84 DAS with a total thermal accumulation of 1,527.3 °C·day, while those in the highland required 104 DAS with a total of 1,572.7 °C·day. Therefore, the higher temperature in the midland environment accelerated the accumulation of heat required for physiological maturity, whereas the cooler conditions in the highland slowed down growth rates but supported greater biomass formation. These results are consistent with the findings of Sattar et al. (2015) and Syukur (2012), who reported that elevated temperatures accelerate the attainment of required heat units and may shorten the vegetative growth duration in root crops.

Table 2. Growth Parameters of Beetroot (*Beta vulgaris* L.) at Different Altitudes

Parameter	Midland (445 m a.s.l.)	Highland (873 m a.s.l.)
Plant height (cm)	27.54	33.65
Number of leaves (leaves)	13.36	15.42
Tuber diameter (cm)	4.46	5.83
Fresh tuber weight (g)	99.67	119.83

Quality assessments of harvested tubers further revealed the influence of altitude. Beets cultivated in the midland exhibited higher betacyanin content and soluble solid concentration (°Brix), resulting in stronger pigmentation (Figure 3) and sweeter taste (Table 2). Meanwhile, highland-grown tubers had greater size and fresh biomass but lower pigment and sugar levels. The findings indicate that altitude not only modifies phenological development but also impacts secondary metabolite production and quality traits. Chen et al. (2021) and Akan et al. (2021) similarly observed that environmental conditions such as temperature and radiation significantly affect betacyanin synthesis and sugar accumulation in beetroot.

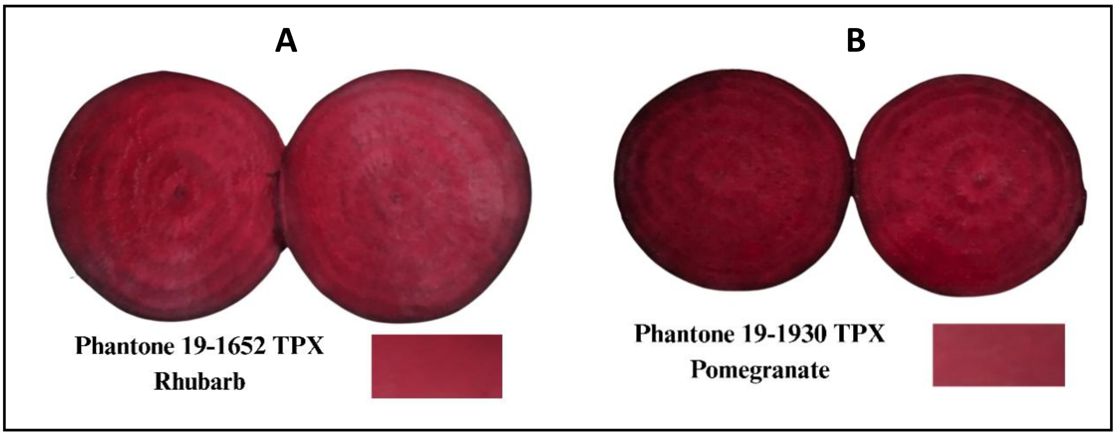

Figure 3. Comparison of the color of beetroot flesh. A. Highland. B. Midland

The correlation analysis revealed a strong positive relationship between thermal unit (HU) and soluble solids (°Brix) (r = 0.74), indicating that higher heat accumulation promoted greater sugar synthesis in beetroot tubers. Increased temperature and heat duration enhanced photosynthetic activity and accelerated the translocation of assimilates, particularly sugars, from leaves to storage tissues. Consequently, plants exposed to higher cumulative heat achieved faster physiological maturity, resulting in tubers with higher °Brix values and sweeter taste. Similar findings were reported by Chen et al. (2021) and Akan et al. (2021), who noted that moderate thermal stress enhances sugar metabolism and betacyanin accumulation in beetroot, improving its nutritional and sensory quality.

In contrast, the correlation between thermal unit and fresh tuber weight was strongly negative (r = –0.79), suggesting that as thermal accumulation increased, tuber biomass decreased. Higher temperatures accelerated the rate of development, reducing the duration available for vegetative and tuber growth. As a result, assimilates were partitioned more toward respiration and secondary metabolite formation rather than cell enlargement and biomass accumulation. This phenomenon aligns with observations by Hasan et al. (2020) and Pradiko et al. (2019), who reported that excessive heat accumulation shortens the crop cycle, leading to early maturity but reduced yield.

Overall, the contrasting relationships show a trade-off between physiological maturity and yield under different air temperature conditions. Midland areas with higher temperatures and faster thermal unit accumulation are able to increase sugar concentration and flavor quality, but tuber size and total fresh weight are smaller. The correlation results explain the differences in characteristics between beetroot cultivation in midland areas and highland areas, namely that beetroot grown in midlands, which have higher temperatures, tend to have smaller tubers but are sweeter, while beetroot grown in highlands develop larger biomass with lower soluble sugar concentrations.

High temperatures during plant growth have been shown to increase sugar synthesis in tubers due to changes in carbohydrate metabolism, resulting in higher sugar accumulation in leaves. Research conducted by Lafta and Lorenzen (1995) shows that high temperatures can increase leaf sucrose levels and simultaneously reduce starch accumulation in leaves, indicating a shift from starch synthesis to sugar accumulation under heat stress conditions. Photoperiod and air temperature serve as critical environmental signals that trigger the biochemical processes necessary for tuber formation, supporting the observation that higher air temperatures can accelerate the physiological maturation of plants and often cause tubers to reach maturity earlier (Guillemette et al., 2024). Increases in air temperature above optimal levels tend to increase the rate of photosynthesis in leaves, which, despite higher sugar levels, does not result in larger tuber sizes, as the plant's resource allocation shifts to sugar production rather than starch accumulation (Mokrani et al., 2022).

Conversely, high temperatures generally have a negative effect on tuber size. Stress caused by high temperatures usually diverts assimilates from the tubers to the vegetative tissues. At prolonged high temperatures, tuber yield, including tuber weight and size, tends to decrease. The decrease in tuber weight and size is caused by increased photosynthetic activity but decreased specific transport of carbohydrates to the tubers (Mokrani et al., 2022). The results of a study by Carpaneto et al. (2005) show that an increase in air temperature reduces the rate of accumulation of non-structural carbohydrates in storage organs such as tubers, because enzymes associated with starch synthesis become less active under heat stress, resulting in reduced size and yield. The transfer of carbohydrates from tubers to other parts of the plant under stress conditions shows how high air temperatures can disrupt normal growth patterns (Mokrani et al., 2022).

Beetroot cultivation carried out in two locations at different altitudes provides strategic advantages in optimizing the utilization and economic potential of a region. beetroots grown in highland environments will produce larger tubers with higher fresh biomass, making them suitable for the fresh vegetable market and direct consumption. On the other hand, beetroots grown in lower-altitude areas produce beetroots with higher soluble solids and betacyanin concentrations, making them more suitable as raw materials for processed food products, functional beverages, and the natural dye industry. Diversifying beetroot cultivation at different altitudes not only supports efficient land use and adaptive crop management under varying agroclimatic conditions, but also contributes to the development of value-added agricultural commodities and local agribusiness opportunities.

CONCLUSION

The result showed that altitude significantly influences the thermal unit accumulation, growth performance, and quality of beetroot cultivated under tropical conditions in East Java, Indonesia. Plants grown in the midland environment (445 m a.s.l.) reached harvest earlier at 84 DAS with a total of 1,527.3 °C·day, while those cultivated in the highland environment (873 m a.s.l.) required 104 DAS to accumulate 1,572.7 °C·day. Higher thermal unit accumulation showed a strong positive correlation with soluble solids (°Brix) ($r = 0.74$) and a strong negative correlation with fresh tuber weight ($r = -0.79$), indicating that increased heat accumulation enhances sugar concentration but reduces tuber biomass in beetroot. Beetroot grown in highlands produce large tubers and are suitable for fresh consumption, while beetroot in midlands have a sweeter taste and higher pigment content, making them potential ingredients for processed foods and natural dyes. Research is still limited to highlands and midlands. Further research should also be conducted in lowland areas with different environmental characteristics to observe the effects on the growth and yield of beetroots and on different varieties.

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