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Relationship between altitudes, morphological traits, and biochemical compositions of *Coffea canephora* Pierre ex A. Froehner in Temanggung, Indonesia

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Abstract

Among various edaphoclimatic factors influencing coffee bean quality, altitude is one of the primary factors that should be taken into account. This study aims to explore the relationship between altitude, morphological traits, and biochemical composition of robusta coffee in Temanggung Regency, the largest coffee-producing area in Central Java Province, Indonesia. Research sites were purposively selected and categorized into two altitude groups: GS, PS, and GN, located at circa 600 m a.s.l., and GT, WO, and TG, located at circa 900 m a.s.l. A total of 15 morphological traits were observed, consisting of eight vegetative and seven generative traits. Caffeine content was measured following the AOAC procedure using UV-Vis spectrophotometry, while brew acidity was evaluated using a pH meter. Several morphological traits of Temanggung robusta coffee demonstrated significant relationships with altitude. Canopy and stem diameter showed negative correlations with altitude, with correlation coefficients of -0.366 and -0.408, respectively. Conversely, fruit width ($r = 0.041$), bean length ($r = 0.049$), and bean thickness ($r = 0.047$) exhibited positive correlations. Regarding biochemical composition, caffeine content stood out by displaying a strong positive correlation with altitude ($r = 0.816$). Additionally, several morphological traits, including the number of primary branches, the number of productive branches, the number of fruits per bunch, and traits related to fruits and beans, appear to be advantageous for selection and breeding programs. Understanding these relationships provides valuable insights for developing superior Temanggung robusta coffee plants adapted to specific altitudinal conditions.

[Keywords: altitude, correlation, phenotype, robusta coffee, topographical conditions]

Introduction

Coffee plants are woody C3 plants that fall under the genus *Coffea*, which is part of the *Rubiaceae* family, comprising around 500 genera and over 6,000 species. *Coffea canephora* Pierre ex A. Froehner or better known as robusta coffee being one of two commercially coffee in the genus (Achar et al., 2015). Robusta coffee originates from the Congo basin and typically grows at altitudes around 1,200 m a.s.l., with an average air temperature ranging from 24 to 26°C (Damatta et al., 2018). However, robusta coffee has adapted to lowland habitats with mean temperatures between 22 and 30°C. Compared to arabica, robusta is more heat tolerant and 'robust,' making it more resistant to climate change (Kath et al., 2020). The commercial cultivation of robusta coffees is recent and began in the eastern part of the Congo Basin in the 19th and early 20th centuries, followed by its introduction into Java (Lim, 2013). Subsequently, its cultivation spread to new regions of Asia and Latin America and it is currently the second most cultivated coffee type after arabica. Robusta coffee has a bold and bitter flavor, in contrast to arabica coffee, and makes up about 35% of the total coffee production worldwide. Additionally, robusta coffee is a more affordable alternative to arabica coffee (Tsegay et al., 2020).

The potential of coffee plantations in Indonesia is significant, largely due to the high economic value of coffee. The most commonly cultivated varieties in the country are robusta and arabica coffee, with

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robusta plantations typically covering larger areas than those of arabica. These coffee plantations are distributed across various regions in Indonesia, including Sumatra, Java, Bali, Sulawesi, Aceh, and Nusa Tenggara (Rusmawan et al., 2024). Temanggung Regency serves as the primary hub for coffee production (Pinasthika et al., 2015), accounting for approximately 41.34% of the total coffee output in Central Java (BPS-Statistics Jawa Tengah Province, 2024). In 2023, the area yielded 22,316.50 tons of robusta coffee and 3,260.53 tons of arabica coffee (BPS-Statistics Jawa Tengah Province, 2024), indicating the majority of robusta coffee production. Currently, about 90% of coffee plants cultivated in Indonesia are robusta, while the remainder consists of arabica and liberica coffee types (*Coffea liberica* W. Bull ex Hiern) (Randriani et al., 2014).

An increase in the average global atmospheric temperature serves as a key indicator of global warming, which, in turn, leads to climate change (Manik & Timotiwu, 2022). Global warming not only impacts climate patterns but also influences the growth and development of plants, particularly coffee. Coffee typically thrives in high altitude areas characterized by relatively low air temperatures. These areas are influenced by elevation, slope aspect or slope direction, light exposures, and the presence of shade trees (Ahmed et al., 2021; Hartono et al., 2021). However, climate change presents a significant challenge, as it is projected to reduce coffee production worldwide and diminish the suitability of land for coffee plantations by 2050 (Grüter et al., 2022; IPCC, 2023; Kath et al., 2022). As rainfall patterns and air temperatures continue to shift in many coffee-growing regions, such as Southeast Asia (Kath et al., 2020), alterations in plant growth area are thought to rely on the plants' ability to adapt (Nicotra et al., 2010). Consequently, it is vital to study specific crops like coffee, as they represent a crucial economic resource for many low-income families.

Among the various edaphoclimatic factors that influence coffee bean quality, Ferreira et al. (2022) identified altitude and air temperature as the primary factors. Microclimates created by altitude and solar radiation result in varying qualities of coffee beans. A decrease in altitude is generally accompanied by an increase in air temperature, which is a critical determinant of coffee quality. Specifically, for every 1,000 meters increase in altitude, the temperature decreases by approximately 6.5°C (Cavcar, 2000), or about 0.65°C for every 100 meters of altitude gained. Research conducted by Pangestika et al. (2021) demonstrated variations in the morphological characteristics of Temanggung robusta coffee plants grown at altitudes of 600 and 900 meters above sea level. These variations were observed in canopy diameter, plant height, leaf width, fruit length, fruit thickness, bean length, and bean thickness. Furthermore, a study by Randriani et al. (2016) indicated that growing conditions at different altitudes affect the growth and yield components of Sidodadi robusta coffee in Bengkulu.

Numerous studies have explored how altitude impacts coffee quality, physical attributes, and biochemical composition; however, no similar research has been conducted on Temanggung Robusta coffee. Investigating the relationship between altitude, morphological traits, and biochemical composition of robusta coffee in Temanggung is essential. This exploration will enhance the understanding of the environmental factors affecting its growth, particularly altitude, along with other topographical conditions such as degree of slope, slope orientation, and environmental parameters, including average air temperature, average air humidity, soil temperature, and soil pH. Moreover, climate change leads to increased air temperatures at higher altitudes, rendering these regions less suitable for coffee cultivation. As highlighted by Wang et al. (2016), areas situated above 500 m a.s.l., which are typically utilized for coffee growing, are experiencing a more accelerated rise in temperature compared to lower elevations.

Additionally, the insights gained from this study regarding the correlation among the morphological traits of coffee plants are essential for improving the selection process. Grasping the interrelationship between vegetative and generative traits, along with the yield components, is critical for plant selection and breeding strategies. Recognizing these relationships makes identifying high-yield plants in their early growth stages feasible with an operational cost reduction since plant breeders don't need to wait for the entire crop cycle (Wardiana & Pranowo, 2020). This study analyzes the relationship between topographical conditions, morphological traits, and biochemical composition, as well as the interrelationship among the morphological traits and biochemical compositions in Temanggung robusta coffee.

Material and Methods

This study was performed through exploratory, descriptive research conducted through field surveys and laboratory experiments. Field research was conducted in six villages in Temanggung Regency, Central Java, Indonesia, using a survey method to observe the morphological traits of robusta coffee plants in the private coffee farms. The observation was conducted during August 2020 and March 2021. The observation sites were selected purposively in two altitude groups, circa 600 and 900 m a.s.l., as shown in Table 1 and Figure 1. The sites in the altitude group of circa 600 m a.s.l. are Gesing Village (GS), Pringsurat Village (PS), and Gentan Village (GN). In comparison, sites in the altitude group of circa 900 m a.s.l. are Getas Village (GT), Wonokerso Village (WO), and Getas Village (GT).

Observation sites at circa 600 and 900 m a.s.l. were selected because the two altitude groups host several robusta coffee properties, i.e., morphological traits and biochemical compositions that can be compared. Temanggung Regency is characterized by diverse topography, ranging from 400 to over 1000 m a.s.l., making it quite challenging to select similar sites for comparison. The environmental background, agronomic practices, and environmental parameters measurement for each observation site are consecutively detailed in Table 2, Table 3, and Figure 2.

The laboratory experiment was conducted for the biochemical compositions analysis of Temanggung robusta coffee. It was analyzed at the Pharmacy Laboratory of Setia Budi University in Surakarta, following Association of Official Analytical Chemists (AOAC) procedures and utilizing the UV-Vis Spectrophotometry method.

Table 1. Sites, altitudes information, and soil types of the observation sites

Observation sites	Altitude	Latitude and longitude	Soil type
Gesing Village, Kandangan Subdistrict (**GS**)	640 m a.s.l.	7°14'43"S and 110°10'44"E	Yellowish-red Latosol (Feralsol)
Pringsurat Village, Pringsurat Subdistrict (**PS**)	680 m a.s.l.	7°20'34"S and 110°17'53"E	Andosol
Gentan Village, Kranggan Subdistrict (**GN**)	720 m a.s.l.	7°17'59" S and 110°14'57" E	Reddish-brown Latosol
Getas Village, Kaloran Subdistrict (**GT**)	900 m a.s.l.	7°16'41" S and 110°17'24" E	Reddish-brown Latosol
Wonokerso Village, Pringsurat Subdistrict (**WO**)	930 m a.s.l.	7°17'16" S and 110°18'41" E	Reddish-brown Latosol
Tlogopucang Village, Kandangan Subdistrict (**TG**)	1030 m a.s.l.	7°11'53" S and 110°12'39" E	Yellowish-red Latosol (Feralsol)

Figure 1. Map of robusta coffee observed farms in Temanggung Regency, Central Java, Indonesia; GS = Gesing Village 640 m a.s.l., PS = Pringsurat Village 680 m a.s.l., GN = Gentan Village 720 m a.s.l., GT = Getas Village 900 m a.s.l., WO = Wonokerso Village 930 m a.s.l., and TG = Tlogopucang Village 1030 m a.s.l.

Table 2. Environmental background of the observation sites

Sites	Shading trees	Degree of slope	Slope orientation	Hydrological condition	Land suitability
GS	Silk trees (*Albizia* spp.), Coconut trees, Mahogany trees	± 4°, very gentle slope	Southwest	Rainfed farm, annual rainfall 2000-2500 mm	Adequately suited to the limiting climatic factors
PS	Silk trees (*Albizia* spp.), Banana trees, Coconut trees	± 2°, very gentle slope (nearly flat)	South	Rainfed farm, annual rainfall 2500-3000 mm	Very suitable
GN	Silk trees (*Albizia* spp.), Coconut trees	± 9°, gentle slope	West	Rainfed farm, annual rainfall 2500-3000 mm	Very suitable
GT	Silk trees (*Albizia* spp.), Coconut trees	± 14°, moderate slope	South	Rainfed farm, annual rainfall 2000-2500 mm	Very suitable
WO	Silk trees (*Albizia* spp.), Coconut trees, Avocado trees	± 2°, very gentle slope (nearly flat)	West	Rainfed farm, annual rainfall 2500-3000 mm	Very suitable
TG	Silk trees (*Albizia* spp.), Coconut trees	± 13°, moderate slope	South	Rainfed farm, annual rainfall 2000-2500 mm	Adequately suited to the limiting climatic factors

Table 3. Agronomic practices of the observation sites

Sites	Current land use	Coffee plant prunning	Weeding	Fertilization
GS	Field coffee farm	Shaping prunning regularly	Manual weeding, regularly	Manure, compost, chemical fertilizer (N-P-K); regularly
PS	Field coffee farm near residential area	Without prunning	Manual weeding, irregular	Manure, compost; irregular
GN	Terraced coffee farm	Shaping prunning regularly	Manual weeding, regularly	Manure, compost, chemical fertilizer (N-P-K); regularly
GT	Forest-based terraced cofee farm	Shaping prunning, almost regularly	Manual weeding, regularly	Manure, compost, chemical fertilizer (N-P-K); irregular
WO	Field coffee farm near residential area	Without prunning	Manual weeding, irregular	Manure, compost, chemical fertilizer (N-P-K); irregular
TG	Terraced coffee farm	Shaping prunning, regularly	Manual weeding, regularly	Manure, compost, chemical fertilizer (N-P-K); regularly

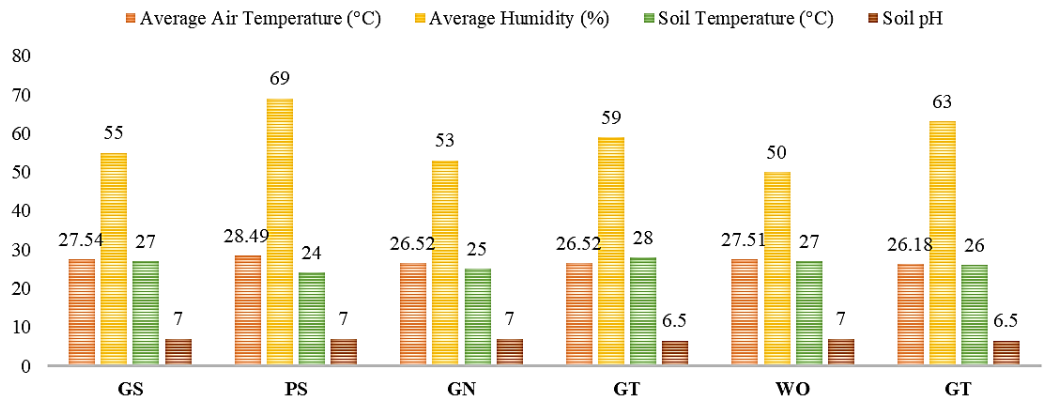

Figure 2. Environmental parameter measured in the observation sites; GS = Gesing Village 640 m a.s.l., PS = Pringsurat Village 680 m a.s.l., GN = Gentan Village 720 m a.s.l., GT = Getas Village 900 m a.s.l., WO = Wonokerso Village 930 m a.s.l., and TG = Tlogopucang Village 1030 m a.s.l.

Observation of morphological traits

Five robusta coffee farms were randomly selected from each site. A total of 15 morphological traits were observed; eight were vegetative, and seven were generative stages. The measurements for vegetative traits included tree canopy diameter, which was determined at the broadest point of the canopy (Randriani et al., 2016); and trunk diameter, measured 10 cm from the base of the trunk or 10 cm from the graft joint (Anthony et al., 1996). Other vegetative traits included plant height, the number of primary or plagiotropic branches (Prastowo & Arimarsetiowati, 2019), the number of productive branches—that is, the primary branches that bear coffee fruit—as well as leaf length and width, measured on the fifth leaf from the branch tip (Randriani et al., 2016).

Additionally, leaf petiole length was assessed from the base of the petiole to the base of the leaf blade on the same fifth leaf (Anthony et al., 1996). Regarding generative traits, measurements included the number of fruits per bunch, counted three times on different primary branches (Randriani et al., 2016). Other generative measurements included fruit length, width, and thickness, as depicted in Figure 3 (Ismail et al., 2014; Ramadiana et al., 2018; Randriani et al., 2016), along with bean length, width, and thickness, outlined in Figure 4 (Ramadiana et al., 2018; Randriani et al., 2016; UPOV, 2008).

Biochemical composition measurement

The preparation of ground coffee involved using red-picked coffee fruits sourced from each farmer's forest farm, which were processed using the dry method. The coffee fruits were naturally sun-dried for approximately 14 days until the moisture content in the beans reached about 15%, ensuring they were not susceptible to mold and were safe for storage. After drying, the fruits were separated from the outer skin and coffee husk, yielding coffee beans (Worku et al., 2018). These coffee beans were then expertly roasted in a medium-to-dark roasting facility at temperatures ranging from 210 to 225°C (Diviš et al., 2019). Once roasted, the beans were ground into coffee powder, which was subsequently prepared for analysis of the biochemical composition. Caffeine content was determined in duplicate using the AOAC (2000) procedure with a UV-Vis spectrophotometry method. The intricate and well-structured procedure is meticulously outlined in the work of Maramis et al. (2013). The acidity of the coffee brew was evaluated using a pH meter in accordance with the AOAC (2000) guidelines. The detailed process can be derived from the research conducted by Komaria et al. (2021).

Statistical analysis

A multivariate analysis of robusta coffee phenotypes, including morphological traits and biochemical composition, with the environmental parameters, was conducted and visualized with a Principle Component Analysis (PCA) biplot in PAST (PAleontological Statistics) software. A linear correlation analysis examining the relationships between altitude, morphological traits, and biochemical compositions was conducted using SPSS (Statistical Package for the Social Sciences) software to evaluate the direct correlation between the two variables. This analysis utilized the Pearson Correlation method, with results represented in tables. Furthermore, relationships among various morphological traits were analyzed and visualized in a correlation plot using OriginPro2025 software. The relationships among biochemical compositions were also calculated using SPSS software, employing descriptive statistics with the Pearson Correlation method. All statistical analyses were performed with a significance level set at 5% (α = 0.05). The criteria for interpreting the Pearson correlation coefficient (r) are illustrated in Table 4.

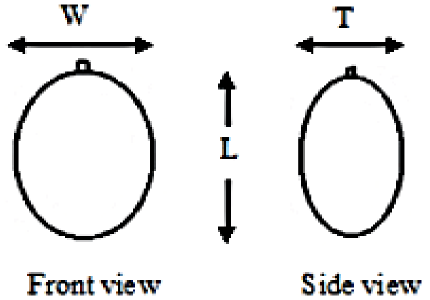

Figure 3. Measurement of fruit length, width, and thickness.

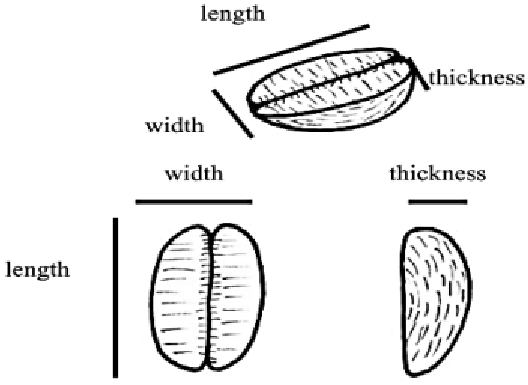

Figure 4. Measurement of bean length, width, and thickness.

Table 4. The criteria for interpreting Pearson correlation coefficient (Meghanathan, 2016)

Range of correlation coefficient values	Level of correlation	Range of correlation coefficient values	Level of correlation
0.80 to 1.00	Very strong positive	-0.80 to -1.00	Very strong negative
0.60 to 0.79	Strong positive	-0.60 to -0.79	Strong negative
0.40 to 0.59	Moderate positive	-0.40 to -0.59	Moderate negative
0.20 to 0.39	Weak positive	-0.20 to -0.39	Weak negative
0.00 to 0.19	Very weak positive	0.00 to -0.19	Very weak negative

Results and Discussion

Relationship between environmental parameters and phenotype of robusta coffee plants

The phenotypic variation of Temanggung robusta coffee was investigated by examining both vegetative and generative morphological traits and biochemical composition through multivariate analysis in relation to environmental parameters. The association between these environmental factors and the coffee phenotypes was illustrated using a Principal Component Analysis (PCA) biplot, as shown in Figure 5. According to the multivariate analysis conducted PCA, a significant relationship exists between the morphological characteristics of Temanggung Robusta coffee and environmental parameters such as air temperature, humidity, soil temperature, and soil pH. As illustrated in Figure 5, PCA examines data distribution based on the correlation matrix. Ideally, the cumulative percentage of variance in the principal components should be at least 70%; however, in practice, the total variance may fall short of this threshold (Jolliffe & Cadima, 2016). Despite a relatively low percentage, the two Eigenvalues shown in PC 1 and PC 2 can effectively represent the entirety of the data. Experience has consistently demonstrated that the top two Eigenvalues capture most of the influence or variance within the dataset (Tsoulfidis & Athanasiadis, 2022).

The short green line on the biplot in PCA represents spatial variation, with shorter lines indicating less spatial variation. The biplot is recognized as the most representative and informative graph in a multivariate dataset, with arrows denoting variable markers (Jolliffe & Cadima, 2016). According to the data in this study, the biplot reveals that coffee plants located in the right quadrant differ from those in the left quadrant (Figure 5). Robusta coffee plants from Pringsurat are situated in the upper left quadrant, where they show positive correlations with traits such as trunk diameter (TD), canopy diameter (CD), plant height (PH), leaf width (LW), and air humidity. This pattern indicates that robusta coffee plants from Pringsurat have elevated values for TD, CD, and PH, alongside the highest air humidity among the studied sites. CD, TD, and PH traits exhibit a strong positive correlation, reflected by the narrow-angle between the variables; the smaller the angle, the stronger the correlation between them.

Conversely, robusta coffee plants in Gentan and Wonokerso are found in the lower left quadrant. The robusta coffee plants in Gentan show a positive correlation with the number of fruits per bunch (NFB) and soil pH, indicating that this site bears coffee plants with a high number of fruits per bunch and high soil pH among other places, which is only neutral. In contrast, the coffee plants from Wonokerso are closely associated with the air temperature, indicating that this site experiences relatively high temperatures. Furthermore, Wonokerso is negatively correlated with air humidity, suggesting a high air temperature coupled with low humidity. Notably, robusta coffee plants in Wonokerso also display negative correlations with the number of primary branches (NPB) and productive branches (NPoB), indicating that these plants tend to have fewer primary and productive branches.

In the right quadrant are three sites where robusta coffee plants are found: Gesing, Getas, and Tlogopucang. Gesing is situated near the quadrant's center, indicating it has average or moderate environmental factors and low morphological variables. Regarding environmental parameters, Gesing exhibits moderate conditions that were not as extreme as those in other sites. The morphological and biochemical traits contributing to Gesing include leaf length (LL), leaf petiole length (LPL), caffeine content (CC), fruit length (FL), and brew acidity (BA). Fruit thickness (FT), fruit width (FW), bean thickness (BT), bean width (BW), and bean length (BL) also show a positive correlation with the Gesing site. However, this correlation is less pronounced than that observed for Tlogopucang and Getas. Tlogopucang, located in the upper right quadrant, stands out with a dominant positive correlation with FT and FW. In contrast, Getas is positioned in the center of the right quadrant and demonstrates a strong correlation with BW, BT, BL, and soil temperature. Notably, high soil temperatures

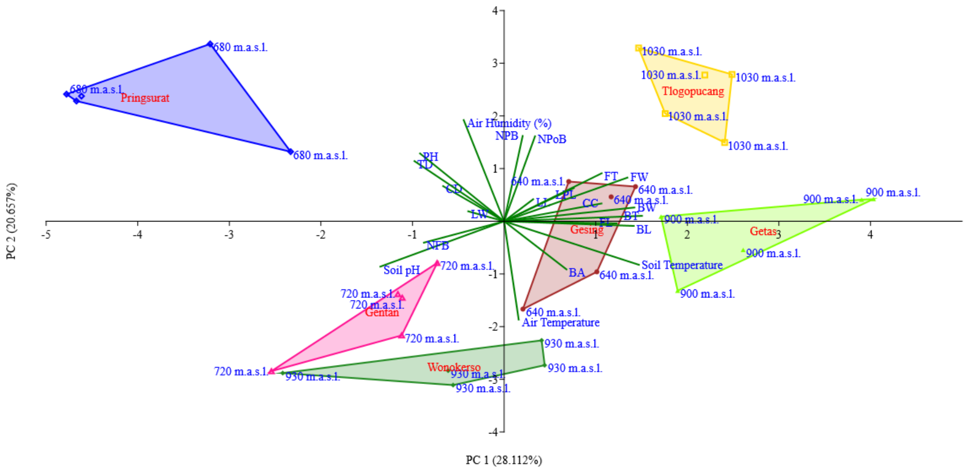

Figure 5. Principle Component Analysis (PCA) biplot of robusta coffee phenotypes and environmental parameters

in Getas are negatively correlated with soil pH. From the information regarding the right quadrant, it is evident that Tlogopucang produces the largest fruit size among all sites, while Getas yields the largest bean size.

The biplot analysis of the entire sites reveals that the patterns of fruit size (FL, FW, and FL) and bean size (BL, BW, and BT) in robusta coffee negatively correlate with traits such as TD, CD, PH, and LW. NFB is also negatively correlated with environmental factors, including soil pH and air humidity. The sizes of fruits and beans, which are the main objectives in robusta coffee cultivation, show a weak positive correlation with leaf length (LL) and leaf petiole length (LPL) but demonstrate a strong positive correlation with the altitude. This trend is particularly evident for two sites circa 900 m a.s.l., namely Tlogopucang at 1030 m a.s.l. and Getas at 900 m a.s.l., which yield the largest fruit and bean size. Conversely, Wonokerso, which also falls within the 900 m a.s.l. altitude group does not produce similarly large fruits and beans. This tendency could be attributed to suboptimal agronomic practices, such as a lack of pruning and inconsistent weeding and fertilization. Furthermore, Wonokerso shows a dominant positive correlation with air temperature, as it has the highest air temperature compared to the other two sites within the same altitude group.

The biochemical composition of caffeine content (CC) is positively correlated with fruit and bean traits such as FT, FW, FL, BW, BT, and BL. This trend indicates that larger fruits and coffee beans will likely yield coffee with higher caffeine content. Additionally, CC shows a positive correlation with altitude, specifically at the Tlogopucang and Getas sites, where coffee beans have a higher caffeine content than other places. On the other hand, brewing acidity (BA) is positively correlated with soil temperature, where higher soil temperatures result in less acidic coffee brews and vice versa. The BA also exhibits a negative correlation with soil pH. Most locations have a neutral pH, while the Getas and Tlogopucang areas show lower soil pH levels of 6.5. At this soil pH of 6.5, robusta coffee plants appear to be better suited for producing larger fruit and seed sizes and coffee brews that are less acidic (higher in pH).

Linear relationship between altitude and morphological traits of robusta coffee plants

Out of the 15 morphological traits analyzed for their correlation with altitude, only five were significant at $\alpha = 0.05$. These traits are canopy diameter (CD), stem diameter (TD), fruit width (FW), bean length (BL), and bean thickness (BT), as the data can be seen in Table 5 and Table 6.

The Pearson correlation between altitude and vegetative traits of robusta coffee plants

The CD and TD of Temanggung robusta coffee exhibit a significant negative correlation with altitude, with correlation coefficients of r = -0.366 and r = -0.408, respectively. This data suggests that as altitude increases, coffee plants tend to have smaller canopy and trunk diameters. This trend contrasts with the findings of Randriani et al. (2016), which indicated that coffee trees at 1,200 m.a.s.l. had larger canopy diameters compared to those at 900 and 600 m.a.s.l. Conversely, our findings align with the conclusions of Coomes & Allen (2007) and Kofidis & Bosabalidis (2008), who stated that plant growth tends to slow down or become stunted at higher altitudes. The reduced growth rates at increased altitudes may result from lower air and soil temperatures (adiabatic effect), shorter growing seasons, heightened wind exposure, and a diminished nutrient supply (Coomes & Allen, 2007).

Table 5. The Pearson correlation coefficients (r) of altitude and vegetative traits of robusta coffee plants

Vegetative Traits	Pearson Correlation Coefficients (r)	P-value
Canopy Diameter (**CD**)	-0.366*	0.046
Trunk Diameter (**TD**)	-0.408*	0.025
Plant Height (**PH**)	-0.13	0.494
Number of Primary Branches (**NPB**)	-0.202	0.283
Number of Productive Branches (**NPoB**)	-0.098	0.608
Leaf Length (**LL**)	0.015	0.939
Leaf Width (**LW**)	-0.066	0.73
Leaf Petiole Length (**LPL**)	0.264	0.158

Note: The Pearson coefficients marked with * indicate significance at $\alpha = 0.05$.

The NPB and NpoB also did not show significant correlations with altitude. This finding contrasts with the research by Roro et al. (2016), which indicated that the number of branches per plant was significantly affected by altitude, ultraviolet (UV) radiation, and the interaction between UV exposure and season. They discovered that the number of branches increased by 33% with UV exposure and 40% without it at lower altitudes, suggesting a negative correlation between altitude and branch quantity in plants. This implies that the number of branches may follow a specific pattern that reflects how well plant species adapt to their growing environment. However, in coffee farming, light intensity is influenced by the presence of shade trees and the exposure of the slope where coffee trees are cultivated (Avelino et al., 2005). Therefore, the NPB and NPoB in robusta coffee plants are related to the overall topographical factors, particularly altitude and slope direction (aspect).

Leaf morphological traits, such as LL, LW, and LPL of Temanggung robusta coffee, demonstrate no significant relationship with altitude. This finding contrasts with many studies investigating the correlation between leaf morphology and altitudinal gradients. For instance, Liu et al. (2020) reported that leaf size—measured by leaf length and width—in three plant species (*Epilobium amurense* Hausskn., *Pedicularis densispica* Franch., and *Potentilla fulgens* Wall. ex Hook.) diminished with increasing altitude, suggesting that plants at higher altitudes possess narrower leaves than those at lower. Similarly, Jahdi et al. (2020) found the same trend, highlighting that environmental factors, including atmospheric CO_2 concentration, air temperature, sunlight, irradiation, and wind, significantly influence leaf morphology and function. In contrast, the morphological characteristics of Temanggung robusta coffee leaves showed no correlation with altitude despite all sites experiencing an air temperature range of 26 to 28°C. This lack of correlation may be attributed to the similar shade conditions present at all sites (Figure 2), as no coffee plants are cultivated in full sun. As a result, the relationship between leaf morphological traits and altitude is insignificant. Furthermore, the observed LPL in Temanggung robusta coffee did not indicate a significant relationship with altitude. Prastowo & Arimarsetiowati (2019) examined morphological variations of robusta coffee at different altitudes in Lampung, Indonesia. They noted that leaf petiole length characteristics align more closely with genetic diversity than with altitude.

Several vegetative traits of robusta coffee, such as PH, NPB, NPoB, LL, LW, and LPL, show no significant association with altitude, suggesting that robusta coffee plants in Temanggung have limited phenotypic plasticity. Phenotypic plasticity refers to a genotype's ability to develop various phenotypes across different temporal and spatial contexts and adjust functional traits in response to abiotic factors José et al. (2024). The absence of phenotypic plasticity in Temanggung's robusta coffee along the altitudinal gradient suggests suboptimal adaptation of these plants to varying altitudes. Consequently, this may influence the yield components, which could impact coffee farmers' economic well-being in the Temanggung Regency. The research by José et al. (2024) supports the idea that coffee plants can change their morphological traits, showing plasticity based on the altitude of their cultivation.

Climate change is believed to have hindered the optimization of morphological character plasticity in robusta coffee plants in Temanggung, leading to similar air temperatures at around 900 m.a.s.l. and 600 m.a.s.l. Climate change in Temanggung indicates the rising air temperatures observed in Central Java. Over the past three decades, the average temperature in Central Java has demonstrated a pronounced upward trend. However, this increase has not been uniform; the central regions, including Temanggung, have experienced a more significant rise than the coastal areas (BMKG, 2021b). Specifically, air temperatures in Central Java have risen by 0.3 to 0.5°C over these 40 years, from 1981-2022 (Fardianto, 2022). This phenomenon can be attributed to increased greenhouse gas emissions and substantial changes in land use. Furthermore, Central Java has undergone alterations in rainfall patterns over the last three decades, from 1990 to 2021. Temanggung, situated in the central part of Central Java, recorded an annual rainfall that was classified as high (between 3000 and 4500 mm/year) from 1991 to 2020 (BMKG, 2021a). Climatological data for Temanggung Regency, which includes monthly temperature, precipitation, and sunshine hours from 1990 to 2021, is illustrated in Figures 6 and 7. This data was obtained from the nearest climatology station, the Class I Climatology Station in Semarang.

The Pearson correlation between altitude and generative traits of coffee plants

Compared to vegetative traits, the generative traits of robusta coffee plants show more correlation with altitude, as the data displayed in Table 6. Specifically, three out of seven generative traits—fruit width (FW), bean length (BL), and bean thickness (BT)—exhibit significant relationships with altitude. In contrast, traits such as the number of fruits per bunch (NFB), fruit length (FL), fruit thickness (FT), and bean width (BW) reveal no significant correlation. Notably, all traits that demonstrate a significant relationship possess positive correlations with altitude, indicating that as altitude increasing, the FW, BL, and BT values also rising.

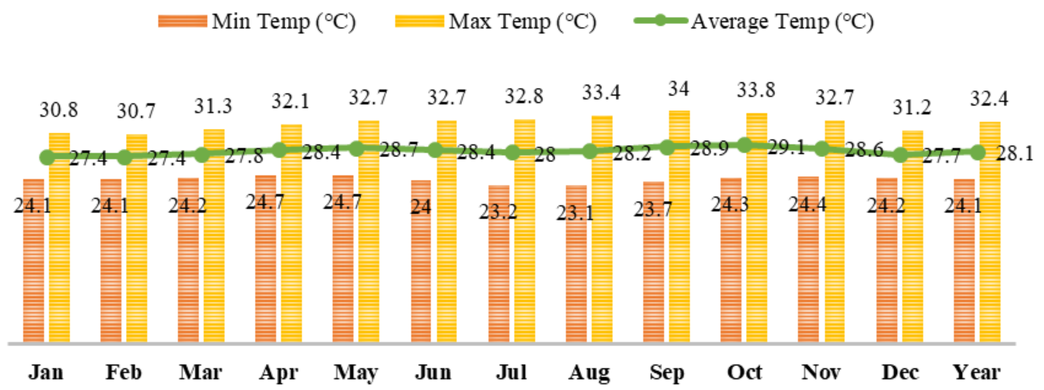

Figure 6. Series of monthly average temperatures (°C) for Temanggung Regency from 1990 to 2021, obtained from the nearest climate station, Class I Climatology Station Semarang

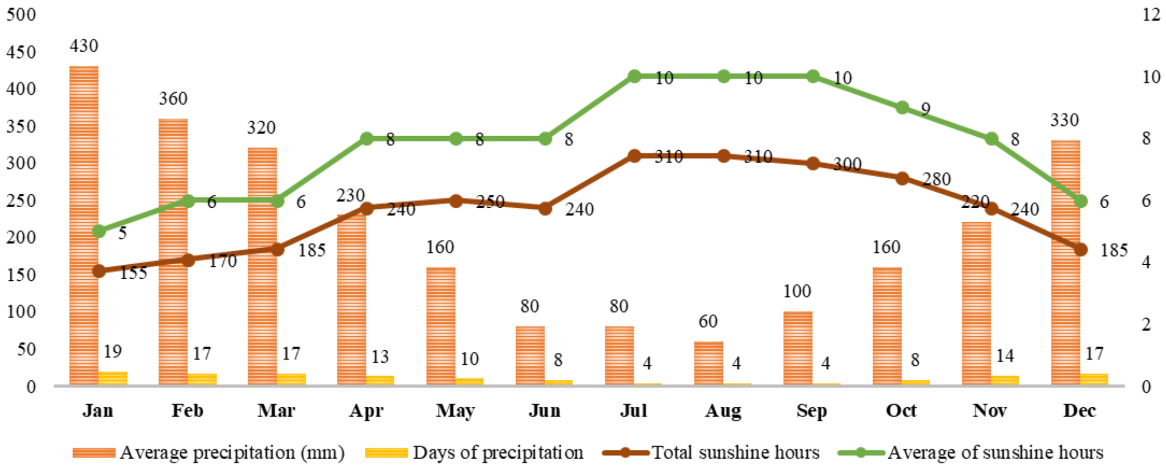

Figure 7. Monthly average precipitation (mm), days of precipitation, average of sunshine hours, and total of sunshine hours for Temanggung Regency from 1990 to 2021, obtained from nearest climate station, Class I Climatology Station Semarang

Table 6. The Pearson correlation coefficients (r) of altitude and generative traits of robusta coffee plants.

Generative Traits	Pearson Correlation Coefficients (r)	P-value
Number of Fruits Per Bunch (**NFB**)	-0.212	0.261
Fruit Length (**FL**)	0.303	0.103
Fruit Width (**FW**)	0.376*	0.041
Fruit Thickness (**FT**)	0.26	0.165
Bean Length (**BL**)	0.363*	0.049
Bean Width (**BW**)	0.194	0.305
Bean Thickness (**BT**)	0.365*	0.047

Note: The Pearson coefficients marked with * indicate significance at α = 0.05.

This finding is consistent with previous research highlighting the critical role of altitude in the cultivation of coffee plants. At higher altitudes, atmospheric oxygen levels are lower, leading to more extended ripening periods for coffee cherries than those grown at lower altitudes Paudel et al. (2021). Coffee plants at elevated sites typically produce larger and heavier beans, whereas fruits in lower areas ripen more quickly, often yielding underdeveloped beans (Worku et al., 2018). Additionally, the results of this study are further corroborated by research conducted by Supriadi et al. (2016), which demonstrated a positive correlation between altitude and the physical quality of coffee beans. Notably, higher altitudes are associated with the improved physical quality of the beans.

While a positive relationship is expected across all examined fruit and bean traits, not all generative traits significantly correlate with altitude. This variation may stem from differences in other microclimatic conditions within the area. For instance, the Wonokerso (WO) site is situated at a higher altitude of 930 m a.s.l. but experiences hotter air temperatures and lower humidity than the Getas (GT) site. This phenomenon suggests that altitude alone is not the sole topographical factor influencing the generative traits of robusta coffee. Other considerations, such as the degree of slope, also play a crucial role. GT and TG sites, known for having the largest fruit and bean sizes, are located on hilly landscapes with the steepest slopes among the studied sites, which are 14° and 13° consecutively. For robusta coffee, slopes below 30% (or below 16°C) are still deemed suitable (Noraini et al., 2024), and all sites in this study have slopes below this threshold. Additionally, coffee grown on expansive sloping land at higher elevations, such as those at the GT and TG sites, tends to receive more optimal sunlight in shorter bursts—particularly in the morning and afternoon—due to the land's orientation towards the east and west throughout the day at lower temperatures (Ferreira et al., 2022). This unique condition may slow photosynthesis and promote more efficient changes in the chemical composition of coffee fruit flesh during ripening (Abubakar et al., 2023).

Regarding aspect or slope orientation, the GT and TG slopes are south facing, whereas the WO site, which belongs to the same altitude group, has a west facing slope. Coffee plants on a west facing slope, WO, typically experience warmer conditions than those on a south facing slope, resulting in quicker fruit ripening. Consequently, the robusta coffee fruits and beans produced on this site tend to be smaller (Abdinasab, 2019). The orientation of the slope is closely linked to the intensity of solar radiation, which in turn affects air humidity in the area. With its west facing slope, the WO site experiences higher air temperatures and lower humidity than the other sites at an altitude of circa 900 m a.s.l. Robusta coffee thrives in high humidity conditions approaching saturation or less humid environments, provided the dry season is brief (DaMatta & Ramalho, 2006). Maintaining the proper humidity level is essential for optimal growth of coffee plants. The ideal relative humidity range for coffee cultivation falls between 40% and 60%. This balance is crucial for promoting healthy growth and developing robust flavor profiles in the beans. When humidity levels drop below 40%, coffee plants may become stressed, leading to various growth challenges. On the other hand, humidity levels exceeding 60% can create favorable conditions for pests and diseases, making it vital to monitor these levels (Rankel, 2024).

The Pearson correlation between altitude and biochemical compositions of robusta coffee bean

The biochemical composition of Temanggung robusta coffee includes caffeine content (CC) and brewing acidity (BA), as the data can be seen in Table 7. A significant relationship exists between altitude and CC (α = 0.01), with a correlation coefficient of r = 0.816. This finding contrasts with the studies conducted by Sridevi & Giridhar (2014), Randriani et al. (2016), and Worku et al. (2018), which reported a decrease in caffeine content with increasing altitude. Similarly, Girma et al. (2020)

Table 7. The Pearson correlation value (r) of altitude and biochemical composition of robusta coffee beans

Biochemical Compositions	Pearson Correlation Value (r)	P-value
Number of Fruits Per Bunch (**NFB**)	0.816**	0.000
Fruit Length (**FL**)	-0.092	0.630

Note: The Pearson coefficients marked with ** indicate significance at α = 0.01.

observed that caffeine and 5-caffeoylquinic acid levels in raw and roasted coffee beans diminished as altitude increased. However, this result aligns with Towaha et al. (2015), who found that the highest caffeine content in Arabica coffee beans occurred at an altitude of 1,600 m.a.s.l. (1.8%), which was not significantly different from the caffeine content at 1,400 m.a.s.l. (0.98%). In contrast, the lowest caffeine content was from 1,200 m.a.s.l. (0.92%). Rodrigues et al. (2007) also noted a similar trend, indicating an increase in caffeine content with rising altitude. Variations in caffeine content among coffee beans may result from differences in genotypes or varieties and the diverse environments in which the coffee is cultivated.

Brewing acidity (BA) is another important biochemical composition, and this study did not exhibit a significant relationship with altitude. Temanggung robusta coffee sourced from altitudes of approximately 600 m.a.s.l. and 900 m.a.s.l. showed no significant difference in brewing acidity, with a correlation coefficient of r = - 0.092. The average pH of BA across all sites ranges from 3.89 to 4.08, making it challenging to identify a significant relationship between BA and altitude. The reason for this pattern remains unclear, as each site possesses distinct microclimates. Notably, Worku et al. (2018) also reported no significant differences in BA with increasing altitude among coffee plants grown without shade. However, several other studies have identified a positive correlation between BA and altitude. For instance, Gamonal et al. (2017) and Malau et al. (2017) noted a positive relationship between acidity and altitude, while Worku et al. (2018) observed a positive correlation between altitude and shade-grown coffee. The acidity in coffee beans is attributed to chlorogenic, quinic, citric, and malic acids, among others. The specific composition contributing to coffee brew acidity can vary based on numerous factors, including coffee species, cultivar, geographical origin, growing altitude, and post-harvest processing (Farah, 2019; Rune et al., 2023). Notably, post-harvest processing is the most influential factor affecting coffee brew acidity, followed by geographical origin and altitude (Amalia et al., 2021; Rune et al., 2023).

Relationship among morphological traits of robusta coffee plants

Relationship among vegetative traits of robusta coffee plants

In this study, not all robusta coffee vegetative traits exhibit significant correlations, as illustrated in Figure 8; however, several noteworthy correlations will be discussed. PH shows a positive correlation with CD (r = 0.37, α = 0.05), TD (r = 0.615, α = 0.01), and LW (r = 0.57, α = 0.01). These findings suggest that taller coffee plants are likelier to possess a larger canopy diameter, trunk diameter, and leaf width. Such interconnected traits contribute to the robust structure of coffee trees. While a dwarf coffee plant structure can enhance yield components by optimizing plant density per hectare (Battistini & Battistini, 2005; Breitler et al., 2022), having a vigorous plant structure is crucial to improving productivity per tree. This vigor can be assessed by examining the stem size of one-year-old plants or by measuring the increase in stem diameter from the first to the second year. Research by Breitler et al. (2022) and Eskes & Leroy (2004) has indicated that the genetic coefficients connecting plant vigor with productivity range from 0.70 to 0.93. Consequently, the vigorous structure of the vegetative traits of Temanggung robusta coffee can lead to increased productivity on a per-tree basis.

LW demonstrates a significant relationship with TD (r = 0.45, α = 0.05) and LL (r = 0.56, α = 0.01) in Temanggung robusta coffee plants, suggesting that an increase in leaf width is associated with a corresponding increase in stem diameter and leaf length. The broad leaves of robusta coffee not only positively correlate with longer leaves but also result in a leaf area supporting the coffee plants' growth and development. Furthermore, LL shows a positive correlation with LPL (r = 0.41, α = 0.05), indicating that leaves with longer petioles can also sustain lengthier leaflets. Research by Vitória et al. (2024) reported a correlation between leaf area and leaf length (r = 0.921) and between leaf area and leaf width (r = 0.823). Similar trends in correlation coefficients between leaf length, width, and area of robusta coffee have been observed by Espindula et al. (2018) and Dubberstein et al. (2019). Examining the correlations among plant variables can yield valuable insights into how variations in one may influence another (Dubberstein et al., 2019; Ercanlı et al., 2018). However, Silva et al. (2023), who assessed genetic variability in various robusta coffee cultivars, found that while some genotypes exhibited

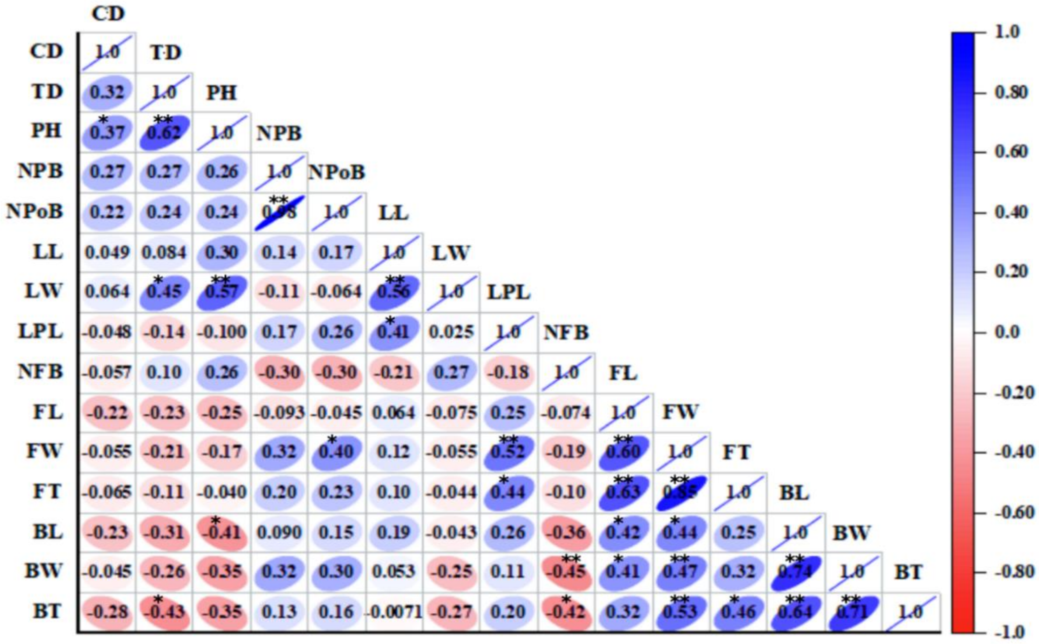

Figure 8. Relationship among morphological traits of Temanggung robusta coffee plants; CD: Canopy diameter, TD: Trunk diameter, PH: Plant height, NPB: Number of primary branches, NPoB: Number of productive branches, LL: Leaf length, LW: Leaf width, LPL: Leaf petiole length, NFB: Number of fruits per bunch, FL: Fruit length, FW: Fruit width, FT: Fruit thickness, BL: Bean length, BW: Bean width, BT: Bean thickness. * and ** are significant at α = 0.05 and α = 0.01, respectively.

a correlation between leaf width and leaf length, this relationship was not consistent across all genotypes studied, suggesting that specific genetic factors may influence the correlation.

The NPB in coffee plants demonstrates a strong positive correlation with the NPoB (r = 0.98, α = 0.01), suggesting that an increase in primary branches will likely result in more productive branches, ultimately enhancing yield components. Paredes-Espinosa et al. (2023) reported similar findings, showing a significant positive correlation between the total number of branches on each plant and the number of fruit-bearing branches (r = 0.91, α = 0.01). The trend indicates that selecting robusta coffee accessions with more plagiotropic (primary) branches can improve the coffee plant's architecture, making it short and dense while enhancing traits critical to yield components. Furthermore, Cerda et al. (2017) and Unigarro et al. (2017) observed that the number of productive internodes, plagiotropic branches, and leaf area are directly associated with the plant's production potential. Therefore, these traits should be considered important components of productivity. Consequently, the breeding and selection program for Temanggung robusta coffee can utilize the NPB trait, as it has a strong positive correlation with NPoB.

Relationships between the vegetative and generative traits of robusta coffee plants

Some vegetative traits of Temanggung robusta coffee correlate with generative traits, namely trunk diameter (TD) with bean thickness (BT), plant height (PH) with bean length (BL), number of productive branches (NPoB) with fruit width (FW), and leaf petiole length (LPL) with FW and fruit thickness (FT). TD demonstrates a negative correlation with BT (r = -0.43, α = 0.05), suggesting that trees with larger trunk diameters tend to produce thinner beans. Additionally, PH negatively correlates with BL (r = -0.41, α = 0.05), indicating that taller robusta coffee trees are more likely to produce shorter beans. These findings contrast the conclusions of Marandu et al. (2004), who argue that stem diameter and plant height are crucial traits in coffee plant selection, as both positively correlate with yield components. Similarly, Montagnon et al. (2001) emphasized that stem diameter and plant height traits can be used to achieve vigorous coffee plants. In the case of Temanggung robusta coffee, the absence of a positive correlation between vigor structures and yield components can likely be linked to the prevalence of aging coffee trees in the region. Many of these trees have been inherited since the 1980s (Septiani & Kawuryan, 2021), even though the maximum productive lifespan of coffee plants is generally around 25 years (Evizal, 2013). The lack of plant rejuvenation in Temanggung's robusta coffee plantations results in vigorous coffee trees; however, with productivity remaining low due to the trees' age.

The absence of a relationship between vigor structures and yield components in Temanggung robusta coffee plants can be attributed to the variations in agronomic practices employed by farmers at each observation site. All sites practice prunning for their coffee plants except for PS and WO, which, based on the plants' habitus' appearance, have only recently undergone mercy prunning. Sites GS, GN, and TG have regular prunning schedules, while site GT has an irregular prunning pattern. In terms of shade, all sites feature protective trees, with the shade trees being relatively similar, including silk, banana, and coconut trees. The shade intensity across all sites is relatively uniform, except for the WO site, which has the lowest shade intensity despite hosting a diverse range of shade trees such as silk, banana, coconut, and avocado. This reduced shade is due to the low density of the shade trees, allowing the farm field to receive more direct sunlight than the other sites. Consequently, the WO site experiences the warmest air temperatures compared to the others. Most robusta coffee plants, except in the WO site, are shielded from direct sunlight, while the majority of coffee plants at the WO are exposed. Furthermore, the WO site is nearly flat, with only a 2° slope, contributing to these conditions.

Another vegetative trait positively correlates with generative traits is the number of productive branches (NPoB) with fruit width (FW), with a correlation coefficient of $r = 0.40$. This result indicates that more productive branches are associated with broader coffee fruits. Fanwoua et al. (2014) explains that the presence of fruits on branches also affects the pattern of assimilate distribution. As the fruit develops, its sink strength increases, leading it to import assimilates from distant sources. Consequently, branches with more fruit tend to bear wider fruits. In Temanggung robusta coffee plants, leaf petiole length positively correlates with fruit width ($r = 0.52$, $\alpha = 0.01$) and fruit thickness ($r = 0.44$). This pattern suggests that longer leaf petioles contribute to larger fruit sizes, particularly in width and thickness. While petiole length may not directly drive fruit size, it can indirectly influence fruit development and overall plant structure, affecting fruit size. Specifically, petiole length influences leaf positioning and light interception, potentially impacting photosynthesis and resource allocation to the fruit (Gao et al., 2022).

Relationship among generative traits of robusta coffee plants

The correlation among the generative traits of coffee plants is more pronounced than the relationship of other traits. NFB is negatively correlated with BW ($r = -0.45$, $\alpha = 0.05$) and BT ($r = -0.42$, $\alpha = 0.05$), suggesting that a higher number of robusta coffee fruits in a bunch tends to result in narrower and thinner beans. Conversely, larger robusta coffee fruits and beans are in smaller quantities within a bunch. This finding aligns with the research conducted by Nappu & Kresna (2016), which demonstrated that Arabica coffee from Enrekang, South Sulawesi, had the highest fruit count per bunch, averaging 10.5 fruits. However, these fruits were smaller and lighter in weight compared to those from other regions. Vaast et al. (2006) noted that a bunch containing excessive coffee fruits can reduce bean size due to competition for carbohydrates during the formation of fruit and beans. To enhance the sustainability of their coffee plantations and improve the quality, size, and weight of the beans, coffee farmers can adopt cultivation management practices such as shading, fruit thinning, and branch pruning, potentially increasing their income. Scheduled fertilization can enhance the potential for a higher number of fruits per bunch, as coffee plants benefit from adequate nutrient supply. All the sites have been implementing effective fertilization practices using manure, compost, and chemical fertilizers containing Nitrogen (N), Phosphate (P), and Potassium (K) compounds. Farmers need to maintain a consistent fertilization schedule, similar to what has been achieved in GS and GN, while the other areas are still managing their fertilization irregularly.

The analysis revealed that FL was correlated positively with FW ($r = 0.60$, $\alpha = 0.01$), FT ($r = 0.63$, $\alpha = 0.01$), BL ($r = 0.42$, $\alpha = 0.05$), and BW ($r = 0.41$, $\alpha = 0.05$). This trend indicates that longer robusta coffee fruits have broader fruits with longer and thicker beans. Additionally, FW exhibited a strong positive correlation with FT ($r = 0.85$, $\alpha = 0.01$), as well as with BL ($r = 0.44$, $\alpha = 0.05$), BW ($r = 0.47$, $\alpha = 0.01$), and BT ($r = 0.53$, $\alpha = 0.01$). The width of robusta coffee fruits positively correlates with thick fruits and long, broad, and thick beans. FT correlated positively solely with BT ($r = 0.46$, $\alpha = 0.05$), reinforcing the observation that thicker robusta coffee fruits also contain thicker beans. Furthermore, BL was positively correlated with BW ($r = 0.74$, $\alpha = 0.01$) and BT ($r = 0.64$, $\alpha = 0.01$), while BW demonstrated a positive correlation with BT ($r = 0.71$, $\alpha = 0.01$). These findings suggest that the size of morphological traits of robusta coffee fruits and beans are interrelated.

Relationship among biochemical compositions of robusta coffee plants

In this study, the correlation between the biochemical compositions of Temanggung robusta coffee was insignificant, with an $r = 0.268$. The CC of Temanggung robusta coffee did not correlate significantly with the BA. While the direct relationship between CC and BA has not been extensively studied, it is noted that robusta coffee possesses a higher caffeine content compared to arabica coffee. The increased caffeine content in robusta coffee reduces the brew's pH because of its lower concentration of organic acids. As a result, the flavor attributes of robusta coffee are usually bolder and bitter, as opposed to being light and tangy. Notably, variations in caffeine content can occur even within the same coffee species grown in different environments, indicating that factors such as the growing area, processing methods, and genetics can influence caffeine content. Additionally, the pH of coffee brew is affected by acidic compounds, particularly carboxylic acids, which are released in free form when glycoside bonds are broken. The pH variations in coffee brew are also shaped by the coffee's growing area, including soil composition and climate, along with genetic variations (Zainuri et al., 2023).

Conclusion

Certain morphological traits of Temanggung robusta coffee exhibit a significant relationship with altitude; namely, both canopy diameter ($r = -0.366$) and stem diameter ($r = -0.408$) show negative correlations, while fruit width ($r = 0.376$), bean length ($r = 0.363$), and bean thickness ($r = 0.365$) positively correlate with altitude. In addition, the biochemical composition of Temanggung robusta coffee, which correlates with altitude, is the caffeine content ($r = 0.816$), demonstrating a robust positive correlation. Furthermore, several morphological traits could be advantageous for the selection and breeding programs of Temanggung robusta coffee plants. These include the vegetative traits that is correlate with generative traits i.e. number of productive branches which positively correlate with fruit width ($r = 0.40$), and the leaf petiole length which also positively correlate with fruit width ($r = 0.52$) and fruit thickness ($r = 0.44$). The PCA biplot effectively differentiated Temanggung robusta coffee plants from various sites based on their distinct morphological and environmental characteristics. It highlighted that Pringsurat (PS) plants showed positive associations with trunk diameter, canopy diameter, and plant height. In contrast, Gentan (GN) and Wonokerso (WO) plants were correlated with fruit quantity and elevated air temperatures, respectively. Sites such as Gesing (GS), Getas (GT), and Tlogopucang (TG) were noted for their larger fruit and bean sizes, which strongly correlated with higher altitudes and lower soil pH. Furthermore, caffeine content was found to be positively related to both larger fruit and bean sizes, as well as higher altitudes, while brewing acidity demonstrated an inverse correlation with soil temperature and pH. Overall, these findings emphasize the significance of environmental factors and effective agronomic practices in enhancing the morphological and biochemical traits of robusta coffee.

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