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A Study on the Yield of Arabica Coffee in Gayo Highland Indonesia: The Significance of Altitudes and Varieties

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Abstract. Rising temperatures and fluctuating rainfall patterns harm both the quality and quantity of coffee yields. However, in the Gayo Highlands, the success of arabica coffee crops is directly linked to altitude. This research aims to determine the effect of altitudes and varieties and their combination on arabica coffee yield components and coffee yield. A factorial randomized complete block design (RCBD), with 6 replications, has been used to determine the effect of altitudes, i.e. low-altitudes (>1000-1200 m a.s.l.), mid-altitudes (>1200-1400 m a.s.l.), and high-altitudes (>1400-1600 m a.s.l.); varieties i.e. Gayo-1 (Timtim), Gayo-2 (Borbor), and Gayo-3 (Ateng Super); and their combination. Coffee in low and mid-altitudes have more productive twigs per-productive branch and more coffee cherries per-plant compared to that in high altitudes. The highest weight of dry coffee beans per-plant is found in mid-altitudes. Varieties only significantly affect the average of productive nodes per-productive twig. The combination of altitudes and varieties has a significant effect on the productive twigs per-productive branch and the weight of 100 coffee cherries. To maximize yield, Gayo-1 is better suited for low and mid-altitudes, Gayo-2 is for mid-altitudes, and Gayo-3 is for low-, mid- and high-altitudes.

Keywords: Gayo-1 (Timtim), Gayo-2 (Borbor), Gayo-3 (Ateng Super), yield components

INTRODUCTION

The Gayo Highlands is one of the main production areas of arabica coffee in Indonesia, which covers 100,792 ha with a production of 73,165 tons (BPS 2023). Most of those coffee farms (> 95%) are managed by smallholders with a size of 1 to 2 ha. Increasing demands for Indonesian arabica coffee (including Gayo arabica) has been reported, particularly due to the advantage of being characterized as having a low acidity and a strong 'body'. Nevertheless, arabica coffee production poses significant sustainable challenges because it is highly susceptible to impact of climate change (Adhikari et al. 2020; Baca et al. 2014). Research examining the influence of global warming on arabica coffee production and its environmental footprint reveals alarming trends. Not only is arabica coffee production markedly decreasing, but it also carries grave implications (Hassard et al. 2014; De Beenhouwer et al. 2016). Yields of arabica coffee, both quantitatively and qualitatively decline if exposed to temperature beyond its ideal range (Magrach and Ghazoul 2015). Increases in temperature and changes in rainfall patterns lead to a decline in arabica coffee production (Bunn et al. 2015; Magrach and Ghazoul 2015).

A modelling study by Schroth et al. (2014) reports that the area suitable for growing arabica coffee in the Gayo Highlands in 2050 may decrease drastically up to 91% of the current coffee farming area. This situation will likely push farmers to look for higher-altitude land, which unfortunately is marked as a protected forest area. This situation threatens the arabica coffee sustainability as well as the forest ecosystem. The production of arabica coffee in the Gayo Highlands, particularly in the altitudes of 900 to 1000 m a.s.l., has shown a significant decline in both quantity and quality compared to that of higher altitudes (Anhar et al. 2021a). However, observations at nearby coffee plantations show that arabica coffee can still produce a quite well yield with proper shade management and good farm maintenance. This indicates the presence of specific local adaptation patterns that can be used to adapt to climate change. Several initiatives have been reported by Verburg et al. (2019) to adjust coffee cultivation systems to climate change, such as planting windbreaks, shading systems, integrated pest and disease management, introduction of new plant varieties, income diversification, soil and water conservation, and forest cover arrangement. Elsewhere, in Indonesia, several studies reported that shade trees act as an important pillar for a sustainable coffee plant agroecosystem (Khoirunnisak et al. 2023; Lisnawati et al. 2017).

The productivity of arabica coffee is strongly influenced by temperature. An increase of only 1 ^{O}C in a farm surrounding air can decrease coffee yields drastically. Generally, as elevation increases, the air temperature tends to decrease about 0.6 ^{O}C per 100 m, or about 1.0 – 1.2 ^{O}C per 200 m rise. Considering cultivation areas of arabica coffee in the Gayo Highlands spread widely across farm elevatations, research needs to be conducted to obtain more detailed information on effect of air temperature decrease on coffee yields in the range of 1000 to 1600 m above sea level (a.s.l.) with interval of 200 m.

Other important information that needs to be examined is the suitability of coffee varieties for a specific location (farm elevation). Farmers in this region experience difficulties in identifying coffee varieties that are well adapted to the site-specific conditions (i.e. climate, soil, shade conditions). As a result, they took initiative to cultivate several varieties across elevations, regardless of its suitability. Currently, there are at least three major varieties cultivated in the region at various farm altitudes, namely Timtim (Gayo-1), Borbor (Gayo-2), and Ateng Super (Gayo-3).

Our research hypotheses are a) farm altitudes, coffee varieties, and the combination of altitude and varieties significantly impact the coffee yield components and coffee yield in the Gayo Highlands; b) there are positive correlations between coffee yield components and coffee yield in the region.

MATERIALS AND METHODS

Study Area

This research was conducted in two main coffee-producing districts in the Gayo Highlands, Aceh, Indonesia, namely Aceh Tengah District and Bener Meriah District. Geographically, the two districts are located at 4º22'14.42" - 4º54'50" N and 96º15'23.60" - 97º17'50" (Hanan et al. 2024) (Figure 1).

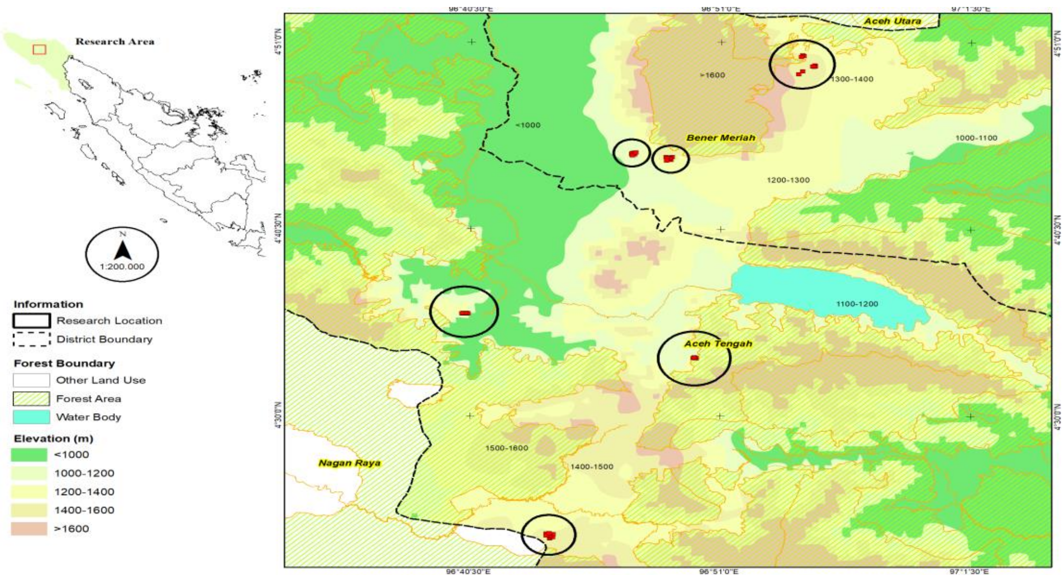

Figure 1. Map of the research area

The coffee agroforestry system with shade plants consisting of lamtoro (*Leuceana leucocephala* (Lam) de Wit) and mix of lamtoro and other horticultural plants such as avocado (*Persea americana* Mill), orange (*Citrus sinensis*) is shown in Figure 2.

Figure 2. **Coffee agroforestry with leucaena as cover crops (left); and with leucaena and other multipurpose trees as cover crops (right)**

The average annual rainfall for the period of 2009-2021 in the Districts of Bener Meriah and Aceh Tengah are 2633.3 mm year^{-1} and 2617.1 mm year^{-1}, respectively. Bener Meriah District is classified in the Type A Climate category (Q = <14.3%), which is a very humid area. On the other hand, Aceh Tengah District (Q = 14.3-33.3%), which is a wet area, is included in the Type B Climate category. In general, the average air temperature is in the range of 25.8-27.5 °C, and the average monthly air humidity is in the range of 81.2-87.1% (BMKG, 2022).

Type of soil most commonly found in the six study areas is Andisol. It is characterized by its dark colour, high porosity, and low density, and is primarily composed of amorphous substances. Due to the rapid decomposition of the porous substrate, allophane minerals, such as allophane and imogolite, are formed (Karim et al. 2019).

Survey and Sampling Methods

There are two coffee harvests every year in the Gayo Highland, namely the March-Juni harvest season and the October-December harvest season. Therefore, this study was conducted during two harvest seasons in 2022: March-June and October-December. The data on coffee yield and its components represent the average of both harvest seasons.

The equipment used includes digital thermometers and hygrometers, electronic scales, buckets for soaking and sorting the coffee beans, plastic sheeting for coffee drying, containers for storage, writing utensils, and other necessary items.

Plot Selection

The coffee plots used in the study comprised of the entire coffee plantation owned by a farmer, with a minimum area of 0.50 hectares, consisting of coffee trees aged between 9 to 15 years and a planting density of 1000 to 1600 trees per hectare. The selected plots had to follow good coffee farming practices by implementing at least four of the six main cultivation techniques, which include adequate shading (more than 100 shade plants per hectare), pruning, weed management, fertilizer application, pest and disease control, and/or soil conservation.

Through interviews with farmers and direct observations of coffee plantations, we identified specific coffee plant plots. The selected plot must fall within one of the altitude categories studied and feature one of the following coffee varieties: Gayo-1 (Timtim), Gayo-2 (Borbor), or Gayo-3 (Ateng Super) varieties. The Gayo-1 (Timtim) variety, also known as Hibrido de Timor, as a natural cross arabica and robusta hybrid, was introduced to Aceh from Timor Island. It is a tall plant type, high yield, resistant to leaf rust, and has a good cup. The Gayo-2 (Borbor) variety was selected from the sympatric population of S795 and Catimor. It is a tall plant type, high yield, resistant to leaf rust, and has a good cup. The Gayo-3 (Ateng Super) variety was selected among

Catimor-based cultivars. It is a dwarf plant type, high yield, resistant to leaf rust, and has a good cup (Hulupi et al. 2013)

Experimental Design

In this study, a randomized completely block design (RCBD) with three replications was utilized across two districts. The study focused on two key factors: altitude and variety. Altitude was divided into three levels - low altitude (>1000-1200 m a.s.l.), mid altitude (>1200-1400 m a.s.l.), and high altitude (>1400-1600 m a.s.l.). The three coffee varieties studied were Gayo-1, Gayo-2, and Gayo-3, and all were grown at the three altitude categories in both districts. The study examined a total of 54 coffee plots, with five plants randomly selected from each plot as plant samples.

Measurement of climatic factors

Between January 2022 and December 2022, we conducted direct field measurement of temperature and humidity (with hourly interval) at different altitudes in our research locations. We used a digitally calibrated temperature and humidity data logger device. The loggers were placed at six locations: two at low altitudes (1050 m and 1100 m a.s.l.), two at mid altitudes (1248 m and 1250 m a.s.l.), and two at high altitudes (1460 m and 1600 m a.s.l.).

Measurement of coffee yield component

The coffee yield components observed include the number of productive branches per plant, the number of productive twigs per productive branch, the number of productive nodes per productive twig, the number of coffee cherries per node, the number of coffee cherries per plant, and the weight of 100 coffee cherries (refer to Figure 3 for more information). The coffee yield component was calculated by taking the average of the coffee yield components over two harvest seasons.

a). Tree level b). Branch level c). Twig level d). Node level e) Cherry level

Figure 3. Coffee yield components; a) Productive branches per plant b) Productive twigs per productive branch; c) Number of productive nodes per productive twig d) Number of cherries per productive node; and e) Weight of 100 coffee cherries.

The number of branches that produce coffee cherries per plant is called the productive branches per plant, as shown in Figure 3 (a). The productive twigs per productive branch, which refers to the average number of twigs that produce coffee cherries per productive branch, is presented in Figure 3 (b). Meanwhile, the number of productive nodes per productive twig, which is the average number of nodes per productive twig, is shown in Figure 3 (c). The number of coffee cherries per node is the average number of coffee cherries found at each node, as seen in Figure 3 (d). Meanwhile, the total number of coffee cherries in one plant is referred to as the number of coffee cherries per plant. Lastly, the weight of 100 coffee cherries (Figure 3 - e) was determined by randomly drawing three samples of 100 cherries from a 12 kg cherry lot collecting from each plot.

Measurement of Coffee Yield

The coffee yield was determined by calculating the average weight of dry coffee beans per plant obtained from two harvest seasons in one year. The harvest and post-harvest processes were carried out following the standard system used by farmers in the research site. Coffee cherries were harvested from each research plot up to a maximum of 12 kg. The cherries were then poured into a container filled with water to separate the sinking cherries from the floating cherries. The coffee cherries were then pulped, fermented for 12 hours, and washed with clean water. The wet coffee grains (bean with parchment) were then dried under the sun for 2-3 days (depending on the weather) until the coffee grains reached 30-35% in moisture. The huller machine was used to remove the parchment from the grains to reveal beans which then were sun-dried again until they reach a water content of 14-15%.

Data analysis

Data of coffee yield components and the coffee yield, namely: the number of productive branches per stem, the number of productive twigs per productive branch, the number of productive nodes per productive twigs, the number of coffee cherries per productive node, the weight of 100 coffee cherries, and the weight of dry coffee beans per plant were all normally distributed. To test the impact of altitude, variety, and the combination of altitude and variety on coffee yields and coffee yield components, parametric tests of RCBD were conducted. The correlation between the coffee yield components and the coffee yield was measured using the Pearson Correlation Test. If the analysis results showed a significant difference, further testing was performed using the Least Significant Difference Test (LSD Test, $p < 0,05$). Statistical analysis was performed using SPSS software version 23.0.3.

RESULTS AND DISCUSSION

Environmental Characteristics of Plots

The study area had an average daily temperature of 20.04 ^{O}C (±3.72) between May 2021 and April 2022. The temperature ranged from a minimum of 6.40 ^{O}C to a maximum of 34.30 ^{O}C. The average daily humidity during this period was 91.70% (±12.14), with a minimum of 32.50% and a maximum of 100%. Table 1 provides the average daily, day, and night temperatures and humidities at low, mid and high altitudes.

Table 1. The average of daily, day, and night temperatures and humidities at different altitudes in May 2021-April 2022

Altitudes (m a.s.l.)	Average Temperature (^{O}C)			Average Humidity (%)		
	Daily	Day	Night	Daily	Day	Night
1075 (1050 and 1100)	21.28	23.57	19.14	92.69	87.01	98.44
1249 (1248 and 1250)	20.59	23.08	18.26	88.96	81.58	96.23
1530 (1460 and 1600)	18.29	20.30	16.41	93.37	88.67	98.08

Note: Daily = 00.00-23.00 hour; Day = 07.00-18.00 hour; Night = 19.00-06.00 hour.

Table 1 shows that the average daily temperature varied by 0.69 ^{O}C per 174 m of altitude difference, or 0.40 ^{O}C per 100 m altitude difference between low and mid altitudes. Meanwhile, between mid and high altitudes, for every 100-meter altitude difference, the average daily temperature difference was 0.82 ^{O}C. During the day, the temperature difference between low and mid altitudes was 0.28 ^{O}C for every 100m of altitude difference. This was lower than the daily averege temperature in the same elevation range. In contrast, the temperature difference between mid and high altitude was 0.99 ^{O}C for every 100 m of altitude difference, which was higher than the daily average temperature differences. During the night, the temperature difference for every 100 m change in low to mid altitude was 0.51°C and in mid to high altitudes was 0.67°C. The average daily humidity at the three altitudes studied ranged from 88.96% to 93.37%, showing no significant difference. The average humidity during the day was between 81.58% and 88.68%, and during the night was between 96.23% and 98.44% at the altitudes studied.

Effect of altitudes on coffee yield components and coffee yield

Altitudes have a very significant effect on the number of productive twigs per productive branch, the number of coffee cherries per plant, and the weight of dry coffee beans per plant, a significant effect on the number of productive branches per plant, but do not have a significant effect on the number of productive nodes per productive twig, the number of coffee cherries per node, and the weight of 100 coffee cherries (Figure 4).

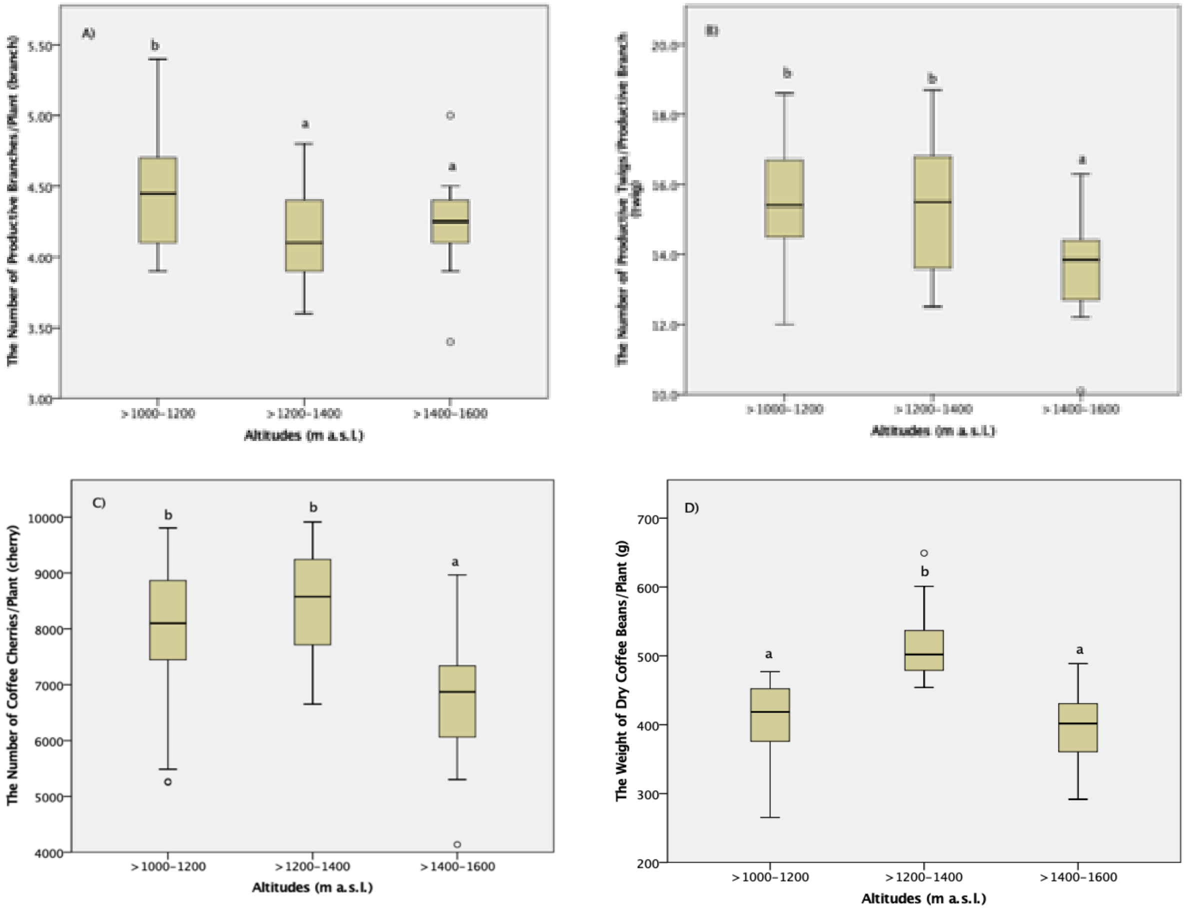

Figure 4. The effect of altitudes on the number of productive branches per plant (A); the number of productive twigs per productive branch (B), the number of coffee cherries per plant (C); and the weight of dry coffee bean per plant (D), RCBD ($p<0.05$); Means followed by the same letter in different boxes are not significantly different at LSD $P<0.05$.

Figure 4 shows that the number of productive branches per plant (A) is better in the low altitudes than in the mid altitudes, but not better than in the high altitudes; the number of productive twigs per productive branch (B) is better in the low altitudes than in the high altitudes, but not better than in the mid altitudes; the number of coffee cherries per plant (C) is better in the mid altitudes than in the high altitudes, but not better than in the low altitudes; and the weight of dry coffee beans per plant (D) is higher in the mid altitudes than in the low and high altitudes.

Generally, coffee trees tend to yield better at low and mid altitudes in terms of the number of productive branches per plant, the number of productive twigs per productive branch, and the number of coffee cherries per plant than at high altitudes. Our discovery aligns with recent research by Sarmiento-Soler et al. (2022) who reported that coffee trees can maintain their productivity and withstand high temperatures despite extreme environmental conditions at lower altitudes. Similarly, DaMatta et al. (2018) also found that coffee trees can maintain their productivity even when exposed to high temperatures. Cerda et al. (2017) and Rahn et al. (2018) suggested that coffee can withstand higher densities and temperatures if there is no restriction on water supply. Overall, the impact of altitudes on coffee growth seems to be a complicated and situation-specific phenomenon. According to additional research, it has been revealed that coffee yield components in low- and mid-altitude regions are potentially influenced by higher temperatures and greater incoming radiation, although not limited by them (DaMatta et al. 2012). In contrast, coffee yield components at higher altitudes may be restricted by cooler temperatures and the presence of clouds, which can decrease incoming radiation.

The weight of dry coffee beans produced by a single plant is influenced by its growing altitude. Coffee trees that grow in mid altitudes yield a higher weight of dry coffee beans per plant compared to those grown in low or high altitudes. Coffee trees at mid altitudes tend to produce a higher weight of dry coffee beans per plant compared to those at low altitudes, despite having similar coffee yield components such as the number of productive twigs per productive branch and the number of coffee cherries per plant. According to a study by Sarmiento-Soller et al. (2019), there is a negative impact of altitude on coffee yield components. These findings are in line with the results of our study, where we observed a significant correlation between altitude and the average weight of the dry coffee beans per plant. It is believed that the reason for the lower quality of coffee beans at low-altitudes is due to the lower ratio of undamaged coffee cherries to dry coffee beans, in comparison to mid-altitudes. Coffee photosynthesis was reported to be highly sensitive to temperatures above 20-25 °C (DaMatta and Ramalho 2006). In areas with warmer climates, high temperatures can reduce the growth of coffee plants. However, they can also be a catalyst for the development and ripening of coffee cherries. This can lead to a reduction in the quality of the coffee as the beans may not fill. During the flowering stage, if the temperature is relatively high, it can lead to abnormal flower development known as "young dead flowers". This is especially true during prolonged dry seasons. DaMatta et al. (2012) found this to be the case, who stated that climate change can lead to increased temperatures that negatively impact the growth, flowering, and fertilization of coffee.

This highlights the importance of shade crops in adapting to solar radiation and extreme temperatures as well as managing coffee plant pests and diseases (Rahn et al. 2018). Coffee berry borer (*Hypothenemus hampei* Ferrari - CBB) attacks and the spread of pathogenic fungi on coffee are lower in shaded cultivation systems compared to open systems (Cardenas et al. 2016). Lowering the temperature around the crops that are grown under shade can help in slowing down the growth of CBB larvae (Jaramillo et al. 2009). Moreover, planting shade crops can also help in the control of pests as it can support species such as birds and ants that are natural predators of pests (Ayalew et al. 2022). According to Olivia et al. (2023), there is a correlation between altitude gradient and the number of CBB per fruit, where the increase in altitude gradient results in a decrease in the number of CBB per fruit. Abubakar et al. (2024) discovered that defective beans caused by floating cherries tend to decrease as the elevation of the farm increases. The study found that high-altitude farms have the lowest average percentage of defective beans (8.3%), while low-altitude farms have the highest percentage of defective beans (14.3%). Olivia et al. (2023) found that dried leftover berries at lower altitudes had the highest levels of damage (37.5%), holes per berry (10.88%), and adult CBB per berry (7.55%). Anhar et al. (2021b) discovered that coffee productivity can be increased by raising the elevation from lower to medium altitudes and increasing the shade density from low to medium in the same region. However, if the elevation is further increased to higher altitudes, the productivity may decline.

The lower yield of dry coffee beans at high altitudes is due to suboptimal physiological activity. We thought higher altitudes would lead to better coffee yields due to suboptimal environmental conditions at lower altitudes. At mid altitudes, the assumption that optimal environmental conditions lead to higher coffee yields has been substantiated. However, at high altitudes, this assumption does not hold. Interestingly, coffee yields at low altitudes remain better, although the difference is not statistically significant. In a comparable study of smallholder plantations in Costa Rica, researchers found that increasing altitude did not positively impact coffee yield. De Bauw et al. (2016) attributed this lack of altitude effect to the soil fertility gradient in the region, where soil richness tends to be higher at lower altitudes. Coffee trees cultivated at higher altitudes yield less coffee compared to those grown at mid and low altitudes. The suboptimal environmental conditions at higher altitudes hinder coffee growth and development. Hence, additional research is necessary to pinpoint potential opportunities and challenges for the sustainable advancement of coffee cultivation at higher altitudes. Equally crucial is the assessment of the implications arising from such research, encompassing both the potential benefits and risks to coffee farmers and the environment.

Effect of varieties on coffee yield components and coffee yield

Varieties only significantly affect the number of productive nodes per productive twig. However, they do not significantly influence other coffee yield components, such as the number of productive branches per plant, the number of productive twigs per productive branch, the number of coffee cherries per plant, the weight of 100 coffee cherries, and overall coffee yield (i.e., the weight of dry coffee beans per plant) (Figure 5).

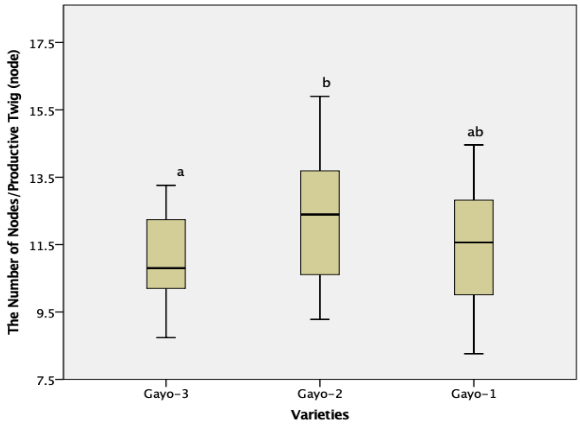

Figure 5. The impact of different varieties on the number of productive nodes per productive twig. RCBD ($p < 0.05$). The means that share the same letter in distinct boxes are not significantly different according to the least significant difference (LSD) test at $p < 0.05$.

Figure 5 illustrates that the number of productive nodes per productive twig is significantly better in the Gayo-2 variety compared to the Gayo-3 variety. However, it is not significantly better than in the Gayo-1 variety. Based on our research findings, the three coffee varieties under examination exhibit a significant impact specifically on the number of productive nodes per productive twig. However, these varieties do not influence any other coffee yield components or coffee yield. This contrasts with a recent study carried out in the same region, examining the same three coffee varieties. The study by Wardiana et al. (2024) revealed that these varieties indeed impact coffee yield across different altitudes. However, their investigation is limited to two specific altitudes: 900 m and 1600 m a.s.l. In the same region, Hulupi et al. (2013) also observed that the Gayo-3 variety yields more coffee cherries per plant annually compared to the Gayo-1 and Gayo-2) varieties. However, despite these findings, they do not endorse the Gayo-3 as a superior variety due to the unstable results. The dwarf coffee varieties such as Gayo-3 exhibit an interesting pattern in their yield. Initially, they tend to produce abundant fruit during the early years of cultivation. However, this high-yield phase is followed by a biennial cycle, where heavy fruiting occurs only every two years. This cyclic behaviour can introduce instability in coffee production. It is worth considering that the timing of research or data collection might have coincided with a fruit-bearing season for the Gayo-3 variety. This alignment could have influenced the observed yield patterns during the study. Understanding these dynamics is critical for developing effective strategies for managing coffee production and overcoming the challenges coffee farmers face. Even in the management of dwarf-type Arabica coffee, there is a significant demand for inputs, particularly in terms of nutrient requirements and maintenance. However, it is important to remember that overfertilizing can be detrimental and needs to be balanced. If the plants receive too much fertilizer, they may wither and eventually die due to their relatively short lifespan (Hulupi et al. 2013).

Effect of combination of altitudes and varieties on coffee yield components and coffee yield

The combination of altitudes and coffee varieties significantly impacts two key factors: the number of productive twigs per productive branch and the weight of 100 coffee cherries. However, this combination does not significantly affect other parameters, such as the number of productive branches per plant, the number of productive nodes per productive twig, the number of coffee cherries per productive node, the number of coffee cherries per plant, and the weight of dry coffee beans per plant (Table 2).

Table 2. The number of productive twigs per productive branch and the weight of 100 coffee cherries across different altitude-variety combinations

Varieties	Altitudes (m a.s.l.)		
	>1000-1200	>1200-1400	>1400-1600
The number of productive twigs per productive branch			
Gayo-1	16.38 (1.97) b A	16.22 (1.52) b B	13.28 (1.96) a A
Gayo-2	14.53 (1.36) a A	16.15 (1.86) b B	12.80 (1.42) a A
Gayo-3	15.82 (1.03) a A	14.15 (1.88) a A	14.28 (2.25) a A
	LSD P<0.05 = 1.91		
The weight of 100 coffee cherries			
Gayo-1	205.0 (8.02) b B	202,4 (8.26) b A	185.3 (12.59) a A
Gayo-2	194.8 (7.60) a AB	192.5 (9.03) a A	192.4 (18.35) a A
Gayo-3	190.5 (3.33) a A	199.1 (5.24) a A	196.6 (7.62) a A
	LSD P<0.05= 11.88		

Note: RCBD (p<0.05); The mean followed by the same lowercase letter on the same line and the same (uppercase) capital letter on the same column is not significantly different at LSD P<0.05; The numbers in brackets are the standard deviation

According to Table 2, the Gayo-1 variety produces a higher number of productive twigs per productive branch at low and medium altitudes compared to high altitudes. The Gayo-2 variety produces a higher number of productive twigs per branch at mid altitudes, compared to low altitudes and high altitudes. The Gayo-3 variety does not produce a different number of productive twigs per productive branch at any altitudes studied. On average, the Gayo-1 variety produces more productive twigs per productive branch than the Gayo-2 and Gayo-3 varieties at low altitudes. However, at mid altitudes, both the Gayo-1 and Gayo-2 varieties produce more productive twigs per productive branch than the Gayo-3 variety. The gayo-1 variety has a better weight of 100 coffee cherries at low and medium altitudes compared to the Gayo-2 and Gayo-3 varieties.

The Gayo-1 is better suited for low and mid altitude areas, while the Gayo-2) is better suited for mid altitudes. DaMatta and Ramalho (2006) reported that some arabica coffee varieties - particularly those that are a blend of robusta coffee and grown under intensive management conditions - have been able to thrive in areas that were previously considered unsuitable due to the high average temperature (up to 24-25 °C). The reason for the good yield of the coffee components being produced at low-altitude areas, especially for a well-adaptive variety, may be due to the presence of shade crops. When coffee plants are grown in full sunlight, they may become stressed due to excess energy generation and other factors such as heat waves. This can cause the leaves to become excessively hot, up to 15-20 °C above the air temperature. However, when shade crops are introduced, they can create a microclimate that provides various ecological and socio-economic benefits, such as improved coffee yield.

Correlation coefficient of coffee yield components and coffee yield

We observe a positive relationship between the number of coffee cherries per plant to both the number of productive branches per plant and the number of productive twigs per productive branch (Table 3). This suggests that the number of productive branches per plant and the number of productive wigs per branch play a crucial role in determining the overall yield of coffee cherries per plant.

Table 3. Pearson's correlation coefficient of coffee yields and coffee yield components

	PBP	PTB	PNT	NCN	NCP	WDB
PBP	1					
PTB	0.455**	1				
PNT	-0.028	-0.206	1			
NCN	-0.308*	-0.231	-0.651**	1		
NCP	0.436**	0.526**	-0.225	-0.028	1	
WDB	-0.117	0.202	-0.51	0.452**	0.195	1

Note: n = 54; PBP = the number of productive branches per plant; PTB = the number of productive twigs per productive branch; PNT = the number of productive nodes per productive twig; NCN = the number of coffee cherries per productive node; NCP = the number of coffee cherries per plant, and WDP = the weight of dry coffee bean per plant

The findings of this research support the results obtained from interviews with farmers, which suggest that pruning is the most significant factor in coffee plantation maintenance that affects coffee yield. Among the two types of pruning practised in Gayo Highland, productive pruning appears to be more effective than shape pruning. Productive pruning involves removing new shoots that grow from the branch and/or twig. If these new shoots are left unpruned, it can adversely affect the number of productive twigs per plant, reducing the number of coffee cherries formed per node and plant, and ultimately lowering the average weight of dry coffee beans per plant. Shape pruning involves cutting plant shoots and maintaining 3-5 main branches as productive branches per plant. From each of these main branches, 10-15 twigs are maintained, depending on the number of shoots emerging from them. A study conducted in Kenya with wide plant spacing suggests that the number of nodes per plant is more important than the number of coffee cherries per node in determining the yield of arabica coffee. However, a report by Sarmiento-Soller et al. (2022) in Uganda shows that the number of productive branches per hectare does not correlate with altitude. In addition, the average number of productive branches per plant is positively correlated with the average number of productive twigs per productive branch. On the other hand, the average number of coffee cherries per productive node is negatively correlated with the average number of productive nodes per productive twig and with the average number of productive branches per plant. Our study also found that the weight of dry coffee beans per plant is strongly and positively correlated with the average number of cherries per node, which is consistent with Sarmiento-Soller et al. (2019), who reported a positive and significant relationship between the number of coffee cherries per node and the number of productive nodes. However, the latter is not significantly correlated with our study.

CONCLUSION

In conclusion**,** the results of this study show that altitudes have a significant influence on the productivity of coffee plants. The number of productive branches per plant, the number of productive twigs per branch, the number of coffee cherries per plant, and the weight of dry coffee beans per plant are all affected by altitudes. Coffee in low and mid altitudes produces a higher number of productive twigs per branch, as well as more coffee cherries per plant, compared to that in high altitudes. Increase in altitude from low to mid increases the weight of dry coffee beans per plant, but then decreases as altitudes increase further to high altitudes. The variety observed only has a significant effect on the average of productive nodes per twig. However, the combination of altitudes and varieties significantly affects the productive twigs per branch and the weight of 100 coffee cherries. To maximize yield, Gayo-1 is better suited for low and mid altitudes, Gayo-2 is better suited for mid altitudes, and Gayo-3 is suitable for low, mid, and high altitudes.

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