Response of Coffee Varieties to Contrasting Soil Moisture Regimes at Seedling Stage

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Abstract

Drought stress has become a devastating and chronic factor affecting growth, yield and quality of arabica coffee (Coffea arabica L). The study was initiated to investigate root traits of coffee varieties associated with drought tolerance. The experiment was carried out in plastic shelter with a factorial randomized complete block design in three replications. A total of 20 treatments combinations viz; ten arabica coffee varieties (five drought tolerant and five sensitive) with two water regimes (well-watered and water stressed) were used. Various root traits were measured and subjected to analysis of variance. It was observed that except for tap root diameter, the remaining root traits of varieties were significantly ($p < 0.05$) affected by soil moisture regimes and recovery periods. Compared to well-watered regime, all the measured root traits were significantly increased under soil moisture stress. The highest taproot length, taproot diameter and root length density were obtained from 74110, while the highest specific root length was recorded from Bultum under both soil moisture stress and recovery periods. At similar conditions variety Angefa had shown the highest root volume, root angle, root to shoot ratio and root mass ratio. However, varieties Mokah, Menasibu and MCH2 were least performed. Overall, the study investigated variability of coffee varieties in root traits and their mechanisms for drought stress adaptation, and declared further exploration using more genotypes.

Keywords: Root angle, Root traits, Soil moisture regimes, Varieties.

Introduction

Coffee *(Coffea arabica* L.), whose centre of origin and diversity is Ethiopia, accounts for more than 62% of the world coffee production (Chalchissa *et al*., 2022) and 90% of the world coffee market (Mohammed and Astaskie, 2010). It accounts for more than 60% of Ethiopia's foreign exchange earnings and 25% of the population's employment opportunity (Tadesse *et al.,* 2020). However, the crop's national average yield remains very low, rarely exceeding 0.64 ton ha^{-1} (CSA, 2022), which can be attributed to varieties of production constraints, including drought stress (Tesfaye and Ismail, 2008).

Drought stress is the most significant limiting factor of crop production, and it is becoming more severe in many parts of the world (Passioura, 2010). During very dry years, coffee yields in some marginal areas with no irrigation can drop by up to 80% (DaMatta and Ramalho, 2006). However, plants have a mechanism for coping either by increasing water uptake by developing a deep and vigorous root system and tapping ground water, or by decreasing water loss by closing stomata and growing small sized leaves (Kozlowski and Pallardy, 2002).

Plant root traits have evolved to be highly responsive and adaptable to their surroundings, with their morphology, growth, and physiology all being closely related to plant genotypes and growth medium properties (Wasaya *et al.,* 2018). For example, deeper root systems can determine water absorption/uptake ability among different root types as an adaptation strategy under drought stress conditions (Bengough *et al.,* 2011 and Wasaya *et al.*, 2018). Many studies have found genetic variation in root characteristics and their functional implications for water uptake (Manschadi *et al.*, 2008), as well as differences in moisture stress adaptation mechanisms among coffee varieties (Mohammed and Astaskie, 2010). Taye and Burkhardt (2013) reported that root traits are used in the characterization and adaptation of plant species to various biotic and abiotic factors (e.g. drought). However, most studies ignored the root part and focused on the above ground part only. Therefore, study was conducted to investigate root traits of coffee varieties with regard to moisture stress.

Material and Methods

Study site

The trial was conducted at Jimma Agricultural Research Center (JARC) nursery site which is located in Jimma zone Oromia regional state, Southwest Ethiopia 365 kilometer away from Addis Ababa and 12 km from Jimma Town. Geographically it lies between 7^0 46' N latitude and 36^0 47' E longitudes at an altitude 1750 meter above sea level. The area receives average annual precipitation of 1532 mm, with approximate minimum and maximum temperature of 11.73°C and 26.11°C, respectively (JARC meteorology station, 2021).

Treatments

A total of ten coffee varieties (Gawe, 74110, Bultum, Chala and Angefa among drought tolerant and Melko CH2, 75227, Mokah, Menasibu, and Koti among sensitive) were selected according to Tesfaye (2006); Robel *et al.,* (2018); JARC, (2018/19) and Mulugeta *et al.*, 2018 and two water regimes (well-watered/non-stressed and water stressed) were used; which made a total combination of 20 treatments.

Experimental, design and procedures

The experiment was conducted under plastic shelter by using factorial randomized complete block design with three replications. A well-dried and sieved top soil with 5mm wire meshe was prepared. Seedling growth media was consisted of top soil, compost, and sand in a 3:2:1 ratio and filled into polythene tube (10 cm width x 24 cm length or 1884 cm3) (Taye *et al*., 1999). All required nursery management practices were carried out (Anteneh *et al*., 2008). Coffee seedlings with four pairs of leaves, uniform growth and healthy appearance were selected and transferred to a larger bottom open

black pot with a size of (23x19) cm or 3945 cm3, which used to increase the area for the growth of the root traits. Seedlings were kept under shelter conditions, then after have of the sampled seedlings were subjected to soil moisture stress until the available soil moisture reached less than 35%, followed by rehydrating for 15 days to assess the varieties' recovery ability. Soil moisture was determined for each sampling day by computing proportion of the moist and dried weights of the soil (one kg from each pot) and averaging them. The moist weight of the sampled soil was taken and oven dried at 105°C for 24 hours to determine moisture content (FAO, 1971). Moisture content was determined using the following formula:

$$\text{Soil moisture on dry weight basis (\%)} = \frac{\text{wt. of moist soil-wt. dry soil}}{\text{Wt. dry soil}} \times 100$$

All the measured root traits were recorded from five plants with the indicated measurement methods in table 1.

Table 1. The root parameters and their measurement methods.

Parameters	Measurement methods
Tap root length	The tap roots length was measured from the collar of the seedling to the tip by using standard ruler
Tap root diameter	The diameter of taproot was of sampled seedling was measured by using caliper.
Specific root length	It was calculated by recording the ratio of root length to total dry mass roots.
Root length density	The root length density was calculated by recording the ratio of total length of roots per unit of soil volume. Soil volume (cm^3): πr^2*h
Root volume	Measured by water displacement method using graduated cylinder 200ml filed with water.
Root angle	The sampled root was measured using a modified protractor with an angle range of 0°- 90° on both sides (Sakhare *et al*., 2019).
Root to shoot ratio	It was calculated by recording the ratio of root dry weight to dry weight shoot (Leaf + Stem). Root-shoot ratio (RSR) = root dry weight/shoot dry weight
Root mass ratio	It was calculated by recording the ratio of root mass to total mass of seedling.

Data analysis

Data were analyzed using a two-way analysis of variance (ANOVA) in R version 4.04, and mean separation was carried out using least significant differences using the *agricolae* packages at 5% probability level (De, 2009). Error bar graph was plotted using *ggplot2* packages for data visualization to describe and compare the dependent and independent variables.

Results and Discussion

Soil moisture content during the study periods

The mean result recorded at each soil moisture stress period of 0, 15, 30, and 15 days recovery periods (45 days after treatment application) revealed no significant differences in the percentage of soil moisture content for all varieties. During stress (0-15) and 15-day recovery periods, the average soil moisture content decreased from 22.48 to 18.26 % and increased to 18.59 %, respectively (Figure 1). However, there was variation between potted coffee seedlings during the severe soil moisture stress period (30 days), and the moisture contents were reduced by approximately 43.34 % from the initial moisture contents.

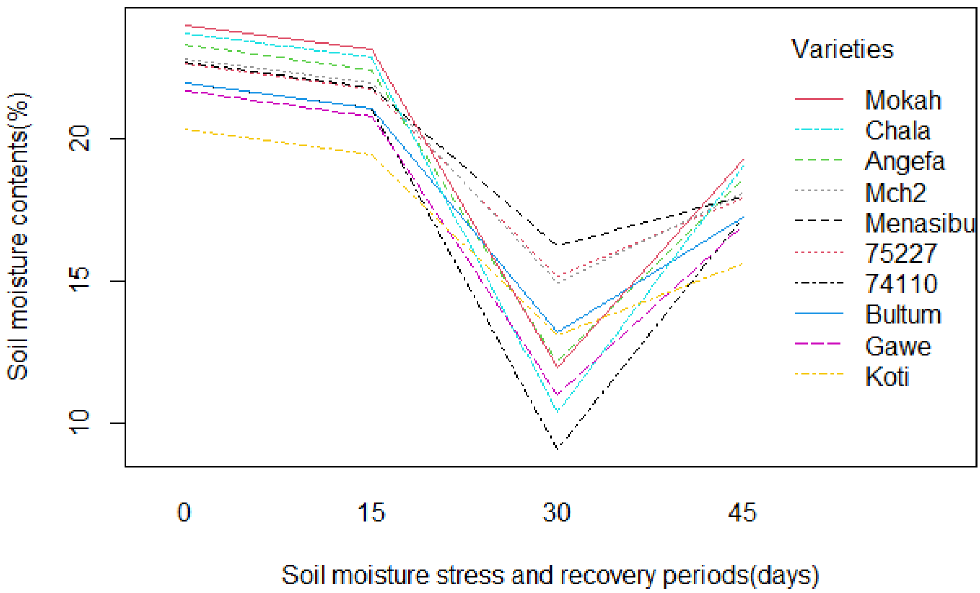

Figure 1. Soil moisture contents during soil moisture stress and recovery periods.

Effect of contrasting soil moisture regime and recovery periods on root traits of coffee varieties

Taproot length and diameter

Soil moisture regimes and coffee varieties had significant effect on all root trait measurements. The result revealed that, most of the measured root traits under moisture stressed condition were significantly increased compared to well-watered regime. Despite variation between varieties, the taproot length of coffee seedlings was significantly increased during soil moisture stress and recovery periods. Under both stress and recovery periods, variety 74110 exhibited the highest mean, followed by Gawe, while the shortest varieties were obtained and ranked as Mokah > 75227 > MCH2 > Menasibu (Figure 2 and Table 3) which is indicated that when tolerant coffee varieties were subjected to soil moisture stress, their root length increased, and they recovered quickly. The result is in line with the finding of (Mohammed, 2004; Robel *et al*., 2018), who reported that coffee plants with deeper root systems extract water from deeper soil layers, allowing the plants to avoid soil moisture stresses. DaMatta *et al*. (2003) also reported that drought-tolerant coffee varieties' possess deeper root systems, which allowed them to gain greater access to water near the soil surface and maintain a more favorable internal water status for a longer period than drought-sensitive coffee varieties. Similarly, the highest taproot diameter also recorded from 74110 followed by Angefa, while the lowest were obtained from Mokah (Figure 3). When drought tolerant varieties were compared to sensitive varieties, both taproot length and diameter of drought tolerant varieties increased during moisture stress by 28%.Clark *et al.* (2008) discovered that larger taproot diameters play a direct role in drought tolerance due to increased penetration and branching. Under water stress conditions, varieties with larger root diameter can support accelerated plant growth while maintaining relatively high transpiration efficiency (Puangbut *et al*., 2009).

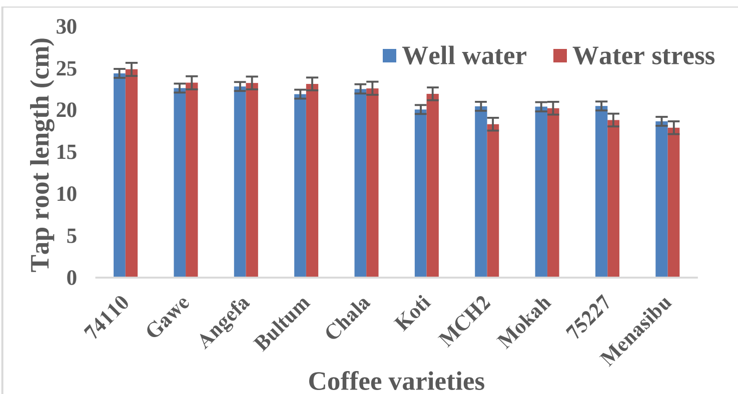

Figure 2. Tap root length of coffee varieties under well water and water stress soil moisture regimes.

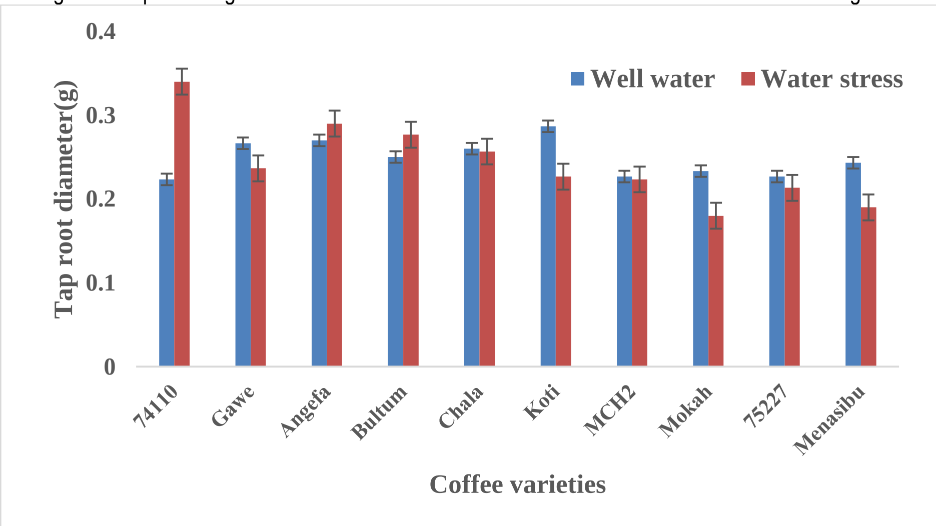

Figure 3. Tap root diameter of coffee varieties under well water and water stress soil moisture regimes. Bars represent the standard error of means of three replications.

Specific root length and Root length density

Specific root length was significantly affected during the stress and recovery periods. Under stress regimes, the specific root length of coffee seedlings was increased by 13% when compared to well-watered. Bultum variety consistently had the highest specific root length at both regimes and recovery periods, while the lowest mean value was obtained from variety Mokah under stressed regime (Figure 4 and Table 3). The specific root length of the Bultum variety increased by 38% on average under stress regimes, compared to Mokah, MCH2, and Koti. This indicates that Bultum had constituent response under both conditions, resulting in the adaptation to stress conditions. Ostonen *et al*. (2007) found that the increases in specific root length improve plant performance and carbon economy in water-stressed conditions. Nahar *et al*. (2018) also found that drought-tolerant varieties had greater specific root length than sensitive ones. The root length density of coffee seedlings increased significantly during soil moisture stress and recovery periods, but decreased completely in well water (Figure 5 and Table 2&3). The highest root length density was obtained from 74110 followed by Angefa and Koti under soil moisture stress, while the lowest was obtained from 75227 (Figure 5). In contrast, the root length density of coffee varieties did not vary under well water condition (Table 3).The RLD of tolerant varieties increased by approximately 22% compared to sensitive varieties under stress regimes. The result suggested under stressed condition, the root length density of coffee seedlings were significantly increased which might be due to the increments of root length and root angle. Franco *et al*. (2011) discovered that increasing root length density increased water uptake capacity and was strongly related to root depth. Huang *et al*. (2000) also reported that varieties with higher root length density in the deep soil layer can maintain water status and stomatal conductance when the soil becomes drier than varieties with lower root length density.

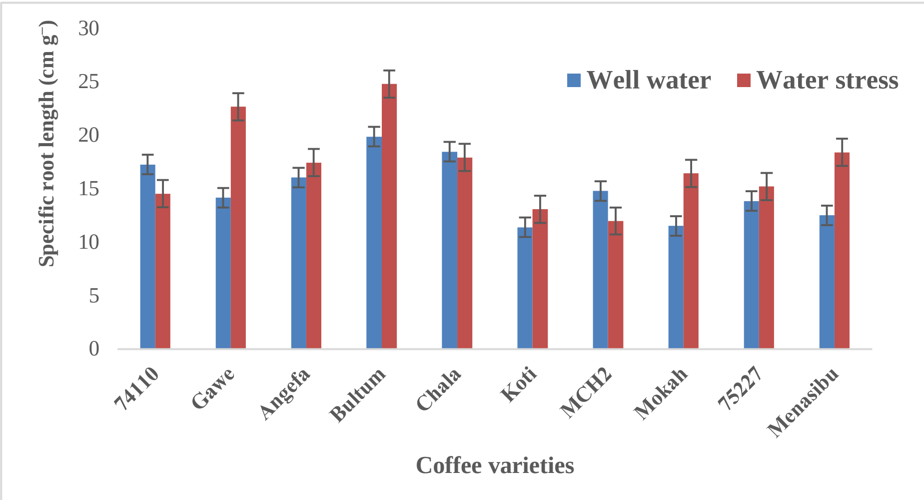

Figure 4. Specific root length of coffee varieties under well water and water stress soil moisture regimes.

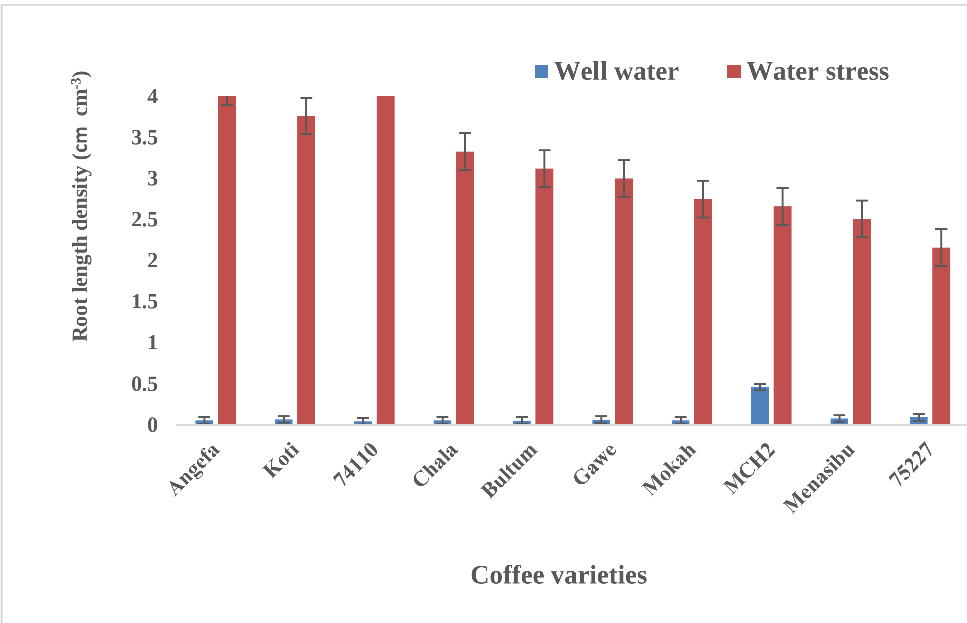

Figure 5. Root length density of coffee varieties under well water and water stress soil moisture regimes. Bars represent the standard error of means of three replications.

Root volume and Root angle

The root volume of coffee seedlings also increased by approximately 13% when comparing the seedlings grown under stress with well-watered condition. Angefa and 74110 exhibited the highest root volume under both regimes and recovery periods, while the lowest were obtained from MCH2 (Figure 6 and Table 3). The root volume of tolerant varieties increased by approximately 34% on average compared to sentive ones. This might be due to an increase in lateral root number and root dry matter production. Tesfaye's (2006) and Mohammed and Astatkie's (2010) reported that coffee seedlings with greater root volume have greater root robustness and, presumably, a higher accumulation of reserves and are used to adapt to soil moisture stress. This accumulation is primarily composed of solutes accumulated by plants and is required to maintain the water gradient and absorb water during times of scarcity in the soil (Banon *et al*., 2006).

Like root volume, the root angle of coffee seedlings were increased by 27.62% under soil moisture stress. Coffeee variety 74110 and Bultum varieties consistently had the highest mean during both stress, recovery periods, while Menasibu, and 75227 had the lowest (Figure 7). Except for Koti (sensitive), the highest root angle was recorded under soil moisture stress from drought tolerant varieties, and their root angle was increased by an average of 21% compared to sensitive ones. This suggested that under stress conditions, the root angle of coffee seedlings increased as root depth increased. Hanzawa *et al.* (2013) found that the root angle and root depth have a positive relationship within each other. The current finding revealed that the average root angle of tolerant varieties was between 40°-60° (medium class), while sensitive varieties were between 0°-40° (wider class) (Sakhare *et al*.,2019). Mohammed (2004) finding conclude that coffee seedling may not develop long root under stress condition.

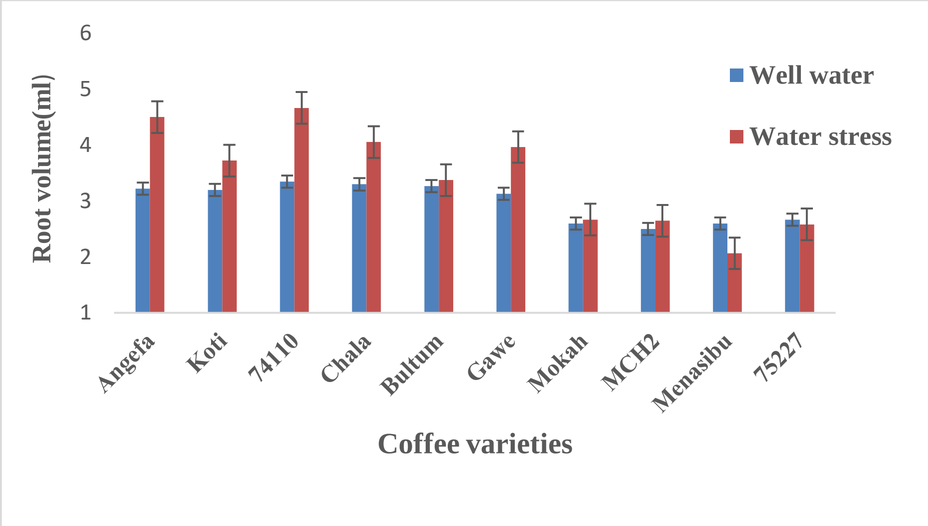

Figure 6. Root volume of coffee varieties under well water and water stress soil moisture regimes.

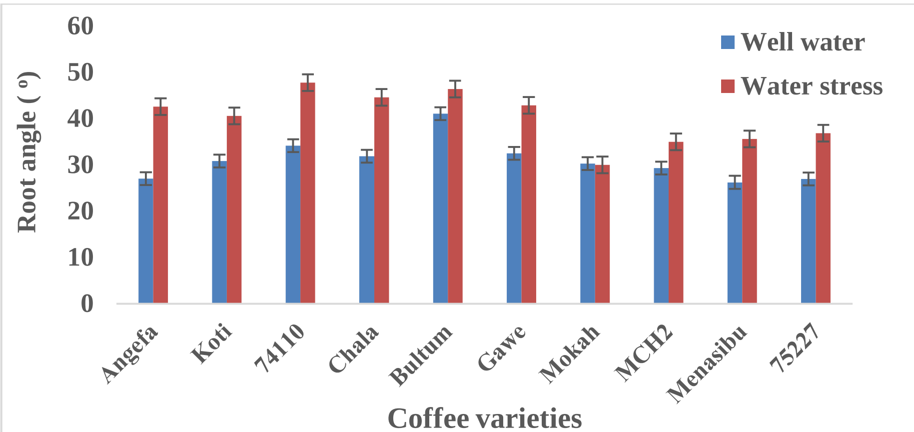

Figure 7. Root angle of coffee varieties under well water and water stress soil moisture regimes. Bars represent the standard error of means of three replications.

Root to shoot ratio and Root mass ratio

Among dry matter production and partitioning, root mass ratio and root to shoot ratio are the most important root traits for drought tolerance adaptation mechanism. Root mass ratio and root to shoot ratio increased by about 12 and 19%, respectively, when exposed to soil moisture stress. Varieties Angefa exhibited the highest mean in both RMR and RSR, followed by Bultum and 74110, while Menasibu, 75227, and MCH2 had the lowest (Figure 8 and 9).When compared varieties, with the exception of Koti (sensitive), RMR and RSR of tolerant varieties were increased by an average of 23 and 69%, respectively. This showed that when coffee seedlings were exposed to moisture stress, they assimilate and partitioned plant biomass toward the root to cope with the stress. Farooq *et al*. (2010) found that increasing dry matter partitioning from shoot to roots is thought to be a plant's adaptive strategy for dealing with drought conditions. Dry matter translocation to roots enhances root growth and subsequently increases water uptake ability of the plants. Increasing the RMR and RSR involves biochemical signaling between the root and the shoot in order to adjust shoot growth during water-limited conditions. In line with the current studies Mohammed and Astatkie (2010) reported that drought tolerant coffee varieties allocated more dry matter to roots than shoots showing the largest root mass ratio.

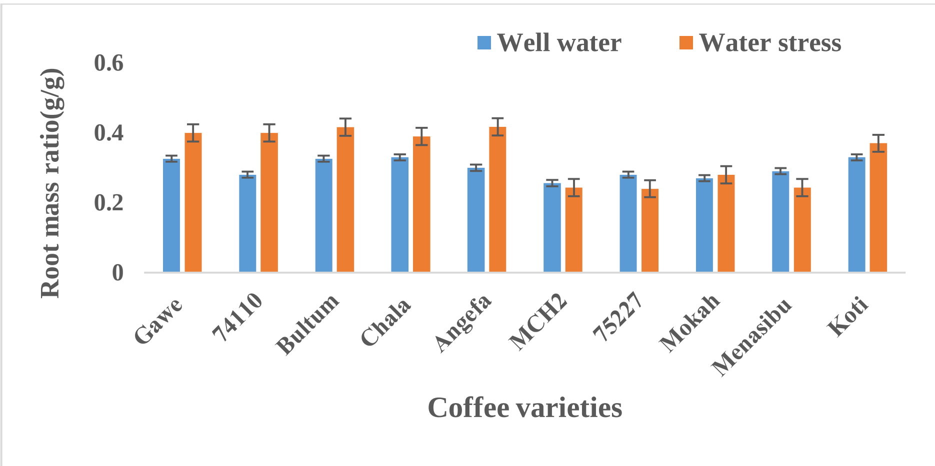

Figure 8. Root mass ratio of coffee varieties under well water and water stress soil moisture regimes.

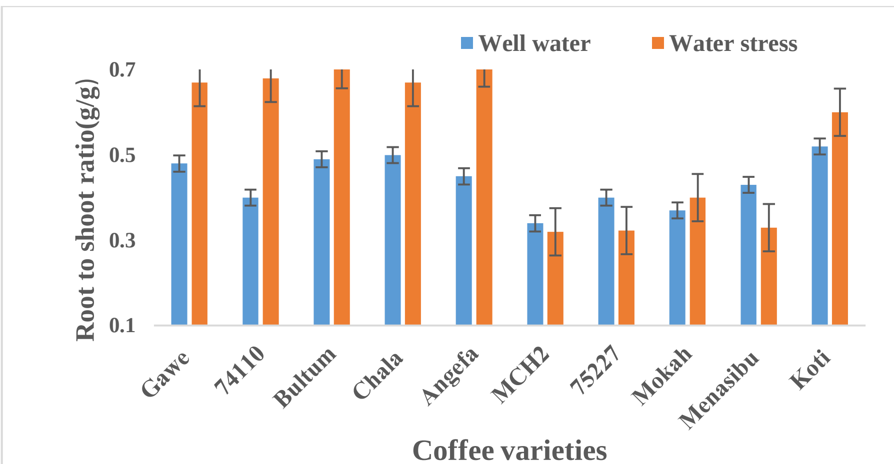

Figure 9. Root to shoot ratio of coffee varieties under well water and water stress soil moisture regimes. Bars represent the standard error of means of three replications.

Table 2. ANOVA for root traits of coffee varieties under well water and water stress regimes.

Source of variation	Mean square								
	df	TRL	TRD	SRL	RLD	RV	RA	RMR	RSR
REP	2	9.46^{ns}	0.0071*	5.04^{ns}	0.05^{ns}	0.31^{ns}	20.4^{ns}	0.017^{ns}	0.08^{ns}
SMR	1	14.13^{ns}	0.00042^{ns}	76.70**	166.87**	2.9**	1269.3**	0.028**	0.163**
VAR	9	8.35*	0.0043**	52.46**	1.55**	2.2**	122.7**	0.014**	0.07**
SMR*VAR	9	2.11*	0.0041***	21.13**	1.54**	0.54**	32**	0.005*	0.029*
Error	38	3.76	0.00088	4.59	0.30	0.17	9.3	0.0021	0.10

Table 3. Means of growth parameters during recovery periods.

Varieties	Growth parameters							
	TRL	TRD	SRL	RLD	RV	RA	RMR	RSR
Gawe	21.50	0.29	15.8	4.56	3.36	38	0.29	0.41
74110	25.37	0.24	16.6	2.76	4.40	42	0.36	0.58
Bultum	24.37	0.22	21.1	2.03	3.46	47	0.37	0.59
Chala	23.37	0.19	19.9	3.16	4.10	35	0.42	0.74
Angefa	22.70	0.24	19.3	3.2	4.60	43	0.37	0.61
MCH2	20.03	0.20	11.0	2.80	2.16	36	0.30	0.37
75227	19.40	0.24	13.4	2.36	2.63	37	0.27	0.40
Mokah	19.19	0.20	14	3.16	2.78	31	0.30	0.43
Menasibu	22.03	0.18	13.0	3.06	2.63	32	0.24	0.33
Koti	19.50	0.20	14.9	3.80	3.20	37	0.33	0.48
CV (%)	2.40	23.19	14.9	9.12	4.13	6.3	6.00	17.12
LSD (p = 0.05)	0.51	0.089^{ns}	3.96**	0.48**	0.23**	4.0*	10.75**	0.14***

Where ^{ns} = non significant * = significant ** = highly significant, *** = very highly significant, SMR = Soil moisture regimes, VAR = Varieties, TRL = Tap root length, TRD = Tap root diameter, SRL = Specific root length, RLD = Root length density, RA = Root angle , RV = Root volume, = Root mass ratio, RSR = Root to shoot ratio.

Summary and Conclusions

This study suggested that the root traits of coffee varieties are the primary traits used for adaptation and tolerance of coffee plant. Most root traits were influenced by soil moisture regime and coffee varieties, with most traits increasing under water stress regimes. Under both stress and recovery condition the highest taproot length, taproot diameter and root length density were obtained from 74110, while Bultum had the highest specific root length. Variety Angefa had the highest root volume and root angle, where the average root angle of tolerant varieties was between 40°-60° (medium class), while sensitive varieties were between 0°-40° (wider class). The highest root to shoot ratio and root mass ratio were obtained from Angefa, followed by Bultum variety while Menasibu, Mokah, 75227, and MCH2 were least performed. The study confirmed that drought tolerant varieties had higher revival capacity and root growth traits than sensitive varieties, indicating that they have mechanisms for drought stress adaptation and a greater ability to recover from moisture stress. In conclusion, root traits are among the most important parameters used to understand the mechanisms of coffee varieties under various conditions, in complementing to physiological and biochemical traits, resulting in efficiency and safety for selecting and developing more promising, productive, and drought-tolerant varieties.

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