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Response of chickpea to varying moisture stress conditions in Ethiopia

Lijalem Korbu[1] | **Asnake Fikre**[1] | **Kassahun Tesfaye**[2] | **Assefa Funga**[1] | **Dagnachew Bekele**[1] | **Chris O. Ojiewo**[3]

[1] Debre Zeit Research Center, Ethiopian Institute of Agricultural Research (EIAR), Debre Zeit, Ethiopia

[2] Ethiopian Biotechnology Institute (EBI),Institute of BiotechnologyAddis Ababa Univ., Addis Ababa, Ethiopia

[3] International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), UN-Avenue, Nairobi, Kenya

Correspondence

Lijalem Korbu, Ethiopian Institute of Agricultural Research (EIAR), Debre Zeit Research Center, Debre Zeit, Ethiopia.
Email: lkorbu.balcha@gmail.com

Asnake Fikre, Ethiopian Institute of Agricultural Research (EIAR), Debre Zeit Research Center, Debre Zeit, Ethiopia.
Email: fikreasnake@yahoo.com

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Abstract

Chickpea (*Cicer arietinum* L.) is an economically important crop grown by nearly one million Ethiopian smallholder farmers. The crop is often considered as "stress-loving," but moisture stress at flowering and grain filling stages could be detrimental. Yield of chickpea is commonly affected by terminal drought stress in the rainfed production system in Ethiopia. The lack of proper field-screening methods has hindered the development of drought-tolerant varieties. This study demonstrates a simple and practical field-level screening method for drought tolerance traits in the conventional breeding programs. A field experiment was conducted using 28 elite chickpea cultivars during the 2018–2019 main cropping season to study their response to moisture regimes of varying drought intensities. We used yield and its components as proxy parameters of screening to select tolerant cultivars. The study revealed significant variation among the cultivars in their response to different moisture regimes. The kabuli cultivars were found more sensitive compared with the desi types. Yield penalty exceeded 70% under severe drought. Conversely, cultivars tested under mild and severe stress drought showed average yield gain of 22 and 48%, respectively, relative to the irrigated treatment. Overall, over 50% yield gain can be obtained in drought-affected rainfed production areas in Ethiopia using supplemental irrigation during pod setting to grain filling stages. For post-rainy-season crops relying on residual soil moisture, such as chickpea, breeding for shorter duration and resilient cultivars are reliable management approaches to minimize drought-caused yield losses.

Abbreviations: BY, biomass yield; DAS, days after sowing; DTF, days to 50% flowering; DTI, drought tolerance index; DTM, days to maturity; DZARC, Debre-Zeit Agricultural Research Center; ET, evapotranspiration; GFP, grain filling period; GGE, genotype × environment plus genotype; GY, grain yield; HI, harvest index; HSW, hundred-seed weight; PHT, plant height; PP, pod yield per plant; RF, rainfed treatment; SP, seeds per pod; SSI, stress susceptibility index; TOL, tolerance index; WS, water-stressed treatment; WW, well-watered treatment.

1 | INTRODUCTION

Chickpea (*Cicer arietinum* L.) is an important cool-season food legume grown and consumed predominantly in the arid and semiarid tropical regions of the world. It is the world's second most important food legume representing an important component of the small-scale crop production (Varshney et al., 2014). It is an excellent source of high-quality edible protein particularly for the underprivileged population (Jukanti et al., 2012). Globally, chickpea is cultivated on an area of 17.85 million ha with an annual production of over 17 Tg (FAOSTAT, 2019). Among chickpea-growing countries, India alone contributes about 70% of the world's total production (Korbu et al., 2020). Ethiopia is the leading chickpea producer in Africa, producing more than 500,000 metric tons per year from an area of ∼243,000 ha of smallholder farms (CSA, 2019; FAOSTAT, 2019), accounting for over 90% of grain production in sub-Saharan Africa (Verkaart et al., 2017).

Chickpea is an economically important crop in Ethiopia grown by more than 900,000 smallholder farmers (CSA, 2019). The crop is well known as one of the major food legumes having great nutritional values for millions of farming communities. Ethiopia has diverse agroecologies with high potential for chickpea production (Fikre et al., 2018; Korbu et al., 2020), making it one of the world's leading countries in terms of productivity per unit area (FAO, 2018). Chickpea is grown during the post-rainy season to escape waterlogging conditions and major diseases associated with high humidity during the rainy season (Korbu et al., 2020). The crop mainly survives on residual moisture mostly on Vertisols, which is characterized as fast cracking causing a rapid soil moisture escape from the root zone.

Moisture stress has been a major threat and the most unpredictable constraint with adverse effects on chickpea production and productivity worldwide (Korbu et al., 2020; Kumar et al., 2018). Drought generally affects overall crop performance starting from germination, and eventually manifested in grain yield (Samarah et al., 2009) and quality (Hussain et al., 2018). Chickpea is mostly grown in the arid and semiarid areas and is commonly regarded as a drought-tolerant crop (Kumar et al., 2018; Turner et al., 2001; Varshney et al., 2014). Despite the relative tolerance of chickpea to drought stress among the cool-season food legumes, severe or prolonged stress is detrimental to its growth and productivity (Daryanto et al., 2015; Pang et al., 2017). Several studies revealed that moisture stress specifically at the reproductive stage can cause up to 70% yield reduction in chickpea (Nadeem et al., 2019; Nayyar et al., 2006).

Different approaches of tackling the challenges of drought stress on chickpea have been suggested in the literature. Studying the root system has long been considered an effective approach used to screen for drought tolerance and improve crop adaptation to drought stress (Passioura, 1983; Vadez, 2014). However, selection of root traits under field conditions is hindered by several practical constraints and is less amenable for rapid screening of a large panel of genetic materials. Drought tolerance in a given genotype is the ability to minimize yield loss under stress condition (Devasirvatham & Tan, 2018). Screening based on agronomic performances, mainly yield and its components, has been used as reliable selection criterion for enhanced tolerance in chickpea (Gaur et al., 2012; Kashiwagi et al., 2013; Kobraee et al., 2010) and many other crops (Ceccarelli et al., 1991; Oppong-Sekyere et al., 2018). Varshney et al. (2011) and Pushpavalli et al. (2015) further denoted that yield-determining traits with high heritability and weak response to environmental variation are of great importance for improving drought tolerance in drought-affected marginal growing environments.

Despite the importance of drought stress in determining yields of chickpea in Ethiopia, little research attention has been given thus far, and studies targeting a range of drought scenarios are generally scanty. Most drought studies are carried out either under controlled or simulated conditions, which have serious limitations of application under field conditions. Screening for drought tolerance under field condition is very challenging as it requires advanced techniques and modern facilities. Besides, there are issues related to cost and infrastructure particularly for conventional breeding programs working on drought improvement. Hence, field screening under the prevailing conditions would give better results and is more realistic as it is closest to the native growing environment (Campos et al., 2004; Saxena et al., 2002).

In this study, we mainly used plant phenology, yield, and its attributes such as number of pods per plant, seeds per pod, seed weight, and harvest index as proxy parameters to identify tolerant cultivars, as grain yield is the ultimate requirement for farmers under water-limiting conditions (Ceccarelli

Core Ideas

- Chickpea is a late-season crop commonly facing drought stress in the Ethiopian rainfed production system.
- The approach used in the present study demonstrated an easy and practical field-based screening for drought tolerance in chickpea under heavy Vertisol growing condition.
- Yield and attributable traits can be used as proxy parameters to measure genotypic responses in chickpea against drought stress.

TABLE 1 Soil physicochemical properties of the Debre-Zeit Agricultural Research Center's main research station

Soil type (FAO nomenclature)	Soil textural class	pH	EC	CEC
			mS cm^{-1}	cmol$_c$ kg^{-1}
Eutric Vertisols	Heavy black clay soil	6.9–7.8	0.077–0.178	44.8–57.7
Vitric Vertisols	Black clay soil	7.1–7.3	0.055–0.087	38.7–47.0
Haplic Andosols	Light clay loam soil	7.3–8.7	0.079–0.210	23.1–32.9

Note. EC, electrical conductivity; CEC, cation exchange capacity (adapted from Tafesse and Esayas, 2003).

et al., 1991; Subbarao et al., 1995). Although this method is a well-established field-screening protocol elsewhere (Saxena et al., 2002), there is no evidence showing its application in Vertisol-grown chickpea in Ethiopia. The approach is regarded as a simple and feasible strategy to improve drought tolerance in conventional crop improvement programs (Trethowan et al., 2002). The parameters used are nondestructive and could also be applied in any adaptation-related studies. The present study is part of an attempt towards developing field screening approaches for Vertisol-based chickpea production that can be easily applied in the conventional trait-based breeding programs targeting water-limited growing environments. The study, therefore, aims (a) to study the response of Ethiopian chickpea cultivars to different moisture stress conditions and determine the effects of drought intensity on phenological and agromorphological traits, (b) to assess the genotypic variability for stress tolerance and identify the most tolerant cultivars suitable for production in moisture-limited growing environments, and (c) to identify key traits and drought indices associated with drought tolerance in chickpea applicable in future field-based screening.

2 | MATERIALS AND METHODS

2.1 | Weather conditions of the study sites

The field experiments were conducted at the Debre-Zeit Agricultural Research Center (DZARC) in Debre Zeit, Ethiopia (8°41′36′′ N, 39°03′17′′ E; 1,880 m asl) starting from early September 2018 to late January 2019 during the main cropping season. The station has three types of natural soils with varying characteristics representative of the common chickpea growing conditions in Ethiopia. The soils of the experimental station have moderately neutral to slightly acidic soil reaction (pH ranges between 6.9 and 8.7) and generally are nonsaline (Tafesse & Esayas, 2003). The physicochemical characteristics of the three major soil types of the experimental station are briefly described below (Table 1). Important weather parameters of the growing season during the study period were recorded from an automatic meteorological station located near to the experimental sites. The average maximum and minimum temperature of the growing season were 24.6 and 9.6 °C, respectively. The mean relative humidity was about 61.7% having a mean evapotranspiration (ET) of 3.9 mm d^{-1}.

2.2 | Plant materials

The plant materials used in this study were 28 commercial chickpea cultivars released by the National Agricultural Research System in Ethiopia (Table 2). The set included the two cultivated chickpea types: kabuli (n = 15) and desi (n = 13). Seeds were obtained from research germplasm genepool of the national chickpea research coordination at DZARC. The materials were grown in the field during the 2018–2019 cropping season at the DZARC's experimental station in Debre Zeit, Ethiopia. Seeds of the 28 cultivars were field planted under three watering regimes and three soil types representing the common chickpea-growing environments in Ethiopia. Different seed planting times were used to cover a range of stress scenarios and sowing durations of chickpea practiced by the majority of farmers.

2.3 | Planting and experimental arrangement

Seed planting was done manually (hand drilling) late in the season using dry planting on soil residual moisture to establish uniform growing condition across all experimental sets and expose the cultivars to the native condition. Treatments included three levels of moisture regimes: rainfed (RF), water stress (WS), and well-watered (WW) treatments. The RF treatment was planted on 2 Sept. 2018 to synchronize the experiment with the common chickpea planting time practiced by the majority of Ethiopian farmers and considered as mild stress conditions (Korbu et al., 2020). The WS and WW treatments were planted on 17 Sept. 2018, 15 d after RF treatment. The WS treatment used delayed planting practice, which represents severe moisture stress growing conditions. The site received 23 mm of rainfall between planting and flowering, 40 d after sowing (DAS), and there was no rain after the onset of the reproductive phase—creating proper conditions for measuring drought stress on the

TABLE 2 Overview of improved chickpea cultivars evaluated under varying moisture regimes in the study

Entry no.	Cultivar designation	Pedigree	Type	Year of release	DTM	Descriptive traits of release
1	DZ-10-11	DZ-10-11	D	1962	123	High local use value & preference
2	DZ-10-4	DZ-10-4	K	1962	115	High local use value & preference (SC-K)
3	Dubie	PGRC1	D	1970	113	Better local adaptations
4	Mariye	K-850-3/27xF378	D	1977	111	Better grain test & use values (SC-D)
5	Arerti	FLIP 89-84c	K	1991	125	Extensive adaptation, AB resistance & yield
6	Shasho	ICCV-93512	K	1991	122	Yield, RR tolerance & adaptation
7	Worku	ICCL-820104	D	1994	135	Better grain yield
8	Akaki	ICCL-820016	D	1995	121	Better grain yield
9	Chefe	ICCV 92318	K	2004	122	RR & AB tolerance, yield & adaptation
10	Habru	FLIP 88-42c	K	2004	115	Earliness, drought tolerance, AB & RR tolerance (TC-K2)
11	Kutaye	ICCV-92033	D	2005	124	Better yield & seed quality
12	Ejere	FLIP 97-263c	K	2005	126	Yield, AB tolerance & earliness
13	Teji	FLIP 97-266c	K	2005	120	Yield, seed quality & RR tolerance
14	Mastewal	ICCV-92006	D	2006	127	Better yield & seed quality
15	Yelibe	ICCV-14808	K	2006	115	Better yield & seed quality
16	Fetenech	ICCV-92069	D	2006	93	Better yield & seed quality
17	Natoli	ICCX-910112-6	D	2007	125	Yield, seed quality & RR tolerance
18	Minjar	ICCV-03107	D	2010	120	Wilt & AB tolerance
19	Kasech	FLIP-9531c	K	2011	110	MS tolerant & seed size
20	Akuri	ICCV-03402	K	2011	98	MS tolerant & seed size
21	Kobo	ICCV-01308	K	2012	100	MS tolerant, seed size & yield
22	Teketay	CJG-74xICCL-83105	D	2013	118	Grain yield, wilt & AB tolerance (TC-D1)
23	Dalota	ICCX-940002	D	2013	120	Grain yield, wilt & AB tolerance
24	Hora	DZ-2012 CK-001/FLIP 04-9c	K	2015	130	Grain yield and seed size
25	Dhera	DZ-2012 CK-009/FLIP 0163	K	2015	131	FW resistance, erect growth (machine harvestable)
26	Dimtu	DZ-2012 CK-031/ICCV-10107	D	2016	122	Seed color, taste and grain yield
27	Koka	DZ-2012 CK-024/ICCV-04305	K	2017	115	Early maturity & drought tolerance (TC-K1)
28	Shola	DZ-2012 CK-019/ICCV-10307	K	2018	125	Large seeded (55.2 g HSW)

Note. D, desi, K, kabuli; DTM, days to maturity; TC-K1 and -K2, kabuli cultivars used as tolerant checks; TC-D1 and -D2, desi cultivars used as tolerant checks; SC-K, susceptible kabuli check; SC-D, susceptible desi check; MS, moisture stress; FW, Fusarium wilt; AB, Ascochyta blight; RR, root rot complex; HSW, hundred-seed weight.

cultivars. The RF and WS treatments were maintained on residual moisture for the entire growth period without the application of irrigation water. The WW treatments used optimal irrigation at 80% field capacity taking into account the daily ET replacement estimated to 6% (3.9 mm d^{-1}) in order to maintain stress-free growing condition based on recommendation for Vertisol-grown chickpea (Desta et al., 2015). Irrigation water was applied to WW plots at seed emergence, late vegetative, and grain filling stages using furrow irrigation.

Plants under each moisture regime were grown on three different growing soil types (light clay loam, black clay or Vertic, and heavy black clay or heavy Vertic soils. A separate treatment (cultivars) randomization was used for each moisture regime across soil types.

All experimental sets were laid down using a randomized complete block design with three replicates. Plots consisted of four rows of 2 m long and 1 m wide (2 m^2) with 30-cm spacing between rows. Seeds were manually planted using hand drilling and plants were maintained without fertilizers. The common diseases of chickpea, mainly blight (*Ascochyta rabiei*), and insect pests such as pod borer (*Helicoverpa armigera*) and cut worm (*Agrotis ipsilon*) were controlled using recommended pesticides throughout the plant growth period. At the full maturity stage, the two central rows of each plot were manually harvested for determination of yield and its attributes.

2.4 | Field screening and phenotypic traits evaluation

Field screening of chickpea cultivars for drought tolerance was undertaken during the post-rainy season from September to January. Phenotypic evaluations (seedling vigor, plant growth rate, growth habit, branching pattern, etc.) and a visual assessment were carried out in the field for the entire growing period (data are not presented). These parameters were used to group cultivars into three maturity groups of late (>110 d), medium (100–110 d) and early (<100 d) maturing. Plant growth response to water stress was started at the early reproductive phase, and cultivars showing stress symptoms, mainly leaf senescence, drop-off, and plant wilting were recorded on weekly intervals beginning 80 DAS and the mean value was used for cultivar rating. Field diagnostic kits were used in order to distinguish between plant wilting due to stress imposed and that caused by major root diseases of chickpea, mainly Fusarium wilt (*Fusarium oxysporum* f. sp. *ciceri)* (Yimer et al., 2018). Data on phenological traits, including days to first flowering, 50% flowering, and days to physiological maturity were recorded starting from 30 DAS.

The key phenological parameters studied were: days to 50% flowering (DTF), the number of days from planting to the date when the first flower emerged on 50% of the plants in a plot; days to maturity (DTM), measured as the interval between date of planting and the date when pods on over 90% of the plants in a plot turned yellow; and grain filling period (GFP), the number of days between DTF and DTM. Plant height (PHT) determines the number of branches and in return the number of pods per plant, and hence was considered as one of the yield attributes for selection in chickpea (Güler et al., 2001; Namvar et al., 2011). The key yield attributable agronomic traits were studied as follows. Plant height (PHT) was a manual measurement (cm) from the base of the stem to the tip of the main shoot of the 10 plants randomly selected from a plot. Pod yield per plant (PP) was the total number of well-filled and normally developed pods counted from the 10 randomly selected plants at harvest. Hundred-seed weight (HSW) was the average dry weight (g) of 100 well-filled seeds from three replicate samples taken from the total plot harvest at 11% seed moisture content. Biomass yield (BY) is the total dry matter weight (kg ha^{-1}) of the two central rows of a plot determined at harvest. Grain yield (GY) is the total seed yield (kg ha^{-1}) obtained from the entire two central rows. Immediately after field harvest, seeds were sun-dried for 5 d, and seed weight and yield were determined at 11% seed moisture content. Harvest index (HI) is calculated as a ratio of GY to BY in percentage. Visual scoring of drought symptom was done on the whole plot on a scale of 1–5 (1 being no symptom and 5 being highly wilting) and general visual observation. The mean value of drought symptom scoring was used to categorize cultivars as tolerant, moderate and sensitive to the imposed stress. Finally, we adopted the commonly used drought stress indices (Table 3) as reliable indicators for field screening (Nautiyal et al., 2002; Sofi et al., 2018). In addition, potential yield (i.e. yield under WW treatment) was compared with yield under severe (WS) and mild (RF) stresses, and the difference was used to calculate drought tolerance index (DTI) and yield penalty caused by the water stress. The DTI was used for quantification of drought tolerance or susceptibility of cultivars (the higher the DTI value, the more tolerant the genotype is). The literature also indicated that these quantitative drought indices offer better selection power among test genotypes (Johansen et al., 1994; Saxena et al., 2002).

2.5 | Statistical analysis

In our field-based screening trial, we followed the empirical selection approach suggested by the literature (Kobraee et al., 2010; Saxena & O'Toole, 2002). This approach uses yield and yield-attributable traits to characterize the test cultivars for their response to stress conditions. Yield and other agronomic data were analyzed using SAS 9.3 statistical packages, and drought-related parameters and stability were analyzed using GGEBiplot in R software as suggested by Frutos et al. (2014) (see also http://www.ggebiplot.com). Data were subjected to the ANOVA after checking the compliance of the data with the assumption of statistical tests (i.e., additivity, normality, and homogeneity of error variances) (Khatun, 2021; Mark & Levine, 1996; Shapiro & Wilk, 1965). Mean separation test was done using the LSD test at $P \leq .05$. An ANOVA-general linear model (ANOVA-GLM) was performed to determine the significance of differences between the cultivars and environments. Pearson correlation was calculated among variables lower than 0.05 error probability. General relationship and correlation coefficients among different phenotypical, morphological, and agronomical traits and drought indices were also determined.

3 | RESULTS

3.1 | Meteorological data analysis of the experimental sites

The monthly precipitation and other weather conditions of the growing season during the study period are presented in Figure 1. The trial site received 23.1 mm of rainfall for the entire growing period (September to end of January) (Figure 1). There was no incidence of rainfall from the

TABLE 3 Drought stress screening indices used in the study based on seed yield of chickpea cultivars

Index	Formula	References
Stress susceptibility index (SSI)	$[1 - (\mathrm{YS/YP})]/[1 - (X_{\mathrm{YS}}/X_{\mathrm{YP}})]$	Fischer and Maurer (1978)
Tolerance index (TOL)	YP – YS	Rosielle and Hamblin (1981)
Mean productivity (MP)	(YS + YP)/2	Rosielle and Hamblin (1981)
Stress tolerance index (STI)	$(\mathrm{YS} \times \mathrm{YP})/X^2_{\mathrm{YP}}$	Fernandez (1992)
Geometric mean productivity (GMP)	$\sqrt{(\mathrm{YP} \times \mathrm{YS})}$	Fernandez (1992)
Drought tolerance index (DTI)	$(\mathrm{YS/YP})/(X_{\mathrm{YS}}/X_{\mathrm{YP}})$	Lan (1998); Fischer and Maurer (1978)
Yield reduction (YR)	1 – (YS/YP)	Choukan et al. (2006)

Note. YS and YP are mean yields of chickpea cultivars under stress and nonstress conditions, respectively; X_{YS} and X_{YP} are mean of yield of all cultivars under stress and nonstress conditions, respectively.

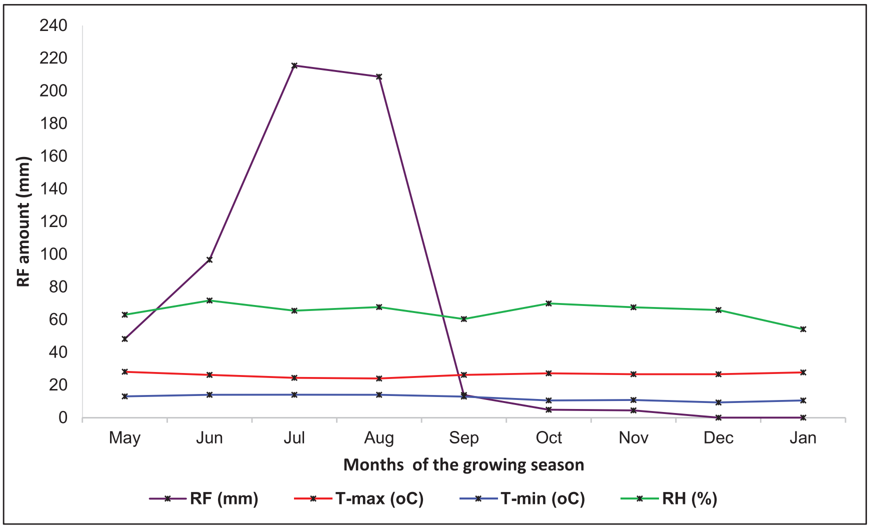

FIGURE 1 Mean monthly meteorological data during chickpea growing season (September to January), 2018–2019. RF = rainfall, T-max = average maximum air temperature, T-min = average minimum air temperature, RH = relative humidity (source: GIS department, Debre-Zeit Agricultural Research Center)

flowering period at 40 DAS onwards, hence the beginning of moisture stress coincides with the reproductive growth phase to generate a reproductive stage water deficit conditions. The average maximum and minimum temperatures were within the expected range. Differences in performance among test cultivars are thus likely due to the water stress conditions.

3.2 | Performance evaluation and visual scoring

The study showed that both water and soil type treatments had significant effects on overall genotype performance, although the interaction had no significant effect on the majority of the traits studied. The ANOVA revealed significant effect on yield and yield-attributable traits except for GFP and average seeds per pod (SP). Moisture regimes, cultivars, and their interaction significantly ($P \leq .01$) affected seed yield and its attributes (DTM, PP, HSW, BY, and HI) with the exception of PHT (explained under 3.3), whereas soil types, cultivars, and their interaction had significant ($P \leq .05$) effect on them (data not shown). Values of yield and its attributable traits decreased with increasing intensity of drought stress.

Mean phenological and agronomic parameters of the 28 improved chickpea cultivars evaluated on three different soil types against three different moisture treatments are summarized in Table 4. The overall (combined) performance analysis revealed high and significant ($P \leq .05$) variation among the means of test cultivars for all agronomic variables except for GFP and PHT. Significant and consistent variation among test cultivars were observed for the majority of agronomic parameters studied across the test environments (Table 4). Cultivars grown under WW treatment generally showed delayed time to flowering and maturity as compared with the WS conditions. Mean PHT was reduced by about 10 cm (24%) as a result of water stress treatment. Grain yield ranged from 660 kg ha^{-1} obtained under WS to 4,763 kg ha^{-1} obtained under WW treatment with combined mean yield of 1,688 kg ha^{-1}. Furthermore, the WS treatment had the fewest pods per plant and substantial reduction in seed weight (Table 4).

Based on their phenological traits taken in the fields, the 28 cultivars were clustered in three groups: late (>110 d), medium (100–110 d), and early (<100 d) maturing. The

TABLE 4 Overall mean grain yield performance and other agronomic traits of chickpea cultivars evaluated under varying moisture regimes and soil types during the study period

Entry (pedigree/cultivar)	Entry no.	DTF	DTM	GFP	PHT	PP	HSW	GY	BY	HI
					cm		g	kg ha^{-1}		%
DZ-10-11	1	51.8	111.3	59.5	40.5	46.0	12.8	1,487	3,921	0.42
DZ-10-4	2	54.8	108.4	53.6	39.8	49.4	12.6	1,091	3,441	0.32
Dubie	3	49.6	108.9	59.3	40.9	45.4	23.9	1,790	4,213	0.44
Mariye	4	55.8	110.9	55.1	38.5	43.9	24.7	1,850	4,461	0.43
Worku	5	51.8	108.8	57.1	41.1	39.3	23.6	1,830	4,824	0.41
Akaki	6	53.1	108.4	55.3	41.7	43.7	21.5	1,948	4,803	0.41
Arerti	7	57.9	110.7	52.8	40.1	39.8	26.2	1,731	4,327	0.39
Shasho	8	58.2	109.8	51.6	40.1	40.6	29.2	1,674	4,349	0.39
Chefe	9	52.7	110.0	57.3	41.2	38.7	33.9	1,213	3,549	0.34
Habru	10	52.2	109.1	56.9	40.6	42.0	33.6	1,174	3,650	0.32
Ejere	11	50.6	110.8	60.2	40.5	42.2	30.7	1,478	4,417	0.33
Teji	12	49.1	110.5	61.4	40.4	35.2	33.5	1,335	3,559	0.37
Kutaye	13	50.5	105.8	55.3	40.7	49.3	20.4	1,989	4,517	0.46
Mastewal	14	52.9	110.6	57.7	40.0	46.6	27.7	1,755	3,958	0.66
Yelibe	15	51.4	104.6	53.2	40.8	39.4	30.7	1,470	3,784	0.38
Fetenech	16	51.0	111.4	60.4	39.1	44.6	21.8	1,749	4,429	0.40
Natoli	17	55.3	109.7	54.4	42.1	44.7	29.5	1,821	5,156	0.37
Minjar	18	49.5	107.1	57.6	40.5	47.9	22.2	1,968	4,724	0.43
Kasech	19	51.6	109.5	57.9	42.7	38.4	33.0	1,546	5,108	0.32
Akuri	20	51.1	110.5	59.4	39.9	43.1	30.3	1,108	3,380	0.34
Kobo	21	58.9	113.8	54.9	41.1	35.7	30.6	1,214	3,773	0.31
Teketay	22	49.7	108.7	59.1	40.7	37.5	29.6	2,003	5,250	0.40
Dalota	23	51.1	108.9	57.8	42.6	40.0	30.0	1,730	4,272	0.42
Hora	24	49.9	110.8	60.9	39.3	30.5	32.2	1,461	3,888	0.39
Dhera	25	57.6	112.1	54.4	41.8	36.4	34.2	1,564	3,573	0.44
Dimtu	26	48.9	109.3	60.4	41.0	35.1	32.2	1,538	3,989	0.42
Koka	27	52.0	108.3	56.3	41.0	38.6	34.8	1,514	3,258	0.48
Shola	28	51.7	106.6	54.9	37.9	31.1	38.7	1,363	3,290	0.39
Mean		52.5	109.0	57.0	42.1	43.0	28.4	1,687.8	4,385.3	0.38
CV, %		9.3	6.4	11.2	9.1	18.9	7.0	15.6	18.8	19.2
LSD (5%)		1.9**	3.2**	3.5*	2.4*	1.97**	1.3**	154.8**	536.9**	0.05**
df		324	324	324	324	324	324	324	324	324

Note. DTF, days to 50% flowering; DTM, days to maturity; GFP, grain filling period; PHT, plant height at harvest; PP, pod yield per plant; HSW, hundred-seed weight; GY, grain yield; BY, biomass yield; HI, harvest index; LSD (5%), LSD at $P = .05$; df, error degrees of freedom (residuals).
*Significant at the .05 probability level. **Significant at the .01 probability level.

late-maturing cultivars combined across test environments include DZ-10-11, Mariye, Arerti, Chefe, Yelibe, Kasech, Kobo, and Dhera, where most of them are kabuli types. The majority of the test cultivars fell under the medium maturity group. The third group is early-maturing cultivars, which includes Teketay, Fetenech, Minjar, and Habru. Interestingly, some cultivars such as Hora, Dimtu, Kutaye, and Akuri showed unique response of early flowering but late maturity, suggesting they may have better drought adaptive responses. Conversely, DZ-10-4, Akaki, Shasho, and Natoli were late in flowering but early in maturity, suggesting higher stress sensitivity response. Grain yield across test environments ranged from 690 kg ha^{-1} at WS to 2,895 kg ha^{-1} at WW with mean value of 1,688 kg ha^{-1} showing over 70% yield reduction compared with mean yield of 2,218 kg ha^{-1} obtained under WW treatment. The high-yielding cultivars across environments include Teketay, Kutaye, Minjar, Natoli, and Akaki, where most of them are the desi cultivars. This was further confirmed by field-level visual-aided scoring of drought symptoms such as injuries and wilting (data not shown).

Mean agronomic performance of the test cultivars grown under three moisture treatments is summarized in Table 5 (see also Supplemental Table S1). Mean grain yield ranged from 1,156 kg ha^{-1} in WS to 2,199 kg ha^{-1} in WW treatments (Table 5), implying supplementation of chickpea crop with adequate irrigation water at reproductive phase could have more than 50% yield advantage. Similarly, biomass yield showed proportional trend between the two contrasting treatments. Agronomic variables including grain traits showed significant variation for different growing environments except for PHT. The ANOVA further revealed that variation due to moisture regime (Table 5) had larger effect on all variables studied compared to variation due to soil types (data not shown, See Table S5). Particularly, PP, HSW, GY, and BY were the traits most significantly influenced by moisture regime. In addition, varying degrees of genotype × environment interaction among the means of the cultivars, particularly seed for pod, and biomass yields, as well as HI were observed (Table 5). Effect of drought on agronomic performance of the cultivars in general varied significantly ($P < .05$) under each soil type (Supplemental Table S5).

The present study has clearly demonstrated that both water stress conditions (RF and WS) caused significant reduction in yield and yield attributable traits in chickpea. However, some of the test cultivars showed high level of adaptive traits and overall agronomic performances under water stress conditions, and thus have potential for drought tolerance. Based on visual assessment and field-level drought scoring, about 11 promising genotypes were identified as tolerant, eight of them showed high level tolerance whereas the remaining three had moderate tolerance. The field-based visual phenotyping was further confirmed by the quantitative drought indices often used such as TOL (tolerance index), SSI (stress susceptibility index), and DTI (see Section 3.5).

3.3 | Trait association and their contribution to grain yield

In terms of trait association and contribution of yield components to the final GY, BY, PP, and HI were important. There was a general trend of positive association of BY with GY under all moisture regimes, but it did not result in significant correlation under severe stress growing condition (Table 6). Hence, BY had a large positive direct contribution to GY under varying stress conditions. Similarly, HI showed high and significant ($P < .01$) correlation with GY, and its contribution was positive and large under all moisture treatments. The major production component traits such as PP, PHT, and SP had positive and significant correlation with GY. On the other hand, grain weight (HSW) showed negative association

TABLE 5 Overall mean yield and yield components of chickpea cultivars evaluated under varying moisture regimes

Treatment	DTF	DTM	GFP	PHT	PP	HSW	GY	BY	HI	df
				cm		g	kg ha^{-1}	kg ha^{-1}	%	
Nonstress (WW)	57 ± 0.34[a]	115 ± 0.37	58 ± 0.49	48 ± 0.47	52 ± 0.89	31 ± 0.18	2,218 ± 32.4	5,230 ± 93.1	0.43 ± 0.01	54
Mild stress (RF)	51 ± 0.23	109 ± 0.45	57 ± 0.45	41 ± 0.28	42 ± 0.67	28 ± 0.17	1,695 ± 21.1	4,705 ± 84.7	0.36 ± 0.02	108
Severe stress (WS)	49 ± 0.17	103 ± 0.30	54 ± 0.33	38 ± 0.23	37 ± 0.46	27 ± 0.11	1,150 ± 11.4	3,221 ± 39.6	0.35 ± 0.01	162
Mean[b]	53	110	58	41	43	28	1,688	4,385	0.38	
Cv (%)	8.2	7.7	9.3	6.8	19.4	7.0	14.7	20.4	21.0	
LSD (5%)	3.63*	5.56**	6.1*	3.62ns†	10.32**	2.6**	433.3**	1215*	0.09**	

Note. WW, well-watered growing environment; RF, rainfed or mild stress growing environment; WS, severe water stress growing environment; DTF, days to 50% flowering; DTM, days to maturity; GFP, grain filling period; PHT, plant height at harvest; PP, pod yield per plant; HSW, hundred-seed weight; GY, grain yield; BY, biomass yield; HI, harvest index; LSD (5%), LSD at $P = .05$; df, error degrees of freedom (residuals).

[a]Values after means are the standard error (SE) estimates.

[b]Overall (grand) mean values under each moisture regime across soil types.

*Significant at the .05 probability level. **Significant at the .01 probability level. †ns, nonsignificant.

TABLE 6 Pearson's correlation between 10 agronomic variables for the three moisture regimes (n = 504)

Variable	DTF	DTM	GFP	PHT	PP	SP	HSW	GY	BY	HI
DTF	1									
DTM	0.36547**	1								
GFP	−0.27999**	0.79126**	1							
PHT	0.151920*	−0.08100ns†	−0.18334**	1						
PP	−0.08240ns	0.08802ns	0.14491**	0.02110ns	1					
SP	−0.08611*	−0.16089**	−0.10936*	0.17512**	−0.11111*	1				
HSW	0.01339ns	0.00519ns	−0.00344ns	0.09857*	−0.26651**	0.03682ns	1			
GY	0.22145**	0.11350*	−0.02842ns	0.32714**	0.61761**	0.11675**	−0.09111*	1		
BY	0.08953*	0.07523*	0.01878ns	0.32152**	0.40354*	0.17509**	−0.08153*	0.53363**	1	
HI	0.13312*	0.14866**	−0.06587ns	−0.10610*	0.08994*	0.05996ns	−0.0200ns	0.37998**	−0.0107ns	1

Note. DTF, days to flowering; DTM, days to maturity; GFP, grain filling period; PHT, plant height; PP, pods per plant; SP, number of seeds per pod; HSW, hundred-seed weight; GY, grain yield; BY, biomass yield; HI, harvest index.
*Significant at the .05 probability level. **Significant at the .01 probability level. †ns, nonsignificant.

with GY, BY, and HI (Table 6). Grain filling period did not result in significant correlation with GY, and some variables such as SP and HSW also had minimum contribution in GY determination.

3.4 | Genotypic clustering using GGE biplot analysis

Recently, GGE (genotype × environment plus genotype) biplot procedures have been widely used for data visualization. They are specifically used to graphically display multivariate data analysis in cultivar evaluation (Yan & Tinker, 2006; Yan et al., 2000). The GGE biplot has also been applied to perform stability analysis and to identify cultivars that show consistent performance across test environments for a given trait of interest (Fasahat et al., 2015). In order to examine the yield stability of the test cultivars across environments, we performed the GGE biplot analysis. The arrowed line in Figure 2b shows the average environment coordination view of the GGE biplot (Yan & Tinker, 2006), which also displays the relative mean performance and stability of the test cultivars. The cultivars were ranked based on their mean performance and representativeness view of biplot for grain yield across the growing environments. Cultivar Teketay (22) was confirmed as the most stable and average performing genotype for yield traits at all environments followed by Mariye (4), Akaki (6), and Kutaye (13), whereas cultivars DZ-10-4 (2) and Kobo (21) displayed the lowest mean grain yield (Figure 2b). Further, the GGE biplot allows to assess the discriminative ability and representativeness of the test environments (Yan & Tinker, 2006). In our analysis, LS-WS (light soil WS) was most representative growing environment whereas LS-RF (light soil RF) and BS-RF (black soil RF) were least representative (Figure 2b). The biplot displayed the variations of the first component (PC1 = 43.60%) and second component (PC2 = 19.56%), which explained more than 63% of the total variation of the test environments. The stability measurement revealed that most desi cultivars showed relatively more stable performance compared with the kabuli types for yield traits. Interestingly, these cultivars have also consistently showed similar results in multisite performance trials conducted across seasons in the country (Fikre et al., 2018).

Furthermore, cultivars were assessed for their responses (i.e., in terms of yield performance) to varying moisture treatments (Table 7). The high-yielding cultivars under WS conditions include Kutaye, Minjar, Teketay, Natoli, and Dalota, most of which were the desi cultivars. Similarly, cultivars were classified based on percentage reduction for key agronomic variables as a result of stress treatments, and it was determined as the percentage of difference between WW and WS treatments. In general, remarkable reductions in all of the agronomic variables were recorded, and only the result of GY is presented (Table 7). The greatest yield reduction of 2,053 kg ha^{-1} (71%) was recorded in the kabuli cultivar Shasho, followed by Yelibe (about 1,742 kg ha^{-1}, 67%), whereas the least reduction was recorded by Koka. On the other hand, yield reduction due to mild stress (RF) treatment relative to the WW check ranged from 3 to 54% (Supplemental Table S2). The greatest yield reduction under this environment was recorded in the kabuli cultivar Hora (54%), whereas the farmer-preferred and most popular cultivars such as Arerti, Minjar, Mastewal, and Akuri had the least yield reduction. Interestingly, Koka again recorded the least (4%) reduction under severe stress WS (Table 7, Supplemental Table S2). This implies that considerable yield gain (>50%) can be achieved in the rainfed production systems (i.e., farmers' practice of late planting) using supplemental irrigation at later growth stages of the crop. The other members of this group also include Hora, Dhera, Ejere, Kasech, Natoli,

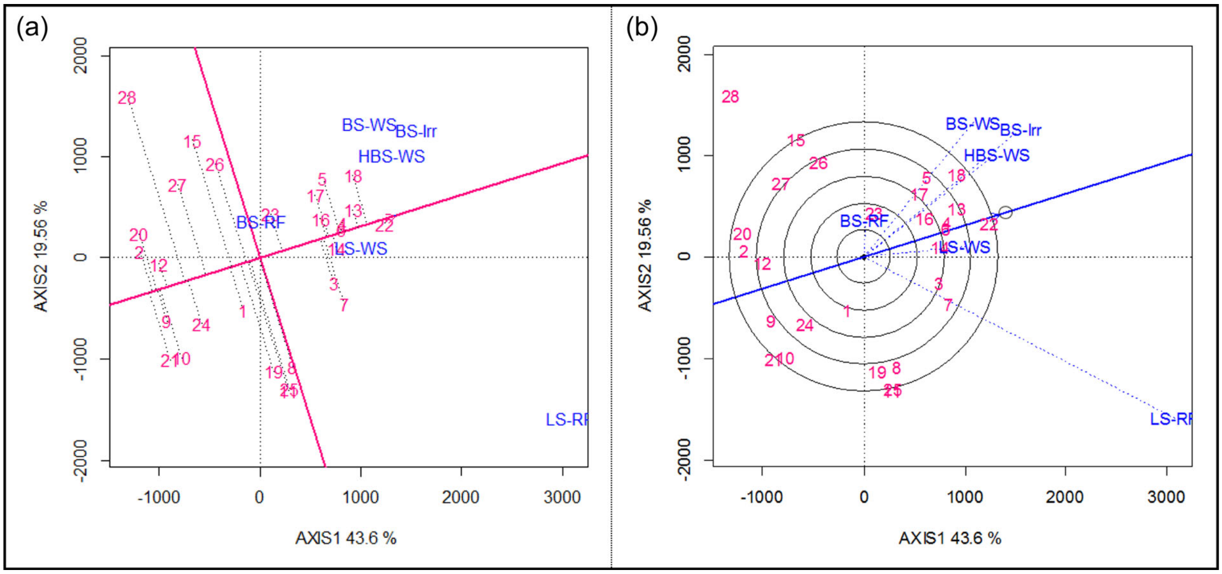

FIGURE 2 Genotype × environment plus genotype (GGE) biplot graph showing stability status of chickpea cultivars, environments, and genotype × environment for grain yield. GGE biplot analysis on the basis of grain yield of where the *x* axis shows Principal Component 1 (PC1) (moisture regime) and the *y* axis indicates Principal Component 2 (PC2) (soil type), and their interaction. (a) Yield stability view of biplot. (b) Discriminativeness vs. representativeness view of the test environments. Numbers (1–28) in the plot represents cultivar ID: DZ-10-11 (1), DZ-10-4 (2), Dubie (3), Mariye (4), Worku (5), Akaki (6), Arerti (7), Shasho (8), Chefe (9), Habru (10), Ejere (11), Teji (12), Kutaye (13), Mastewal (14), Yelibe (15), Fetenech (16), Natoli (17), Minjar (18), Kasech (19), Akuri (20), Kobo (21), Teketay (22), Dalota (23), Hora (24), Dhera (25), Dimtu (26), Koka (27), and Shola (28). Experimental treatments consisting of moisture regime vs. soil type (i.e., growing environment code): BS-Irr (irrigated black soil), BS-WS (water stressed black soil), BS-RF (black soil under rainfed condition), LS-RF (Light soil under rainfed condition), LS-WS (light soil under water stress condition), HBS-WS (heavy black soil under water stress condition)

and Teketay. Interestingly, the popular kabuli cultivar Kobo, which is recommended for irrigated production, was also included in this cluster.

In order to further verify the agronomic performance, the cultivars were evaluated for their responses to different intensities of drought stress. The DTI of each test cultivar was determined for all parameters studied, but only GY is presented here (Table 7). The DTI for GY was calculated as the ratio of yield under WS treatment (yield under water-stressed conditions) to that under WW (potential yield with irrigation) as suggested by Nautiyal et al. (2002). The DTI ranged from 0.29 to 0.88 under WS treatment. Cultivars with high DTI values include Koka, Dalota, Natoli, Dimtu, Mastewal, and Minjar, where many of them were also among the highest yielding cultivars under the stress growing environment. In general, there was wide range of DTI values, which may show a high degree of genetic variation among the cultivars for their response to drought stress conditions.

Most of the kabuli cultivars had higher DTI values and were found better yielders under RF treatment (mild stress) as compared with the desi types (data not shown). Popular drought-tolerant cultivars verified so far in multienvironment screening such as Koka, Teketay, Habru, and Kutaye were also included in this tolerant cluster. About eight desi cultivars (Kutaye, Minjar, Dalota, Natoli, Teketay, Koka, Mastewal, and Dimtu) can be regarded as the most drought tolerant and gave reasonable yield under severe moisture stress treatment. Similarly, Koka, Akuri, and Habru had relatively high DTI values and are also regarded as drought tolerant among the kabuli cultivars. This result was further confirmed by field-level visual assessment of drought scoring (data not shown). Cultivars that had relatively high DTI values under mild stress condition can also be regarded as drought tolerant under farmers' practice of late planting systems.

On the other hand, percentage yield reduction between RF and WS varied widely from 0.95 to 60% (data not shown). Percentage yield reduction showed similar trend as under severe stress. The kabuli cultivar Koka recorded the least yield reduction under both stress conditions. This is entirely in agreement with its name, which was originally designated after the stress testing site called 'Koka' in the Ethiopian Rift Valley growing environment, where it had best performance in the national yield trials (Figure 3). Cultivars that have shown least yield reduction or higher DTI under such environments can also be regarded as drought tolerant. Other candidates in this category also include Mastewal, Dimtu, Natoli, Dalota, Kutaye, and Minjar. Furthermore, cultivars Koka and Shasho have shown the most tolerant and susceptibility responses, respectively, from the kabuli types. Among

TABLE 7 Grain yield performance, percentage yield reduction, and the corresponding drought tolerance index (DTI) values of the 28 chickpea cultivars evaluated under varying moister regimes

Cultivar	Type	Grain yield WW (*a*)	RF (*b*)	WS (*c*)	Mean (*d*)	*e* (*a* − *c*)	YR (*e*/*a* × 100)	DTI (*c*/*a*)
		kg ha^{-1}					%	
Shasho	K	2,895	1,729	842	1,674	2,053	70.9	0.29
Teketay	D	2,623	2,103	1,557	2,003	1,066	40.6	0.59
Kutaye	D	2,607	1,827	1,632	1,989	976	37.4	0.63
Yelibe	K	2,602	1,821	860	1,470	1,742	67.0	0.33
Akaki	D	2,597	2,206	1,430	1,948	1,166	44.9	0.55
Mariye	D	2,563	2,390	1,252	1,850	1,312	51.2	0.49
Dubie	D	2,557	2,135	1,162	1,790	1,395	54.5	0.45
Fetenech	D	2,511	2,029	1,307	1,749	1,204	48.0	0.52
Arerti	K	2,509	2,506	953	1,731	1,556	62.0	0.38
Kasech	K	2,379	1,656	953	1,546	1,426	59.9	0.40
Minjar	D	2,363	2,239	1,613	1,968	750	31.7	0.68
Hora	K	2,322	1,068	1,018	1,461	1,304	56.1	0.44
Ejere	K	2,293	1,552	910	1,478	1,383	60.3	0.40
Natoli	D	2,290	1,621	1,574	1,821	715	31.2	0.69
Worku	D	2,260	2,463	1,333	1,830	927	41.0	0.59
Dhera	K	2,220	1,332	1,204	1,564	1,017	45.8	0.54
Teji	K	2,154	1,291	804	1,335	1,350	62.7	0.37
Kobo	K	2,080	1,052	690	1,214	1,391	66.8	0.33
Dalota	D	2,078	1,424	1,600	1,730	478	23.0	0.77
DZ-10-11	D	2,004	1,475	1,147	1,487	857	42.8	0.57
Shola	K	1,953	1,659	969	1,363	984	50.4	0.50
Mastewal	D	1,925	2,037	1,548	1,755	377	19.6	0.80
Habru	K	1,891	1,080	727	1,174	1,164	61.6	0.38
Chefe	K	1,825	1,219	802	1,213	1,023	56.0	0.44
Dimtu	K	1,666	1,484	1,470	1,538	196	11.8	0.88
Koka	K	1,619	1,554	1,431	1,514	188	11.6	0.88
DZ-10-4	K	1,428	1,543	718	1,093	709	49.7	0.50
Akuri	K	1,367	1,326	862	1,108	505	37.0	0.63
Mean		2,199	1,708	1,156	1,586	1,043	46.3	0.53
SE		32.44	21.14	11.27	10.51			
LSD		486.6**	313.5**	166.5**	154.8**			
df		54	108	162	324			

Note. K, kabuli type; D, desi type; WW, well-watered (irrigated); RF, rainfed (mild stress); WS, severe stress; YR, yield reduction (%); LSD (5%), LSD at $P = .05$; df, error degrees of freedom (residuals).
**Significant at the .01 probability level.

the desi cultivars, Dimtu followed by Mastewal showed the most tolerant responses, and DZ-10-11 followed by Mariye showed the most sensitive or susceptible responses among the desi cultivars. Climate response of chickpea cultivars tested under varying moisture status and soil types is illustrated in Figure 3.

3.5 | Correlation analysis of drought indices

Correlation analysis was performed between drought indices widely used to evaluate cultivar performance under moisture stress conditions. Significant and strong correlations between drought indices and cultivar performance mainly

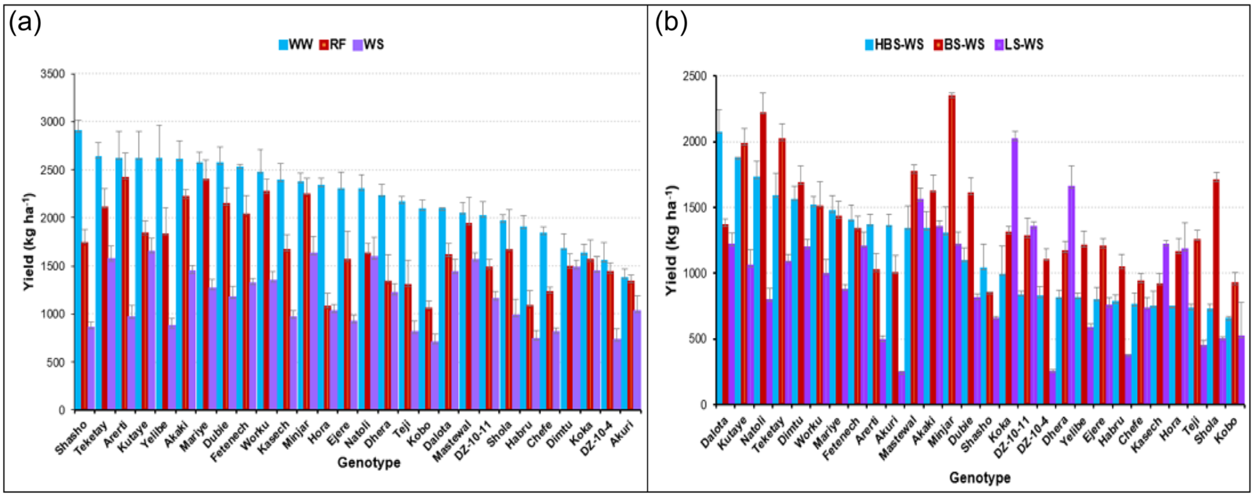

FIGURE 3 (a) Yield (kg ha^{-1}) performance of chickpea cultivars under three moisture regimes: WW = well-watered or stress free, RF = rainfed or mild stress, and WS = severe stress. (b) Genotypic comparison in grain yield (kg ha^{-1}) under experimental treatments combining moisture regime and soil type: HBS-WS = stress under heavy black soil, BS-WS = stress under black soil, and LS-WS = stress under light soil. The error bars on the bar graphs were standard error of means of grain yield of each test cultivar

TABLE 8 Correlation coefficients between indicators of drought tolerance among chickpea cultivars evaluated under severe moisture stress conditions

Variable	YP	YS	TOL	SSI	MP	GMP	STI	HRM
YP	1							
YS	0.377ns†	1						
TOL	0.925**	−0.0045ns	1					
SSI	0.468*	−0.616*	0.759**	1				
MP	0.955**	0.634*	0.771**	0.194ns	1			
GMP	0.804**	0.853**	0.517*	−0.123ns	0.943**	1		
STI	0.793**	0.852**	0.505*	−0.124ns	0.933**	0.996**	1	
HRM	0.589**	0.968**	0.238*	−0.402*	0.800**	0.955**	0.954**	1

Note. YP, potential yield (nonstress); YS, stressed yield. Quantitative drought indices used in the study: TOL, tolerance index; SSI, stress susceptibility index; STI, stress tolerance index; MP, mean productivity; GMP, geometric mean productivity; HRM, harmonic mean productivity.
*Significant at the .05 probability level. **Significant at the .01 probability level. †ns, nonsignificant.

grain yield was found under both stress conditions. The indices were also found to be reliable indicators in this study for selecting tolerant cultivars under stress growing environments (Table 8). Among the drought indices considered, SSI showed significant negative correlation with all the indices under severe stress condition with the exception of mean productivity, which showed a positive but nonsignificant relationship (Table 8). Mean potential grain yield, which was yield under nonstress treatment, showed positive and significant correlation (r = .46) with all indices, whereas yield under stress showed a negative relationship with TOL and SSI but a positive and significant relationship (r = .38) with the rest of the indices (Table 8).

Furthermore, genotypic ranking was performed using SSI index values (Table 9). According to this ranking, among the test cultivars, Koka (SSI = 0.02) showed the most tolerant response whereas Shasho (SSI = 1.56) was the most susceptible, and both are kabuli type cultivars (Table 9). Interestingly, this drought index-based genotypic ranking is consistently in agreement with the results of genotypic responses expressed as percentage yield reduction due to drought stress indicated in Table 7.

TABLE 9 Grain yield and values of drought indices of chickpea cultivars and genotypic ranking based on stress susceptibility index (SSI) value

Cultivar	YP	YS	TOL	STI	MP	GMP	HRM	Rank[a] (SSI value)
	t ha^{-1}							
Koka	1.619	1.604	0.016	0.568	1.611	1.611	1.611	0.021
Dimtu	1.666	1.470	0.196	0.536	1.568	1.565	1.562	0.258
Mastewal	1.925	1.548	0.377	0.652	1.737	1.726	1.716	0.430
Dalota	2.078	1.548	0.531	0.704	1.813	1.793	1.774	0.560
Natoli	2.290	1.574	0.715	0.789	1.932	1.899	1.866	0.686
Minjar	2.363	1.613	0.750	0.834	1.988	1.953	1.918	0.696
Fetenech	2.029	1.307	0.722	0.580	1.668	1.629	1.590	0.781
Akuri	1.367	0.862	0.505	0.258	1.115	1.086	1.057	0.811
Kutaye	2.607	1.622	0.985	0.925	2.115	2.057	2.000	0.829
Teketay	2.623	1.610	1.012	0.924	2.116	2.055	1.995	0.847
Worku	2.260	1.383	0.877	0.684	1.822	1.768	1.716	0.852
Shola	1.659	0.969	0.690	0.352	1.314	1.268	1.224	0.913
DZ-10-11	2.004	1.147	0.857	0.503	1.575	1.516	1.459	0.939
Akaki	2.597	1.430	1.166	0.812	2.013	1.927	1.844	0.986
Dhera	2.220	1.204	1.017	0.585	1.712	1.635	1.561	1.005
Mariye	2.390	1.252	1.138	0.655	1.821	1.730	1.643	1.045
DZ-10-4	1.428	0.718	0.710	0.224	1.073	1.013	0.956	1.091
Yelibe	1.821	0.860	0.961	0.342	1.340	1.251	1.168	1.159
Dubie	2.557	1.162	1.395	0.650	1.860	1.724	1.598	1.197
Chefe	1.825	0.802	1.023	0.320	1.314	1.210	1.115	1.230
Hora	2.322	1.018	1.304	0.517	1.670	1.538	1.416	1.232
Kasech	2.379	0.953	1.426	0.496	1.666	1.506	1.361	1.315
Ejere	2.293	0.910	1.383	0.456	1.601	1.444	1.303	1.324
Habru	1.891	0.727	1.164	0.301	1.309	1.172	1.050	1.351
Arerti	2.509	0.953	1.556	0.523	1.731	1.546	1.381	1.361
Teji	2.154	0.804	1.350	0.379	1.479	1.316	1.171	1.375
Kobo	2.080	0.690	1.391	0.314	1.385	1.198	1.036	1.467
Shasho	2.895	0.842	2.053	0.533	1.868	1.561	1.305	1.556

Note. YP, potential (nonstress) yield; YS, stressed yield; TOL, tolerance index; STI, stress tolerance index; MP, mean productivity, GMP, geometric mean productivity; HRM, harmonic mean productivity.
[a]Genotypic ranking (from tolerant to susceptible) was made based on SSI values.

4 | DISCUSSION

Moisture stress induced terminal drought remains a major threat to chickpea production in a rainfed Vertisol-based cropping system in Ethiopia (Korbu et al., 2020). The crop is mainly grown during post-rainy season on residual moisture causing terminal drought stress leading to remarkable yield loss. Under the Ethiopian context, field screening for drought tolerance can be carried out either in the off-season (December–April) using irrigation, or during the post-rainy season (September–January). The former approach has routinely been carried out for many crops but has the limitation of overriding effects from other factors, especially with the progressively increasing temperature during the dry growing season. Thus, for chickpea, field screening under rainfed environment during the post-rainy season is more realistic and best representative of farmers' cropping system (see Figure 1). Zemede et al. (2019) reported the advantage of this approach in durum wheat (*Triticum durum* Desf.) screening for drought tolerance over the controlled or simulated system. Further, the approach has also been used in large-scale breeding programs in the international research institutions, for instance in the prominent CGIAR (Consultative Group for International Agricultural Research) centers such as ICRISAT (International Crops Research Institute for the Semi-Arid Tropics) and ICARDA (International Center for Agricultural Research in the Dry Areas) (Bidinger, 2002; Saxena et al., 2002). This method of analysis thus provides an effective estimator of major factors that determine yield under drought.

The present field experiment was carried out on three soil types using three watering regimes to represent the common chickpea growing environments in Ethiopia. In general, there were noticeable and negative impacts on yield and its component traits as drought severity increased. Cultivars exposed to mild (RF) and severe (WS) stress conditions showed high and significant reduction in almost all variables studied, which may also be accountable for proportionally high GY reduction. Interestingly, under a given watering regime, effects of drought on agronomic performance of the cultivars varies significantly across the soil types, implying that the intensity or impact of drought is highly dependent on soil type (see also Supplemental Table S5). It is likely that heavy black clay soil, which has high clay content, can conserve moisture for more days and hence plants suffer less from drought. Conversely, the crop suffers more stress in light soils than in any other soil type due to higher sand content and lower water holding capacity. Yield reduction as a result of stress condition ranged from 12 to 71% with an average of 47% across the three soil types. This is similar in magnitude to yield reduction generally observed in farmers' fields in many places in Ethiopia (Korbu et al., 2020), and a comparable yield loss was recently reported from the major chickpea-growing subregions in India (Hajjarpoor et al., 2018). Moisture stress at the reproductive growth stage is, therefore, among the major constraints responsible for an estimated annual grain loss of 250,000 metric tons in the country at large, signifying the urgency of addressing it via the development of proper irrigation facilities and improved farming system practices.

The study further revealed that there is significant variation among the commercial cultivars developed over the last three decades to varying stress conditions for key yield component traits, particularly for pod number, seeds weight, and harvest index (Table 4). The results would help breeders to plan for exhaustive use of the genetic potentials of the cultivars as parental lines for future breeding programs. In addition, there was a large genetic difference between the two chickpea types, kabuli vs desi for their response to water deficit treatments. The kabuli cultivars showed greater sensitivity responses and resulted in remarkable yield reduction probably due to the shortening of the critical reproductive growth period resulting in higher flower and pod abortion (Leport et al., 2006; Nayyar et al., 2005). This suggests that breeding for stress tolerance and varietal selection in the kabuli types may also need to consider other physiological traits such as water use efficiency, seedling vigor, growth habits, canopy architecture, and so on for the development of cultivars with durable tolerance to sustain productivity in drought-prone areas.

The desi types, on the other hand, had better adaptation to severe stress treatment. Elsewhere in the world, the desi types conserved more adaptive traits than the kabuli types like seed coat variation and resilience traits to major stresses. Hence, this might have been revealed distinctly in the current response variability between the two types. This could also be explained by the fact that the desi chickpeas are ancient subspecies and have longer tradition of cultivation history in Ethiopia, and the crop has evolved adaptive traits in due course (Keneni et al., 2012; van der Maesen et al., 2007). This implies that the desi germplasm represents untapped genetic resources and have potential sources of adaptive traits in future breeding programs (Fikre et al., 2020). Overall, a wide-range response among the cultivars to varying moisture regimes indicates high genetic variability in the breeding germplasm pool—a potential for future improvement for drought tolerance and adaptive traits in the crop.

It has long been known that drought stress impedes morphological traits like PHT, number of leaves, and canopy architecture in many crops (Farooq et al., 2012; Hussain et al., 2018). Results of the present study (Table 5) showed that chickpea cultivars grown under stressed condition showed reduced time to flowering on average by 15 d compared with the nonstressed (favorable) condition. Pushpavalli et al. (2015) and Maqbool et al. (2015) reported similar results in chickpea lines evaluated under field conditions where stress treatment caused high and significant changes in most of the agronomic traits studied. Our results further confirmed earlier reports (Nayyar et al., 2005, 2006) that chickpea in general is highly sensitive to moisture stress at later growth stages despite the presence of considerable genetic variation among the cultivars for major drought tolerance contributing characters.

Among the component traits studies, PP, PHT, BY, and HI were very closely associated with and consistently had positive contribution to the final GY irrespective of the moisture regime (Table 5). This suggests that these traits are more stable and reliable indicators of drought tolerance in chickpea across growing environments examined in this study, which is also in agreement with previous investigations made on chickpea (Kobraee et al., 2010; Silim & Saxena, 1993). Similar positive relationship between agronomic characters and seed yield was reported under other abiotic stresses like salinity (Jha et al., 2014; Vadez et al., 2012). On the other hand, SP and grain weights had minimum contribution in grain yield determination, which is also in agreement with the report of Purushothamana et al. (2016). Furthermore, the present study identified eight chickpea cultivars showing high level of drought tolerance responses based on field-level drought scoring and overall performance evaluation. Cultivars showing superior overall performance under severe stress condition are potentially suitable for production in drought-prone growing environments in Ethiopia. The cultivars can also be used as donor parents in the breeding programs where novel adaptive traits can be transferred into elite lines for enhancing drought tolerance (Maqbool et al., 2017; Sachdeva et al., 2020). Most importantly, they are extremely useful in basic studies of trait discovery in the pre-breeding programs. Likewise, cultivars showing the most tolerant and most susceptibility responses were identified from both kabuli and desi chickpea cultivars. These contrasting parents may be used as checks in future multienvironment drought screening trials. The identification and mapping of genes and quantitative trait loci responsible for contrasting phenotypes would also be an important study area of the future.

The results of correlation analysis between popular drought tolerance indices and yield performance were important (Farshadfar et al., 2001). The indices were widely used in previous studies and reported as highly informative to evaluate cultivar performance in chickpea (Saxena et al., 2002; Talebi et al., 2013) and recently in groundnuts (Oppong-Sekyere et al., 2018). The results of this study also showed significant and strong correlation between the indices and cultivar performance (Table 8), which is in agreement with the reports of Saxena et al. (2002), Talebi et al. (2013), and Johansen et al. (1994). Drought response study conducted in Iran using 64 chickpea genotypes obtained similar results (Rezai et al., 2015), indicating the consistency of the indices as reliable indicators and are capable to identify genotypes combining tolerance and good agronomic performance.

Both the mild (RF) and severe (WS) moisture stress field experiments, which are representative of the commonly chickpea production practices in Ethiopia, resulted in remarkable reduction in yield and yield attributable traits. Reduction in seed yield were to the extent of 54 and 71% when the cultivars are subjected to mild and severe stress treatments, respectively, compared with the nonstress control, and this is in the range of previous reports (Leport et al., 2006; Shamsi et al., 2010). The study, on the other hand, showed that cultivars tested under severe and mild stress treatments gave average yield advantage of 48% and 22%, respectively as a result of irrigated (WW) treatment. Interestingly, the kabuli types were more responsive to supplemental irrigation compared to the desi types, and hence are better fit for irrigated chickpea production in the country. By contrast, the desi types performed better under stress growing environments. This result is in agreement with previous studies of Nayyar et al. (2006) and Krishnamurthy et al. (2010), who reported distinctive variation between the two types in their response to water stress. A recent study by Purushothamana et al. (2016) also reported similar results in chickpea genotypes tested under varying drought treatments.

In terms of stress intensity, our hypothesis that considered the two stress treatments used in this field experiment as mild and severe was further proved by percentage yield reduction, which is in agreement with recent reports on other legume crops (Chiulele et al., 2011; Molaaldoila et al., 2016). The nonstress treatment, on the other hand, showed considerable yield gains, demonstrating the importance of supplementary irrigation to late-planted chickpea whereby millions of farmers in the rainfed production system can ensure economic advantages by reducing terminal drought effects that cause yield losses (Oweis et al., 2004; Shamsi et al., 2010). The next step to the present study is to evaluate the superior cultivars identified in a wider drought-prone growing environments to further verify the stability of the traits.

5 | CONCLUSION

Despite the generalized notion that considers chickpea as a drought-tolerant crop, most commercial cultivars showed high sensitivity even to mild stress conditions. Grain yield reduction due to severe moisture stress exceeded 70%, emphasizing drought as an important bottleneck limiting chickpea production in Ethiopia. The lack of simple and efficient field-screening methods has hampered fast-track of drought-tolerant lines. Although yield has been the primary breeding objective in any production improvement programs, varietal selection based on yield data per se under drought condition may not give a reliable result, as yield is the most complex trait. In addition, yield differences under nonstress and stress conditions cannot effectively discriminate the cultivars into tolerant and susceptible. Dissecting the specific yield-determinant traits is, therefore, the best approach of screening under drought stress conditions to select cultivars for stress adaptation. In this study, we mainly used yield and its component traits as proxy parameters of screening for drought tolerance under field conditions. Given the challenges of screening using root traits under field conditions, the approach provides rapid and effective method of field screening. The study identified PP, PHT, BY, and HI among the key yield-attributes conferring drought tolerance in chickpea, which can potentially be used in selection indices, and more importantly in stress breeding programs for the development of drought adaptive cultivars. Furthermore, traits showing higher and strong association with drought adaptation can be used for the development of diagnostic markers for use in marker-assisted breeding.

From a breeding viewpoint, the approach used here demonstrates a simple and cheap field-level screening method for adaptation-related traits, which may also be adopted for other crops threatened by terminal drought. The approach provides an effective method of evaluating factors that determine yield under drought stress conditions. The results further suggest that chickpea varietal recommendation targeting the native chickpea growing environments virtually represented by this study should be accompanied by appropriate agronomic practices mainly soil moisture conservation and planting time. A key finding is that the delayed planting method used, which is a representative of the traditional chickpea cropping practice, caused noticeable yield loss. The practice thus needs proper technological intervention to prevent additional yield losses, which is of particular importance in the context of agroclimatic changes.

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AUTHOR CONTRIBUTIONS

Lijalem Korbu: Conceptualization; Data curation; Formal analysis; Investigation; Methodology; Validation; Visualization; Writing-original draft; Writing-review & editing. Asnake Fikre: Conceptualization; Methodology; Project administration; Resources; Supervision; Writing-original draft; Writing-review & editing. Kassahun Tesfaye: Conceptualization; Investigation; Methodology; Project administration; Supervision; Writing-review & editing. Assefa Funga: Data curation; Formal analysis; Methodology; Software; Writing-original draft. Dagnachew Bekele: Formal analysis; Investigation; Methodology; Writing-original draft; Writing-review & editing. Chris O. Ojiewo: Methodology; Resources; Writing-original draft; Writing-review & editing.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

ORCID

Lijalem Korbu https://orcid.org/0000-0002-8301-8729
Asnake Fikre https://orcid.org/0000-0002-6274-9346

REFERENCES

Bidinger, F. R. (2002). Field screening for drought tolerance: Principles and illustrations. In N. P. Saxena & J. C. O'Toole (Eds.), *Field screening for drought tolerance in crop plants with emphasis on rice: Proceedings of an International Workshop on Field Screening for Drought Tolerance in Rice* (pp. 109–124). ICRISAT and the Rockefeller Foundation.

Campos, H., Cooper, M., Habben, J. E., Edmeades, G. O., & Schussler, J. R. (2004). Improving drought tolerance in maize: A view from industry. *Field Crops Research*, *90*(1), 19–34. https://doi.org/10.1016/j.fcr.2004.07.003

Ceccarelli, S., Acevedo, E., & Grando, S. (1991). Breeding for yield stability in unpredictable environments: single traits, interaction between traits, and architecture of genotypes. *Euphytica*, *56*, 169–185. https://doi.org/10.1007/BF00042061

Chiulele, R., Mwangi, T., Ehlers, J., & Ndeve, A. (2011). Assessment of cowpea genotypes for variability to drought tolerance. *African Crop Science Conference Proceedings*, *10*, 531–537.

Choukan, R., Taherkhani, T., Ghannadha, M. R., & Khodarahmi, M. (2006). Evaluation of drought tolerance in grain maize inbred lines using drought tolerance indices. *Iranian Journal of Agricultural Science*, *8*, 79–89.

CSA (Central Statistical Agency of Ethiopia). (2019). *Agricultural sample survey 2018/19 (2011 E.C.) Report on area and production of major crops*. CSA.

Daryanto, S., Wang, L., & Jacinthe, P. -. A. (2015). Global synthesis of drought effects on food legume production. *PLOS ONE*, *10*, e012740. https://doi.org/10.1371/journal.pone.0127401

Desta, F., Bissa, M., & Korbu, L. (2015). Crop water requirement determination of chickpea in the central vertisol areas of Ethiopia using FAO CROPWAT model. *African Journal of Agricultural Research*, *10*(7), 685–689.

Devasirvatham, V., & Tan, D. K. Y. (2018). Impact of high temperature and drought stresses on chickpea production. *Agronomy*, *8*(145).

FAO. (2018). *World food and agriculture: Statistical pocketbook 2018*. FAO.

FAO. (2019). *FAOSTAT database*. Retrieved October 2021 from https://www.fao.org/faostat/en/

Farooq, M., Hussain, M., Wahid, A., & Siddique, K. (2012). Drought stress in plants: An overview. In R. Aroca (Ed.), *Plant responses to drought stress: From morphological to molecular features* (pp. 1–33). Springer.

Farshadfar, E., Ghanadha, Sutka, J., & Zahravi, M. (2001). Generation mean analysis of drought tolerance in wheat (*Triticum aestivum* L). *Acta Agronomica Hungarica*, *49*(1), 59–66. https://doi.org/10.1556/AAgr.49.2001.1.7

Fasahat, P., Rajabi, A., Mahmoudi, S., Noghabi, M., & Rad, J. (2015). An overview on the use of stability parameters in plant breeding. *Biometrics & Biostatistics International Journal*, *2*(5), 49–159.

Fernandez, G. C. (1992). Effective selection criteria for assessing plant stress tolerance In C. G. Kuo (Ed.), *Proceedings of a Symposium on Adaptation of Vegetables and Other Food Crops in Temperature and Water Stress* (pp. 257–270). Asian Vegetable Research and Development Center.

Fikre, A., Desmae, H., & Ahmed, S. (2020). Tapping the economic potential of chickpea in sub-Saharan Africa. *Agronomy*, *10*(11), 1707. https://doi.org/10.3390/agronomy10111707

Fikre, A., Funga, A., Korbu, L., Eshete, M., & Girma, N. (2018). Stability analysis in chickpea genotype sets as tool for breeding germplasm structuring strategy and adaptability scoping. *Ethiopian Journal of Crop Science*, *6*(2), 19–37.

Fischer, R., & Maurer, R. (1978). Drought tolerance in spring wheat cultivars. I. Grain yield responses. *Australian Journal of Agricultural Research*, *29*, 897–912. https://doi.org/10.1071/AR9780897

Frutos, E., Galindo, M. P., & Leiva, V. (2014). An interactive biplot implementation in R for modeling genotype-by-environment interaction. *Stochastic Environmental Research and Risk Assessment*, *28*(7), 1629–1641. https://doi.org/10.1007/s00477-013-0821-z

Gaur, P. M., Jukanti, A. K., & Varshney, R. K. (2012). Impact of genomic technologies on chickpea breeding strategies. *Agronomy*, *2*(3), 199–221. https://doi.org/10.3390/agronomy2030199

Güler, M., Sait Adak, M., & Ulukan, H. (2001). Determining Relationships among yield and some yield components using path Coefficient analysis in Chickpea (*Cicer arietinum* L). *European Journal of Agronomy*, *14*, 161–166. https://doi.org/10.1016/S1161-0301(00)00086-1

Hajjarpoor, A., Vadez, V., Soltani, A., Gaur, P., Whitbread, A., Suresh Babu, D., Gumma, M. K., Diancoumba, M., & Kholová, J. (2018). Characterization of the main chickpea cropping systems in India using a yield gap analysis approach. *Field Crops Research*, *223*, 93–104. https://doi.org/10.1016/j.fcr.2018.03.023

Hussain, M., Farooq, S., Hasan, W., Ul-Allah, S., Tanveer, M., Farooq, M., & Nawaz, A. (2018). Drought stress in sunflower: physiological effects and its management through breeding and agronomic alternatives. *Agricultural Water Management*, *201*, 152–166. https://doi.org/10.1016/j.agwat.2018.01.028

Jha, U. C., Chaturvedi, S. K., Bohra, A., Basu, P. S., Khan, M. S., & Barh, D. (2014). Abiotic stresses, constraints and improvement strategies in chickpea. *Plant Breeding*, *133*(2), 163–178. https://doi.org/10.1111/pbr.12150

Johansen, C., Krishnamurthy, L., Saxena, N. P., & Sethi, S. C. (1994). Genotypic variation in moisture response of chickpea grown under line-source sprinklers in a semi-arid tropical environment. *Field Crops Research*, *37*(2), 103–112. https://doi.org/10.1016/0378-4290(94)90038-8

Jukanti, A., Gaur, P., Gowda, C., & Chibbar, R. (2012). Nutritional quality and health benefits of chickpea (*Cicer arietinum* L): A review. *British Journal of Nutrition*, *108*, S11–S26. https://doi.org/10.1017/S0007114512000797

Kashiwagi, J., Krishnamurthy, L., Gaur, P. M., Upadhyaya, H. D., Varshney, R. K., & Tobita, S. (2013). Traits of relevance to improve yield under terminal drought stress in chickpea (*C arietinum* L). *Field Crops Research*, *145*, 88–95. https://doi.org/10.1016/j.fcr.2013.02.011

Keneni, G., Bekele, E., Assefa, F., Imtiaz, M., Debele, T., Dagne, K., & Getu, E. (2012). Phenotypic diversity for symbio-agronomic characters in Ethiopian chickpea (*Cicer arietinum* L) germplasm accessions. *African Journal of Biotechnology*, *11*(63), 12634–12651.

Khatun, N. (2021). Applications of normality test in statistical analysis. *Open Journal of Statistics*, *11*(01), 113–122. https://doi.org/10.4236/ojs.2021.111006

Kobraee, S., Shamsi, K., Rasekhi, B., & Kobraee, S. (2010). Investigation of correlation analysis and relationships between grain yield and other quantitative traits in chickpea (*Cicer arietinum* L). *African Journal of Biotechnology*, *9*(16), 2342–2348.

Korbu, L., Tafes, B., Kassa, G., Mola, T., & Fikre, A. (2020). Unlocking the genetic potential of chickpea through improved crop management practices in ethiopia a review. *Agronomy for Sustainable Development*, *40*(2). https://doi.org/10.1007/s13593-020-00618-3

Krishnamurthy, L., Kashiwagi, J., Gaur, P. M., Upadhyaya, H. D., & Vadez, V. (2010). Sources of tolerance to terminal drought in the chickpea (*Cicer arietinum* L.) minicore germplasm. *Field Crop Research*, *119*, 322–330. https://doi.org/10.1016/j.fcr.2010.08.002

Kumar, P., Boora, K. S., Kumar, N., Batra, R., Goyal, M., Sharma, K. D., & RC, Y. (2018). Traits of significance for screening of chickpea (*Cicer arietinum* L.) genotypes under terminal drought stress. *Journal of Agrometeorology*, *20*(1), 40–45.

Lan, J. (1998). Comparison of evaluating methods for agronomic drought resistance in crops. *Acta Agriculturae Boreali-Occidentalis Sinica*, *7*, 85–87.

Leport, L., Turner, N. C., Davies, S. L., & Siddique, K. H. M. (2006). Variation in pod production and abortion among chickpea cultivars under terminal drought. *European Journal of Agronomy*, *24*(3), 236–246. https://doi.org/10.1016/j.eja.2005.08.005

Maqbool, M. A., Aslam, M., & Ali, H. (2017). Breeding for Improved drought tolerance in chickpea (*Cicer arietinum* L.). *Plant Breeding*, *136*, 300–318. https://doi.org/10.1111/pbr.12477

Maqbool, M. A., Aslam, M., Ali, H., Shah, T. M., Farid, B., & Zaman, Q. U. (2015). Drought tolerance indices based evaluation of chickpea advanced lines under different water treatments. *Research on Crops*, *16*(2), 336–344. https://doi.org/10.5958/2348-7542.2015.00049.2

Mark, L., & Levine, B. (1996). *Basic business statistics: Concepts and applications* (5th ed.). Prentice-Hall.

Molaaldoila, Y., Al-Hadi, A., Al-Mosanif, E., & Al-Hakimi, K. (2016). Genotypic variation for agronomical and physiological traits affecting drought resistance in common bean (*Phaseolus vulgaris* L.). *International Journal of Plant Breeding and Crop Science*, *3*(1), 109–122.

Nadeem, M., Li, J., Yahya, M., Sher, A., Ma, C., Wang, X., & Qiu, L. (2019). Research progress and perspective on drought stress in legumes: A review. *International Journal of Molecular Sciences*, *20*(10). https://doi.org/10.3390/ijms20102541

Namvar, A., Sharif, R. S., & Khandan, T. (2011). Growth analysis and yield of chickpea (*Cicer arietinum* L) in relation to organic and inorganic nitrogen fertilization. *Ekologija*, *57*(3), 97–108. https://doi.org/10.6001/ekologija.v57i3.1915

Nautiyal, P. C., Rachaputi, N. R., & Joshi, Y. C. (2002). Moisture deficit–induced changes in leaf water content, leaf carbon exchange rate and biomass production in groundnut cultivars differing in specific leaf area. *Field Crops Research*, *74*, 67–79. https://doi.org/10.1016/S0378-4290(01)00199-X

Nayyar, H., Kaur, S., Singh, K. J., Dhir, K. K., & Bains, T. (2005). Water stress-induced injury to reproductive phase in chickpea: evaluation of stress sensitivity in wild and cultivated species in relation to abscisic acid and polyamines. *Journal of Agronomy and Crop Science*, *191*(6), 450–457. https://doi.org/10.1111/j.1439-037X.2005.00184.x

Nayyar, H., Kaur, S., Singh, S., & Upadhyaya, H. D. (2006). Differential sensitivity of desi (small-seeded) and kabuli (large-seeded) chickpea genotypes to water stress during seed filling: effects on accumulation of seed reserves and yield. *Journal of the Science of Food and Agriculture*, *86*(13), 2076–2082. https://doi.org/10.1002/jsfa.2574

Oppong-Sekyere, D., Akromah, R., Kena, A., Larweh, V., & Ozias-Akins, P. (2018). Screening and selection of drought-tolerant groundnut varieties based on yield performance. *International Journal of Plant Breeding and Crop Science*, *5*(3), 463–473.

Oweis, T., Hachum, A., & Pala, M. (2004). Water use efficiency of winter-sown chickpea under supplemental irrigation in a Mediterranean environment. *Agricultural Water Management*, *66*, 163–179. https://doi.org/10.1016/j.agwat.2003.10.006

Pang, J., Turner, N., Khan, T., Du, Y. L., Xiong, J. L., Colmer, T., Devilla, R., Stefanova, K., & Siddique, K. H. M. (2017). Response of chickpea (*Cicer arietinum* L.) to terminal drought: leaf stomatal conductance, pod abscisic acid concentration, and seed set. *Journal of Experimental Botany*, *68*(8), 1973–1985.

Passioura, J. B. (1983). Roots and drought resistance. *Agricultural Water Management*, *7*, 265–280. https://doi.org/10.1016/0378-3774(83)90089-6

Purushothamana, R., Krishnamurthy, L., Upadhyaya, H. D., Vadez, V., & RK, V. (2016). Shoot traits and their relevance in terminal drought tolerance of chickpea (*Cicer arietinum* L.). *Field Crops Research*, *197*, 10–27.

Pushpavalli, R., Zaman-Allah, M., Turner, N. C., Baddam, R., Rao, M. V., & Vadez, V. (2015). Higher flower and seed number leads to higher yield under water stress conditions imposed during reproduction in chickpea. *Functional Plant Biology*, *42*(2), 162–174. https://doi.org/10.1071/FP14135

Rezai, M., Shabani, A., Nakhjavan, S., & Zebarjadi, A. (2015). Screening drought tolerant genotypes in chickpea using stress tolerance score (STS) method. *International Journal of Advanced Biological and Biomedical Research*, *3*(1), 119–128.

Rosielle, A. A., & Hamblin, J. (1981). Theoretical aspects of selection for yield in stress and non-stress environments. *Crop Science*, *21*, 943–946. https://doi.org/10.2135/cropsci1981.0011183X002100060033x

Sachdeva, S., Bharadwaj, C., Singh, R. K., Jain, P. K., Patil, B. S., Roorkiwal, M., & Varshney, R. (2020). Characterization of ASR gene and its role in drought tolerance in chickpea (*Cicer arietinum* L.). *PLOS ONE*, *15*(7), e0234550. https://doi.org/10.1371/journal.pone.0234550

Samarah, N. H., Haddad, N., & Alqudah, A. M. (2009). Yield potential evaluation in chickpea genotypes under late terminal drought in relation to the length of reproductive stage. *Italian Journal of Agronomy*, *3*, 111–117. https://doi.org/10.4081/ija.2009.3.111

Saxena, N. P., & O'Toole, J. C. (Eds.) (2002). *Field screening for drought tolerance in crop plants with emphasis on rice: Proceedings of an International Workshop on Field Screening for Drought Tolerance in Rice*. ICRISAT and the Rockefeller Foundation.

Saxena, N., Krishanamurthy, L., & Johansen, C. (2002). Genetic improvement of drought tolerance in chickpea at ICRISAT. In N. P. Saxena & J. C. O'Toole (Eds.), *Field screening for drought tolerance in crop plants with emphasis on rice: Proceedings of an International Workshop on Field Screening for Drought Tolerance in Rice* (pp. 128–137). ICRISAT and the Rockefeller Foundation.

Shamsi, K., Kobraee, S., & Haghparast, R. (2010). Drought stress mitigation using supplemental irrigation in rainfed chickpea (*Cicer arietinum* L) varieties in Kermanshah, Iran. *African Journal of Biotechnology*, *9*(27), 4197–4203.

Shapiro, S. S., & Wilk, M. B. (1965). An analysis of variance test for normality (complete samples). *Biometrika*, *52*(3/4), 591–611. https://doi.org/10.2307/2333709

Silim, S. N., & Saxena, M. C. (1993). Adaptation of spring-sown chickpea to the Mediterranean basin. II. Factors influencing yield under drought. *Field Crops Research*, *34*, 137–146. https://doi.org/10.1016/0378-4290(93)90002-5

Sofi, P. A., Rehman, K., Ara, A., & Gull, M. (2018). Stress tolerance indices based on yield, phenology and biomass partitioning: A review. *Agricultural Reviews*, *39*(4), 292–299.

Subbarao, G. V., Johansen, C., Slinkard, A. E., Nageswara Rao, R. C., Saxena, N. P., Chauhan, Y. S., & Lawn, R. J. (1995). Strategies for improving drought resistance in grain legumes. *Critical Reviews in Plant Sciences*, *14*(6), 469–523. https://doi.org/10.1080/07352689509701933

Tafesse, D., & Esayas, A. (2003). *Soils of the Debre Zeit Agricultural Research Center and its subcenters* (Technical Paper 79). Federal Democratic Republic of Ethiopia, Ethiopian Agricultural Research Organization.

Talebi, R., Ensafi, M., Baghebani, N., Karami, E., & Mohammadi, K. (2013). Physiological responses of chickpea (*Cicer arietinum*) genotypes to drought stress. *Environmental and Experimental Biology*, *11*, 9–15.

Trethowan, R. M., Ginkel, M., & Rajaram, S. (2002). Progress in breeding for yield and adaptation in global drought affected environments. *Crop Science*, *42*, 1441–1446. https://doi.org/10.2135/cropsci2002.1441

Turner, N. C., Wright, G. C., & Siddique, K. H. M. (2001). Adaptation of grain legumes (pulses) to water-limited environments. *Advances in Agronomy*, *71*, 193–271. https://doi.org/10.1016/S0065-2113(01)71015-2

Vadez, V. (2014). Root hydraulics: The forgotten side of roots in drought adaptation. *Field Crops Research*, *165*, 15–24. https://doi.org/10.1016/j.fcr.2014.03.017

Vadez, V., Rashmi, M., Sindhu, K., Muralidharan, M., Pushpavalli, R., Turner, N. C., Krishnamurthy, L., Gaur, P. M., & Colmer, T. D. (2012). Large number of flowers and tertiary branches, and higher reproductive success increase yields under salt stress in chickpea. *European Journal of Agronomy*, *41*, 42–51. https://doi.org/10.1016/j.eja.2012.03.008

van der Maesen, L. J., Maxted, N., Javadi, F., Coles, S., & Davies, A. M. (2007). Taxonomy of *Cicer* revisited. In S. S. Yadav, R. Redden, W. Chen, & B. Sharma (Eds.), *Chickpea breeding and management* (pp. 14–46). CABI International.

Varshney, R., Pazhamala, L., Kashiwagi, J., Gaur, P., Krishnamurthy, L., & Hoisington, D. (2011). Genomics and physiological approaches for root trait breeding to improve drought tolerance in chickpea (*Cicer arietinum* L.). In A. Costa de Oliveira & R. K. Varshney (Eds.), *Root genomics* (pp. 233–250). Springer. https://doi.org/10.1007/978-3-540-85546-0_10

Varshney, R. K., Thudi, M., Nayak, S. N., Gaur, P. M., Kashiwagi, J., Krishnamurthy, L., Jaganathan, D., Koppolu, J., Bohra, A., Tripathi, S., Rathore, A., Jukanti, A. K., Jayalakshmi, V., Vemula, A., Singh, S. J., Yasin, M., Sheshshayee, M. S., & Viswanatha, K. P. (2014). Genetic dissection of drought tolerance in chickpea (*Cicer arietinum* L). *Theoretical and Applied Genetics*, *127*, 445–462. https://doi.org/10.1007/s00122-013-2230-6

Verkaart, S., Munyua, B. G., Mausch, K., & Michler, J. D. (2017). Welfare impacts of improved chickpea adoption: A pathway for rural development in Ethiopia? *Food Policy*, *66*, 50–61. https://doi.org/10.1016/j.foodpol.2016.11.007

Yan, W., Hunt, L. A., Sheng, Q., & Szlavnics, Z. (2000). Cultivar evaluation and mega-environment investigation based on GGE biplot. *Crop Sciences*, *40*, 597–605. https://doi.org/10.2135/cropsci2000.403597x

Yan, W., & Tinker, N. A. (2006). Biplot analysis of multi-environment trial data: Principles and applications. *Canadian Journal of Plant Science*, *86*(3), 623–645. https://doi.org/10.4141/P05-169

Yimer, S. M., Ahmed, S., Fininsa, C., Tadesse, N., Hamwieh, A., & Cook, D. R. (2018). Distribution and factors influencing chickpea wilt and root rot epidemics in Ethiopia. *Crop Protection*, *106*, 150–155. https://doi.org/10.1016/j.cropro.2017.12.027

Zemede, A., Mekbib, F., Assefa, K., & Bishaw, Z. (2019). Variability in Ethiopian durum wheat under rainfed environment subjected to drought at anthesis. *Ethiopian Journal of Agricultural Science*, *29*(2), 17–29.

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