EVALUATION OF FINGER MILLET (*Eleusine coracana* L.) GENOTYPES FOR DROUGHT TOLERANCE USING MORPHO-PHYSIOLOGICAL AND ROOT TRAITS

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DECLARATION AND RECOMMENDATION

Declaration

I declare that this thesis is my original work and has not been presented in this university or any other for the award of a degree.

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Recommendation

This thesis has been submitted with our approval as University supervisors.

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DEDICATION

I affectionately dedicate this thesis to my spouse, Kelvin and daughters, Joy and Ann for their endless support and inspiration throughout the study period.

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ABSTRACT

Water one of the most limiting factor of crop production under drought endemic environments. Water stress affects the morphology and the physiological metabolism of the plant. Finger millet (*Eleusine coracana* L.) is one of the crop species with resilience to various adverse climate change effects and with high nutritional value. However, its production and yield over the years have declined due to its low preference in favour of modern cereals, drought stress and limited availability of improved varieties. This study was conducted to evaluate in finger millet genotypes for drought tolerance based on morpho-physiological traits. In the first experiment, twenty-four finger millet lines were evaluated alongside a check P224 under field conditions. The experiment was laid in a 5 × 5 triple Lattice design in three replications at two locations for one season. In the second experiment, twenty-four finger millet lines and one commercial check P224 were screened for root-shoot morphological features in polyvinyl chloride pipes under rain out shelter (ROS) conditions in randomized complete block design (RCBD) with three replications. In the third experiment, nine elite finger millet lines including a check P224 selected from first and second experiments based on good root-shoot features, morpho-physiological traits and high yield were evaluated. A split plot design in RCBD was used with water regime as the main plot and the lines as the sub-plot under ROS. Results from experiment one revealed significant ($P<0.05$) difference among the genotypes, locations and genotype-by-location interactions for morphological, physiological and agronomic traits evaluated. Advanced lines ICFX1420314-2-1-1-1, KNE 814 × Ex Alupe (P) P8-1-1-1-1 and ICFX1420415-3-1-1-2 were outstanding for drought tolerance as they displayed low evapotranspiration rate, high water use efficiency, increased root growth and high grain yield. In experiment two, three lines, ICFX1420431-3-3-1, ICFX1420314-2-1-1-1 and ICFX1420396-5-5-1-1 were identified to have deep rooting system, increased number of root hairs, high root density and root to shoot ratio. Experiment 3 further confirmed the performance of the top nine ranked finger millet lines from experiments 1 and 2 based on agronomic, morpho-physiological and root traits, and high grain yield. In this experiment, morpho-physiological and root traits such as increased root growth, shoot dry weight, root dry weight and grain were identified as parameters that are associated with water use efficiency among finger millet lines studied. In summary, this study identified two elite lines ICFX1420314-2-1-1-1 and ICFX1420431-3-3-1, which can serve as promising parental stock for breeding programmes aimed at improvement of drought tolerance for increased finger millet production in semiarid areas. These lines are also potential candidates for formal release to farmers for commercialization.

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LIST OF ABBREVIATIONS AND ACRONYMS/ SYMBOLS

AEZ	Agro-ecological zones
ASALs	Arid and semi-arid lands
DAS	Days after Sowing
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Statistics
FC	Field capacity
HI	Harvest index
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
LAI	Leaf area index
NUE	Nitrogen use efficiency
p. a	per annum
PH	Plant height
RCBD	Randomized complete block design
RLD	Root length density
RWC	Relative water content
SB	Shoot biomass
SDW	Shoot dry weight
SRL	Specific root length
TB	Total biomass
TDM	Total dry matter
TDW	Total dry weight
TRL	Total root length
Viz.,	Namely
WUE	Water use efficiency

CHAPTER ONE

INTRODUCTION

1.1 Background information

Finger millet (*Eleusine coracana* L.) is an important cereal crop utilized by a large segment of population living in marginal areas of sub-Saharan Africa and Asia (Chivenge *et al.,* 2015). It is one of the small millet cereals (Goron & Raizada, 2015) which originated from the Ethiopian highlands of Africa (Singh & Kumar, 2016). Finger millet was domesticated in the eastern African sub-humid uplands (Assefa *et al.*, 2013) making it well suited for Africa's climate. It is the most important small millet in the tropics covering 12% of global millet production area and is cultivated in more than 25 countries in Africa and Asia (Kumar *et al.*, 2016). In eastern and central Africa, it is produced in Uganda, Kenya, Tanzania, Rwanda, Burundi, eastern Democratic Republic of Congo, Ethiopia, Sudan and Somalia (Gebreyohannes *et al.*, 2021; Mulualem & Melak, 2013). Among the cereal grains, finger millet ranks fourth on a global scale of production after sorghum (*Sorghum bicolor*), pearl millet (*Cenchrus americanus*) and foxtail millet (*Setaria italica*) (Maharajan *et al.,* 2019; Upadhyaya *et al.*, 2013;Vetriventhan *et al.,* 2016). However, in Africa finger millet is second and represents 19% of millet production, after pearl millet (76%) (Upadhyaya *et al.*, 2013). Finger millet production is estimated to be 31 million tonnes with an area of 32,554,127 ha under production (FAOSTAT, 2022; Krishna *et al.*, 2020). India is the leading producer of finger millet with approximately 11.6 million tonnes, whereas Africa produces about 14.8 million tonnes annually. Other major producers are China, Ethiopia, Niger, Nigeria, and Sudan (FAOSTAT, 2022).

Sub-Saharan Africa comprises 43 % of the area classified as arid, with erratic rainfall and nutrient poor soils (FAO, 2017). In Kenya, the arid and semi-arid lands (ASALs) account for approximately 89% of the total land mass and are inhabited by resource poor farmers who depend on rain-fed agricultural production systems (Cervigni & Morris, 2016). Under these ASAL conditions rainfall is unpredictable and unevenly distributed hence water is the most limiting factor to successful crop production (Birch, 2018). Therefore, there is need to identify interventions likely to improve crop production under rain-fed conditions such as the adoption of drought resilient crops like finger millet. Finger millet adapts to a wide range of environments. It serves as a food security crop because of its high nutritional value, excellent storage qualities and its importance as a low input crop (Dida *et al.*, 2007; Gupta *et al.*,2017). Finger millet being drought tolerant forms an integral component of the low input farming systems and plays a critical role in agriculture and food security. Finger millet seeds can resist storage pests for as long as 10 years, ensuring round the year food supply or even during a crop failure (Mgonja *et al.,* 2013; Thilakarathna & Raizada, 2015). Finger millet needs less water than other cereals and can grow in the regions that are too hot and dry for other crops. This adaptive advantage enables it to have lower risk of failure compared to other cereals in such marginal environments. The main goal in arid and semi-arid regions is to produce more food with less water which as a result enhances food security to meet the requirements of the increasing population (Moumeni *et al.,* 2011).

The current scenario of low crop yields to complete crop failures is occasioned by drought, increased temperatures and erratic weather patterns attributed to climate change (Gladys, 2017). Drought affects morphological, physiological, biochemical and molecular processes in plants resulting in growth inhibition, stomata closure with consecutive reduction of transpiration, decrease in chlorophyll content and inhibition of photosynthesis and protein changes (Murtaza *et al.,* 2016). Anjum *et al.* (2011) suggested that when plants are grown under desiccation stress, they exhibit a sequence series of morphological, physiological, bio-chemical, cellular and molecular changes that severely compromise their growth, development and productivity. However, there exists a gap in the understanding of the physiological mechanisms underlying finger millet responses to drought (Assefa *et al.,* 2013). In addition, root hydraulics is among the poorly studied traits yet they contribute to significant drought tolerance (Vadez *et al.,* 2012).

The development of drought resistant cultivars depends on the identification of traits that can be used in a breeding and selection programme. For most crops, there is need to understand those traits that are inherent in drought stress resistant genotypes and are based on a plant’s morphology, physiology and anatomy. Breeding drought resilient crops is one way to increase grain yield. However, the breeding progress in finger millet has been slow during the past decades due to lack of understanding of the traits and mechanisms of drought tolerance (Bernier *et al.,* 2009). Hence, this study was conducted to evaluate finger millet lines for morphological, physiological and root-shoot traits associated with drought tolerance and understand their contribution to yield performance under stress conditions in order to identify suitable lines for targeted key finger millet growing areas of Kenya.

1.2 Statement of the problem

Finger millet biodiversity constitutes an ecological advantage for millions of small scale and traditional farmers in sub-Saharan Africa, playing a vital role in their agricultural systems, food security, livelihood and cultural identity. However, the crop is neglected and its production has declined in not only Kenya and sub-Saharan region but globally. Subsistence farmers under rain fed conditions in arid and semi-arid lands (ASALs) of Kenya where drought stress is a common feature often cultivate finger millet. Rainfall in these areas range from 300-500 mm per annum (p.a.) thus, finger millet invariably encounters drought stress during growth and early reproductive phase. Such drought stress results in grain yield losses of up to 32 per cent (ICRISAT, 2012; Taylor, 2016). Furthermore, a majority of finger millet farmers still grow low-yielding landraces due to limited access to improved drought tolerant commercial varieties hence incur yield losses. There is therefore need to develop and avail new resilient and drought tolerant varieties to mitigate the effects of climate change for sustained livelihoods of smallholder farmers in Kenya. Despite finger millet being recognized as a drought resilient crop, the underlying mechanisms being the basis of inherent drought tolerance are still not well understood. Therefore, identification of donor lines for morphological, physiological and root traits conferring tolerance to drought stress would be potentially useful for breeding programmes aimed at yield improvement under drought conditions. This is because, once identified, these traits can be used to identify high yielding genotypes in a faster and less expensive manner, thereby shortening the breeding period. In addition, root hydraulics represents the neglected but a significant component of drought adaptation especially in finger millets because of limited studies conducted so far. This is because they are below ground and their measurement is tedious and expensive, as it requires specialized technologies unlike above ground shoot and yield traits. Knowledge on measurements on root traits in finger millet will assist in predicting performance of finger millet lines for adaptation to drought and high temperatures.

1.3 Study Objectives

1.3.1 Broad objective

To contribute to increased finger millet production in the arid and semi-arid lands of Kenya through evaluation of finger millet genotypes for morpho-physiological and root traits associated with drought tolerance.

1.3.2 Specific objectives

i. To identify elite drought tolerant finger millet lines based on morpho-physiological characteristics and high grain yield.
ii. To determine the root-shoot characteristics associated with drought tolerance in the finger millet lines.
iii. To determine the morpho-physiological characteristics for water use efficiency of the finger millet lines under varying moisture regimes.

1.4 Hypotheses

1. There are no elite finger millet lines with superior morphological and physiological attributes for drought tolerance and high grain yield.
2. There are no root-shoot characteristics modulating drought tolerance among the finger millet lines.
3. There is no significant difference among the finger millet lines morpho-physiological characteristics for water use efficiency under varied water regimes.

1.5 Justification of the study

For agricultural production to keep pace with the expected demographic increase and food insecurity there is need to embrace crop varieties with enhanced nutraceutical value and improved stress tolerance. Changing climate has led to unpredictable rainfall and increased temperatures, which have resulted in low crop yields and sometimes complete crop failures of the preferred cereals such as maize. This has aggravated household's food insecurity and malnutrition. The average undernourishment for Africa for instance was 20.4% in 2016; the values ranged from a high of 31.4% in eastern Africa to a low of 8.4% in northern and southern Africa (FAO, 2017). Finger millet is one of the most nutritious cereals that could be the key to solving malnutrition problem among women and children. However, its availability and consumption is low and has been steadily declining over the recent years because it has been neglected by food crops research programmes in Africa thus contributing to mean grain yield of less than 1,000 kg ha^{-1} (Taylor, 2016) even though the yield potential is much higher (Onyango, 2016). Drought stress has been the most limiting abiotic stress in finger millet production. In spite of drought tolerant finger millet lines yielding relatively, well with limited supply of water. Limited work has been done to explore its tolerance mechanisms to drought possibly because it has been neglected in favour of modern cereals like maize and rice. In addition, farmers' dependence on landraces of finger millet cultivars coupled with lack of access to quality seed has led to decline in production. In Kenya for instance, the yield potential of variety P224 released in 1989 was 2,500 kg ha^{-1} but according to FAO (2017), about 10,000 farmers were cultivating it. Other varieties recently released and their basis of drought tolerance have not been evaluated and documented include U15, KAK *wimbi* 3, SEC 915, Snapping green, EUFM 501, KNE 814 purple and EUFM 503. Despite sufficient variability existing within the finger millet germplasm to select for drought tolerance, there is scanty information available on morpho-physiological and root traits. To date, most of the studies in Kenya have not provided quantitative measurements of finger millet's morphological, physiological and root drought resilience characteristics even though drought has been established as the major constraint to finger millet production. Consequently, information on the morphological, physiological and root traits associated with water use efficiency and drought tolerance in the selected finger millet lines will be an important tool towards increasing efficiency in millet improvement programmes to effectively aid in identifying suitable varieties adapted to drought and heat conditions.

CHAPTER TWO

LITERATURE REVIEW

2.1 General overview

Finger millet is a hardy crop and quite resilient to a variety of agro climatic adversities, like poor soil fertility and limited rainfall. It can contribute significantly in addressing food and nutritional security, especially in developing countries due to its high nutritional values (Devi *et al.,* 2014; Wambi *et al.,* 2021). Improving the productivity of finger millet, therefore, holds great potential to reduce poverty and hunger, the number one and two objectives of the Sustainable Development Goals (SDGs) of the United Nations (Dawson *et al.,* 2019). This is vital, particularly in sub-Saharan Africa, which is dominated by arid and semi-arid lands and more vulnerable to climate change (Kimani *et al.,* 2015). It is a staple food crop grown by subsistence farmers in the semi-arid tropics and sub-tropics of the world under rain-fed conditions (Thilakarathna & Raizada, 2015). The crop is largely consumed by marginalized inhabitants of semi-arid Asia and Africa and sold to provide subsistence farmers with additional income (Chandra *et al.,* 2016). However, finger millet growth and production is constrained by abiotic factors predominantly water stress (Mukami *et al.,* 2019). Further the situation is currently aggravated by the global climate change scenarios and the increasing population that has led to high demand for food and (Morison *et al.,* 2008). The development of drought tolerant cultivars depends on the identification of traits that can be used in a breeding and selection programme (Praba *et al.,* 2009). For finger millet, there is need to assess those traits that are inherent in drought stress tolerant genotypes based on a plant's morphology, physiology and root anatomy. Gosa *et al.* (2019) proposed the need for research and breeding efforts to be devoted to identifying and selecting for morpho-physiological, and biochemical traits that increase water use efficiency and yield under water limiting conditions. Tadele (2019) suggested the need to focus on improving crops relevant to the smallholder farmers and underprivileged consumers in the developing countries of the semi-arid tropics globally. Finger millet has the potential to improve household food security in semi-arid regions because of its adaptability to such environments (Taylor, 2016). Development of crop species that are adapted to drought endemic environments could potentially increase their production and productivity.

2.2 Botany of finger millet and agronomic requirements

Finger millet belongs to the genus *Eleusine* that includes eight species of diploid and tetraploid annual and perennial herbs. Finger millet together with tef (*Eragrostis tef*) belong to the subfamily Chloridoideae. The genus displays great variability and diversity for most traits of agronomic importance since the cultivated species also have several races and sub-races (Mirza & Marla, 2019). The species has two subspecies, *africana* and *coracana* (L) Gaertn. Subspecies *africana* has two races, *africana* and *spontanea*, while *coracana* has four races; *elongata, plana*, *compacta* and *vulgaris* (Mirza & Marla, 2019).

Finger millet is adaptable to a wide range of environmental and climatic conditions, thrives at higher elevation than most other tropical cereals and tolerates salinity better than most cereals. The crop is a robust, tufted and tiller producing grass which grows up to 170 cm tall and matures in approximately 120 to 130 days (Talwar *et al.*, 2020). Finger millet panicle has florets, which grow into finger-like structures ranging from 4 to 19 cm. The spikes can bear up to 70 alternate spikelets. Each spikelet contains 4 to 7 seeds (Upadhyaya *et al.,* 2007). The leaves can grow up to 20 cm broad and usually green (Ashwini *et al.,* 2014).

Finger millet is adapted to semi-arid and humid conditions and commonly produced in maize production areas. It performs well at altitudes between 1000 and 2000 m above sea level. It requires a minimum temperature of 8 -10 ℃ to germinate but needs a mean temperature of 26- 29 ℃ for its optimum growth. It requires well-distributed rainfall ranging from 500-1000 mm per growth cycle.

2.3 Production of finger millet

Finger millet is an important crop grown extensively in various regions of South Asia and Africa (Gupta *et al.,* 2017). It is estimated that 3.8 tonnes of finger millet are produced annually under an area of 32,554,127 ha worldwide (Indiastat, 2019; Numan *et al.*, 2021). Globally, 3,834,021 tonnes of finger millet grain are produced each year (FAOSTAT, 2022). Despite its importance for food security and livelihoods, finger millet productivity is low. (<2.47 tonnes/ha) compared with the potential yield of >6 tonnes/ha (Gebreyohannes *et al.,* 2021). Finger millet is the world's fourth most significant cereal crop. According to FAOSTAT dataset (2022), the world leading grain producers of finger millet include India with 10M tonnes, Nigeria with 5M tonnes and Niger with 2.9M tonnes. In Africa, Nigeria is the leading producer at 5M tonnes per annum while in eastern Africa, the major producers are Uganda, Ethiopia, and Kenya (FAOSTAT, 2022). Uganda is the highest producer with 841, 000 tonnes in an area of 412, 000 ha. In Kenya the annual finger millet production is 260, 000 tonnes with a total area of 185, 000 ha under production and an estimated yield of 750 kg ha^{-1} (Ndungu *et al.,* 2017). In Kenya, the main producing areas are Kakamega, Kisii, Bomet, Elgeyo Marakwet, Kericho, Nandi, Nakuru, Kuria, Migori, Machakos, Kitui, Baringo counties and the coastal region (FAOSTAT, 2022).

In Kenya, good agricultural practices such as the use of modern varieties or application of chemical fertilizer are widely adopted in maize production with little regard in finger millet production (Handschuch & Wollni, 2016). This can be attributed to the fact that most finger millet farmers are in marginal areas and resource-constraint (Mgonja *et al.,* 2013). In addition, data in calorie consumption trends in Kenya indicate that millet has lost share among the cereals. Its share has fallen from 6% in 1961 to about 1% in 2011. Despite its significance, the research and development of finger millet have been overlooked, especially in Africa, which is evident from the scarcity of literature on the crop and production records.

2.4 Role of finger millet in food security and nutrition

2.4.1 Economic importance of finger millet

Finger millet is an important crop in the semiarid tropics because of its use as human food, as well as feed for livestock. Mal *et al.* (2010) showed that finger millet has the ability to improve livelihood by serving as a staple food, weaning food, and cash crop, which will go a long way to provide income-generating opportunity. It serves as a sustainable and food security crop that is important for its nutritive and cultural values as well as excellent storage qualities (Dida *et al.,* 2007; Gull *et al.*, 2014; Maharajan *et al.*, 2021). Finger millet plays a significant role in the economy of the developing world especially in countries with extensive areas of marginal land used for crop cultivation. Kubo, (2016) demonstrated that finger millet has high amylase activity which leads to high ethanol concentrations in the alcoholic beverages. Gull *et al.* (2014) stated that finger millet is a sustainable crop that is particularly significant for its cultural and nutritive values and exceptional storage qualities.

2.4.2 Agronomic importance of finger millet

Finger millet is the most important among millets grown in many regions of Kenya. Ceasar *et al.* (2018) reported that the finger millet has been considered as a drought tolerant crop due to its adaptation for semi-arid tropical climate. Compared with other major cereals such as rice, wheat and barley, it is relatively drought-tolerant due to its C_4 photosynthesis pathway and adaption to grow under harsh and marginal agroecosystems (Gebreyohannes *et al.,* 2021; Luitel *et al.*, 2019). Since C_4 plants are able to close their stomata for long periods, they can significantly reduce moisture loss through the leaves (Rutnell, 2010). Finger millet is least affected by insect pests and diseases and has high rejuvenation capacity after alleviated stress conditions (Thilakarathna & Raizada, 2015). Finger millet has fewer storage pests than other cereals which makes the grain quality deterioration to be delayed thus making it to be an important food security crop in famine prone areas (Upadhyaya *et al.,* 2007). Also its ability to store for over 10 years without significant deterioration in nutritional quality (Rurinda *et al.*, 2014) makes it an ideal crop for food security.

2.4.3 Nutritional and health-related importance of finger millet

Finger millet is commonly referred to as *ragi* in India and wimbi in Kenya. It is no longer termed as a coarse cereal but rather referred to as a neutraceutical crop and is viewed as a potential solution for malnutrition and hidden hunger worldwide (Gupta *et al.,* 2017). It is a food crop of importance for the semi-arid and sub-humid tropics of Africa (Gupta *et al.,* 2012; Kerr, 2014). Grains are used as human food and the straws as animal feed and are considered as a poor man's food (Ceasar *et al.,* 2018; Wambi *et al.,* 2021). Finger millet grains are reported to contain large quantities of iron, calcium, dietary fibre, polyphenols and proteins (Goron & Raizada, 2015). The seeds of finger millet contain valuable amino acids especially methionine (Devi *et al.,* 2014) which is lacking in the diets of hundreds of millions of the poor who live on starchy cereals like cassava. Other reports indicate that finger millet is rich in lysine, threonine and valine (Devi *et al.,* 2014). Its seed coat is rich in phytochemicals like dietary fibre and polyphenols and is also very high in minerals especially calcium (Devi *et al.,* 2014; Syeunda *et al.,* 2020). Finger millet is considered to be an anti-diabetic grain as it was reported to have a lower glycaemic index compared to other cereals like rice, wheat and sorghum (Mudryj *et al.,* 2014) and slow digestion (Chandrashekar, 2010). Nutritional composition of finger millet alongside other major cereals is represented in Table 2.1. Rajput *et al.* (2019) explained that millets have a great potential in alleviating protein calories malnutrition (PCM) and mineral deficiency diseases common among school going children as they are protein and minerals rich supplementary foods. It has several health benefits attributed to its polyphenol and dietary fibre contents. Finger millet contains a healthy content of inexpressible carbonic hydrates therefore used for malnutrition, diabetes and AIDS patients because sugar is slowly released from the millet-based diet. The straws and crop residues are the main sources of livestock feed for farmers in developing countries (Wambi *et al.,* 2021). In Ethiopia, finger millet straw is the most palatable to livestock and fetches the highest price compared to the straw from other cereals (Yami, 2013). Finger millet is therefore an ideal crop for reshaping food insecurity of people due to its nutritional richness, high photosynthetic efficiency and better tolerance to biotic and abiotic stresses compared to other crops (Kumar *et al.,* 2017).

Table 2.1: Nutritional composition of finger millet and major cereal grains.

Nutrients	**Finger millet**	**Wheat**	**Rice (white)**	**Rice (brown)**	**Maize**
Proximate composition					
Moisture (g)	13.1	12.8	13. 7	12.4	10.4
Energy (kcal)	336	346	345	362	365
Protein (g)	7.7	11.8	6.8	7.5	9.4
Fat (g)	1.5	1.5	0.5	2.7	4 .7
Total dietary fibre (g)	11.5	12.5	4.1	3.4	7.3
Carbohydrate (g)	72.6	71.2	78.2	76.2	74.3
Minerals (g)	2.7	1.5	0.6	0	0
Minerals and trace elements					
Calcium (mg)	350	30	10	33	0
lron (mg)	39	3.5	0.7	1.8	2.7
Magnesium (mg)	137	138	64	143	127
Phosphorus (mg)	283	298	160	264	210
Manganese (mg)	5.94	2.29	0.51	0	0
Molybdenum(mg)	0.102	0.051	0.05	0	0
Zinc (mg)	2.3	27	1 .3	2.02	2.21
Sodium (mg)	11	17.1	0	4	35
Potassium (mg)	408	284	0	268	287
Vitamins					
Thiamine (mg)	0.42	0.45	0.06	0.41	0.39
Riboflavin (mg)	0.19	0.17	6	4	2
Niacin (mg)	0	55	1 .9	4 3	36
Total Folic acid (µg)	18.3	36.6	8	20	0
Vitamin E (mg)	22	0	0	0	0

Source: Mudryj *et al.* (2014).

2.5 Effects of drought on growth and yield of finger millet

In arid and semi-arid environments where finger millet is the dominant crop, drought or inadequate moisture is the major abiotic stress affecting productivity. Agronomically, drought is defined as insufficient availability of moisture in the soil for optimum plant growth and development (Begna, 2020). Classically, plant resistance to drought has been divided into escape, avoidance and tolerance strategies (Aroca, 2013), but these strategies are not mutually exclusive and in practice, plants may combine a range of response types (Bacelar *et al.*, 2012). Plants that escape drought exhibit high levels of developmental plasticity, being able to complete their life cycle before physiological water deficits occur (Aroca, 2013). Escape strategies rely on successful reproduction before the onset of severe stress. Drought avoidance involves maintaining high tissue water potential to minimize or avoid tissue dehydration and collapse, or tolerating low tissue water potential. Dehydration avoidance could be associated with maximizing water uptake and minimizing water loss (Aroca, 2013). Water loss may be minimized by closing stomata, decreasing canopy leaf area through reduced growth and shedding of older leaves, and reducing light absorbance through rolled leaves.

Drought negatively affects finger millet growth, yield, membrane integrity, pigment, osmotic adjustment, water relations and photosynthetic activity (Ajithkumar & Panneerselvam, 2014). A study in two landraces of finger millet, in which a drought treatment was imposed four weeks after sowing, resulted in 100% yield loss and over 30% biomass damage (Maqsood & Ali, 2007). Intermittent stress in rain fed situation affects seed germination and early seedling establishment which are vital for crop growth and productivity of finger millet (Gupta *et al.*, 2017).

Seghatoleslami *et al.* (2008) reported that water deficit (50% of water requirement) in finger millet decreased the plant height, productive tillers, 1000 seed weight, harvest index (HI) and grain yield. The reduction in plant height was attributed to reduced internode length and ear length which subsequently reduced the seed yield and number of seeds per ear. Seghatoleslami *et al.* (2008) also reported that the most sensitive stage for moisture stress is ear emergence period in proso millet (*Panicum miliaceum*). Ibrahim *et al.* (2013) reported that continuous drought stress treatment significantly decreased the grain yield and harvest index in sorghum.

Upadhyaya *et al.* (2013) observed that moisture stress decreased grain yield in a local variety of pearl millet compared to the improved variety (PRM-1) mainly due to decreased grain number per ear and decreased test weight. Incidence of water stress at seedling stage lead to higher dry root weights, longer roots, coleoptiles and higher root to shoot ratios (Kashiwagi *et al.*, 2005). They reported that water stress significantly affected the root-shoot ratio (R/S) as the decrease in water supply contributed to increase in R/S of the studied seedlings. Long roots were found to be positively correlated with high harvest index (Kashiwagi *et al.*, 2005) in chickpea under severe situations of water stress. Water stress taking place at both pre-flowering and post-flowering stages of development has the most adverse effect on yield during and after anthesis. Stress during flowering and anthesis leads to the failure of fertilization because of the impairment of pollen and ovule function (Prasad *et al.*, 2008) which in turn results in lower grain yield. Negative effect of moisture stress on growth and yield have also been reported on maize (Aslam *et al.*, 2003), wheat (Akram, 2011) and tropical legumes (Farooq *et al.*, 2017).

2.6 Finger millet nutrient relations

The understanding of the interactive effect of water and nitrogen (N) availability, associated with the ability of crops to efficiently use these resources, is a crucial issue for stabilizing cereal production in semi-arid tropics both in medium and low agro-ecologies. Del Pozo *et al.* (2019) stated that there is need for breeding programmes to focus on developing higher yielding genotypes with higher water and N use efficiencies especially under water stress conditions. Nitrogen is one of the most important mineral nutrients because of its numerous effects on plant growth and yield. A number of fundamental processes such as water and nutrient uptake, protein metabolism, photosynthesis, carbon partitioning, and enzyme and plant hormonal activities are genetically regulated. Drought induced reductions in uptake and translocation of N, P and K in various plant species is presumably due to reduced root volume and in dry soils and unavailability of the nutrients (Noman *et al.*, 2018).

Abid *et al.* (2016) and Mobasser *et al.* (2014) established that, water limitations accompanied by low N was the main constraint to wheat yield and it affected the leaf water relations, chlorophyll fluorescence and photosynthetic processes leading to restricted plant growth rate, early senescence, reduced grain filling duration with limited grain weight and poor crop productivity. Finger millet responds well to N application (Gupta *et al.*, 2012). Jha *et al.* (2012) reported that increases in yield and grain protein content in finger millet was attributed to N fertilizer application rates of up to 40 kg N ha^{-1} in Andhra Pradesh, India. The authors concluded that the economic optimum rate of N fertilizer for finger millet was 43.5 kg ha^{-1} under rain-fed conditions. Maruthi *et al.* (2011) reported that finger millet grain yield gain was 23.1 kg per kg of nitrogen at 20 kg N ha^{-1}, while the yield benefit declined to 19.9 kg per kg of nitrogen at 60 kg N ha^{-1}. These results suggested that application of the correct dose of N fertilizer is important in order to maximize the profits of poor finger millet farmers. Gupta *et al.* (2014) evaluated the N use efficiency (ratio of grain yield to N supply) and N utilization efficiency (ratio of grain yield to total N uptake) of three finger millet genotypes under different N inputs of 0, 20, 40, 60 kg N ha^{-1}, and 7500 kg farm yard manure ha^{-1}) under greenhouse conditions. They established that there was genotypic variation among the finger millet genotypes in response to different N inputs where, some varieties were highly responsive. Gupta *et al.* (2014) recommended that identification of genotypes with high N use efficiency and N utilization efficiency especially under low available soil N levels could be of benefit to farmers who cannot afford N fertilizer or who do not have access to N fertilizer sources. Development of new finger millet varieties with high yield potential under low or high nutrient input conditions has been reported (Goron & Raizada, 2015).

2.7 Physiological traits associated with drought tolerance

Among the physiological traits that are differentially regulated during moisture deficit, osmotic adjustment is a major mechanism in drought avoidance thus enable the plant to produce grain. Osmotic adjustment, which refers to the lowering of the osmotic potential in the cytoplasm due to the accumulation of compatible solutes such as proline, glycine betaine and organic acids, contributes to turgor maintenance of shoots and roots (Ajithkumar & Panneerselvam, 2014). According to Fleury *et al.* (2010), plant physiology improves the understanding of the complex system of drought tolerance. This provides breeders with greater knowledge of the gene function and provides new tools for plant improvement to increase crop yield (Tuberosa & Salvi, 2006).

Dai *et al.* (2012) observed that stress occurring 14 days after anthesis up to maturity in foxtail millet, resulted in leaf senescence, loss of leaf chlorophyll, decreased photosynthetic rate and catalase activities. In another study, Babu *et al.* (2014) evaluated 10 finger millet genotypes for drought tolerance in terms of water use efficiency and identified drought tolerant genotypes as those varieties possessing higher total dry matter and grain yield under the stress situations. Delayed senescence, high chlorophyll content and chlorophyll fluorescence as well as low canopy temperature and high transpiration efficiency are physiological traits that confer drought tolerance to sorghum (Awari *et al.,* 2017).

2.8 Morphological traits associated with drought tolerance

Morphological traits not only affect stress tolerance to limiting soil moisture, but they also indicate how adaptive genotypes cope with water stress (Anjum *et al.,* 2011). These traits have the important role in determining yield components and are used in breeding programmes for improving grain yield and introducing commercial varieties (Mollasadeghi *et al.,* 2011). Sharma *et al.* (2018) reported that green tissues above the flag leaf node are the main contributors to the synthesis and production of carbohydrates required to fill the grains. In fact, flag leaves contribute about 40% of the carbohydrates for grain filling. The results reported by Boussakouran *et al.* (2019) indicated that water regime significantly decreased grain yield per plant and all morphological traits above flag leaf. Varieties with longer flag leaf and peduncle had increased resistance to drought. They further concluded that morphological traits above the flag leaf node are useful tools to select for grain yield in water-limited environments.

2.9 Root traits associated with drought tolerance

Root architecture is an important component of plant growth and drought tolerance adaptations. Among the traits that are highly correlated with drought tolerance, architecture of roots is one of the most promising for drought escape and could be used positively in drought tolerance breeding programmes (Sharma *et al.*, 2018). Increased root biomass, root length density (RLD) and rooting depth are often considered to be primary drivers of drought avoidance (Comas *et al*., 2013a). Moumeni *et al.* (2011) in a gene expression analysis reported that about 55% of genes differentially expressed in roots of rice in response to drought stress treatments. The specific root length (SRL) is typically positively related to N uptake rates Lavinsky *et al.* (2016) and negatively related to root life span (Rose, 2017). SRL can further be indicative of resource availability as it responds to variation in nutrient (Freschet *et al.* 2015; Leuschner *et al.*, 2013) and water availability (de Vries *et al.*, 2016).

2.10 Effects of water stress on plant physiological processes

2.10.1 Relative water content (RWC)

Aroca (2013) evaluated drought effects on the water relations of four cultivars which were subjected to water stress at vegetative and anthesis stages and observed that leaf water potential and relative water content (RWC) decreased with increased leaf temperature under moisture stress conditions. In a different study, Boutraa (2011) reported that water stress in wheat affected the leaf RWC, leaf water potential, osmotic potential, turgor potential and growth and yield components. Almeselmani *et al.* (2013) identified physiological characters associated with yield improvement in durum wheat under rain fed conditions. The traits associated with drought tolerance were mainly higher RWC and chlorophyll content.

2.10.2 Water use efficiency (WUE)

Water-use efficiency (WUE) is the biomass produced per unit amount of water transpired. The ratio of grain production to crop water usage, water use efficiency (WUE), offers a quick way to determine whether crop productivity is limited by water availability or other variables (Bhouri *et al.*, 2021). Breeding crop varieties that are more efficient in their water use is among the strategies required to improve the productivity of water use in both irrigated and rain-fed agriculture (Condon *et al.*, 2004). According to Owueis *et al.* (2000), WUE is considered an important determinant of yield under stress and even as a component of crop drought resistance. Water-use efficiency has also been used to imply that rain fed plant production can be increased per unit water used, resulting in ‘‘more crop per drop’’. Boutraa (2011) stated that WUE is one of the best approaches to determine the water productivity and reported that a crop with high WUE will have greater grain yield under water stress conditions than a crop with low WUE. Over time, plants have evolved in a range of drought tolerance adaptive mechanisms such as WUE to counteract the detrimental effects of drought (Krishnamurthy *et al.*, 2016).

2.11 Effects of moisture stress on root traits

The effects of root density on yield will depend on soil moisture distribution and competition within the plant population. Jongrungklang *et al.* (2012) in their study on peanut (*Arachis hypogaea*) found out that more profuse roots in the deeper soil layer correlated with higher yield under water stress conditions and they concluded that a higher root length density (RLD) at depth was responsible for more water extraction. Shibairo *et al.* (2016) reported that under drought stress conditions, plant experiences difficulty in water uptake by roots or higher transpiration rate and that drought impacts on growth, yield, membrane integrity, pigment content, osmotic adjustment, water relations and photosynthetic activity. Kumar (2010) examined rooting depth and root biomass for drought tolerance in six genotypes of chickpea under irrigated and rain fed situations and reported that the higher dry matter of roots, rooting depth, root : shoot ratio and plant water status was directly associated with grain yield under rain fed conditions. These studies agree with those of Kashiwagi *et al.* (2005) who reported that increased root biomass, RLD and rooting depth are often considered to be primary drivers of drought avoidance. White and Kirkegaard (2010) showed that the extensive root branching and long root hairs are primary determinants of moisture extraction from dry soil and deduced that the genotypes with higher roots maintained the cooler leaf temperatures for longer period under water stress in wheat. In another study, Awari *et al.* (2017) evaluated 13 sorghum genotypes in root box structure under drought conditions and reported that the root length, root volume and root fresh mass were significantly higher in irrigated condition than rain fed condition. Correlation studies indicated that root traits *viz.;* root weight, root number and root length showed significant and positive correlation with grain yield.

2.12 Finger millet nitrogen use efficiency (NUE)

Nitrogen is one of the most important nutrients in all crop production systems (Goron *et al.* 2015) as it is required to synthesize photosynthetic enzymes as well as all other N components of the plant. Nitrogen availability is a key factor in crop production since it is the nutrient that most often limits crop production (Shukla *et al.,* 2004). Studies concerning nitrogen management in finger millet are mainly focused on the amount of nitrogen applied, timing of application, and varietal responses to N (Goron & Raizada, 2015). Several studies have shown that Nitrogen application can increase millet production efficiently (Maman *et al.,* 2006; Rostamza *et al.,* 2011). Finger millet is valued for its high NUE compared to other grain crops such as maize (Goron *et al.,* 2015). Variation among finger millet genotypes for NUE has been observed in preliminary studies by Thilakarathna and Raizada (2015) with some genotypes identified as having higher responsiveness to applied N (Gupta *et al.,* 2012; Gupta *et al.,* 2013).

2.13 Evaluation for drought tolerance

The morphological and physiological traits that affect yield in drought conditions are expressed either under well-watered or drought stress conditions. Saddam *et al.* (2014) evaluated ten accessions of sorghum for their drought tolerance at seedling stage at three water levels of 50% field capacity (FC), 75% FC and 100% FC. At 50% water stress the shoot length, root length, leaf area, root fresh weight, root dry weight among other traits were decreased compared to100% field capacity. Talwar *et al.* (2020) evaluated a set of 38 finger millet accessions in both field and mini-lysimeters under both well-watered and water-stressed conditions and found that reproductive growth was more sensitive to water stress than vegetative growth. They also deliberated that water use followed by transpiration efficiency were the two major contributors toward shoot biomass; whereas, harvest index followed by transpiration efficiency were the major contributors toward grain yield under water stress conditions. Matsuura *et al.* (2016) evaluated seeds of proso millet (*Panicum miliaceum*), little millet (*Panicum sumatrense*), wild millet (*Setaria glauca*) and foxtail millet (*Setaria italica*) in polyvinylchloride (PVC) tubes in a greenhouse to determine the effect of pre- and post-heading water deficit on growth and grain yield. They initiated water stress treatment 25 days after sowing. They found that the grain yield of *S. italica* and *S. glauca* decreased by 80 and 70% respectively, under water stress; and that of *P. miliaceum* and *P. sumatrense* decreased by 36 and 20%, respectively. This study broadly evaluated selected finger millets genotypes for its potential in its utilization as drought tolerant crop in Kenya

ASAL areas, with specific goal of identifying traits associated with drought tolerance that could be deployed in breeding programs to enhance food and nutritional security.

CHAPTER THREE

IDENTIFICATION OF DROUGHT TOLERANT FINGER MILLET (*Eleusine coracana L.*) LINES BASED ON MORPHO-PHYSIOLOGICAL CHARACTERISTICS AND HIGH YIELD

Abstract

Drought stress is a major abiotic stress prevalent in many parts of sub-Saharan Africa affecting yield and quality of a number of crops. Finger millet is a key staple food crop in eastern Africa, and is largely cultivated by subsistence farmers who largely rely on rain fed agriculture. Despite its importance, finger millet productivity is adversely affected by frequent drought episodes that cause economic losses. Lack of drought tolerant varieties further exacerbates yield losses incurred. The objective of this study was to identify high yielding and drought tolerant finger millet lines based on associated morphological and physiological characteristics. Twenty-four advanced finger millet lines preselected for drought tolerance from ICRISAT and Egerton University seed units alongside a check P-224 were evaluated for drought tolerance and yield at two drought endemic locations in the main cropping season in 2020. The experiments were laid out in 5 × 5 triple Lattice design replicated three times. Results showed that genotype main effect was significant ($P < 0.001$) for seedling vigour, peduncle length, plant height, number of productive tillers number of fingers and harvest index ($P < 0.01$) and finger length ($P < 0.05$). Location effect was significant ($P < 0.001$) for plant stand, number of fingers, finger length and days to 50% flowering, at $P < 0.01$ for peduncle length and yield at $P < 0.05$ significance level. Genotype x location interaction was significant ($P < 0.001$) for number of fingers, yield and harvest index. There was a positive and significant ($P < 0.001$) relationship among the physiological traits comprising evapotranspiration rate, root relative water content, harvest index, 1000 - seed weight and grain yield. Among the morphological traits, positive and significant correlations ($P < 0.001$) were recorded between shoot biomass and root biomass, shoot biomass and total biomass. Leaf area index exhibited a positive significant relationship with light intensity, shoot biomass, root biomass, total biomass and yield. From this study, three lines, ICFX1420314-2-1-1-1, KNE 814 × Ex Alupe (P) P8-1-1-1-1 and ICFX1420415-3-1-1-2 were identified as drought tolerant due to their short stature, early flowering, increased root biomass, increased stomatal conductance, increased CO_2 assimilation, high chlorophyll contents and subsequently higher photosynthetic rates and increased grain yields in both

locations. The elite genotypes identified is a step towards deployment of potentially high yielding and drought tolerant finger millet varieties in eastern Africa.

3.1 Introduction

Finger millet is one of the most nutritious food crops extensively grown in Asia and Africa (Upadhyaya *et al.*, 2007). Like other underutilized cereals, finger millet has received less attention by the research community and other practitioners at the expense of major staple crops such as maize, rice and wheat as argued by Mabhaudhi *et al.* (2019), resulting in low productivity and limited area under cultivation. For instance, the yield of finger millet has been very low for many years (Tadele & Assefa, 2016). The low productivity of these crops is due to numerous challenges including though not limited to abiotic factors such as drought as well as unproductive seed varieties (Naylor *et al.*, 2004; Pingali, 2012). The scenario is further exacerbated through the reality that, widely consumed and traded cereal crops such as maize, wheat, and rice are rain-fed, and their productivity has been declining and is projected to decline further because of the effects of climate change (Aryal *et al.*, 2020). Studies carried out on the evaluation of finger millet germplasm, accessions or cultivars reported great variation in the degree of drought tolerance among different varieties (Bartwal *et al.*, 2016; Bartwal & Arora 2017). However, drought tolerant finger millet lines have not yet been identified in Kenya where the arid and semi-arid land covers 80% and home to about 38% of the population (Kogo *et al.*, 2021). These areas are characterized by low agricultural productivity, poverty, and food insecurity resulting from frequent crop failure due to the tendency of farmers growing non-adaptable crop species and varieties (Onyango, 2016), as well as unreliable rainfall, high temperatures, and poor soil fertility (Jerop *et al.*, 2020).

Finger millet is mostly adapted to temperature ranges of 11°C to 28°C. However, it can thrive well under hot conditions where temperatures are as high as 35°C. It requires moderate rainfall ranging from 500 mm to 1000 mm. The crop is grown on reddish brown lateritic soils having good drainage and adequate water holding capacity (Prasad & Staggenborg, 2009). Finger millet has been reported to be among the most stress resilient crops in stress conditions such as high temperatures, low moisture and poor soils (Gupta *et al.*, 2017). In addition, it has been suggested that it can be used in the improvement of other economically important crops. Although finger millet is drought tolerant its growth is adversely affected by both intermittent and terminal droughts. The crop is largely grown by subsistence farmers who rely on rain fed agriculture hence prone to the risk of drought. Such farming conditions therefore require drought tolerant varieties for improved productivity.

Feeding the fast growing human population with balanced nutritional diet under unpredictable severe weather events is a challenging task globally. The climate change crisis is expected to cause shifts in food production and yield loss, causing a severe threat to food security (Dhankher & Foyer, 2018). A key strategy to adapt to a changing climate is to develop and promote elite germplasm with stable yields that can survive under hostile weather conditions such as the underutilized crop species. Focusing and exploiting the large reservoir of underutilized crops like finger millet would provide a more diversified agricultural system and an alternative healthy food resource, ensuring food, and nutritional security (Mabhaudhi *et al.*, 2019).

Drought, high temperatures (heat stress) and high salinity are major environmental factors limiting plant growth and crop productivity. In efforts geared towards feeding the ever-increasing world population, agricultural research advances have to contend with these adverse environmental factors. Drought stress probably ranks as the most important environmental factor limiting global crop productivity. Despite the many advantages offered by the cultivation of finger millet, in Africa there is limited research on tolerance to drought in finger millet. Finger millet can perform better under adverse soil and weather conditions compared to other crops. It is tolerant to harsh conditions mainly high temperature, low rainfall, low fertility soils and is therefore preferably grown in areas where other cereals such as maize fail.

The production of finger millet is significantly hampered by factors such as low yielding varieties, limited research consideration and drought emanating from climate change (Mgonja *et al*., 2013). Improving finger millet for key morpho-physiological traits such as shoot length, root length and their ratios (shoot: root length), plant height, seed germination and early seedling growth is key to the improvement for drought adaptation (Mude *et al.*, 2020) reported water use efficiency, harvest index and biomass as being important for resilience to drought in cereal crops. In contrast, decrease in root growth, relative water content and lipid peroxidation was found to show a considerable level of tolerance to drought stress (Mukami *et al.,* 2020). Millet improvement in Kenya in the past has laid emphasis on selecting for high yielding lines without considering key traits required for adaptation; however, such a strategy has led to deployment of varieties that perform dismally under drought conditions (Mukami *et al.*, 2020). Most of the varieties developed for medium potential areas end up being grown where they are not suitable. Therefore, the present investigation was under taken to identify finger millet lines with enhanced tolerance to drought based on morpho-physiological traits for use in breeding programmes and for possible deployment as improved drought tolerant varieties.

3.2 Materials and methods

3.2.1 Description of the experimental sites

The study was conducted in the field at two locations; Agricultural Training Centre (ATC) Koibatek in Baringo County and ATC Soin in Kericho County in 2020. ATC Koibatek is located at 1°35'S, 36°66'E and elevated at an altitude of 1890 meters above sea level and falls in the Upper Midland zone 4 (UM4) agro-ecological zone (AEZ). The area receives an average annual rainfall of 767 mm with the mean temperatures ranging between 18.2 ℃ and 24.3 ℃. Mean minimum and maximum temperatures are 10.9 ℃ and 28.8 ℃, respectively. Soils in this area are Vitric andosols with moderate to high soil fertility, well drained deep to sandy loam soils (Jaetzold & Schmidt, 2012). ATC Soin is located between latitude 0^{o} 23'S and longitude 35º 02'E with an altitude of about 2002 m above the sea level and falls in the Lower Midland zone 3 (LM3) AEZ. The area receives an average annual rainfall of between 700 and 1,400 mm with moderate temperatures of 17 ℃ and low evaporation rates. Temperatures range is between 10 ℃ and 29 ℃ volcanic rocks characterize the soils in this area (Jaetzold & Schmidt, 2012).

The meteorological data for the study areas during the growing season were obtained from Weather Forecast stations in the two Agricultural Training Centre in the counties. The monthly average air temperatures as well as total rainfall during the growing seasons was recorded. Six months' average data for rainfall were 312.5 mm and 298.5 mm while the average temperatures were 20.8 ℃ and 22.8 ℃ for Baringo and Kericho, respectively as indicated in Figures 3.1 and 3.2. The weather data for temperature, humidity and rainfall were recorded during the period between June and December 2020. Based on the 2020 climate data, the temperatures varied between a minimum of 12 to 15 ℃ and a maximum of 21 to 28 ℃ at the study locations. Relative humidity ranged from a minimum of 58% and a maximum of 88 % indicated in Figure 3.3 All the figures 3.1, 3.2 and 3.3 were presented according to the data obtained during the study period.

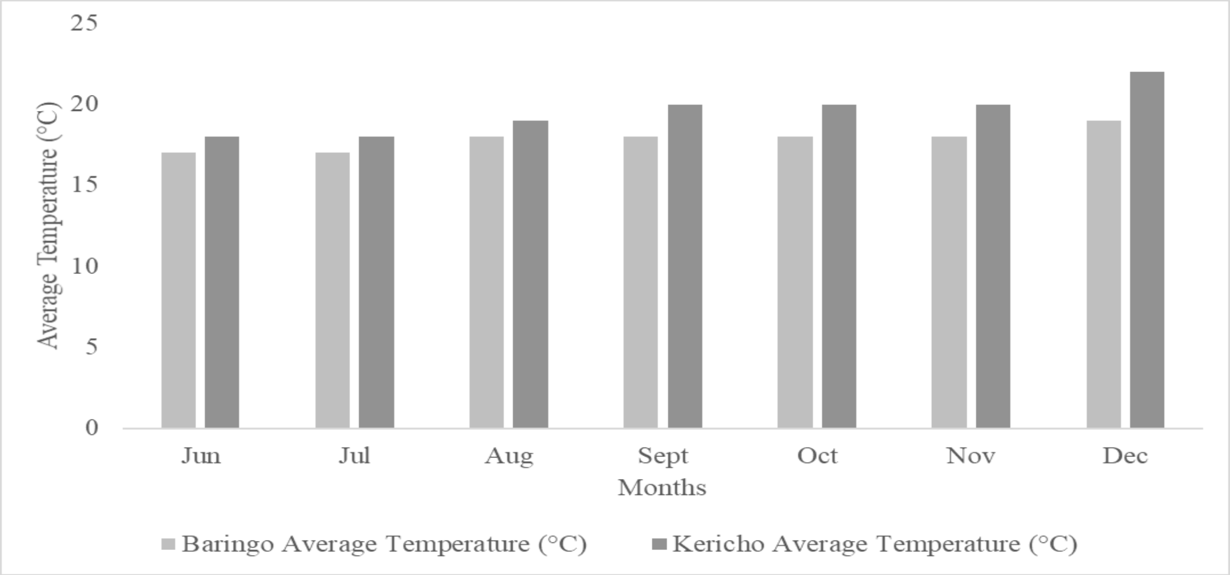


Figure 3. 1: The monthly average temperature (℃) during the study period.

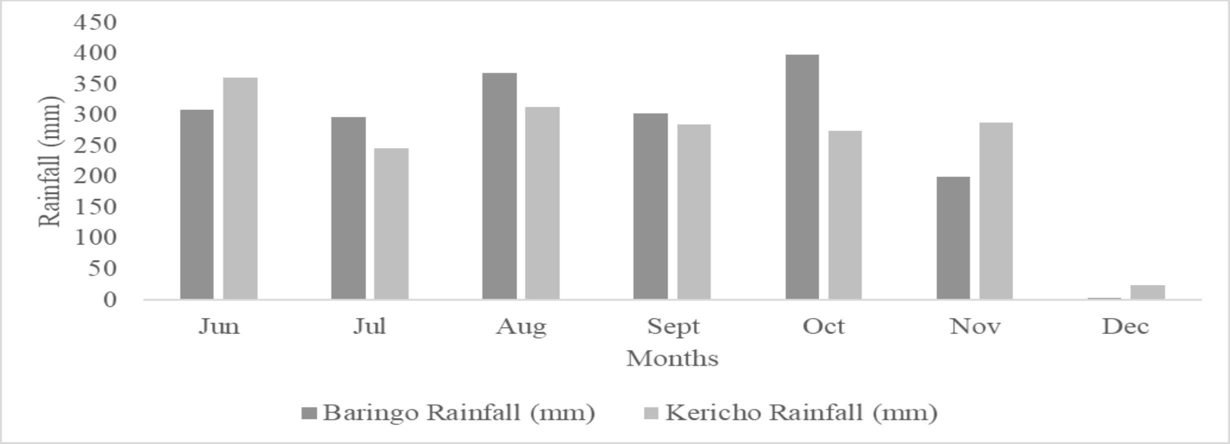


Figure 3. 2: The monthly Rainfall (mm) during the study period.

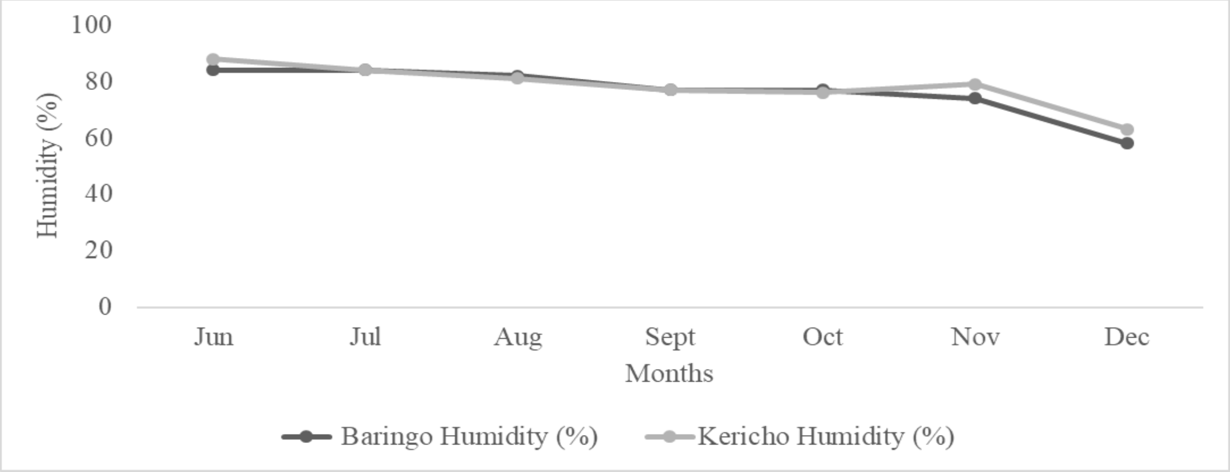


Figure 3. 3: The monthly relative humidity (%) during the study period.

3.2.2 Study genotypes

The study genotypes comprised of 24 advanced finger millet lines and one commercial check variety P224. All the study materials were obtained from ICRISAT, KALRO and Egerton University Seed Units. Details of the genotypes used in the study are given in Table 3.1 below.

Table 3.1: List of genotypes used in the study and their source information.

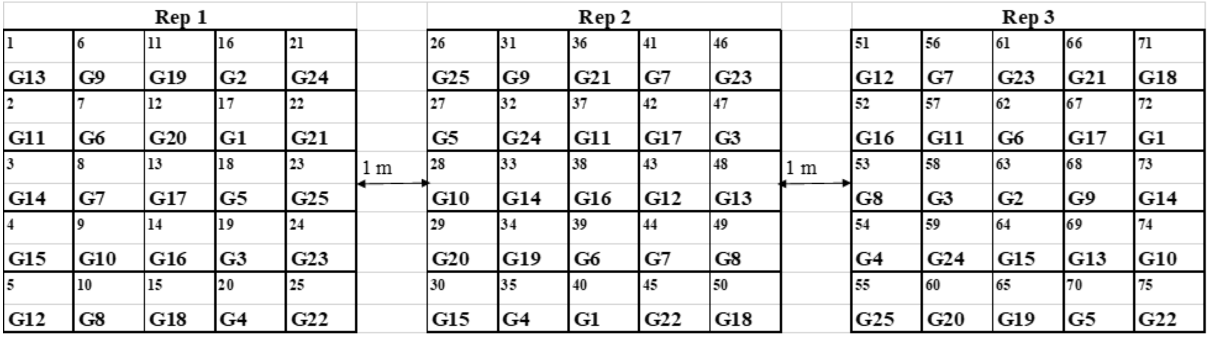
Entry no.	Genotype	Source of germplasm
1	EX Alupe(G) × KNE 814 P1-1-2-3-1	ICRISAT
2	EX Alupe (G) × KNE 814 P4-2-1-4-1	ICRISAT
3	ICFX 1420311-3-6-1-2	ICRISAT
4	ICFX 1420312-3-2-1-1	ICRISAT
5	ICFX 1420313-1-2-3-1	ICRISAT
6	ICFX 1420313-3-2-1-1	ICRISAT
7	ICFX 1420314-2-1-1-1	ICRISAT
8	ICFX 1420314-6-2-1-1	ICRISAT
9	ICFX 1420315-2-2-1-2	ICRISAT
10	ICFX 1420342-3-1-2-2	ICRISAT
11	ICFX 1420396-5-5-1-1	ICRISAT
12	ICFX 1420414-7-12-1-1	ICRISAT
13	ICFX 1420414-7-4-1-1	ICRISAT
14	ICFX 1420415-3-1-1-2	ICRISAT
15	ICFX 1420419-3-2-1-1	ICRISAT
16	ICFX 1420420-9-6-3-1	ICRISAT
17	ICFX 1420424-2-1-1-1	ICRISAT
18	ICFX 1420431-1-3-1-2	ICRISAT
19	ICFX 1420431-2-5-1-1	ICRISAT
20	ICFX 142036-3-3-1-1	ICRISAT
21	ICFX 1420437-1-4-1-1	ICRISAT
22	ICFX 1420448-1-1-1-1	ICRISAT
23	KNE 814 × Ex Alupe (P) P7-9-3-2-2	Egerton seed unit
24	KNE 814 × Ex Alupe (P) P8-1-1-1-1	Egerton seed unit
25	P224- check	KALRO

ICRISAT - International Crops Research Institute in the Semi-Arid Tropics, KALRO - Kenya Agricultural and Livestock Research Organisation.

3.2.3 Field evaluation

The field experiment was conducted during the long rains from June to November 2020 under rain fed conditions. Prior to the finger millet experiment in 2020, the field was fallow. Land preparations were done according to ICRISAT recommendations (ICRISAT, 1992). Before planting the millet, ploughing and harrowing was done. All the seed of 25 genotypes used in the study were planted on June 13, 2020 and June 14, 2020 in ATC Soin and ATC Koibatek locations, respectively. The finger millet was drilled by hand at a seeding rate of 3.2 kg ha^{-1} and a depth of 2 cm in furrows and covered lightly after sowing. Two weeks after emergence the finger millet planted were thinned to one plant per hill leaving a spacing of 10 cm between seeds. All the plots received di-ammonium phosphate (DAP) fertilizer, which was applied at the rate of 20 kg ha^{-1} to supply a basal fertilizer dose of 10 kg P ha^{-1}. Calcium ammonium nitrate (CAN) was used for top dressing at the rate of 30 kg ha^{-1}. Weeding was done by hand where the first weeding was carried out two weeks after emergence and the second weeding two weeks after the first weeding. Other management practices of chemical application for pest and disease control was done regularly depending on field scouting.

The experimental designed was a 5×5 triple *Lattice* with five blocks consisting of five plots per block and replicated three times (Gomez & Gomez, 1984). Each plot was planted with one genotype that was composed of four rows of 2 m length forming a plot size of 4 m^2. The rows were 15 cm apart from each other with 13 plants per row. Overall, each plot contained 52 plants. For plot management and data collection a separation distance of 50 cm between plots in a replicate and 1 m path between the replicates was left. Two middle rows were used for data collection and yield measurements in every plot. Two middle rows were used for data collection and yield measurements in every plot. In the field layout (Figure 3.4), plot numbers are indicated at the top of every plot while genotypes are indicated with G followed by the entry numbers.



Rep 1						Rep 2						Rep 3				
1 G13	6 G9	11 G19	16 G2	21 G24		26 G25	31 G9	36 G21	41 G7	46 G23		51 G12	56 G7	61 G23	66 G21	71 G18
2 G11	7 G6	12 G20	17 G1	22 G21		27 G5	32 G24	37 G11	42 G17	47 G3		52 G16	57 G11	62 G6	67 G17	72 G1
3 G14	8 G7	13 G17	18 G5	23 G25	1 m	28 G10	33 G14	38 G16	43 G12	48 G13	1 m	53 G8	58 G3	63 G2	68 G9	73 G14
4 G15	9 G10	14 G16	19 G3	24 G23		29 G20	34 G19	39 G6	44 G7	49 G8		54 G4	59 G24	64 G15	69 G13	74 G10
5 G12	10 G8	15 G18	20 G4	25 G22		30 G15	35 G4	40 G1	45 G22	50 G18		55 G25	60 G20	65 G19	70 G5	75 G22

Figure 3.4: Experimental layout.

3.2.4 Data collection

Data were taken from three randomly selected and labelled plants in the two mid rows from each of the plots following the International Board for Plant Genetic Resources (IBPGR, 2011) plant descriptor for finger millet. The data collection process was divided into four. At the time of germination and 50% of flowering for physiological measurements (chlorophyll content and relative water content). Morphological trait measurements were carried out at 50% physiological maturity. These comprised of dry shoot weight, dry root weight and total biomass. At physiological maturity, the plants were uprooted and the biomass was divided into shoot and root. The shoot was oven dried whereas the root was washed using tap water and dried in the oven at 70 °C for 24 hours; and dry weight was taken using an electric balance. Total biomass (TB) which is the sum mass of all the above ground parts of the plant and root characteristics of the plant was also determined. Harvest index (HI) defined as the ratio of grain yield to the total biomass at maturity was calculated by dividing grain dry weight to plant total biomass and expressed in per cent.

Yield components, seedling vigour, plant height, total number of tillers and productive tillers, finger number and finger size were taken as per the IBPGR descriptor (Appendix A). Seedling vigour was scored on a scale of 1 to 3 three weeks after emergence, where; 1 = seedling vigorous, 2 = intermediate in vigour and 3 = very poor (Oduori, 2008). Number of days to 50% flowering was observed visually and recorded when 50% of the plants in the centre rows had flowered (shaded pollen grains and not when the panicles emerged). The days to flowering were then computed as number of days after sowing to flowering.

Plant height (PH) was measured from the base of the main tiller to the tip of the finger at the dough stage approximately 40 DAS with the use of a meter rule. Numbers of productive tillers were counted as the number of the basal tillers bearing mature ears for each line per replication. The mean tiller number per plant was calculated by taking the average of the total number of tillers for the harvested plants. After harvest, the tillers from three plants were oven dried for 48 hours at 70 °C and weighed. The number of fingers (NF) were counted from three plants of each genotype per replication at dough stage, while the finger size measured using a ruler from base to the tip of longest finger in the main tiller. At maturity, the fingers were harvested from three plants from the middle of each plot and oven dried at 70 ℃ to constant weight. The fingers were weighed, mechanically threshed and cleaned. The millet seeds were oven dried again for 12 hours at 70 ℃ before determination of their final weight. Yield was then calculated on an area basis in kg ha^{-1}. Because finger millet seeds are small, a sample of 1000 kernels of each millet genotype was taken and its weight was recorded using an electric balance.

Physiological traits, leaf area index (LAI), leaf chlorophyll content (CC), photosynthetic rate, net leaf exchange rates (CER), stomatal conductance, transpiration rate and relative water content (RWC) were determined. LAI was measured on six middle plants from the two mid rows in each plot using the AccuPAR LP-80 Ceptometer. Simultaneous incident (above canopy) and transmitted (below canopy) photosynthetically active radiation (PAR) measurements were recorded.

LAI was then calculated using the formula: $\frac{1}{k} -\ln t/i$……………………………. Equation (1)

Where k is the finger millet extinction coefficient = 0.5, t is the transmitted light and i is the incident light (Francone *et al.,* 2014). Light intensity (LI) was also calculated using the formula:

LI = $\frac{Incident\ light - transmitted\ light}{Incident\ light}$…………………………………….....Equation (2)

Leaf chlorophyll content (µmol m^{-2}) was taken using the chlorophyll fluorescent meter at vegetative state (40 DAS), the flowering stage, and grain filling stages. Photosynthetic rate was recorded as µmole CO_2 m^{-2} s^{-1} using Infrared Gas Analyser. Stomatal conductance and instantaneous transpiration on the uppermost fully expanded leaves was measured at booting stage using the Infrared Gas Analyser (IRGA). Net leaf CO_2 exchange rates was measured on selected leaves using a portable Infrared Gas Analyser, fitted with Parkinson Leaf chamber. The parameters measured by Infrared Gas Analyser (IRGA) and their units are Photosynthetic rate (P, µmolCO_2 $\mathrm{m}^{-2}\mathrm{s}^{-1}$), Stomatal conductance (GS, mol $H_2\mathrm{O}\mathrm{m}^{-2}\mathrm{s}^{-1}$) and Transpiration rate (E, mmol $H_2\mathrm{O}\mathrm{m}^{-2}\mathrm{s}^{-1}$).

Relative water content (RWC); is an important indicator of water status in plants; it reflects the balance between water supply to the leaf tissue and transpiration rate. It was calculated at vegetative and grain filling stages. Fresh weight (Fw) of leaves were weighed immediately after harvesting while dry weight (Dw) was measured after drying the leaves in an oven at 80 °C for three days. Leaf RWC was then calculated and expressed in percentage (Barrs, 1968; Mude *et al.*, 2020).

RWC= $\frac{(Fw- Dw\ )}{Fw} X\ 100$…………………………………………………. Equation (3)

Where RWC = relative water content, Fw = fresh weight and Dw = dry weight

3.2.5 Statistical analyses

All the data collected were subjected to combined analysis by means of general linear model (GLM) using PROC GLM in SAS computer software version 9.4 and the means separated using Tukey's Honestly Significant Difference at 5% probability level (P<0.05). The following statistical model was used for the analysis.

$Y_{ijkl} = \mu + G_i + L_j + VL_{ij} + \beta_k + \gamma_l + \varepsilon_{ijkl}$ ....Equation (4)

Where Y_{ijkl} denotes the value of the observed trait in the i^{th} genotype in j^{th} location within k^{th} replicate, μ = general mean, G_i = the effect of i^{th} genotype, L = the effect of the j^{th} location, GL = the effect of interaction of the i^{th} genotype in j^{th} location, β_k = the effect of k^{th} incomplete block, γ_l = effect of l^{th} replicate in the in the k^{th} incomplete block with the i^{th} genotype and $\mathcal{E}_{ijklm}$ = experimental error.

3.3 Results

3.3.1 Mean squares and mean performance for agronomic traits of the test lines

Significant ($P<0.001$) main effects due to genotype were observed for seedling vigour, peduncle length, plant height and number of productive tillers; genotypes significantly varied for number of fingers and harvest index at $P<0.01$ and for finger length at $P<0.05$ (Table 3.2). There was significant difference for location on plant stand, number of fingers, finger length and days to 50% flowering at $P<0.001$ significance level while location effect was significant for peduncle length and yield at $P<0.05$ level. Genotype x location interaction had significant effects on number of fingers, yield and harvest index at $P<0.001$ level of significance.

Finger millet genotypes expressed significant variation across the locations for ten phenotypic traits, comprising seedling vigour, plant maturity, days to first, and 50% flowering, peduncle length, plant height, number of productive tillers, number of fingers, finger length, thousand grain weights, grain yield and harvest index (Table 3.2).

Table 3.2: Mean squares for yield and yield related traits for 25 finger millet genotypes using 10 quantitative traits across two locations

Source of variation	**Df**	**SV (#)**	**NF (#)**	**FL (cm)**	**PL (cm)**	**PHT (cm)**	**NPT (#)**	**Days to 50% flowering**	**Yield (kg ha^{-1})**	**1000 SW (g)**	**Harvest index**
Replication	2	0.14	1.62	1.06	0.03	31.96	0.07	2.66	3592.09	0.07	0.18
Genotype (G)	24	0.11^{***}	2.33^{**}	3.99^{*}	3.93^{***}	207.73^{***}	5.48^{***}	4.98	2464.27	0.03	1.48^{***}
Location (L)	1	0	3116.76^{***}	2167.52^{***}	2.23^{*}	36.02	0.52	11284.01^{***}	152049.37^{*}	21.69^{**}	73.18^{**}
G x L	24	0.02	1.05^{***}	1.87	0.67	18.74	0.19	5.87	2323.55^{***}	0.04	0.25^{***}
Block	26	0.02	0.37	1.3	1.46	83.01	0.15	9.68	403.6	0.05	0.08
CV		14.9	6.15	11.96	11.53	10.5	7.67	2.44	5.81	9.14	6.99
R^2		0.72	0.99	0.95	0.5	0.7	0.94	0.97	0.94	0.86	0.96

Df- degree of freedom, SV- seedling vigour, NF- number of fingers, FL- finger length (cm), PL- Peduncle length, PHT- Plant height (cm), NPT- number of productive tillers, 1000 SW- 1000 seed weight (g), *** Significant at $P<0.001$, ** significant at $P<0.01$, * significant at $P< 0.05$ and CV- Coefficient of variation.

Variation was observed for the general performances of the lines across the sites as illustrated in Figure 3.5. The acute angle between the two locations as illustrated in Figure 3.5 demonstrated the similarity among the locations in ranking genotypes for yield under drought. Most genotypes were clustered around the origin showing lack of sensitivity to the different locations. However, genotype KNE 814 × Ex Alupe (P) P8-1-1-1-1 was more adapted to ATC Soin while genotypes ICFX 1420314-2-1-1-1 and ICFX 1420437-1-4-1-1 were ranking better in ATC Koibatek.

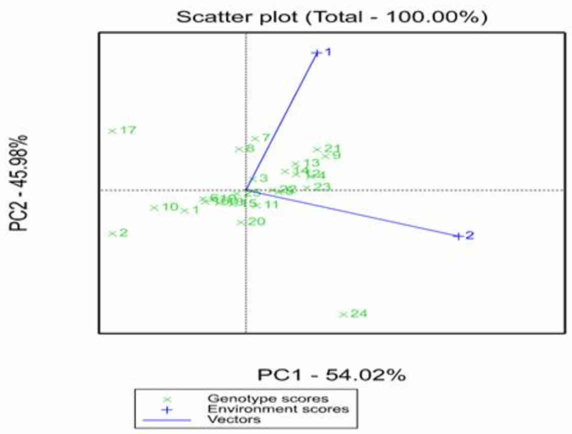


Figure 3.5: Scatter plot of seed yield for 25 genotypes evaluated at two drought prone locations, ATC Koibatek (1) and ATC Soin (2) for one season. Genotypes are presented in green while the location vectors are blue in colour.

Generally, Koibatek had better grain yield performance with an average of 313.89 kg ha^{-1} compared to Soin with 250.22 kg ha^{-1}. In ATC Koibatek, the highest grain yield was observed in line ICFX 1420437-1-4-1-1 (358.50 kg ha^{-1}) and lowest in line EX Alupe (G) × KNE 814 P4-2-1-4-1 (256.50 kg ha^{-1}) compared to the check P224 (309.58 kg ha^{-1}) (Table 3.3). In ATC Soin, line KNE 814 × Ex Alupe (P) P8-1-1-1-1 had the highest grain yield of 333.30 kg ha^{-1}; the lowest was line ICFX 1420424-2-1-1-1 that had 166.00 kg ha^{-1} while the check P224 had 246.40 kg ha^{-1} (Table 3.3). Overall, seven genotypes were ranked top with grain yield above 300 kg ha^{-1} across the two locations. The top most ranked was genotype ICFX 1420315-2-2-1-2 with an average grain yield of 318.19 kg ha^{-1}. Sixteen genotypes expressed grain yield performance above 250 kg ha^{-1}. Two genotypes had low grain yield <250 kg ha^{-1} and these were EX Alupe (G) × KNE 814 P4-2-1-4-1 (224.93 kg ha^{-1}) and ICFX 1420342-3-1-2-2 (246.02 kg ha^{-1}). In summary, eight lines ICFX1420415-3-1-1-2, ICFX1420437-1-4-1-1, ICFX1420448-1-1-1-1, KNE 814 × Ex Alupe (P) P7-9-3-2-2,

ICFX1420415-3-1-1-2, ICFX1420437-1-4-1-1, ICFX1420448-1-1-1-1, KNE 814 × Ex Alupe (P) P7-9-3-2-2 showed above mean performance in yield in both locations (Table 3.3).

Quantitative traits including, plant height, days to 50% flowering and yield were significantly higher ($P<0.05$) among the lines studied in ATC Koibatek as compared to ATC Soin as shown in (Table 3.3). The lines had the highest mean performance of 75.38 cm for plant height in ATC Soin as compared to ATC Koibatek, which was 12.37 cm. In ATC Soin, line EX Alupe (G) × KNE 814 P1-1-2-3-1 was the shortest with 50.17 cm whereas line ICFX 1420314-2-1-1-1 showed reduced stature (10.93 cm) in ATC Koibatek. Seedling vigour, peduncle length and the number of productive tillers had no significant difference in performance in the two locations. However, significant variations for number of productive tillers and peduncle length were observed among the genotypes studied. Lines, EX Alupe (G) × KNE 814 P1-1-2-3-1, ICFX 1420314-2-1-1-1, ICFX1420424-2-1-1-1, ICFX 1420315-2-2-1-2 and ICFX 1420415-3-1-1-2 showed the highest number of productive tillers in both locations. Similarly, lines ICFX1420420-9-6-3-1, ICFX1420424-2-1-1-1, KNE 814 × Ex Alupe (P) P7-9-3-2-2, ICFX1420415-3-1-1-2, ICFX1420312-3-2-1-1 and ICFX1420315-2-2-1-2 showed the longest peduncle lengths in both locations. There were significant variations recorded for number of fingers and finger lengths among the genotypes across the locations. Among the genotypes studied, eight lines ICFX1420311-3-6-1-2, ICFX1420314-2-1-1-1, ICFX1420315-2-2-1-2, ICFX1420414-7-4-1-1, ICFX1420415-3-1-1-2, ICFX1420419-3-2-1-1, ICFX1420437-1-4-1-1 and ICFX1420448-1-1-1-1 exhibited the highest number of fingers in both locations. Lines ICFX1420314-2-1-1-1, ICFX1420314-6-2-1-1, ICFX1420414-7-12-1-1, ICFX1420448-1-1-1-1 and KNE 814 × Ex Alupe (P) P8-1-1-1-1 had the longest fingers in both locations. There were significant variations recorded for days to flowering among the genotypes across the locations. The difference between the earliest flowering 88 days (ICFX 1420314-2-1-1-1), and latest 95 days (ICFX 1420419-3-2-1-1) was 6 days in ATC Koibatek and early flowering 71 days (ICFX 1420415-3-1-1-2) and late flowering 77 days (ICFX 1420414-7-12-1-1 and ICFX 1420314-2-1-1-1) in Soin was also 6 days (Table 3.3).

Table 3.3: Mean performance of 25 genotypes evaluated for 8 agronomic traits in Koibatek and Soin locations.

Genotypes	Koibatek	Soin	Koibatek	Soin	Koibatek	Soin	Koibatek	Soin
	PHT		PL		PV		NPT	
EX Alupe(G) × KNE 814 P1-1-2-3-1	12.27	50.17	12.27	11.50	1.00	1.00	7.00	6.67
EX Alupe (G) X KNE 814 P4-2-1-4-1	12.67	69.83	12.67	12.50	1.65	1.23	4.00	4.17
ICFX 1420311-3-6-1-2	12.00	80.00	12.00	11.67	1.09	1.00	4.67	4.44
ICFX 1420312-3-2-1-1	13.00	80.17	13.00	13.33	1.13	1.33	5.33	5.29
ICFX 1420313-1-2-3-1	11.93	74.50	11.93	11.17	1.00	1.00	4.33	4.34
ICFX 1420313-3-2-1-1	12.40	74.67	12.40	12.00	1.00	1.00	4.67	4.86
ICFX 1420314-2-1-1-1	10.93	82.17	10.93	10.50	1.00	1.00	7.33	7.42
ICFX 1420314-6-2-1-1	11.80	76.67	11.80	12.00	1.24	1.23	4.33	5.19
ICFX 1420315-2-2-1-2	11.60	74.33	12.67	12.83	1.00	1.00	7.00.	6.89
ICFX 1420342-3-1-2-2	11.93	68.00	11.93	12.33	1.00	1.00	4.00	4.00
ICFX 1420396-5-5-1-1	12.67	84.33	12.67	12.33	1.00	1.00	4.33	5.03
ICFX 1420414-7-12-1-1	12.40	80.33	12.40	10.83	1.13	1.33	5.67	5.34
ICFX 1420414-7-4-1-1	12.07	74.83	11.53	11.50	1.00	1.00	4.33	4.44
ICFX 1420415-3-1-1-2	12.67	77.17	12.67	13.00	1.45	1.66	7.33	6.46
ICFX 1420419-3-2-1-1	12.67	72.83	11.60	10.67	1.09	1.33	5.67	6.03
ICFX 1420420-9-6-3-1	14.00	80.67	14.00	14.17	1.24	1.13	5.67	6.09
ICFX 1420424-2-1-1-1	13.27	78.50	13.27	14.17	1.00	1.00	6.67	6.56
ICFX 1420431-1-3-1-2	11.93	73.67	11.93	11.67	1.00	1.00	6.00	6.16

ICFX 1420431-2-5-1-1	11.73	73.67	11.73	11.83	1.23	1.13	3.67	3.89
ICFX 142036-3-3-1-1	12.80	77.33	12.80	12.67	1.00	1.00	5.00	5.58
ICFX 1420437-1-4-1-1	11.53	71.33	12.07	11.50	1.00	1.00	4.33	4.27
ICFX 1420448-1-1-1-1	12.13	73.83	12.13	12.17	1.24	1.24	4.67	4.74
KNE 814 × Ex Alupe (P) P7-9-3-2-2	13.73	69.00	13.73	13.17	1.00	1.00	4.00	4.33
KNE 814 X Ex Alupe (P) P8-1-1-1-1	12.33	87.33	12.33	12.83	1.00	1.00	3.67	4.22
P224- check	12.80	79.17	12.80	10.83	1.00	1.00	5.33	5.53
Means	12.37	75.38	12.37	12.13	1.10	1.10	5.16	5.28

Table 3.3: Continued….

Genotypes	Koibatek	Soin	Koibatek	Soin	Koibatek	Soin	Koibatek	Soin
	NF		FL		FFLW		Yield (kg ha^{-1})	
EX Alupe(G) × KNE 814 P1-1-2-3-1	4.94	12.33	6.00	13.37	94.33	75.33	287.1	224.2
EX Alupe (G) X KNE 814 P4-2-1-4-1	5.59	14.33	4.53	12.70	93.67	73.33	256.5	193.4
ICFX 1420311-3-6-1-2	5.66	14.67	7.13	14.47	96.00	75.33	323.8	250.6
ICFX 1420312-3-2-1-1	5.78	13.00	7.00	13.57	93.33	75.33	335.9	279.8
ICFX 1420313-1-2-3-1	4.44	14.67	6.73	16.00	91.33	75.33	317.9	267.4
ICFX 1420313-3-2-1-1	4.81	14.67	7.47	15.60	92.00	74.67	299.8	230.6
ICFX 1420314-2-1-1-1	6.06	15.67	7.93	14.90	88.67	72.67	356.4	241.3
ICFX 1420314-6-2-1-1	5.09	14.33	7.60	15.17	90.33	75.33	345.3	235.9
ICFX 1420315-2-2-1-2	6.04	16.33	6.73	15.67	91.00	72.67	354.5	281.9
ICFX 1420342-3-1-2-2	5.00	15.67	7.73	13.90	90.67	75.33	284.2	207.8
ICFX 1420396-5-5-1-1	4.49	14.33	7.27	14.03	91.33	75.33	303.6	259.7
ICFX 1420414-7-12-1-1	5.11	14.67	7.93	15.07	92.67	76.00	334.9	271.8
ICFX 1420414-7-4-1-1	5.68	14.67	7.33	13.90	93.00	76.67	343.4	268.6
ICFX 1420415-3-1-1-2	5.44	15.33	6.73	15.90	91.33	70.67	335.6	265.3
ICFX 1420419-3-2-1-1	5.76	14.67	5.73	14.70	95.00	73.33	300.6	247.1
ICFX 1420420-9-6-3-1	5.11	13.33	6.00	15.27	94.67	76.00	297.6	232.4
ICFX 1420424-2-1-1-1	5.11	13.33	6.87	14.37	92.33	76.00	337.8	166.0
ICFX 1420431-1-3-1-2	4.56	13.33	6.73	14.67	94.67	76.00	299.2	239.9

ICFX 1420431-2-5-1-1	5.24	15.33	7.20	14.13	92.33	72.67	300.9	235.4
ICFX 142036-3-3-1-1	5.20	13.67	6.00	11.60	90.00	76.00	287.5	256.3
ICFX 1420437-1-4-1-1	6.27	15.67	8.53	13.83	91.00	74.67	358.5	275.9
ICFX 1420448-1-1-1-1	5.99	15.67	7.33	17.40	91.33	75.33	318.5	263.8
KNE 814 × Ex Alupe (P) P7-9-3-2-2	5.70	14.33	6.40	15.53	91.33	76.00	326.1	280.7
KNE 814 X Ex Alupe (P) P8-1-1-1-1	4.23	13.00	7.27	14.80	92.00	76.67	309.6	333.3
P224- check	5.78	14.00	8.20	13.93	92.00	76.00	232.03	246.4
Means	5.32	14.44	6.98	14.58	92.25	74.91	313.89	250.22

PHT- plant height (cm), PL-peduncle length (cm), PV-plant vigour (#), NPT-number of productive tillers (#), NF-number of fingers (#), FL-finger length (cm), FFLW-days to fifty percent flowering (days), yield (kg ha^{-1}).

3.3.2 Response of physiological traits among test genotypes

Genotype main effects were significant ($P<0.05$) for leaf area index and ($P<0.001$) for evapotranspiration rate, leaf RWC, root RWC, stomatal conductance, chlorophyll content, CO_2 assimilation and photosynthetic rate (Table 3.4). Significant effects for location ($P<0.05$) were observed on leaf area index, light intensity and evapotranspiration rate. Effects due to interaction between genotypes and location were significant ($P<0.001$) for leaf area index, light intensity, evapotranspiration rate, root RWC, stomatal conductance, chlorophyll content and photosynthetic rate and ($P<0.05$) for shoot biomass (Table 3.4)

Table 3.4: Analysis of variance for 25 finger millet genotypes based on twelve morpho - physiological traits across two locations.

Source of variation	**Df**	**LAI**	**LI**	**ET**	**LRWC**	**ST**	**CC**
Replication	2	0.01***	0.06***	71.79***	252.23***	0.018	5.46***
Genotype (G)	24	0.001*	0.009	67.61***	27.68***	10.77***	30.19***
Location (L)	1	0.19*	1.49*	4429.36*	524.35	0.352	0.396
G x L	24	0.0005***	0.008***	6.94***	0.28	1.67***	3.41***
Block	26	0.0002	0.003	2.39	18.54	0.17	0.90
CV		11.39	12.26	8.01	6.73	9.59	9.09
R^2		0.95	0.92	0.97	0.71	0.98	0.94

Table 3.4: Continued…

Source of variation	**Df**	**RRWC**	**SBIO**	**TBIO**	**RBIO**	**COA**	**PR**
Replication	2	44.34***	157.14***	1800.00***	168.58***	3819.34*	7.64
Genotype (G)	24	109.37***	62.79***	235.69***	236.13***	9571.79***	285.38***
Location (L)	1	227.43	839.65	3750	1122.79	52.81	33.77
G x L	24	0.39	7.48*	0	7.31	1051.62	119.70***
Block	26	0.88	7.94*	161.2	5.5	897.38	21.04
CV		4.39	6.16	19.92	5.18	7.84	13.07
R^2		0.97	0.92	0.53	0.97	0.83	0.92

Df- degree of freedom, CV - coefficient of variation, * significant at $P< 0.05$, ** significant at $P<0.01$ and *** significant at $P<0.001$, LAI - Leaf area index, LI - light intensity, ET - Evapotranspiration rate (mmol $H_2O m^{-2} s^{-1}$), LRWC - Leaf relative water content, ST - Stomatal conductance (mol $H_2O m^{-2} s^{-1}$), CC - Chlorophyll content (µmol m^{-2}), RRWC -

Root relative water content, SBIO - Shoot biomass (g), TBIO - Total biomass (g), RBIO - Root biomass (g), COA - CO_2 assimilation (molm^{-2}s^{-1}), PR - Photosynthetic rate (µmolCO_2 m^{-2}s^{-1}).

Variation among the genotypes was present for morpho-physiological traits (Table 3.5). Generally, root biomass was highest in Soin (44.10) compared to Koibatek (38.62). In the two locations line ICFX 1420314-2-1-1-1 was consistent with highest root biomass in Koibatek (52.81) and Soin (59.81) (Table 3.5). Similarly, lines, EX Alupe (G) X KNE 814 P4-2-1-4-1, ICFX1420314-2-1-1-1, ICFX1420414-7-12-1-1, ICFX1420414-7-4-1-1, ICFX1420415-3-1-1-2, ICFX1420419-3-2-1-1, ICFX1420437-1-4-1-1, ICFX1420448-1-1-1-1, KNE 814 × Ex Alupe (P) P7-9-3-2-2, KNE 814 X Ex Alupe (P) P8-1-1-1-1 and the check P-224 showed consistent above mean performance in root biomass in both locations. Lines ICFX 1420415-3-1-1-2, ICFX1420314-2-1-1-1 and KNE 814 X Ex Alupe (P) P8-1-1-1-1 had high photosynthetic rate across the two locations with an average rate above 5 µmolCO_2 m^{-2}s^{-1}. Stomatal conductance was highest in line ICFX1420415-3-1-1-2 with an average above 7 mol H_2Om^{-2}s^{-1} and lowest in line ICFX1420314-6-2-1-1 with an average of 0.14 mol H_2Om^{-2}s^{-1} in both Koibatek and Soin. CO_2 assimilation and chlorophyll content varied significantly among the finger millet lines across the two locations. CO_2 assimilation was highest in line KNE 814 × Ex Alupe (P) P7-9-3-2-2 in Koibatek (532.33 molm^{-2}s^{-1}), and Soin (509.67 molm^{-2}s^{-1}), lowest in line ICFX1420420-9-6-3-1 with an average of 307.33 molm^{-2}s^{-1}, both in Koibatek and in Soin. CO_2 assimilation was constantly high in both locations for lines, EX Alupe (G) X KNE 814 P4-2-1-4-1, ICFX1420313-3-2-1-1, ICFX1420414-7-4-1-1, ICFX1420415-3-1-1-2 and ICFX1420448-1-1-1-1. Chlorophyll content was highest in lines ICFX1420314-2-1-1-1, ICFX1420415-3-1-1-2 and KNE 814 X Ex Alupe (P) P8-1-1-1-1 with an average above 10.00 µmolCO_2 m^{-2}s^{-1}, both in Koibatek and in Soin (Table 3.5).

Table 3.5: Means of 25 genotypes evaluated for morpho- physiological traits in Koibatek and Soin locations in Kenya.

	Koibatek	Soin	Koibatek	Soin	Koibatek	Soin	Koibatek	Soin	Koibatek	Soin
Genotype	RBIO		PR		ST		COA		CC	
EX Alupe(G) × KNE 814 P1-1-2-3-1	33.90	39.23	4.54	3.82	4.54	3.82	357.67	357.67	6.34	6.43
EX Alupe (G) X KNE 814 P4-2-1-4-1	40.78	45.78	4.28	4.44	3.21	0.19	374.33	374.33	7.59	7.72
ICFX 1420311-3-6-1-2	38.82	44.03	2.67	4.15	2.67	4.15	352.00	352.00	9.66	9.58
ICFX 1420312-3-2-1-1	36.78	41.78	2.87	3.36	2.87	3.36	345.67	345.67	10.50	11.57
ICFX 1420313-1-2-3-1	29.70	34.70	2.45	2.41	2.45	2.41	351.33	342.00	10.59	9.74
ICFX 1420313-3-2-1-1	38.20	41.21	2.81	2.36	2.80	2.36	379.33	463.33	6.80	7.08
ICFX 1420314-2-1-1-1	52.81	59.81	5.21	5.08	4.28	4.44	380.67	351.00	15.88	14.32
ICFX 1420314-6-2-1-1	34.36	39.35	0.14	0.14	0.14	0.14	364.33	364.33	6.80	6.57
ICFX 1420315-2-2-1-2	18.95	28.16	3.44	3.50	3.44	3.50	360.00	439.67	9.26	9.26
ICFX 1420342-3-1-2-2	36.93	43.51	2.60	2.49	2.60	2.49	337.67	323.33	11.67	12.55
ICFX 1420396-5-5-1-1	36.25	41.25	2.77	2.22	2.77	2.22	363.00	348.67	11.34	12.03
ICFX 1420414-7-12-1-1	40.27	47.76	0.20	0.15	0.20	0.15	363.67	363.67	7.53	11.91
ICFX 1420414-7-4-1-1	38.64	52.99	2.69	3.74	2.69	3.74	372.33	372.33	12.99	11.19
ICFX 1420415-3-1-1-2	41.95	46.95	7.62	7.06	7.62	7.06	532.33	509.67	15.69	15.88
ICFX 1420419-3-2-1-1	44.94	49.94	3.10	2.68	3.10	2.68	351.00	347.00	8.59	8.62
ICFX 1420420-9-6-3-1	33.01	38.01	0.12	3.85	0.12	3.85	307.33	307.33	8.51	8.51
ICFX 1420424-2-1-1-1	33.55	38.55	5.19	4.91	4.49	4.37	368.00	368.00	8.29	9.98
ICFX 1420431-1-3-1-2	38.99	43.63	1.91	2.70	1.91	2.70	337.33	337.33	8.46	8.40

ICFX 1420431-2-5-1-1	32.99	33.29	3.48	3.59	3.48	3.59	350.33	350.33	8.82	7.98
ICFX 142036-3-3-1-1	32.79	43.73	2.91	3.47	2.91	3.47	355.00	340.00	11.91	10.69
ICFX 1420437-1-4-1-1	42.11	43.77	1.96	4.00	1.96	4.00	356.67	372.33	7.17	7.16
ICFX 1420448-1-1-1-1	49.36	54.33	3.80	0.19	5.80	4.91	368.33	335.00	12.05	11.79
KNE 814 × Ex Alupe (P) P7-9-3-2-2	41.90	48.99	3.47	3.47	3.47	3.47	454.67	447.67	11.86	11.76
KNE 814 X Ex Alupe (P) P8-1-1-1-1	50.93	56.82	5.19	5.08	4.49	3.47	380.67	369.33	13.66	14.02
P224- check	46.57	44.80	3.70	3.70	3.70	3.58	369.33	360.67	7.96	7.15
Means	38.62	44.10	3.14	3.24	3.14	3.23	369.32	369.71	10.00	10.11

RBIO- Root Biomass (g), PR- Photosynthetic Rate (μmolCO_2 $m^{-2}s^{-1}$), ST-Stomatal conductance (mol $H_2O m^{-2}s^{-1}$), COA- CO_2 Assimilation ($molm^{-2}s^{-1}$), CC- Chlorophyll Content (μmol m^{-2}) .

3.3.3 Correlations between agronomic and morpho- physiological traits

Significant positive correlation at *P*<0.001, *P*<0.01 and *P*<0.05, respectively were observed between grain yield and evapotranspiration rate, root RWC, number of fingers, finger length, days to 50% flowering, harvest index and 1000 grain weight (Table 3.6). The correlation between evapotranspiration rate and root relative water content, days to 50% flowering, harvest index, 1000 seed weight and yield was positive and significant (*P*<0.001). Root relative water content exhibited a positive and significant correlation with days to 50% flowering, harvest index and yield (Table 3.6). Similarly, a positive significant response was observed between number of fingers and finger length, 1000-grain weight, leaf area index, light intensity and all biomass traits studied as well as yield. Harvest index showed positive and significant correlations with 1000-grain weight and yield. Among the biomass traits, positive and significant correlations (*P*<0.001) were recorded between shoot biomass and root biomass, shoot biomass and total biomass. Likewise, root biomass was correlated with total biomass *P*<0.001. Leaf area index exhibited a positive significant relationship with, shoot biomass, root biomass, total biomass and yield. LAI showed a negative significant correlation with light intensity. There was a significant association between the biomass traits and yield. Leaf photosynthetic rates were positively correlated with total biomass and yield.

Table 3.6: Pearson’s correlation coefficients for selected yield and morpho- physiological traits of test finger millet genotypes.

Traits	ET	RRWC	NF	FL	NPT	FFLW	HI	TSW	LAI	LI	SBIO	RBIO	TBIO	Yield
ET		0.191^{*}	-0.794^{***}	-0.713^{***}	-0.253^{***}	0.736^{***}	0.537^{***}	0.650^{***}	-0.544^{***}	-0.505^{***}	-0.31	-0.27	-0.223	0.611^{***}
RRWC			-0.243^{**}	-0.242^{**}	0.131	0.218^{**}	0.442^{***}	0.224	-0.271	-0.257	0.094	-0.603^{***}	-0.269	0.191^{*}
NF				0.934^{***}	0.024	-0.945^{***}	-0.699^{***}	0.841^{***}	0.803^{***}	0.753^{***}	0.429^{***}	0.359^{***}	0.315^{***}	0.635^{***}
FL					-0.011	-0.903^{***}	-0.652^{***}	0.809^{***}	0.815^{***}	0.761^{***}	0.406^{***}	0.344^{***}	0.312^{***}	0.553^{***}
NPT						0.030	-0.174^{*}	-0.092	-0.027	-0.008	0.174	0.168	0.175	0.161
FFLW								0.676^{***}	0.818^{***}	-0.814^{***}	0.776	0.437^{***}	0.274^{***}	0.269^{***}
HI								0.651^{***}	-0.650^{***}	-0.606^{***}	0.483^{***}	0.581^{***}	0.493^{***}	0.687^{***}
TSW									-0.729^{***}	-0.717^{***}	0.426^{***}	0.426^{**}	0.316^{***}	0.316^{***}
LAI										-0.932^{***}	0.425^{***}	0.349^{***}	0.341^{***}	0.544^{***}
LI											0.422^{***}	0.308^{***}	0.333^{***}	0.565^{***}
SBIO												0.059	0.383^{***}	0.262**
RBIO													0.566^{***}	0.164*
TBIO														0.200*
Yield														1.000

$^{***}P<0.001$, $^{**}P<0.01$, ET– evapotranspiration rate (mmol $H_2Om^{-2}s^{-1}$), RRWC– root relative water content, NF – number of fingers, NPT– number of productive tillers, FL–finger length (cm), FFLW– days to 50% flowering, HI – harvest index, TSW – thousand seed weight (g), LAI – leaf area index, LI – light intensity, SBIO – shoot biomass (g), RBIO – root biomass (g), TBIO – total biomass (g).

3.4 Discussion

Plants deploy different strategies for adaptation to drought conditions. Drought adapted crop genotypes may thus deploy avoidance, escape or tolerance mechanisms under both terminal and intermittent droughts. However, genotypes that possess these adaptive mechanisms hardly express desirable agronomic characteristics. This study focused on identifying genotypes with causal morphological and physiological traits linked to drought adaptation and displaying superior agronomic performance. According to past research reports, evaluation of crops for traits related to drought adaptation is a real limitation (Nadeem *et al.,* 2020). The reason being that most of the approaches used are tedious and may involve destructive sampling (Gebreyohannes *et al.,* 2021).

According to results of the analysis of variance, significant variation among the genotypes revealed in this study for all the traits studied signified the existence of differences among the finger millet lines for drought tolerance. This indicated the presence of sufficient genotypic variation in the genetic material studied, which could be useful parental stock for breeding in drought improvement programmes and possible release for commercial production of promising lines. Adequate genotypic variation for drought tolerance was also reported in finger millet germplasm in Uganda and Ethiopia (Owere *et al.,* 2016). The difference in means for the agronomic traits observed across the two sites especially, number of productive tillers, number of fingers, finger length and yield could be attributed to environmental differences across the two locations. These could be associated with variations in soil type, rainfall patterns and temperature. The findings are similar to earlier studies where significant differences were reported on agronomic traits (Dramadri, 2018). High yields obtained in ATC Koibatek site indicated the level of drought tolerance among the genotypes as revealed by superior number of fingers, finger length, number of productive tillers and early flowering. These findings are similar with earlier reports, which found superior agronomic performance under drought conditions (Shanker, 2016; Tadele, 2016). According to Bennani *et al.* (2016), reduced number of days to flowering and heading was a mechanism deployed by drought-adapted genotypes to escape from drought stress.

Among phenotypic target traits for selection, seedling vigour was high in most of the genotypes. High-vigour seeds are necessary for seedling establishment and sustainable crop productivity, especially under unfavourable conditions (Duval *et al.,* 2012). High-vigour seeds can improve seed germination and seedling emergence, increase crop yield and reduce the cost of agriculture production (Ventura *et al.,* 2012). These results agree with those of Struik *et al.* (2007) who deduced that seedling vigour is a candidate trait for evaluating wheat for drought tolerance at the early growth stage. Vigorous healthy seedlings are water and nutrient use efficient and can compete against weeds (Zhang *et al.*, 2015). Ahmad *et al.* (2015) evaluated 50 wheat (*Triticum aestivum*) genotypes for different seedling traits including seedling vigour and successfully identified eight potentially drought-tolerant genotypes.

Plant height was significantly reduced in the high yielding genotypes. Shorter plants exhibit reduced percentage of dry matter accumulation in vegetative parts thereby improving the grain yield. Semi-dwarf stature of wheat was seen to induce increased yields through more efficient utilization of available assimilates associated with crop lodging (Divashuk *et al.,* 2013). These findings are in agreement with previous studies which reported reduced plant height to be associated with increased yield (Koocheki *et al.,* 2014; Mohammadi *et al.,* 2012). The reduced plant height indicates a reduction in the moisture demand and prevents moisture loss due to transpiration (Zhang *et al.,* 2018). In wheat, reduced plant height was reported to reduce photosynthesis and nutrient translocation, especially during the stem elongation stage due to low moisture content (Sarto *et al.,* 2017). The reduced plant height resulted in increased grain yield (Grover *et al.,* 2018) which possibly resulted from increased partitioning of assimilates to the ear. This further resulted in higher harvest index (HI) and lodging resistance (Divashuk *et al.,* 2013). These results indicated that plant height is one of the reliable morphological trait for selecting drought tolerant genotypes to obtain a high yield potential.

Number of productive tillers showed negative correlation with grain yield and yield components. It indicates that increase in tillering capacity resulted in decline in the number of fertile floret per spikelet, finger width, finger weight and consequently thousand-grain weight decreases. Lule *et al.* (2012) also reported similar findings where after evaluating one hundred forty-four finger millet landraces they found a negative correlation between the number of tillers and grain yield.

Positive and significant correlations were observed between days to flowering and grain yield and yield components. Similar findings were reported by Ganapathy *et al.* (2011) and Chandra *et al.* (2013) that late maturity was positively associated with grain yield and its components. In this study, 1,000-grain weight, finger number, finger length, days to maturity and harvest index were positively correlated with grain yield. Similarly, Bezaweletaw *et al.* (2006), in their study found 1,000-grain weight, finger number, finger length, days to maturity, and HI to have positive and significant effects of on grain yield per plant. Wolie *et al.* (2013) and Kumar *et al.* (2016) found out that grain yield correlated positively with biomass and harvest index in finger millet. Thus, direct selection for 1,000-grain weight, finger number, finger length, days to maturity and harvest index would be helpful to increase yield.

Significant and positive relationship was observed between harvest index (HI) and grain yield. This relationship indicates that an increase in HI may lead to a yield increase since HI is the ratio of harvested grain to total shoot dry matter, and this can be used as a measure of reproductive efficiency. Harvest index. can influence yield as it is the proportion of the whole plant mass that is partitioned to the seed (Pachepsky *et al.,* 2011). Significant positive association between HI and grain yield have also been reported (Jyothsna *et al.,* 2016). Harvest index also showed positive correlation with photosynthetic rate. This means that increased photosynthesis will result to enhanced biomass production. The results are in tandem with those of Reddy (2020) who reported a positive significant relationship between HI and photosynthetic rate. Harvest index also showed positive and significant phenotypic correlation with number of tillers per plant and finger length, which suggests that enhancing these traits would increase harvest index along with grain yield. Interestingly, the HI was negatively correlated with leaf area index and light intensity (Table 3.6), suggesting that both leaf area and light intensity are important under low light conditions to determine the biomass and grain yield of finger millet. These findings are in agreement with those of Reddy and Gowda (2020) who reported a reduction in above ground biomass and grain yield in finger millet under low light intensity.

Three lines, ICFX1420314-2-1-1-1, KNE 814 × Ex Alupe (P) P8-1-1-1-1 and ICFX1420415-3-1-1-2 were considered drought tolerant and high yielding across the two locations because of their consistency in performance. Genotypic superiority observed for yield could be attributed to the presence of quantitative trait loci (QTLs) modulating accumulation of yield under drought. However, grain yield being a complex trait is highly influenced by diverse environmental factors including both biotic and abiotic factors. Therefore, high variation observed for yield was attributed to environmental stimuli within the two locations. Similar findings reported that high variation in grain yield was attributed to both genetic and environmental factors (Malambane & Jaisil, 2015; Mukami *et al.,* 2019).

Significant differences in means for the physiological traits across the two locations indicated the differences in the genetic make-up among the lines in their physiological responses to environmental stress across the two study locations (Anjum *et al.,* 2011; Mukami *et al.,* 2019). The low values recorded by the genotypes on photosynthetic rate and chlorophyll content could be due to the drought effects in both locations. Drought affects chlorophyll content reducing the photosynthetic activities of most crops including finger millet (Fathi & Tari, 2016). Agele *et al.* (2018) reported that drought stress caused a large decline in leaf chlorophyll a, b and total chlorophyll content in cacao. Similar findings were earlier reported where reduction in chlorophyll content was found to be a mechanism to drought response, which aid in reducing the light absorbed by chloroplast (Gu *et al.,* 2017).

Significant differences in leaf photosynthetic rates and total biomass existed among the 25 finger millet genotypes studied in this experiment. Total biomass accumulation is a function of the rate of biomass production (associated with leaf area production, leaf area retention, and net photosynthetic rate) and growth duration (Kamal *et al.,* 2022). These results suggested that total biomass production was primarily a function of leaf photosynthetic rate. These results agree with the report of Peng *et al.* (1991) who evaluated 22-grain sorghum lines under field conditions. They found the lines to exhibit significant genetic variation in leaf photosynthetic rate, total biomass production and grain yield. Significant positive correlations existed between leaf photosynthesis and total biomass and grain production under both well-watered and water-limited conditions.

Total biomass allocation plays a major role in determining the yield and drought tolerance of crops. Genotypes allocate biomass differently between roots and shoots (Weiner, 2004) and there are indications that drought tolerance can be improved via traits such as root length and biomass allocation (Griffiths & Paul 2017; Paustian *et al.* 2016). Increased root biomass recorded in this study is a plant avoidance mechanism in response to drought when drought increases the proportion of root biomass relative to above ground biomass (Zhou *et al.,* 2018). Root biomass is a function of number, length, and diameter of seminal and nodal roots as well as lateral roots. Therefore, increased root biomass recorded in this study might be due to increase in one or of combinations of these root system components. These results agree with those of Chen *et al.* (2020) who established that biomass allocation pattern influences drought tolerance in wheat. Plants that invest significantly in root biomass increase their potential for water and nutrient absorption, which directly influence their growth potential (Wasaya *et al.,* 2018). Large root biomass is important in dryland farming conditions where crops have to explore large volumes of soil to extract enough moisture for growth (Ehdaie *et al*., 2012). Changes in stomatal conductance cause changes in leaf water potential by changing the transpiration rate. High photosynthesis and stomatal conductance observed (Table 3.5) indicated that photosynthetic CO_2 fixation in the genotypes was not affected by water stress, further suggesting that they can compete successfully on drier sites.

The high photosynthesis and stomatal conductance exhibited by these genotypes further indicates a high photosynthetic water use efficiency.

Shoot, root and total biomass showed significant negative correlation with grain yield (Table 3.6). No significant correlations were found between net photosynthesis rate and stomatal conductance, and photosynthesis and transpiration rates. These results agree with those obtained by Chen and Hao (2015) who reported transpiration rate, stomatal conductance and water use efficiency (WUE) to be non-influential on yield development in wheat. In contrast, Sharma *et al.* (2015) observed a positive correlation between water use efficiency and grain yield in pearl millet. The lack of significance of these traits could have been attributed to enzyme inactivation because of high leaf temperature and low leaf water potential (non-stomatal limitation). It's possible that both net photosynthetic rate and transpiration rate which depend on stomatal conductance, were proportionally affected by water deficit and as a result there was no significant correlation observed between net photosynthetic rate and stomatal conductance (Frih *et al.*, 2021). The significant (P <0 .05) effects of the interactions involving genotype and location on the traits such as shoot biomass, root biomass, total biomass and grain yield (Table 3.3) suggest that genotypic and environmental factors are crucial for biomass allocation and yield improvement in finger millet.

The leaf area index (LAI) showed a significant positive relationship with biomass (shoot, root and total biomass) at harvest as well as grain yield. The LAI is an important indicator of radiation and precipitation interception, energy conversion, and water balance in crops (Jeon *et al.*, 2022). From the results it can be deduced that and increase in LAI would result in increased biomass as well as yield. These results agree with those of Liu *et al.* (2022) who evaluated the performances of wheat genotypes by estimating agronomic variables, such as total above ground biomass at key stages and yield using LAI data. Further, leaf area index showed a significant negative correlation with light intensity. This indicated that an increase in light intensity resulted to a decrease in the leaf area index. Hence, the decreased leaf area with decreased light intensity resulted in decreased biomass and grain yield in all the genotypes. Low light intensity reduces the leaf expansion rates and delays the complete expansion of leaf, thus decreases leaf area per plant under shade conditions (Fan *et al.*, 2018). In the present study, the leaf area was reduced under low light intensities, which might be due to higher allocation of biomass towards stem elongation than to leaves (Wu *et al.*, 2017). Plants often absorb more light energy than they can process in photosynthesis. It has been reported that high light intensities cause irreparable photo inhibitory damages to plant, particularly when water deficit stress occurs at the same time High light intensities and water deficit stress negatively affect plant physiological processes. Furthermore, low light intensity increases the lower leaf senescence, which might lead to reduced current photosynthesis with higher respiratory demands Anjum *et al.* (2020); this could be the reason for lower leaf area under low light intensities in the present study.

The positive and significant association recorded of morphological traits root, shoot and total biomass and physiological traits photosynthesis rate, evapotranspiration rate, chlorophyll content, stomatal conductance and CO_2 assimilation with agronomic traits such as plant height, number of productive tillers per plant, number of fingers, finger length and days to maturity, indicate that these traits can be improved simultaneously through selection.

3.5 Conclusion

From the present study, three lines, ICFX1420314-2-1-1-1, KNE 814 × Ex Alupe (P) P8-1-1-1-1 and ICFX1420415-3-1-1-2 were identified as drought tolerant due to their short stature, early flowering, higher root biomass, higher stomatal conductance, higher CO_2 assimilation, high chlorophyll contents and subsequently higher photosynthetic rates and increased grain yields in both locations as compared to check (P224). In contrast, the most susceptible lines were ICFX1420431-1-3-1-2, EX Alupe (G) × KNE 814 P1-1-2-3-1 and ICFX1420342-3-1-2-2, which exhibited low root biomass, shoot biomass and reduced CO_2 assimilation across the two locations. However, further evaluation of these lines under farmer-managed trials in more locations would be useful for identifying their agronomic potential, yield stability and end user preferences. The above stated three finger millet lines identified in this study are useful for deployment as commercial varieties. Also the identified lines ICFX1420314-2-1-1-1, KNE 814 × Ex Alupe (P) P8-1-1-1-1 and ICFX1420415-3-1-1-2 have good drought associated traits and can be utilized as parents in crossing programmes for improvement of drought tolerance and high yield in ASALs areas of Kenya.

CHAPTER FOUR

EVALUATION OF ROOT-SHOOT CHARACTERISTICS ASSOCIATED WITH DROUGHT TOLERANCE IN FINGER MILLET (*Eleusine coracana* L.) UNDER RAIN OUT SHELTER CONDITIONS

Abstract

Finger millet has gained considerable attention worldwide due to its nutritional and health benefits. It is adapted to dry and hot climates and plays a major role in food and nutritional security in arid and semi-arid areas of Africa. Plant roots play a significant role in plant growth by exploiting soil resources via the uptake of water and nutrients. The objective of the study was to identify root-shoot plant characteristics associated with drought tolerance in finger millet. This study evaluated 24 advanced lines of finger millet against a commercial variety P224 in randomised complete block design with three replications in a rainout shelter at Egerton University, Njoro in Kenya. Results showed significant ($P<0.001$) differences among the 25 finger millet lines for root dry weight (RDW), root to shoot ratio (RSR), total dry weight (TDW), rooting length (RL), root surface area (RSA), specific root length (SRL), root length density (RLD), root volume (RV) and root tips. The effect due to finger millet lines was also significant ($P<0.01$) for seedling vigour and shoot dry weight. Correlation analysis indicated positive significant correlation among major root and shoot traits, which are known to confer drought tolerance among crop species. Positive correlation ($P<0.001$) between RDW and SDW, RL and RSA were observed among the finger millet lines evaluated. The results from this study demonstrate the potential of exploiting root-shoot traits that are critical in selection for drought tolerance for increased finger millet production. Significant root traits associated with drought tolerance will be useful for indirect selection of finger millet lines in local and regional breeding programmes.

4.1 Introduction

Drought stress is the most significant production constraint of finger millet (*Eluisine corancana*) in sub-Sahara Africa. Finger millet is a cheaper source of nutritious food for the resource poor (Hassan *et al.,* 2021). In arid and semi-arid environments where finger millet is the dominant crop, drought or inadequate moisture is the major abiotic stress affecting productivity (Tadele, 2016). Improving finger millet for drought-prone areas to attain food security in resource-limited ecosystems is a major research priority. Drought stress is responsible for the greatest crop loss worldwide and is expected to worsen thereby heightening international interest towards the drought resilient crops (Comas *et al.,* 2013). Past breeding efforts in finger millet laid emphasis on architectural or physiological characters observed on the aerial part such as shoot height or resistance to biotic factors and grain yield with limited consideration for root functional traits (Vadez *et al.,* 2012). Therefore, a better understanding of root functional traits and how the traits are related to increasing crop productivity under drought conditions is necessary.

The root serves not only as the source of water uptake for the plant, but also plays a crucial role in the signalling of the drought response to the stem, leaves and reproductive organs (Tadele, 2018). The root system is the interface between the plant and the soil, which constitutes the water and nutrient pool for the plant. Roots have evolved to be responsive and extremely adaptive to local environment and their morphology, growth and physiology are closely related to plant genotype (Wasaya, 2018). Root traits associated with maintaining plant productivity under drought include small fine root diameters, long specific root length and considerable root length density.

Drought tolerance is most desirable attribute as the maintenance of crop productivity under drought can be accomplished by drought avoidance or desiccation prevention, through matching crop water use with water availability and recovery of growth following rewetting (Passioura, 2012). Roots acquire water and nutrients from the soil hence, the morphological and physiological characteristics of roots play a major role in determining shoot growth and overall production (Ghosh & Xu, 2014). The root system size, properties and distribution ultimately determine plant access to water. The importance of root architecture for water and nutrient acquisition has been well documented in both monocots and dicots and could be successfully used for root trait-targeted genetic improvement. For instance, targeted modifications of root architecture in pea to increase phosphorus acquisition efficiency were achieved (Lynch, 2011). In addition, large root system with greater root prolificacy and rooting depth was shown to influence not only transpiration through soil moisture utilization but also shoot biomass production and harvest index under terminal drought stress (Kashiwagi *et al.*, 2005; Kashiwagi *et al.*, 2013; Ramamoorthy *et al.,* 2017). Matsui and Singh (2003) evaluated cowpeas using a root box method and found more profuse (higher root length density) and deeper root systems to be desirable traits for drought adaptation. In their study, the best cultivars were reported to have a higher root dry matter per unit of leaf area and a downward movement of roots indicating that they would invest more in deeper rooting for water capture.

The effects of root density on yield will depend on soil moisture distribution and competition within the plant population (Thidar *et al.,* 2020). Root length, root surface area and root volume directly affect the ability of crops to absorb and transport nutrients and water (Wang *et al.*, 2019). Blum (2010) reported that deeper roots allows the crop to access more water, maintain high stomata conductance and hence photosynthesis, and are indicated by cooler canopies. The access of water to a plant is determined by its root system properties, structure and distribution, thus improving root traits to increase the uptake of soil moisture and maintain productivity underwater stress is of major interest (Comas *et al.,* 2013b). A study of root systems throughout the growing season is vital for understanding the control of drought tolerance in finger millet owing to the exposure of the crop to both intermittent and terminal droughts that occur during plant growth and development. In this study, root-shoot traits was evaluated for 25 selected genotypes under rain out shelter to determine their contribution to enhanced drought tolerance in ASALs.

4.2 Materials and methods

4.2.1 Site description

Egerton University, Njoro lies 0°22'S, 35º 56'E and at an altitude of 2,238 m above sea level. It has a tropical climate and the temperatures ranges between 15 °C - 21 °C. The area receives a mean annual rainfall of 1200 mm and is bimodal with long falling between March and August while the short rains fall between September and December (Jaetzold & Schimdt, 1983; Ondieki *et al.*, 2013).

4.2.2 Finger millet genotypes evaluated.

Twenty-four advanced finger millet lines were evaluated for root traits associated with drought tolerance alongside a commercial variety P-224 (Table 3.1). These lines were acquired from the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Kenya Agricultural and Livestock Research Organization (KALRO) and Egerton University seed unit.

4.2.3 Experimental procedure

The experiment was conducted at Egerton University Agronomy teaching and research field (Field 7) under rainout shelter (ROS) conditions for one cycle The shelter was similar to that described by Jefferies (1993) and Upchurch *et al.* (1983) and measures 15.5m long × 7.5m wide (Fig 4.1). Translucent sheets (which allow up to 90% of photosynthetic photon flux density to pass through) covered the roof (Fig 4.1).

Figure 4. 1: Mobile Rain out shelter with Translucent sheets

The study was conducted in Polyvinyl chloride (PVC) cylinders measuring 1.2 m long and 0.02 m inner radius (Figure 4.2). The cylinders were placed in 1.2 m deep cement pits at a spacing of 5 cm. The experiment was laid in a randomized complete block design (RCBD) (Gomez & Gomez, 1984) with three replicates.

Figure 4.2: Finger millet seedlings emergence in Polyvinyl chloride pipes in rain out shelter at Field 7, Egerton University.

Reddish clay loam forest soil with moderate structure and natural fertility was collected from uncultivated land of Field 7 at Egerton University and placed in PVC pipes for the experiments. The cylinders were filled with an equal mixture (w/w) of forest soil and sand. The sand was used to decrease the soil bulk density and to facilitate root growth and subsequent root extraction. Initial calibration of the soil water to be used was done before planting to determine the water holding capacity which ranged between 0.28 to 0.48 cm3 cm-^{3} lower limit-upper limit respectively for the 0 - 120 cm PVC pipe soil layer and the volume of the water added each time (Kimurto *et al.*, 2005). The PVC pipes were fully soaked with water and left for 24 hours to drain. This was done to equilibrate the soil moisture content to 70 % near field capacity (FC) to create the conditions similar to those in the field at sowing time. Di-ammonium phosphate (DAP) fertilizer was applied at the rate of 0.07 kg per pipe to supply 20 kg N per hectare and 20 kg P_2O_5 per hectare. DAP was thoroughly mixed with the soil before planting the seeds. Four seeds of each line were sown in the cylinder and irrigated with 1,500 ml of water to achieve uniform emergence. Thinning was done two weeks after emergence to allow two plants per pipe. Weeding was done by physically uprooting weedy species once they had emerged. All other agronomic operations were done as per the crop recommendations. Watering was continued until 35 days after sowing (DAS) when the roots were extracted; washed gently and analysed using the *Win*Rhizo^{TM} software (Figure 4.2). Roots were extracted from the PVC pipes by gently washing out the soil particles and other debris at the plant age of 35 days after sowing (DAS) from the lower end of pipe. When approximately three quarters of the soil-sand mixture was washed away, the cylinders were erected gently on a 2 mm sieve so that the entire root system could be removed. The extracted root system was mostly in one piece with very few small segments of detached roots trapped by the 5mm sieve. The root bounds were rinsed free of medium under running water. The washed roots were blotted dry and put in *khaki* bags. The root system was then divided into segments of 15 cm, which were then placed in the scanning trays for analysis.

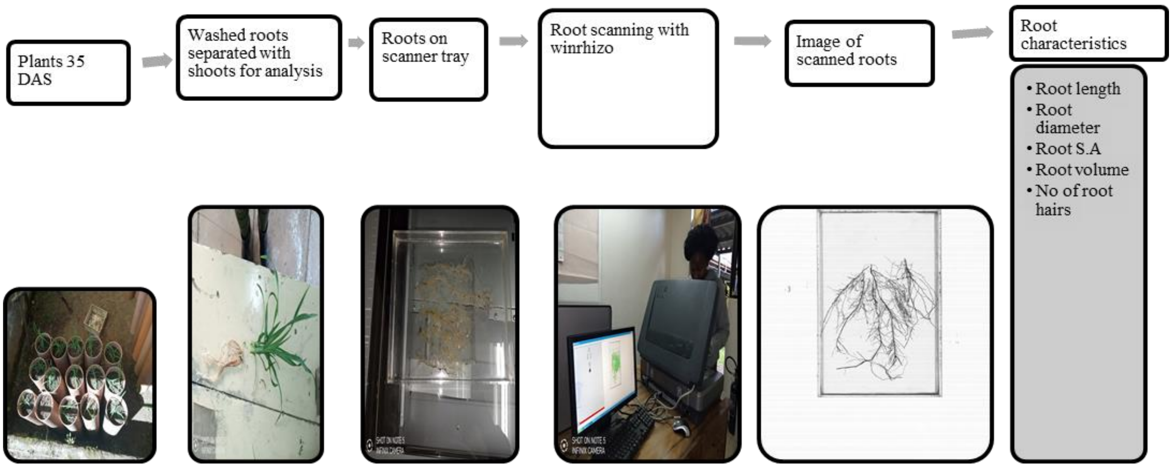


Figure 4.3: Root analysis using *Win*Rhizo^{TM} software.

4.2.4 Data collection

Data on shoot dry weight (SDW) (g) was collected by separating shoots from roots followed by oven drying at 80 ^{0}C for 72 hours and their weights recorded using electrical balance (Ramamoorthy *et al.*, 2017). The SDW was used as an indicator of plant growth vigour. The below ground characteristics namely root biomass, root length (RL) (cm), root length density (RLD), root volume (RV) and total biomass (TB) were studied. The scanned roots were oven dried at 80 ^{0}C for 72 hours and their weights recorded using electrical balance to obtain the root dry weight (RDW) (g). The RDW was used as an indicator for drought tolerance. Root to shoot ratio (R: S) was calculated using root and shoot dry weights which was then calculated as the ratio of roots dry weight to shoot dry weight. Total dry weight (TDW) (g) was calculated by combining the SDW and RDW. Total root length (TRL), root surface area (RSA), primary root length (RL), total root volume (RV), root average diameter (AD), total root tips and total root forks were the major root traits analysed by the *Win*Rhizo^{TM} software. Specific root length (SRL) was determined by dividing the root length over the root dry weight (RDW) in metres per gram (mg^{-1}) (RL/RDW). Root length density (RLD) calculated as RLD (mm^{-3}) = Length of roots (cm)/volume of soil core (cm^3) (Zaman-Allah *et al.*, 2011). The soil volume was calculated using the following mathematical expression.

Soil volume = $\pi r^2 h$ … …………………………………………….…….Equation (1)

Where; $\pi = 3.14$; r = PVC pipe inner radius = 20 cm; h = PVC pipe height = 120 cm.

4.2.5 Statistical analyses

All the data collected were subjected to analysis of variance (ANOVA) using PROC GLM in SAS computer software version 9.4 and the means separated using Tukey's HSD at 5% probability level (P<0.05). The following statistical model was used:

$Y_{ijk} = \mu + g_i + b_j + \varepsilon_{ijk}$ ……………………………….……………...Equation (2)

Where Y_{ijk} denotes the j^{th} block effect on the i^{th} genotype in k^{th} experimental unit; $\mu =$ general mean, $g_i =$ the effect on the i^{th} genotype, $b_j =$ the block effect of the j^{th} block and $\varepsilon_{ijk} =$ the random error.

4.3 Results

4.3.1 Analysis of variance and genotypic performance for root and shoot traits in 25 finger millet lines

The analysis of variance results showed significant (P<0.001) differences among the 25 finger millet lines for root dry weight, root to shoot ratio, total dry weight, rooting length, root surface area, specific root length, root length density, root volume and root tips. The effect due to finger millet lines was also significant (P<0.01) for seedling vigour and shoot dry weight (Table 4.1).

Table 4.1: Mean squares for root and shoot traits among test genotypes evaluated for drought tolerance at Egerton University, Njoro.

Source of variation	**Df**	**SV**	**RDW(g)**	**SDW(g)**	**RSR**	**TDW(g)**	**RL (cm)**	**RSA**	**SRL (cmg^{-1})**	**RLD (cmcm^{-3})**	**RV (cm^{3})**	**Tips**
Replicate	2	0.36	0.037	1.76	0.0207	2.91	1492530	74940	2083876	0.0005	0.0002	124187
Genotype	24	0.308^{**}	0.0001^{***}	0.002^{**}	0.058^{***}	0.005^{***}	4572^{***}	320^{***}	1310630^{***}	0.005^{***}	0.2773^{***}	6726^{***}
CV%		16.29	15.27	18.63	8.67	13.73	18.35	18.94	9.2	19.73	19.16	14.06

***, ** Significant at *P*<0.001 and *P*<0.01, respectively, Df- degree of freedom, SV- seedling vigour, RDW- root dry weight (g), SDW- shoot dry weight (g), RSR- root to shoot ratio, TDW- total dry weight (g), RL- rooting length (cm), RSA- root surface area (cm^{2}), SRL- specific root length (cmg^{-1}), RLD-root length density (cmcm^{-3}), RV- root volume (cm^{3}).

The results on genotypic performance of the evaluated finger miller lines on root and shoot traits are presented in Table 4.2. The results demonstrated significant mean variation for seedling vigour among the tested finger millet lines. The highest seedling vigour score was 2.67 (ICFX1420313-3-2-1-1, ICFX1420314-2-1-1-1, KNE 814 × Ex Alupe (P) P7-9-3-2-2, ICFX1420431-1-3-1-2 and ICFX1420342-3-1-2-2) while the lowest was 1.33 (ICFX1420311-3-6-1-2). On the shoot parameters, shoot dry weight and root to shoot ratio was significant for the 25 finger millet genotypes. For the shoot dry weight, the highest weight was observed in ICFX1420312-3-2-1-1 (0.23g) and lowest in EX Alupe (G) × KNE 814 P1-1-2-3-1 (0.118g) while for the root to shoot ratio, the highest ratio was recorded in ICFX1420342-3-1-2-2 (0.854) and lowest in ICFX1420315-2-2-1-2 (0.128).

Root parameters among the finger millets genotypes varied significantly for root dry weight, rooting length, root surface area, specific root length, root length density, root volume and root hairs (tips). Genotype ICFX1420431-1-3-1-2 (0.041g) had the highest root dry weight while ICFX1420315-2-2-1-2 (0.018g) had lowest. Root length varied significantly among the finger millet with the longest root length being observed in P224 (306.43 cm) and lowest in ICFX1420315-2-2-1-2 (116.91 cm). Total dry weight was high in line ICFX1420431-1-3-1-2 **(**0.329 g) and lowest in line ICFX1420448-1-1-1-1 (0.171). Line ICFX1420313-3-2-1-1 and the check P224 had the longest specific rooting length (4734 and 4762 cm respectively) while line ICFX1420312-3-2-1-1 had the shortest 2165 cm. Root length density was highest in line ICFX1420431-1-3-1-2 (0.063) and lowest in line ICFX1420415-3-1-1-2 (0.005). The highest root volume was observed in line ICFX1420431-1-3-1-2 (1.190 cm^3) and lowest in lines ICFX1420313-1-2-3-1, ICFX1420314-6-2-1-1, ICFX1420315-2-2-1-2, KNE 814 X Ex Alupe (P) P8-1-1-1-1 and the check P224. For the number of root hairs (tips) the highest performance was observed in ICFX1420342-3-1-2-2 (257) and lowest in ICFX1420313-1-2-3-1 (50) (Table 4.2).

Table 4.2: Means of 25 finger millet genotypes evaluated for root and shoot traits related to drought tolerance under rain out shelter.

Genotype	**SV**	**RDW (g)**	**SDW (g)**	**RSR**	**TDW (g)**	**RL (cm)**
EX Alupe(G) × KNE 814 P1-1-2-3-1	2.33ab	0.025 cde	0.118 b	0.167 lm	0.191 cde	181.2 bc
EX Alupe (G) X KNE 814 P4-2-1-4-1	2.00 ab	0.025 cde	0.196 ab	0.202 i-m	0.232 a-e	163.7 bc
ICFX 1420311-3-6-1-2	1.33 b	0.029 a-e	0.202 ab	0.232 f-l	0.257 a-e	218.3 abc
ICFX 1420312-3-2-1-1	2.00 ab	0.039 ab	0.235 a	0.282 e-h	0.290 abc	201.7 abc
ICFX 1420313-1-2-3-1	2.00 ab	0.024 cde	0.169 ab	0.188 klm	0.212 b-e	168.5 bc
ICFX 1420313-3-2-1-1	2.67 a	0.026 b-e	0.182 ab	0.232 f-l	0.235 a-e	179.7 bc
ICFX 1420314-2-1-1-1	2.67 a	0.037 abc	0.212 ab	0.296 d-g	0.276 a-d	232.8ab
ICFX 1420314-6-2-1-1	2.00 ab	0.027 a-e	0.186 ab	0.300 def	0.248 a-e	171.4 bc
ICFX 1420315-2-2-1-2	2.33 ab	0.018 e	0.153 ab	0.128 m	0.185 de	116.9 c
ICFX 1420342-3-1-2-2	2.67 a	0.031 a-e	0.143 ab	0.854 a	0.224 b-e	209.3 abc
ICFX 1420396-5-5-1-1	2.33 ab	0.027 b-e	0.150 ab	0.324 cde	0.198 cde	146.6 bc
ICFX 1420414-7-12-1-1	2.00 ab	0.027 b-e	0.162 ab	0.216 h-l	0.204 cde	159.2 bc
ICFX 1420414-7-4-1-1	2.33 ab	0.020 de	0.156 ab	0.157 lm	0.191 cde	144.8 bc
ICFX 1420415-3-1-1-2	2.00 ab	0.031 a-e	0.199 ab	0.269 e-j	0.241 a-e	198.0 abc
ICFX 1420419-3-2-1-1	2.00 ab	0.032 a-d	0.214 ab	0.251 e-k	0.310 ab	176.1 bc
ICFX 1420420-9-6-3-1	2.00 ab	0.027 b-e	0.171 ab	0.202 i-m	0.216 b-e	165.5 bc
ICFX 1420424-2-1-1-1	2.00 ab	0.028 a-e	0.182 ab	0.302 def	0.277 a-d	195.7 bc
ICFX 1420431-1-3-1-2	2.67 a	0.041 a	0.216 ab	0.430 b	0.329 a	237.4 ab
ICFX 1420431-2-5-1-1	2.00 ab	0.033 a-d	0.193 ab	0.362 bcd	0.313 ab	213.4 abc

ICFX 142036-3-3-1-1	2.00 ab	0.030 a-e	0.156 ab	0.272 e-i	0.204 cde	159.6 bc
ICFX 1420437-1-4-1-1	2.00 ab	0.034 a-d	0.208 ab	0.192 j-m	0.227 a-e	194.1 bc
ICFX 1420448-1-1-1-1	2.00 ab	0.025 cde	0.130 ab	0.284 e-h	0.171 e	228.1 ab
KNE 814 × Ex Alupe (P) P7-9-3-2-2	2.67 a	0.027 a-e	0.165 ab	0.262 e-k	0.211 b-e	153.3 bc
KNE 814 X Ex Alupe (P) P8-1-1-1-1	2.00 ab	0.030 a-e	0.173 ab	0.391 bc	0.240 a-e	162.9 bc
P224- check	2.00 ab	0.024 cde	0.184 ab	0.219 g-l	0.287 a-d	306.4 a
LSD	1.114	0.013	0.105	0.077	0.103	108.91
CV (%)	16.29	15.27	18.62	8.67	13.73	18.35

Means followed by the same letter within the same column are not significantly different.

SV- seedling vigour, RDW- root dry weight (g), SDW- shoot dry weight (g), RSR- root to shoot ratio, TDW- total dry weight (g), RL- rooting length (cm), LSD – Least significance difference and CV – Coefficient of variation.

Table 4.2 Continued….

Genotype	**RSA (cm^2)**	**SRL (cm)**	**RLD ($cmcm^{-3}$)**	**RV (cm^3)**	**Tips**
EX Alupe(G) × KNE 814 P1-1-2-3-1	48.9 a-d	3348 b-g	0.020 e-j	0.220 g-j	83.0 d-h
EX Alupe (G) X KNE 814 P4-2-1-4-1	47.8 a-d	3085 c-i	0.033 cde	0.462 c-f	56.3 gh
ICFX 1420311-3-6-1-2	57.8 ab	2483 ghi	0.025 d-i	0.310 e-h	91.7 d-g
ICFX 1420312-3-2-1-1	49.0 a-d	2165 i	0.043 bc	0.236 ghi	120.0 cd
ICFX 1420313-1-2-3-1	41.5 a-d	3498 b-f	0.014 g-j	0.027 k	50.3 h
ICFX 1420313-3-2-1-1	47.5 a-d	4734 a	0.029 c-g	0.032 jk	84.0 d-h
ICFX 1420314-2-1-1-1	49.3 a-d	3259 b-g	0.054 ab	0.820b	135.3 c
ICFX 1420314-6-2-1-1	54.9 abc	2946 c-i	0.039 bcd	0.021 k	61.0 fgh
ICFX 1420315-2-2-1-2	25.6 d	3592 bcd	0.026 d-i	0.016 k	69.7 e-h
ICFX 1420342-3-1-2-2	49.4 a-d	3556 bcd	0.028 c-h	0.395 d-g	257.0 a
ICFX 1420396-5-5-1-1	32.6 bcd	3510 b-e	0.012 hij	0.032 jk	90.0 d-h
ICFX 1420414-7-12-1-1	33.7 bcd	2596 e-i	0.015 g-j	0.175 h-k	62.0 fgh
ICFX 1420414-7-4-1-1	30.0 cd	3865 abc	0.023 d-i	0.476 cde	83.0 d-h
ICFX 1420415-3-1-1-2	45.5 a-d	2702 d-i	0.005 j	0.635 bc	209.3 b
ICFX 1420419-3-2-1-1	45.4 a-d	2872 d-i	0.031 c-f	0.276 fgh	73.7 e-h
ICFX 1420420-9-6-3-1	37.2 bcd	3128 c-h	0.011 ij	0.452 c-f	71.3 e-h
ICFX 1420424-2-1-1-1	54.5 abc	2837 d-i	0.027 d-i	0.279 fgh	63.0 fgh
ICFX 1420431-1-3-1-2	56.9 ab	4151 ab	0.063 a	1.190 a	108.3 cde

ICFX 1420431-2-5-1-1	57.6 ab	3412 b-g	0.028 c-h	0.794 b	84.3 d-h
ICFX 142036-3-3-1-1	33.1 bcd	3239 b-h	0.016 f-j	0.064 ijk	98.3 c-f
ICFX 1420437-1-4-1-1	42.0 a-d	2302 hi	0.015 g-j	0.550 cd	82.0 d-h
ICFX 1420448-1-1-1-1	37.6 bcd	3442 b-f	0.014 g-j	0.191 h-k	59.0 fgh
KNE 814 × Ex Alupe (P) P7-9-3-2-2	34.7 bcd	3528 b-e	0.015 g-j	0.130 h-k	64.7 fgh
KNE 814 X Ex Alupe (P) P8-1-1-1-1	39.9 bcd	2557 f-i	0.034 cde	0.023 k	70.0 e-h
P224- check	68.3 a	4762 a	0.033 cde	0.025 k	79.0 d-h
LSD	26.89	951.52	0.016	0.19	41.073
CV (%)	18.94	9.2	19.73	19.16	14.06

Means followed by the same letter within the same column are not significantly different.

RSA- root surface area (cm^2), SRL- specific rooting length (cmg^{-1}), RLD-root length density ($cmcm^{-3}$), RV-root volume (cm^3), LSD – Least significance difference and CV – Coefficient of variation.

4.3.2 Correlation analysis of studied morphological and root traits

Positive correlation ($P<0.001$) between root dry weight (RDW) and shoot dry weight (SDW), rooting length (RL) and root surface area (RSA) were observed (Table 4.4). Significant positive correlation was also detected between SDW and total dry weight (TDW), RL and RSA at $P<0.001$. SDW exhibited significant positive correlation with TDW, RL and RSA at $P<0.001$. There was a significant ($P<0.001$) positive correlation between TDW and RL and RSA. Significant ($P<0.001$) positive correlation was observed between RL and RSA (Table 4.3).

Table 4.3: Correlation coefficients among the morphological and root traits studied.

Variables	**RDW**	**SDW**	**RSR**	**TDW**	**RL**	**RSA**
SV	-01762	-0.1920	0.1597	-01915	-0.2017	-0.1985
RDW		0.9836^{***}	0.0450	0.9862^{***}	0.9712^{***}	0.9666^{***}
SDW			-0.0245	0.9927^{***}	0.97143^{***}	0.9691^{***}
RSR				0.0104	0.0563	0.0412
TDW					0.9796^{***}	0.9793^{***}
RL						0.9886^{***}

***significant at $P<0.001$, SV- seedling vigour, RDW- root dry weight (g), SDW- shoot dry weight (g), RSR- root to shoot ratio, TDW- total dry weight (g), RL- rooting length (cm), RSA- root surface area (cm^2).

Significant positive correlation was observed between SRL and forks at $P<0.05$ significance level and number of crosses at 0.001 significance level, respectively (Table 4.4). A negative and significant correlation was observed between SRL and average root diameter at 0.001 significance level. Root length density (RLD) showed significant ($P<0.01$) positive correlation with root volume (RV). The number of root hairs (tips) showed a significant positive correlation with forks at $P<0.05$ and average diameter at $P<0.01$.

Table 4.4: Relationship among the root traits studied.

Variables	**RLD**	**RV**	**Tips**	**Forks**	**AD**
SRL	0.0115^{ns}	-0.1062^{ns}	-0.0942^{ns}	0.2541^{*}	-0.4680^{***}
RLD		0.2992^{**}	0.1334^{ns}	0.2003^{ns}	0.2242^{ns}
RV			0.0283^{ns}	0.0122^{ns}	0.0699^{ns}
TIPS				0.2856*	0.3217^{**}
Forks					0.1262^{ns}

*, **, ******, ** Significant at *P*<0.001 and *P*<0.01, respectively, RLD- root length density, SRL- specific rooting length (cm), RV- root volume (cm^3), AD- average root diameter (cm), Tips- number of root hairs.

4.4 Discussion

This study revealed that finger millet genotypes differ in root-shoot physical characteristics which have been directly associated with drought tolerance. Understanding of the role of these key root traits paly towards drought tolerance and yield accumulation among the finger millet genotypes can provide useful information for formulation of breeding strategies towards improving cultivars that are less tolerant to moisture deficits. The root systems of crops are essential in the uptake of water and nutrients from the soil and improved root systems is critical for enhanced climate resilience among cultivated crops. Root length and root density are considered essential root architectural features that directly affect water and nutrients acquisition in the soil strata (Lynch & Wojciechowski, 2015). Root length can be used to predict root response to changes in the growing environment. The ratio of length to mass is an important indicator of fine root morphology and is a good parameter to use in relation to root absorption of water and nutrients. Root initiation, growth and development can be attributed to genetic make-up of the crop and the prevailing environmental conditions, which translates to a complex quantitative system. In this study, significant effects observed among the genotypes for all the root traits studies revealed the genotypic variation among the genotypes. The observed differences among the finger millets lines can be linked to the response of the plants to acclimatize with the prevailing moisture deficit conditions. Similar findings have earlier been reported by Gupta *et al.* (2015) and Mude *et al.* (2020) where significant influence in root and shoot growth under water deficit conditions in finger millet were observed.

Root length values ranged from 306.43 cm (P224) to 116.91 cm (ICFX1420315-2-2-1-2). Finger millet lines with increased root length were identified since a long root enables the plant to reach deeper, more humid layers of soil, for example during drought. Increase in root length allows for efficient water uptake for better plant growth and development (Awad *et al.,* 2018). Increased root length and density have been reported to be key factors in conferring adaptation towards moisture deficits in crops (Zhang *et al.,* 2021) Deeper roots can extract more water from depth thus avoiding water deficits at critical growth stages (Atta *et al*., 2013). The response of root growth to water deprivation usually includes growth enhancement of first- and second-order roots and inhibition of lateral roots growth. When water scarcity is severe, a drought avoidance programme is implemented to direct root growth and branching into resource-rich regions (Singhvi *et al*., 2019). Root length is affected by growth angle that determines the direction of horizontal and vertical distribution of roots in the soil. In a study by, Singh *et al*. (2011) positive correlation was reported between rooting depth and root angle. Wider root angles could reduce the energy inputs to penetrate in deeper soil profile for water access on moisture-deprived soils (Meister *et al*., 2014).

Root diameter is considered crucial for water uptake. Smaller root diameters may be beneficial to plants under drought because plants with smaller root diameters may have faster root growth and translocation of assimilates (Comas *et al.,* 2013). Smaller root diameters may also benefit plants under drought by increasing the surface to volume ratios of roots (Comas *et al.,* 2013). For instance, in water-deficit soils, deep and thick root systems with smaller root diameters allow for efficient water uptake as compared with thick and shallow roots (Yamuachi *et al*., 2021; Zhan *et al*., 2015). In a related study, Pederson *et al*. (2021) indicated that smaller root diameters may be less prone to lose water from the root surface, and thus it may contribute to drought adaptation.

The number of root hairs had a significant and positive correlation with average root diameter. Root hairs enhance the root surface area and may mediate higher penetrability on soil profile. Distribution of root hairs in time and space regulates water and nutrient acquisition by positioning root-foraging activity in specific soil horizon (Zhan *et al*., 2015). The frequency, abundance and length of root hairs has been considered important for drought tolerance as it determines the balance between the capture of mobile and immobile resources (Burton *et al.,* 2013). Mobile resources, like N and water, are captured more efficiently by fewer but longer laterals capable of exploring larger volumes of soil with greater spatial dispersion among roots. However, larger and the greater number of root hairs creates overlapping resource depletion around roots zones thereby decreasing resource capture efficiency. In addition, increased root hairs places root closer together, which may increase competition for water among roots reducing the uptake efficiency.

Aboveground biomass is an important indicator for productivity under drought stress. In this study, shoot dry weight recorded positive and significant effects on rooting length and root surface area. Root dry weight, shoot dry weight and total dry weight also exhibited a positive significant relationship at $P<0.001$. Root and shoot development are shown to be interdependent and shoot growth supplies the roots with carbon and photosynthates, in return root growth supplies the shoot with water and nutrients. When fewer roots are initiated, the fewer carbon and other resources that need to be invested in root growth and maintenance, which could save photosynthate and improve the growth of shoots. Similar results were reported by Bean *et al.* (2021) who found out that, shoot biomass production had a positive correlation with total root length.

The results from this study indicate a practical implication, since in rain fed or water stress environments, the topsoil dries before the subsoil and, as drought stress progress, roots exploit deeper soil horizons to capture water and nutrients (Yamuachi *et al*., 2021; Zhan *et al*., 2015). Therefore, finger millet lines with deep root systems would have the capacity to capture water from deep soil profile to acclimatize with the prevailing water stress conditions.

4.5 Conclusion

The results reported in this study demonstrated that root traits were critical in the identification of drought tolerant genotypes due to their association with agronomic performance of finger millet genotypes under random drought conditions. The key traits linked to water stress tolerance were specific root length, root length density (RLD), root hairs and root to shoot ratio. Therefore, these traits can be deployed for development of drought tolerant finger millet lines in breeding programmes aimed at enhancing drought tolerance and yield for marginal production environments. Based on the results of this study, three lines, ICFX1420314-2-1-1-1, ICFX1420431-1-3-1-2 and ICFX1420312-3-2-1-1 were identified to be having the identified shoot-root characteristics associated with drought tolerance.

CHAPTER FIVE

DETERMINATION OF MORPHO-PHYSIOLOGICAL CHARACTERISTICS FOR WATER USE EFFICIENCY IN FINGER MILLET (*Eleusine coracana* L.) LINES UNDER VARYING MOISTURE REGIMES

Abstract

Finger millet (*Eluisine coracana* L.) is largely grown in low rainfall areas in eastern Africa. Water deficit experienced under such growing conditions influences the crop's physiological and morphological traits thus greatly affecting grain yield. The objective of this study was to determine the morpho-physiological features for water use efficiency of finger millet under varying moisture regimes. Nine finger millet lines alongside one check were planted in a split plot design arranged in randomized complete block design with three water levels as the main plot and finger millet lines as the sub-plot. The finger millet lines were evaluated for physiological and morphological parameters. Results revealed that effects due to water level were significant for number of fingers and root surface area ($P \leq 0.05$), yield ($P \leq 0.01$), shoot dry weight, root length, root volume and specific root length ($P \leq 0.001$). The finger millet lines were significant ($P \leq 0.001$) for all the physiological and morphological parameters measured. Water use efficiency (WUE) was not significant for finger millet lines planted in the three water levels of 75%, 50% and 25% near field capacity (FC) with an average of 39 kg ha^{-1} mm^{-1}. The results showed that water use efficiency was negatively correlated with number of fingers (r = -0.99*) and root volume (r = -0.99**) but positively correlated to specific root length (r = -0.99*). Regression analysis indicated that biomass was observed to contribute to WUE accounting for 14.79%, 13% and 33.8% at L1 (75% FC), L2 (50% FC) and L3 (25% FC), respectively. Based on these results, increased root growth, shoot dry weight, root dry weight and high root length density were the identified parameters for water use efficiency. These traits could be used for indirect selection for drought tolerance, particularly in the early stages of drought tolerance breeding thus lowering the cost of multi-location field evaluation in breeding programs.

5.1. Introduction

Finger millet (*Eluisine coracana* L.) is a C_4 grass that is well adapted to semi-arid areas. Water use efficiency (WUE) is an important attribute in plants that describes how the plants use available water for carbon fixation (Farooq *et al*., 2019). According to Blum (2009), under moisture stress conditions improvement in WUE leads to increased yield, as the crops with higher WUE have higher transpiration rates and water use resulting in higher CO_2 assimilation. Although factors such as soil type and climate variability affect crop performance under drought, crop type and land management practices had significant effects on crop WUE (Mbava *et al*., 2020). A number of crop management schemes are known to increase water availability and promote greater WUE. However, there are useful combinations of management practices that may fit particular agro-ecological regions (Chiroma *et al.,* 2008).

Water use efficiency is the ability of the crop to produce biomass per unit of water transpired and one of the criteria used to evaluate drought tolerance in plants (Ibrahim *et al*., 1986; Jaleel *et al*., 2008). WUE can be improved using soil management, crop husbandry, water management and crop competition management (Farooq *et al*., 2019). Pikul and Aase (1995) reported that minimum tillage exhibited a trend towards improving WUE because of improved soil water availability through reduced evapotranspiration. Soil management practices increase soil water holding capacity; improve the ability of roots to extract more water which improves WUE leading to increase in crop yield (Hatfield *et al*., 2001). Floral initiation and grain filling are the most sensitive growth stage of water stress as it can result in over 60% yield loss (Hattendorf *et al*., 1988; Tadele, 2016). In a study of two landraces of finger millet, drought stress imposed four weeks after sowing resulted in 100% yield loss and 30% biomass damage (Maqsood *et al*., 2007). Results from a study on pearl millet (*Pennisetum americanum* L.) revealed that when water stress occurs from one month before flowering initiation to full flowering could result in 7% yield loss. A higher WUE and conserving water at vegetative stage due to lower leaf conductance and smaller leaf canopy can lead to availability of water at reproductive and grain filling growth stages, which has been positively correlated with increased grain yield (Araújo *et al*., 2015; Zaman-Allah *et al*., 2011).

Finger millet is resilient to extreme climatic and soil conditions that are prevalent in semi-arid regions of Asia and Africa (Tadele, 2016). It is grown under extreme environmental conditions with inadequate moisture and poor soil fertility, which is poorly suited to the major crops (Mason *et al*., 2015). Besides being a drought tolerant crop, finger millet has low photorespiration and consequently utilizes the low moisture in the semi-arid areas (Brutnell *et al*., 2010). A wide range of abiotic stresses including soil moisture, solar radiation, temperature and soil nutrients (Kumar *et al.,* 2014) influences the growth of finger millet and yields. Low plant population densities as well as water stress that in turn reduce radiation and WUE (Payne, 2000) can affect grain and biomass yield. The phenology of finger millet such as flowering and maturity may be affected by climate change and this has an overall impact of earlier occurrence. The earlier occurrence of the phenological phases results in a shorter time for biomass accumulation and low crop yields (Olesen *et al*., 2011).

Climate change increases the risk of drought and reduce agricultural production in arid and semi-arid areas hence, it is important to select drought resilient crops in order to mitigate water shortage (Misra, 2014). Evaluation for drought tolerance using root characteristics is difficult because of its complex methodology compared with shoot characteristics. Increased WUE, could compromise grain yield due to reduced rate of transpiration and crop water use (Blum, 2009; Sinclair, 2012). The strategic combination of specific root and shoot traits appear to be key for improved drought tolerance in finger millet. It is important to evaluate different root and shoot traits in the same group of genotypes under drought stress as well as under optimal conditions (Polania *et al*., 2017). The approach helps to identify crop characteristics that are important for drought tolerance.

Finger millet is an important crop in developing countries due to its great contribution to food security. However, it has not been sufficiently studied and hence enlisted among the neglected and underutilized crops by the African Orphaned Crops Consortium (AOCC). Finger millet is bound to provide an alternative climate-smart crop since it is capable of adapting to challenging environment better than the major crops of the world. It is therefore important to identify crop management options that optimize WUE without interfering with attainable yield under limited water availability. Therefore, this study aimed at determining the morpho-physiological features responsible for water use efficiency in finger millet under varying moisture regimes.

5.2 Materials and methods

5.2.1 Experimental site

The experiment was carried out at Egerton University agronomy teaching and research field (Field 7) located 0^o 22’ 11.0” S, 35^o 55’ 58.0” E and elevated at 2127 m. a. s. l. The area receives a mean annual rainfall of 1200 mm and the temperatures ranges between 15°C - 21°C. The soils at the experimental site are well drained, sandy loams which are dark brown in colour characterized by a pH of 6 (Jaetzold & Schimdt, 1983; Ondieki *et al.,* 2013).

5.2.2 Genotypes evaluated

Nine top ranking finger millet lines and a check P224 variety were used in evaluation for drought tolerance under varied moisture regimes (Table 5.1). These lines were selected from experiments under chapters 3.0 and 4.0, respectively, based on their superiority for grain yield (>1000 kg ha^{-1}), number of productive tillers (>5 per plant), thousands grain weights (>20 grams) and root length (>50 cm) which were adopted as standard for selection.

Table 5.1: List of advanced finger millet lines evaluated for drought tolerance.

Genotypes	Drought reaction
ICFX1420431-3-3-1	Tolerant
ICFX 1420312-3-2-1-1	Tolerant
ICFX 1420314-2-1-1-1	Tolerant
ICFX 1420314-6-2-1-1	Tolerant
ICFX 1420396-5-5-1-1	Tolerant
ICFX 1420414-7-4-1-1	Tolerant
ICFX 1420415-3-1-1-2	Tolerant
ICFX 1420437-1-4-1-1	Tolerant
KNE 814 X Ex Alupe (P) P8-1-1-1-1	Tolerant
P224- check	Susceptible

5.2.3 Experimental procedure

The experiment was conducted under rain out shelter (ROS) conditions in polyvinyl chloride (PVC) pipes measuring 1.2m long and 20.0 cm in diameter. The pipes were placed in 1.2 m deep cement pits at a spacing of 5 cm. The experiment was laid in a split plot arrangement in randomized complete block design (RCBD) (Gomez & Gomez, 1984) and replicated three times, with water regime as the main plot and the lines as the sub-plot. Four seeds of each line were sown in the PVC cylindrical pipes and each irrigated with 2,000 ml of water to achieve uniform emergence. Adequate watering was done up to 14 days after sowing (DAS) after which water stress treatment was introduced. Three water regimes; L1 - high moisture (75% FC), L2 - medium moisture (50% FC) and L3 - low moisture (25% FC) were imposed. Every five alternate days 1.5, 1.0, and 0.5 litres of water were used to replenish the high, medium and low moisture levels, respectively (Muriuki *et al*., 2019). In this study L1, L2 and L3 were used to refer to water levels of 1.5, 1.0 and 0.5 litres, respectively. This was maintained until 35 DAS (end of vegetative growth). Watering was done until flowering stage, that is75 DAS when the roots were extracted washed gently and analysed using the

WinRhizo^{TM} software. Soil moisture content was measured using gravimetric method every 30 days.

Roots were extracted from the PVC pipes by gently washing out the soil particles and other debris at physiological maturity from the lower end of pipe. When approximately three quarters of the soil-sand mixture was washed away, the cylinders were erected gently on a 2 mm sieve so that the entire root system could be removed. The extracted root system was mostly in one piece with very few small segments of detached roots trapped by the 5mm sieve. The root bounds were rinsed free of medium under running water. The washed roots were blotted dry and put in khaki bags. The root system was then divided into segments of 15 cm, which were placed in the scanning trays for analysis (Figure 4.1).

5.2.4 Data collection

Data was collected on stomatal conductance and instantaneous transpiration, which was measured on the uppermost fully expanded leaves using the Infrared Gas Analyser (IRGA) at 21, 28 and 35 DAS. Data on the days to 50% flowering were calculated from the difference between sowing date and date when the ears had emerged from 50% of main tillers. Soil moisture content was determined using the gravimetric method (where the soil samples were oven dried at 80 ^{0}C for 72 hours and their weights recorded using electrical balance) every 30 days and thereafter- percent soil moisture calculated using the formula described by DeAngelis, (2007).

% soil moisture= $\frac{weight\ of\ wet\ soil\ (g)-\ weight\ of\ dry\ soil\ (g)}{weight\ of\ dry\ soil\ (g)} \times 100$…………………Equation (1)

Data on shoot dry weight (SDW) in grams was collected by separating shoots from roots followed by oven drying at 80 °C for 72 hours and their weights recorded using electrical balance (Ramamoorthy *et al.*, 2017). The SDW was used as an indicator of plant growth vigour. The root characteristics included root biomass; root length (RL), root length density (RLD), root volume (RV) and total biomass (TB) were also recorded. The scanned roots were oven dried at 80 ^{0}C for 72 hours and their weights recorded using electrical balance to obtain the root dry weight (RDW) in grams. Root to shoot ratio (R: S) was calculated using root and shoot dry weights which was then calculated as the ratio of roots dry weight to shoot dry weight. Total dry weight (TDW) (g) was calculated by combining the SDW and RDW. Total root length (TRL), total surface area (TSA), primary root length (RL), total root volume (RV), root average diameter (AD), total root tips, total root forks and total root crossings were the major root traits analysed by the *Win*Rhizo^{TM} software.

Specific root length (SRL) was determined using the following formula and was expressed in centimetres per gram (cmg^{-1}).

$$\mathrm{SRL} = \frac{Root\ length}{Root\ dry\ weight}$$ …………………………………………………… Equation 2

Root length density (RLD) was calculated using the following formula as described by Zaman-Allah *et al*. (2011) and was presented in cmcm $^{-3}$.

$$\mathrm{RLD} = \frac{Length\ of\ roots\ (cm)}{volume\ of\ soil\ core\ (\mathrm{cm3})}$$ …………………………………………...Equation 3

The soil volume was calculated using the following mathematical expression:

Soil volume = πr^2 h ……………………………………….…………...Equation 4

Where; $\pi = 3.14$; r = PVC pipe inner radius = 0.20 m; h = PVC pipe height = 1.20 m.

Net leaf CO_2 exchange rates (CER) were measured on selected leaves using a portable Infrared Gas Analyser, fitted with Parkinson Leaf chamber. Biomass WUE was determined by measuring the ratio of amount of water applied from sowing to physiological maturity and the total shoot biomass harvested and expressed in $\mathrm{kg\,ha^{-1}mm^{-1}}$. It was then calculated using the formula given by Briggs and Shantz (1913);

$$\mathrm{WUE_{biomass}} = \frac{\text{Total biomass or yield}}{\sum \text{Evapotranspiration}}$$ ……………………………………………Equation 5

5.2.5 Statistical data analyses

All the data collected were subjected to analysis of variance (ANOVA) using *PROC GLM* in Statistical Analysis System (SAS) version 9.4 using the following statistical model.

$$Y_{ijk} = \mu + R_i + W_j + RW_{ij} + G_k + WG_{jk} + \varepsilon_{ijk}$$ ………………………Equation 6

Where Y_{ijk} = denoted the observation of the i^{th} replicate, j^{th} level of main - plot factor and k^{th} level of the sub- plot factor, μ = overall mean, R_i =Effect due to i^{th} replicate, W_j= Effect due to j^{th} main-plot factor water levels, RW_{ij} = Effect due to interaction between i^{th} replicate and j^{th} water levels; G_k = Effect due to k^{th} sub-plot factor genotypes; WG_{jk} = Effect due to interaction between j^{th} water levels and k^{th} genotypes; ε_{ijk}= random error.

Mean comparisons was done using least significant difference (LSD) at 5% probability to separate the different finger millet lines using the following formula described by Gomez & Gomez (1984) as shown below.

$$LSD = t\alpha/_2\sqrt{\frac{2MSE}{r}}$$ ……………………………………………………Equation (7)

Where, t= critical value from the t-distribution table, MSE = mean square error and r is the number of replicates.

Pearson's correlation coefficient analysis was used to assess the associations among the physiological and morphological parameters using the following formula by Cohen *et al.* (2014) as shown below.

$$r = \frac{n(\sum xy)-(\sum x)(\sum y)}{\sqrt{[n\sum x^2-(\sum x)^2)(n\sum y^2-(\sum y)^2]}} \text{ .... Equation (8)}$$

Where; r = Pearson's correlation coefficient, n = the number of samples, x = the independent variable and y is the dependent variable.

Linear regression was conducted using SAS *PROC REG* to determine relationship between WUE and biomass using the following equation.

$Y_i = \beta_0 + \beta_1 X_{1(i)} + \varepsilon_i$.. (Equation 9)

Where Y_i = response variable corresponding to X_i; β_0 = is the y intercept; β_i= is the slope of the regression line; ε_i= random error component.

5.3 Results

5.3.1 Analysis of variance for physiological and morphological parameters

Watering regimes affected root and shoot biomass production. The analysis of variance revealed significant effects for main plot (water level) for number of fingers and surface area at $P \leq 0.05$, grain yield at $P \leq 0.01$, and shoot dry weight, root length, root volume and specific root length at $P \leq 0.001$ (Table 5.2). The sub-plots (genotype) effects were significant ($P \leq 0.001$) for shoot dry weight, root dry weight, number of fingers, number of tillers, plant height, root length, total root length, surface area, average root diameter, root length density, root hairs (tips), forks, root volume, specific root length, yield, evapotranspiration, net leaf CO_2 exchange rates and water use efficiency. Two-way interaction between the main plot (water level) and sub-plot (genotype) showed no significant effects for all the traits studied (Table 5.2).

Table 5.2: Means squares for three water levels and ten finger millet genotypes for the physiological, morphological traits and yield.

Source of variation	**Df**	**SDW**	**RDW**	**NF**	**NT**	**PHT**	**Moisture**	**RL**	**TRL**
		g				**cm**	**%**	**cm**	
Replication	2	105.26	36.20	5.05	3.08	3328.55	2.44	312807.23	16313.14
Water levels	2	15.14***	0.16^{ns}	1.00*	0.48^{ns}	3.89^{ns}	0.30^{ns}	7950.53***	2079.24^{ns}
Replication × Water level	4	1.79	0.01	0.11	0.59	6.97	0.55	47.77	510.83
Genotype	9	25.38***	0.84***	1.62***	5.82***	240.90***	3.46^{ns}	152476.58***	21099.77***
Water level × genotype	18	0.61^{ns}	0.04^{ns}	0.10^{ns}	0.33^{ns}	13.71^{ns}	10.97^{ns}	53.50^{ns}	387.51^{ns}
Error	54	1.58	0.12	0.25	0.47	38.76	3.98	55.00	1166.90
CV (%)		5.36	7.62	9.38	18.62	15.87	6.47	0.60	1.31
R^2		0.85	0.93	0.68	0.73	0.82	0.52	0.99	0.79

*, ** and *** significant at $P \leq 0.05$, 0.01 and 0.001, respectively; ns - not significant; CV - Coefficient of variation; SDW - shoot dry weight (g); RDW - root dry weight (g); NF - number of fingers; NT - number of tillers; PHT - plant height (cm); RL - root length (cm); TRL - total rooting length (cm).

Table 5.2: continued…

Source of variation	Df	RSA	AVD	CER	RLD	RV (cm^3)	Tips
		cm^2	cm		(cmcm^{-3})		
Replication	2	11892.26	0.00008	1543.01	2.91	23.04	144180.01
Water levels	2	4117.54*	0.00044	232.41	4.14	18.91***	9190.01
Replication × Water level	4	219.36	0.00024	42.60	1.59	0.79	3981.56
Genotype	9	38480.12***	0.00068***	20687.24***	1.89***	56.86***	289599.03***
Water level × genotype	18	499.55	0.00014	73.03	1.33	0.59	1454.55
Error	54	911.20	0.00022	145.80	3.73	0.35	3553.69
CV (%)		7.95	14.84	3.06	15.54	6.18	3.03
R^2		0.89	0.47	0.96	0.57	0.97	0.94

*, ** and *** significant at $P \leq 0.05$, 0.01 and 0.001, respectively; CV - Coefficient of variation; RSA - Surface area (cm^2); AVD - Average diameter (cm); CER - Net leaf CO_2 exchange rates, RLD - Root length density (cmcm^{-3}); RV - Root volume (cm^3); Tips - number of root hairs.

Table 5.2: continued…

Source of variation	**Df**	**SRL (cmg^{-1})**	**Yield**	**ET**	**WUE**
			kg ha^{-1}		**kg ha^{-1}mm^{-1}**
Replication	2	60270.74	24408.50	6.04	6.16
Water levels	2	1019.74***	4214.17**	1.93	0.42
Replication × Water level	4	3.11	138.27	0.12	0.94
Genotype	9	1997.66***	313087.36***	180.47***	12.56***
Water level × genotype	18	3.56	471.58	0.35	0.59
Error	54	2.54	858.58	3.98	3.83
CV (%)		0.66	3.02	8.04	4.99
R^2		0.99	0.98	0.89	0.40

*, ** and *** significant at $P \leq 0.05$, 0.01 and 0.001, respectively; CV - Coefficient of variation; SRL - Specific rooting length (cmg^{-1}); ET - Evapotranspiration (mmol H_2Om^{-2}s^{-1}); WUE - Water use efficiency (kg ha^{-1}mm^{-1}).

5.3.2 Effect of water regimes on physiological and morphological characteristics.

The study showed that the different water levels imposed adverse effect on growth characteristics of the finger millet genotypes studied (Table 5.3). There was no significant effect for water levels 1.5 litres (L1) and 1.0 litres (L2) on shoot dry weight. However, water level of 0.5 litres (L3) showed significant effects on the shoot dry weight. Similarly, there was a significant effect for L2 on number of fingers and plant height. The highest number of fingers 5.52 and plant height of 40.88 cm was recorded in L2 while short plants (37.36 cm) were observed in L1. There was no significant difference for the three water levels on percent moisture content, total rooting length, average diameter, net leaf CO_2 exchange rates, rooting length density and evapotranspiration and water use efficiency. The longest rooting length 1246.96 cm was recorded in L3 while the shortest 1215.03 cm in L1. The highest root surface area and root volume were recorded in L3 (392.94cm^2 and 10.47 cm^3 respectively. The highest number of tips (root hairs) 1982.80 were observed at L1. The finger millet lines accumulated a high biomass (984.09 kg ha^{-1}) at 1.5 litres water level (L1) and the least (960.48 kg ha^{-1}) at water level of 0.5 litres (L3) (Table 5.3).

Table 5.3: Means of ten finger millet genotypes at three water levels for yield and physiological parameters measured.

Water level [a]	**SDW**	**RDW**	**NF**	**NT**	**PHT**	**Moisture**	**RL**	**TRL**	**RSA**	**AVD**	**CER**
	g				**cm**	**%**	**cm**		**cm^2**	**cm**	
Level $_{1.5}$	22.87b	4.47a	5.19b	3.60a	37.36b	30.95a	1215.03c	2602.62a	370.95b	0.10a	396.93a
Level $_{1.0}$	23.28b	4.62a	5.52a	3.63a	40.88a	30.78a	1225.50b	2604.74a	374.92b	0.09a	394.17a
Level $_{0.5}$	24.26a	4.58a	5.22b	3.83a	39.47ab	30.77a	1246.96a	2617.98a	392.94a	0.10a	391.37a
LSD ($_{0.05}$)	0.65	0.17	0.25	0.35	3.22	1.03	3.83	17.68	15.62	0.007	6.25
Mean	23.47	4.55	5.31	3.68	39.24	30.83	1229.16	2608.45	379.60	0.10	394.15

Water levels [a]	**RLD**	**RV**	**Tips**	**SRL**	**Yield**	**ET**	**WUE**
					kg ha^{-1}		**kg ha^{-1} mm^{-1}**
Level $_{1.5}$	0.0012a	9.11b	1982.80a	245.83a	984.09a	25.05a	39.32a
Level $_{1.0}$	0.0012a	9.08b	1970.82ab	245.20a	970.46ab	24.83a	39.14a
Level $_{0.5}$	0.0012a	0.47a	1948.33b	235.43b	960.48b	24.54a	39.09a
LSD$_{(0.05)}$	0.0001	0.30	30.85	0.82	15.16	1.03	1.01a
Mean	0.012	9.55	1967.31	242.15	971.67	24.81	39.18

Table 5.3: Continued…

Means followed by the same letter within the same column are not significantly different.

Water levels [a] - Amount of water in litres; SDW - shoot dry weight (g); RDW - root dry weight(g); NF - number of fingers; NT - number of tillers; PHT - plant height (cm); RL - root length (cm); TRL - total rooting length (cm); RSA - Surface area (cm^2); AVD - average diameter (cm); CER -net leaf CO_2 exchange rates, RLD - root length density ($cmcm^{-3}$); RV - root volume (cm^3); Tips - number of root hairs; SRL - specific rooting length (cmg^{-1}); ET - evapotranspiration (mmol $H_2Om^{-2}s^{-1}$); WUE - water use efficiency (kg ha^{-1} mm^{-1}).

5.3.3 Performance of finger millet lines based on physiological and morphological characteristics

The physiological and morphological characteristics are relevant indicators for assessing the performance of finger millet under water stress. The lines studied varied with respect to the physiological and morphological traits (Table 5.4). Finger millet line ICFX1420312-3-2-1-1 exhibited the highest plant height of 43.54 cm and forks of 10744.7. Line ICFX1420314-2-1-1-1 showed the highest mean values of 4.93 g and 31.78%, respectively with respect to root dry weight and percentage moisture content. Among the evaluated finger millet lines, ICFX1420314-2-1-1-1 and ICFX1420314-6-2-1-1 showed the highest number of tillers (4). Line ICFX1420396-5-5-1-1 exhibited the highest shoot dry weight of 26.98 g while ICFX1420414-7-4-1-1 showed high number of tillers (6.03) and total rooting length of 2672.28 compared to the check P224. Finger millet line ICFX1420437-1-4-1-1 had the highest mean values of 1461.11 cm for root length, 472.33 cm^2 for surface area, 0.0014 cm^2 for root length density, 2255.78 for number of root hairs (tips) and 259.11 cm for the specific rooting length (Table 5.4).

Lines ICFX1420431-3-3-1 and ICFX1420312-3-2-1-1 had high yield (1376.11 kg ha^{-1} & 1133.61 kg ha^{-1}) and high WUE (40.53 & 40.04 kg ha^{-1} mm^{-1}) compared to the check P224 for yield (713.50 kg ha^{-1}) and WUE (39.93 kg ha^{-1} mm^{-1}), respectively (Table 5.4). Yield differed among the finger millet lines with line ICFX1420431-3-3-1-2 exhibiting high biomass, evapotranspiration, net leaf CO_2 exchange rates and water use efficiency of 1376.11 kg ha^{-1}, 34.45, 512.55 and 40.53 kg mm^{-1} ha^{-1}, respectively (Table 5.4 and Figure 5.1). The check variety P224 expressed a high average diameter of 0.12 compared to lines ICFX1420314-2-1-1-1, ICFX1420314-6-2-1-1 and ICFX1420396-5-5-1-1 that exhibited low average diameter of 0.09 (small diameter). Similarly, variety P224, displayed a high root volume of 14.44 cm^3 while ICFX1420314-2-1-1-1 exhibited a low root volume of 6.88 cm^3 (Table 5.4).

Table 5.4: Means of nine genotypes and a check evaluated for physiological parameters at Egerton University, Field 7.

Genotype	**SDW**	**RDW**	**NF**	**NT**	**PHT**	**Moisture**	**RL**	**TRL**	**RSA**	**AVD**
		g			cm	%	cm		cm^2	cm
ICFX 1420312-3-2-1-1	21.33 f	4.69 abc	5.83 ab	3.33 bcd	43.54 a	31.06 ab	1258.78 d	2519.69 g	415.17 b	0.11abc
ICFX 1420437-1-4-1-1	24.12 bc	4.43 cd	4.91 de	3.00 de	30.69 b	31.03 ab	1160.33 g	2622.31 cde	472.33 a	0.10 bc
ICFX 1420414-7-4-1-1	22.74 de	4.52 bcd	6.04 a	3.11 cde	42.09 a	30.70 ab	1242.11 e	2672.28 a	406.70 b	0.10abc
ICFX 1420396-5-5-1-1	23.22 cde	4.82 ab	5.58 bc	3.67 bc	41.91 a	31.33 a	1263.11 d	2597.64 ef	412.92 b	0.09 c
ICFX 1420396-5-5-1-1	26.99 a	4.37 cd	5.24 cd	4.56 a	43.39 a	29.42 b	1322.11 b	2643.93 abc	354.29 c	0.09 c
ICFX 1420314-2-1-1-1	24.79 b	4.93 a	5.56 bc	4.89 a	41.20 a	31.78 a	1461.11 a	2589.22 f	323.33 d	0.09 c
P224[q]	24.01 bc	4.93 a	5.16 cde	3.78 b	38.91 a	30.51 ab	1295.11 c	2632.59 bcd	468.68 a	0.11 a
KNE 814 X Ex Alupe (P) P8-1-1-1-1	21.46 f	4.64 abcd	5.22 cd	3.22 bcd	43.02 a	31.08 ab	1219.78 f	2605.63 def	352.56 c	0.09 c
ICFX 1420431-3-3-1-2	22.33 ef	4.34 d	4.73 e	2.56 e	29.35 b	30.69 ab	996.11 i	2543.58 g	295.61 de	0.11 ab
ICFX 1420314-6-2-1-1	23.77 bcd	3.95 e	4.90 de	4.78 a	38.28 a	30.76 ab	1073.11 h	2657.57 ab	294.49 e	0.09 c
LSD$_{(0.05)}$	1.19	0.31	0.46	0.65	5.7	1.88	7.00	32.28	28.52	0.014

Means followed by the same letter within the same column are not significantly different.

[q] - check (P224); SDW - shoot dry weight; RDW - root dry weight; NF - number of fingers; NT - number of tillers; PHT - plant height; RL - root length; TRL - total rooting length; RSA - root surface area; AVD - average diameter.

Table 5.4: Continued…

Genotype	**RLD**	**RV**	**Tips**	**SRL**	**Yield**	**ET**	**COA**	**WUE**
	($cmcm^{-3}$)	**(cm^3)**		**(cmg^{-1})**	**kg ha^{-1}**			**kg ha^{-1} mm^{-1}**
ICFX 1420312-3-2-1-1	0.001 ab	11.00 c	2077.89 b	255.33 c	1133.61 b	28.31 b	439.78 b	40.04 a
ICFX 1420437-1-4-1-1	0.001 a	11.87 b	2255.78 a	259.11 a	862.49 h	23.03 e	364.11 fg	37.45 cd
ICFX 1420414-7-4-1-1	0.001 ab	9.54 d	1938.11 cd	257.33 b	921.61 f	24.33 de	376.22 de	37.87 bcd
ICFX 1420415-3-1-1-2	0.001 ab	9.40 d	2061.11 b	241.67 e	892.22 g	23.89 de	371.89 ef	37.36 d
ICFX 1420396-5-5-1-1	0.001 ab	8.33 e	2063.33 b	237.00 f	963.62 e	24.58 cde	380.44 de	39.21 abc
ICFX 1420314-2-1-1-1	0.001 bc	6.89 f	1906.89 de	231.33 g	1050.71 c	26.17 c	393.89 c	40.14 a
P224[q]	0.001 cd	14.44 a	1958.22 cd	243.11 e	713.59 j	17.85 g	356.89 g	39.93 a
KNE 814 X Ex Alupe (P) P8-1-1-1-1	0.001 bcd	8.79 e	1988.56 c	231.11 g	802.01 i	20.30 f	359.00 g	39.65 ab
ICFX 1420311-3-6-1-2	0.001 d	9.78 d	1569.58 f	253.56 d	1376.11 a	34.46 a	512.56 a	40.53 a
ICFX 1420314-6-2-1-1	0.001 cd	5.52 g	1853.67 e	212.00 h	1000.81 d	25.21 cd	386.78 cd	39.69 a
LSD$_{(0.05)}$	0.0002	0.55	56.34	1.51	27.69	1.88	11.41	1.85

Means followed by the same letter within the same column are not significantly different.

[q] - check (P224); COA - net leaf CO_2 assimilation rates; RLD - root length density ($cmcm^{-3}$); RV - root volume (cm^3); Tips - number of root hairs; SRL - specific rooting length (cmg^{-1}); ET - evapotranspiration (mmol $H_2Om^{-2}s^{-1}$); WUE - water use efficiency (kg ha^{-1} mm^{-1}).

The performance of the finger millet lines based on yield and water use efficiency varied significantly (Figure 5.1). Lines ICFX1420311-3-6-1-2 and the check P224 had the highest water use efficiencies of above 39 kg ha $^{-1}$ mm^{-1}.

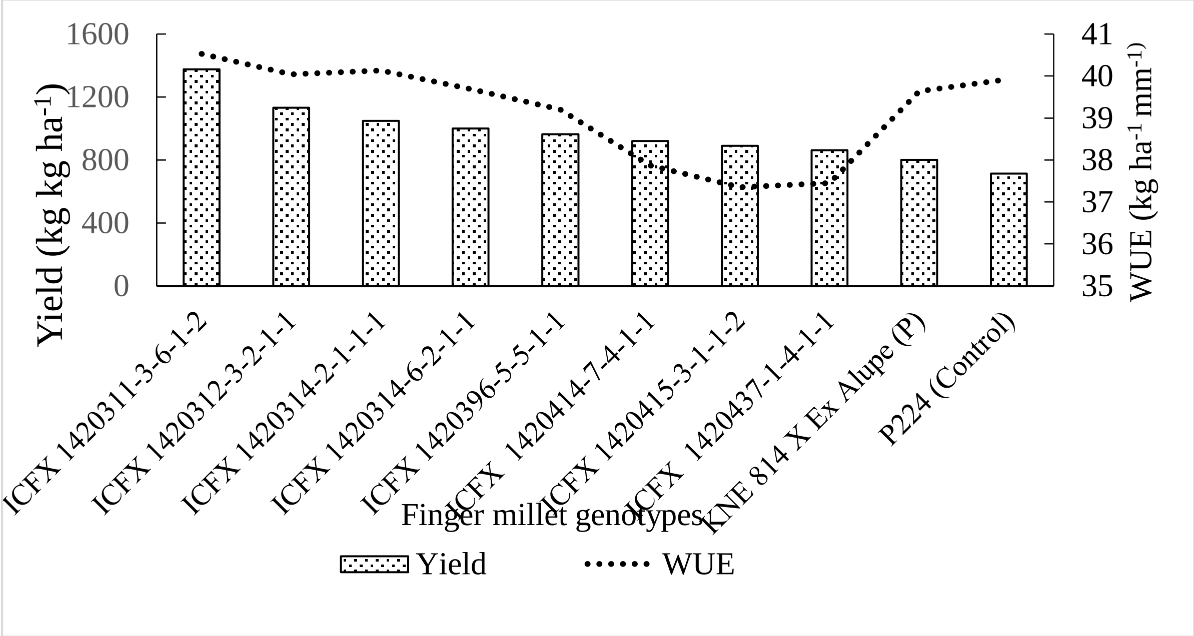


Figure 5.1: Biomass (yield) and WUE of ten lines evaluated at Egerton University, Njoro Kenya.

5.4.5 Correlation and regression analysis for physiological parameters

There was a significant (*r* = 0.99*) positive correlation between number of tillers and number of fingers (Table 5.5). A significant (*r* = 0.99*) positive correlation was observed between root length and shoot dry weight. Similarly, a significant positive correlation between total rooting length and number of fingers (*r* = 0.99*) and number of tillers (*r* = 0.99**) was observed. Significant (*r* = 0.99*) positive correlation was observed between surface area and number of tillers and total rooting length. In contrast, net leaf CO_2 exchange rates was negatively correlated with moisture (*r* = -0.99*). Similarly, number of root hairs was negatively correlated with shoot dry weight (-0.99*) and root length (r = -0.99**). Significant positive correlation was observed between crossing and root dry weight (*r* = 0.99***). However, there was a negative significant correlation between specific rooting length and number of fingers (*r* = 0.99**), number of tillers (*r* = -0.99*), total rooting length (*r* = -0.99*) and root volume (*r* = -0.99*). Yield showed a negative correlation with plant height (*r* = -0.99*). Evapotranspiration was negatively correlated with shoot dry weight (*r* = -0.997*) and surface area (*r* = -0.99*). The water use efficiency was negatively correlated with number of fingers (*r* = -0.99*) and root volume (*r* = -0.99**), however, it was positively correlated to specific root length (*r* = 0.99*) (Table 5.5)

	SDW	RDW	NF	NT	PHT	Moisture	RL	TRL	RSA	AVD	CER	RV	Tips	SRL	Yield	ET
SDW																
RDW	0.88															
NF	0.98	0.76														
NT	0.99	0.79	0.99*													
PHT	0.94	0.98	0.85	0.87												
Moisture	-0.76	-0.97	-0.60	-0.63	-0.93											
RL	0.99*	0.89	0.97	0.97	0.95	-0.78										
TRL	0.98	0.79	0.99*	0.99**	0.87	-0.64	0.98									
RSA	0.99	0.81	0.99	0.99*	0.89	-0.67	0.98	0.99*								
AVD	0.23	-0.26	0.42	0.39	-0.11	0.45	0.19	0.38	0.34							
CER	0.70	0.95	0.54	0.57	0.90	-0.99*	0.73	0.58	0.61	-0.52						
RV	0.95	0.69	0.99	0.99	0.79	-0.52	0.94	0.98	0.98	0.51	0.46					
Tips	-0.99*	-0.90	-0.96	-0.97	-0.95	0.79	-0.99**	-0.97	-0.98	-0.17	-0.74	-0.93				
SRL	-0.97	-0.74	-0.99**	-0.99*	-0.83	0.58	-0.96	-0.99*	-0.99	-0.45	-0.52	-0.99*	0.95			
Yield	-0.94	-0.98	-0.86	-0.88	-0.99*	0.92	-0.95	-0.88	-0.90	0.08	-0.89	-0.80	0.96	0.84		
ET	-0.997*	-0.84	-0.98	-0.99	-0.91	0.71	-0.99	-0.99	-0.99*	-0.29	-0.66	-0.96	0.99	0.98	0.92	
WUE	-0.95	-0.70	-0.99*	-0.99	-0.80	0.54	-0.94	-0.99	-0.98	-0.49	-0.48	-0.99**	0.94	0.99*	0.82	0.97

Table 5.5: Pearson's correlation coefficients for physiological parameters and yield.*, ** and *** significant at $P \leq 0.05$, 0.01 and 0.001, respectively; SDW - shoot dry weight; RDW - root dry weight; NF - number of fingers; NT-number of tillers; PHT - plant height (cm); RL - root length (cm); TRL - total rooting length (cm); RSA - Surface area (cm^2); AVD - Average diameter (cm); CER - Net leaf CO_2 exchange rates; RV - Root volume (cm^3); Tips - number of root hairs; SRL - Specific rooting length (cmg^{-1}); ET - evapotranspiration (mmol $H_2Om^{-2}s^{-1}$); WUE - Water use efficiency (kg ha^{-1} mm^{-1}); Yield - (kg ha^{-1}).

The regression analysis show that a unit increase in yield resulted from increased WUE with $R^2 = 0.148$, $R^2 = 0.130$, $R^2 = 0.338$ for L1 (75% FC), L2 (50% FC) and L3 (25% FC) respectively. Among the three water levels, L3 had a slightly more WUE compared to both L1 and L2 (Figure 5.2).

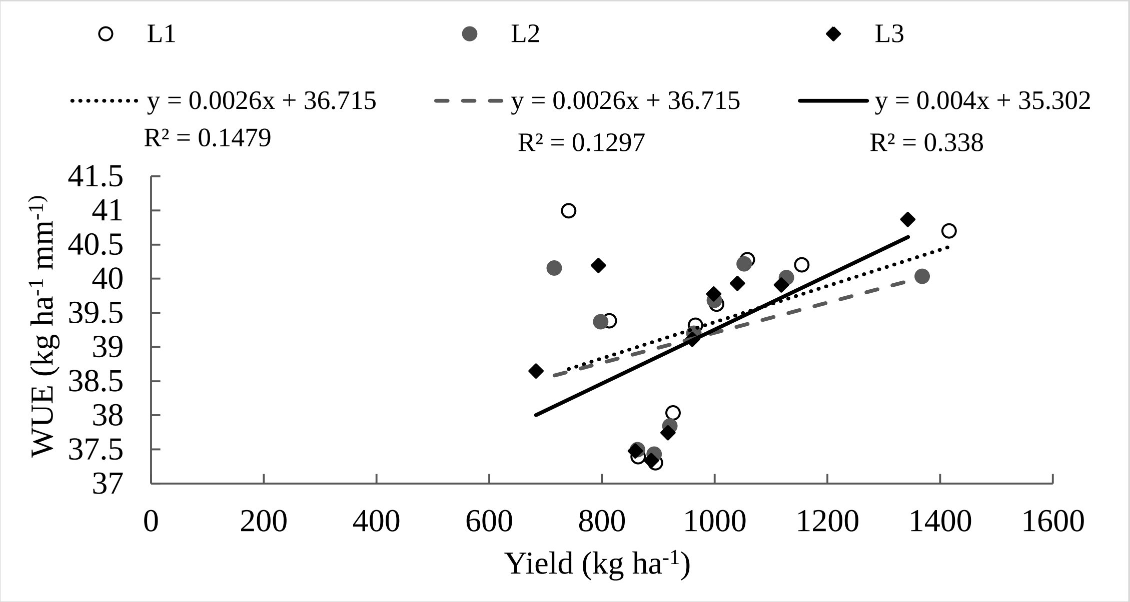


Figure 5.2: Relationship between water use efficiency (WUE) and finger millet biomass. Slope shows trend of WUE as Yield increases for each water level.

5.4 Discussion

The morphological evidence gathered in this study has shown that finger millet growth is highly sensitive to water deficit stress. All plants exposed to water deficit presented significant changes in their shoot and root morphology. In this study, watering regimes significantly influenced the number of fingers, root surface area, crossing and yield, shoot dry weight, root length, root volume and specific root length. Shoot dry weight (SDW) and root length (RL), had the highest mean performance in the water level 0.5 litres (L3). Root formation has been found to increase in length during water stress, with roots growing deep into the soil in search for moisture. Similar findings were reported by Mangena *et al.* (2018) reported increased root growth in water-stressed plants than in the control.

The performance of the finger millet lines studied varied significantly on root dry weight, number of fingers, number of tillers, plant height, total root length, surface area, average root diameter, root length density, root hairs (tips), forks, root volume, specific root length, evapotranspiration, net leaf CO_2 exchange rates, water use efficiency and grain yield. In a related study, Umar *et al.* (2014) reported significant differences among finger millet accessions for plant height, number of tillers and leaf length which attributed to the genetic variation among the finger millet genotypes Water levels and finger millet lines had no significant effect on the morpho-physiological responses in this study. These results were in contrast with those reported by Talwar *et al.* (2020) who established significant interaction effect between water stress levels and finger millet genotypes. Similarly, Leite *et al.* (2021) reported no significant genotype × water regime interaction effect in maize (*Zea mays* L. var. everta) for shoot dry weight, root dry weight, shoot dry weight / root dry weight ratio, leaf weight and stem diameter.

Water stress has been shown to have negative impact on morphological traits in plants including shoot and root as well as the physiological characteristics (Leite *et al*., 2021). The results revealed that the highest shoot dry weight, root length, surface area and root volume were attained at water level of 0.5 litres (L3). Under drought stress conditions, increased root to leaf surface and high number of root hairs has been reported to enhance acquisition of water and nutrients (Comas *et al*., 2013). Reports show that root length and grain yield are some of the parameters of interests for selection of genotypes under water stress conditions (Akinwale e*t al*., 2018). A high-water level of 1.5 litres (L1) led to increased grain yield that can be attributed to enhanced root and shoot growth for efficient translocation of water and plant photosynthates (Wasson *et al.,* 2012). Maqsood *et al.* (2007) reported an increase of 4.05 t ha^{-1} in grain yield when the finger millets were planted under irrigation.

Stomata closure has been highlighted as one of the key plant responses to low water levels. Prolonged periods of closed stomata lead to low photosynthesis that is directly associated with reduced biomass accumulation (Krishnamurthy *et al.*, 2016). C4 photosynthetic pathway crops have rapid stomatal opening than C3 crops, which could be explained by smaller stomatal size and higher stomatal density. Enhancing the speed of stomatal closure has been linked with up to 16% increase in water use efficiency (Ozeki *et al.*, 2022). This study revealed that WUE ranged between 40.53 and 37.35 kg ha^{-1} mm $^{-1}$ among the tested finger millet lines in the different water levels. There was a high WUE under low moisture compared to high moisture regime among the finger millet lines. Similar results of high WUE have been reported in pearl millet and pearl millet forage under water stress conditions (Crookston *et al*., 2020; Rostamza *et al*., 2011).

Water stress causes changes in physiological and biochemical processes responsible for plant growth and productivity, reducing photosynthesis, leaf size and area, stomatal conductance, CO_2 assimilation and consequently the yields of plants (Khatoom & Singh, 2017). Water stress regimes resulted in decrease in plant height due to decreased availability of water as observed at L1 and L3 in the finger millet lines studied. Similarly, there was reduced root volume in L3, which can be attributed to enhanced water uptake efficiency. Lines ICFX1420396-5-5-1-1 and ICFX1420314-6-2-1-1 attained a high biomass that could be attributed to the increase in number of tillers. Krishna *et al*. (2021) reported low number of fingers per plant, which was positively correlated with the number of tillers under water stress conditions. Genotypes that accumulate high amount of shoot biomass have been linked to high drought tolerance compared to high root biomass. The tolerance has been attributed to the fact that less photo-assimilates are stored in the roots to explore larger extension of the soil (Jin *et al*., 2018; Leite *et al*., 2021). Plant height was negatively correlated to shoot biomass. Tall plants have longer duration to maturity hence prolonged vegetative growth thereby partitioning more assimilates to shoot biomass accumulation. Taller plants have also been correlated with small stalk diameter that are prone to lodging characteristics and predispose panicles to insect pest and damage consequently reducing grain yield. In a different study conducted on sorghum (*Sorghum bicolar*) and maize, Pereira and Lee (1995) reported smaller panicles and poorly fertilized fingers in tall genotypes.

Shoot dry weight was positively correlated to root length. An effective way of biomass accumulation under water stress conditions has been attributed to efficient capturing soil moisture by extensive root system or differences in the effective depth of water extraction (Singh, 2010). Finger millet is known to develop extensive fibrous root system that enhance extraction of water from deep soil profile when the top soil dries. These results agree with those of Blum (2006) who found out that drought adapted genotypes have the ability to capture water from deep soil horizon through the well develop fibrous root system. Lorens *et al*. (1987) concluded that deeper rooting profile contributes to the maintenance of higher leaf water potential and leaf turgor pressure during water stress. Crop growth stage and water stress have been shown to contribute significantly on biomass accumulation and grain. In a study by Talwar *et al.* (2020), water stress at reproductive stage significantly reduced grain yield than shoot biomass much more severely than at vegetative stage. The occurrence of water stress during the reproductive phase is regular feature in most of the rain fed crops including finger millet, since in the rain fed agricultural system the precipitation reduces towards the flowering and grain filling growth stages. These findings should provide a strong foundation to select genotypes that are able to withstand water stress throughout the crop cycle.

In water stress environment, crops often seem to coordinate photosynthesis and transpiration, which have been linked with genetic variation in transpiration efficiency across and within crop species (Ober, 2008). Genotypes with greater transpiration efficiency are considered for selection to ensure greater shoot biomass productivity under water stress conditions for improved water use efficiency (Krishnamurthy *et al.*, 2016). Results from this study showed that WUE is highly correlated with specific root length and negatively correlated with number of fingers and root volume. In a related study, Ali *et al*. (2014) reported a positive significant correlation between WUE and morpho-physiological traits. The relationship between WUE and biomass for different water levels shows that increase in dry mater increases the WUE and among the three water levels. High moisture levels (L1) had a slightly high gain in WUE compared to L2 and L3. These results suggest that plants grown in water levels (L1) accumulated high dry matter compared to those plants grown under water stress (L3). This variability could be associated with the genotypic variations and water stress levels. Crookston *et al.* (2020) also reported similar findings in pearl millet. In contrast, Rostamza *et al*. (2011) reported that low water levels increased water use efficiency in pearl millet.

5.5 Conclusion

Findings of this study revealed that there was variation between the finger millet genotypes and water levels for most of the morphological and physiological traits. Water use efficiency (WUE) was not significant for finger millet lines planted in the three water levels [75%, 50% and 25% field capacity (FC)]. Increased root growth, shoot dry weight, root dry weight and grain were good indicators for WUE. The genetic variation that exists among the finger millet lines provide scope for exploiting diverse gene source for improving the drought tolerance in finger millet production. Based on the results of this study, three lines, ICFX1420431-3-3-1, ICFX1420314-2-1-1-1 and ICFX1420396-5-5-1-1 had higher WUE and could be recommended for use in breeding to improve water use under drought stress production environments. Water use efficiency can be considered useful criteria for plant screening drought tolerance under water stress condition.

CHAPTER SIX

GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 General discussion

Finger millet is considered is a drought-resilient crop with better grain productivity in semiarid environments compared to other cereals such as maize (*Zea mays*) (Onyango, 2016). Physiological and biochemical mechanisms through which the plants respond to moisture deficits has been considered important to enhance drought stress tolerance within the finger millet genotypes (Mude *et al.,* 2020). Evaluating finger millet genotypes for drought tolerance using morpho-physiological and root traits is the most effective way to identify donor lines which confer tolerance to drought stress. These donor lines will be beneficial to finger millet breeding programmes intended to improve yield under drought environments. The information obtained on the morpho-physiological and root traits will be an effective tool in increasing efficiency in finger millet improvement programmes. The strategy will be take the shortest time and it will be cost-effective, therefore reducing the breeding period of finger millet. Recently, in Kenya, drought has emerged as the major constraint on finger millet production. Most of the commercial varieties grown by farmers for example U15, KAK wimbi 3, SEC 915, Snapping green, EUFM 501, KNE 814 purple, EUFM 503 have very low yields in the ASAL areas and this has led to reduction in yield of finger millet. Evaluating finger millet genotypes for drought tolerance is a major concern. Three experiments were conducted with the aim of contributing to increased finger millet production in the arid and semi-arid lands of Kenya through improvement of finger millet genotypes for morpho-physiological and root traits associated with drought tolerance.

The first experiment involved evaluating and identifying high yielding and drought tolerant finger millet lines based on associated morphological and physiological characteristics. Twenty-four advanced finger millet lines pre-selected for drought tolerance from ICRISAT and Egerton University seed units alongside a check P-224 were evaluated for drought tolerance and yield at two drought stress locations (ATC Soin and ATC Koibatek) in the main cropping season in 2020. From the results, three lines, ICFX1420314-2-1-1-1, KNE 814 × Ex Alupe (P) P8-1-1-1-1 and ICFX1420415-3-1-1-2 were identified as drought tolerant due to their increased root growth, shoot dry weight, root dry weight and grain yield, which were, identified indicators for improved water use efficiency. They also exhibited the key traits linked to water stress tolerance such as long specific root length, high root length density, increased number of root hairs and increased root to shoot ratio. These lines will be useful for deployment as commercial varieties and can be used as parents in crossing programmes for improvement of drought tolerance and high yield in ASALs areas of Kenya.

The second experiment involved identifying shoot-root plant characteristics associated with drought tolerance in finger millet. In this experiment, twenty-four advanced lines of finger millet were evaluated against a commercial variety P224 laid out in RCBD with three replications in rain shelter at the Agronomy teaching and research field 7 of Egerton University. The results from the second study, indicated significant (P<0.001) differences among the 25 finger millet lines for root dry weight, root to shoot ratio, total dry weight, rooting length, root surface area, specific root length, root length density, root volume and root tips. In addition, root traits can play significant role in the selection of drought tolerance due to wide range of variability among the finger millet lines. Long specific root length, increased biomass, high root length density, increased number of root hairs (tips) and increased root to shoot ratio among other traits were identified as shoot-root plant characteristics associated with drought tolerance in finger millet. In that regard, lines ICFX1420314-2-1-1-1, ICFX1420431-1-3-1-2 and ICFX1420312-3-2-1-1 were identified to be having the identified shoot-root characteristics associated with drought tolerance among the finger millet genotypes studied.

The third experiment involved determining the morpho-physiological features for enhanced water use efficiency of finger millet under varying moisture regimes. From 25 selected genotypes, nine finger millet lines alongside one check were tested in a split plot design arranged in randomized complete block design (RCBD) with three water levels as the main plot and finger millet lines as the sub-plot. The finger millet lines were evaluated for physiological and morphological parameters. In this experiment, there was variation between the finger millet genotypes and water levels for the morphological and physiological traits. Water use efficiency (WUE) was not significant for finger millet lines planted in the three water levels 75%, 50% and 25% field capacity (FC). Increased root growth, shoot dry weight, root dry weight and grain yield were identified as pointers for improved water use efficiency among the finger millet genotypes studied. Based on these results, lines ICFX1420431-3-3-1, ICFX1420314-2-1-1-1 and ICFX1420396-5-5-1-1 were identified as drought tolerant due to their increased water efficiency.

In summary, two lines, ICFX1420314-2-1-1-1 and ICFX1420431-3-3-1 showed consistence in performance in all the experiments and were therefore identified to be drought tolerant as per the above-described characteristics

6.2 Conclusions

The findings of this study observed that:

i. Among the finger millet lines evaluated, there exist superior lines, ICFX1420314-2-1-1-1 and ICFX1420431-3-3-1, which are well adapted to drought stress and can be directly associated with morpho-physiological traits.
ii. Root-shoot characteristics that is specific root length, root length density, root hairs, root length density and root to shoot ratio identified can be used as major indicators for drought tolerance in finger millet to increase production and incomes of smallholder farmers in arid and semi-arid areas.
iii. Water use efficiency among finger millet lines was associated with morpho-physiological traits such as increased root growth, shoot dry weight, root dry weight and grain, which can be incorporated in breeding programs for enhancement of drought tolerance and grain yield in finger millet.

6.3 Recommendations

1. Finger millet lines, ICFX1420314-2-1-1-1 and ICFX1420431-3-3-1, which showed high water use efficiency and higher grain yield, are potential candidates for formal release to farmers for commercialization. However, further testing may be required under participatory variety selection before submitting them for national performance trials (NPTs).
2. Specific root-shoot traits (root length, root length density, root length density and root to shoot ratio) can be used as key indicators in screening for drought tolerance in finger millets genotypes for dryland areas, hence should be introgressed in breeding programs.
3. Association mapping studies should be initiated to identify genes associated with key morpho-physiological traits modulating drought tolerance and yield in finger millet for marker-enabled breeding.
4. Experimental confirmation of any antinutrient content in the grains of the finger millet lines selected should be evaluated alongside study of consumer preferences.

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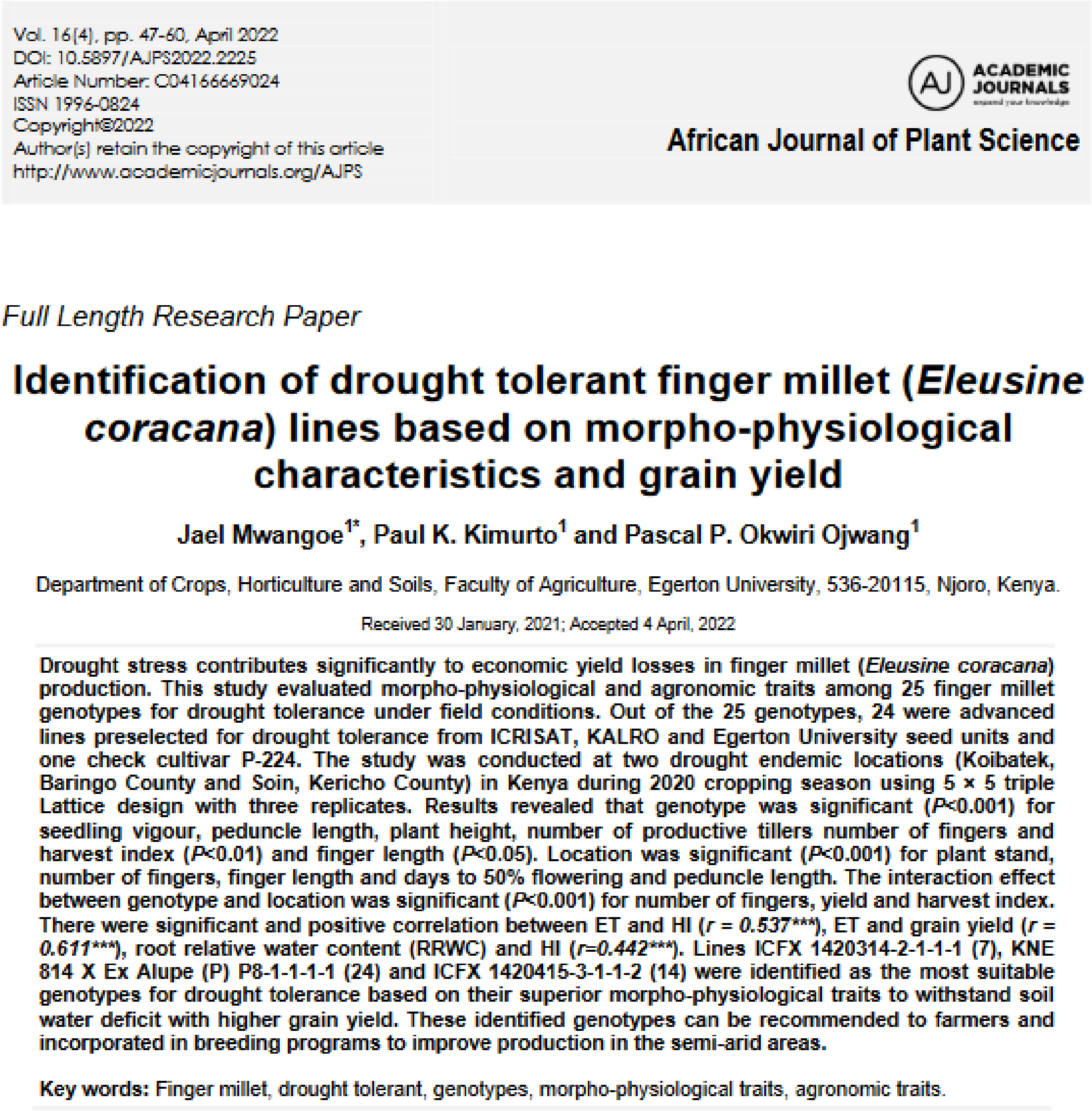
LIST OF APPENDICES

Appendix A: Research paper



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Identification of drought tolerant finger millet (*Eleusine coracana*) lines based on morpho-physiological characteristics and grain yield

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Drought stress contributes significantly to economic yield losses in finger millet (*Eleusine coracana*) production. This study evaluated morpho-physiological and agronomic traits among 25 finger millet genotypes for drought tolerance under field conditions. Out of the 25 genotypes, 24 were advanced lines preselected for drought tolerance from ICRISAT, KALRO and Egerton University seed units and one check cultivar P-224. The study was conducted at two drought endemic locations (Koibatek, Baringo County and Soin, Kericho County) in Kenya during 2020 cropping season using 5 × 5 triple Lattice design with three replicates. Results revealed that genotype was significant ($P<0.001$) for seedling vigour, peduncle length, plant height, number of productive tillers number of fingers and harvest index ($P<0.01$) and finger length ($P<0.05$). Location was significant ($P<0.001$) for plant stand, number of fingers, finger length and days to 50% flowering and peduncle length. The interaction effect between genotype and location was significant ($P<0.001$) for number of fingers, yield and harvest index. There were significant and positive correlation between ET and HI ($r = 0.537$*), ET and grain yield ($r = 0.611$***), root relative water content (RRWC) and HI ($r=0.442$***). Lines ICFX 1420314-2-1-1-1 (7), KNE 814 X Ex Alupe (P) P8-1-1-1-1 (24) and ICFX 1420415-3-1-1-2 (14) were identified as the most suitable genotypes for drought tolerance based on their superior morpho-physiological traits to withstand soil water deficit with higher grain yield. These identified genotypes can be recommended to farmers and incorporated in breeding programs to improve production in the semi-arid areas.**

Key words: Finger millet, drought tolerant, genotypes, morpho-physiological traits, agronomic traits.

Appendix B: Morphological quantitative and qualitative traits for finger millet diversity studies (IBPGR, 2011)

Quantitative traits	Description
Time to plant maturity (PM)	Number of days from sowing to 50% of the plants in the plot reaching maturity stage (readiness for harvest)
Plant height (PH)	Average length of 10 plants from ground level to tip of inflorescence (ear) recorded at dough stage
Productive tillers (NT)	Average number of basal tillers from 10 plant samples which bear mature ear
Panicle length (PL)	Average length of 10 plants in centimetre from base to tip of longest spike (finger) on main tiller at dough stage
Number of fingers (NF)	Average number of finger counted from 10 plant samples per main plant ear
Panicle weight (PW)	Average weight of 10 fingers from main plants in a plot at harvest in gram
Finger length (FL)	average length of peduncles of 10 plant samples taken from top most node to base of the thumb finger in centimetre
Thousand grain weight	weight of thousand seeds in gram
Grain yield per plant (GY)	Average yield of ten plants in gram
Harvest index (HI)	The ratio of grain yield to biological yield per plant times 100
Biomass weight	Total weight of biomass at harvest

Appendix C: Table of means of the 25 finger millet genotypes.

Entry no.	Genotype	SV	PL	PH	NPT	NF	FL	LAI	LI	ET	Yield	LRWC	RRWC	SBIO	RBIO	HI	FFLW	**ST**	PR	COA	CC
1	EX Alupe(G) × KNE 814 P1-1-2-3-1	1.00c	11.88ba	50.75d	6.83ba	8.63ef	9.68bac	0.109egdf	0.46bdac	18.57fehdg	255.63ihgf	61.14ba	28.63egdf	36.33bdac	28.75ik	3.60fjihkg	84.33	4.18dc	30.03cbd	357.67fed	6.38l
2	EX Alupe (G) X KNE 814 P4-2-1-4-1	1.44ba	12.58ba	62.58dc	6.94ba	9.96ebdac	8.61c	009g	0.34e	16.58hg	224.92i	60.77ba	27.30hgf	34.96fdec	43.28gdfce	2.93l	83.5a	4.36c	20.91f	374.33ced	7.65jkihl
3	ICFX 1420311-3-6-1-2	1.05c	11.83ba	80.33ab	4.55hgh	10.16bdac	10.80bac	0.116egdfc	0.42ebdac	20.43cebd	287.21ebdgcf	58.66ba	25.70hji	32.61hfdegi	56.31a	3.41jlik	85.66a	3.41gfe	22.24fcedg	352fed	13.83b
4	ICFX 1420312-3-2-1-1	1.23bac	13.17ba	79.25bac	5.31edf	9.38ebdcf	10.28bac	0.127ebdac	0.44ebdac	22.55cb	307.82bac	59.56ba	26.05hjgi	35.79bdec	39.28gjikh	3.89feihdg	83.33a	3.11hgfi	29.13fcebd	345.57fed	11.03fed
5	ICFX 1420313-1-2-3-1	1.00c	11.55ba	73.58bac	4.33hg	9.55ebdacf	11.36bac	0.109egdf	0.41ebdac	21.75cbd	292.65ebdac	57.60ba	36.92b	40.49a	32.20i	4.19fcebd	83.33a	2.42jlk	25.72fcedg	346.67fed	12.66cbd
6	ICFX 1420313-3-2-1-1	1.00c	12.20ba	74.16bac	4.76edf	9.73ebdacf	11.53ba	0.132bdac	0.47bac	18.31fehdh	265.21ehg	61.43ba	27.69hegf	31.66hfegi	39.70gkikh	4.13fcebdg	83.33a	2.58jhki	26.80fcebdg	521.00a	6.93kl
7	ICFX 1420314-2-1-1-1	1.00c	10.72b	81.58ba	5.50ed	10.86a	11.41bac	0.147ba	0.49a	16.84hg	298.82ebdac	59.94ba	28.81edf	29.27hi	41.42gdfieh	4.62b	83.66a	1.70m	30.52cbd	365.83cfed	11.91cbd
8	ICFX 1420314-6-2-1-1	1.23bac	11.90ba	78.50bac	4.76egf	9.71ebdac	11.85a	0.132bdac	0.47bdac	18.09fehg	290.59ebdacf	55.83b	23.61jk	39.04bac	36.85jlik	3.50jlihk	82.83a	0.14n	25.67fcedg	364.33cfed	6.77kl
9	ICFX 1420315-2-2-1-2	1.00c	12.75ba	73.50bac	4.08hg	10.72ba	11.20bac	0.09gf	0.47bdac	23.21b	318.19a	59.57ba	40.53a	34.28fdeg	23.55m	5.50a	81.83a	3.47gfe	48.63a	399.83cbd	9.26fihg
10	ICFX 1420342-3-1-2-2	1.00c	12.13ba	66.83bdc	4.00hg	10.33bac	9.81bac	0.108egdf	0.42endac	19.38fcehdg	246.02ih	54.80b	24.43jik	30.34hgi	40.21gjfieh	3.58jihkg	82.00a	2.54jhki	48.60a	330.50fe	12.01cbd
11	ICFX 1420396-5-5-1-1	1.00c	12.50ba	84.16a	4.68egf	9.41ebdcf	10.65bac	0.131bdac	0.43ebdac	15.88h	281.66ebdhgcf	61.81ba	28.50egdf	30.72hfgi	38.75gjikh	4.35cbd	83.33a	2.49jlki	26.80fcebdg	355.83fed	11.68ced
12	ICFX 1420414-7-12-1-1	1.23bac	11.62ba	81.16ba	7.37a	10.35bac	11.50ba	0.116egdfc	0.41ebdac	18.76fehdg	303.33bdac	56.24b	37.94ab	40.78a	44.01dfce	3.66fjeihg	84.33a	0.17n	31.74cb	363.67cfed	9.73feg
13	ICFX 1420414-7-4-1-1	1.00c	11.51ba	76.25bac	6.89ba	10.17bdac	10.61bac	0.09egf	0.41ebdac	18.77fcebdg	305.99bac	53.65b	26.44hgif	30.98hfgi	51.96ba	3.60fjihkg	84.83a	3.21hgf	29.42cebd	372.33ced	13.65cb

14	ICFX 1420415-3-1-1-2	1.56a	12.83ba	76.75bac	4.30hg	10.80a	11.31bac	0.124ebdfc	0.46ebdac	22,72cb	300.43ebdac	55.83b	22.19lk	28.27i	44.45dce	4.37cbd	82.00a	7.34a	21.14feg	421.33cb	10.69fed
15	ICFX 1420419-3-2-1-1	1.21bac	11.13ba	73.41bac	5.84dc	10.21bdac	11.21bac	0.116egdfc	0.45ebdac	19.76fcebdg	273.81edhgcf	60.87ba	26.36hgif	32.29hfdegi	47.44bc	3.94fceihdg	84.16a	2.89jhgki	28.17fcebdg	349fed	8.60jkihg
16	ICFX 1420420-9-6-3-1	1.19bc	14.08a	79.16bac	5.87dc	9.22edcf	10.63bac	0.113egdfc	0.43ebdac	20.12fcebd	265.00ehgf	60.60ba	27.58hegf	32.32hfdegi	35.51lk	4.11fcebdg	85.33a	1.98ml	19.93g	307.33f	8.51jkihg
17	ICFX 1420424-2-1-1-1	1.00c	13.71ba	78.25bac	6.61bac	9.22edcf	10.61bac	0.114egdfc	0.43ebdac	17.89fehg	251.91ihg	65.46a	33.98c	31.01hfgi	36.04jlk	4.53cb	84.16a	5.13b	24.76fcedg	368cfed	9.133jfihg
18	ICFX 1420431-1-3-1-2	1.00c	11.80ba	73.50bac	6.07dc	8.94edf	10.70bac	0.144egdfc	0.43ebdac	17.69fehg	269.55edhgf	56.33b	23.37lk	35.82bdec	41.31gdfieh	3.72feihg	85.33a	2.30mlk	34.19b	337.33fed	8.42jkihg
19	ICFX 1420431-2-5-1-1	1.18c	11.78ba	74.00bac	3.78h	10.28bac	10.66bac	0.115egdfc	0.39ebdac	19.61fcedg	268.10edhgf	59.46ba	30.19ed	31.57hfegi	33.14ljk	4.25cebd	81.500a	3.53dfe	30.06cbd	19.61fcedg	8.40jkihg
20	ICFX 142036-3-3-1-1	1.00c	12.73ba	77.66bac	5.29edf	9.43ebdcf	8.80bc	0.106egdf	0.40ebdac	19.88fcebdg	271.87edhgcf	61.44ba	30.46d	39.79ba	38.26jikh	3.70feihg	83.00a	3.19hgf	27.51fcebdg	347.50fed	15.88a
21	ICFX 1420437-1-4-1-1	1.00c	11.78ba	72.00bac	4.38hg	10.55bac	10.71bac	0.107egdf	0.42ebdac	19.86fcebdg	317.18ba	58.33ba	26.77hgif	30.17hgi	42.94gdfceh	4.06fcebhdg	82.83a	2.97jhgfi	25.63fcedg	364.50cfed	7.16jkl
22	ICFX 1420448-1-1-1-1	1.24bac	12.51ba	70.25bac	4.70egf	10.82a	12.36a	0.98egf	0.36ed	18.74fehdg	291.15ebdacf	54.96b	20.82l	30.93hfgi	51.84ba	3.57jihkg	83.33a	5.35b	46.60a	351.67fed	11.92cbd
23	KNE 814 × Ex Alupe (P) P7-9-3-2-2	1.00c	13.45ba	71.16bac	4.16hg	10.01bdac	10.96bac	0.112egdf	0.41ebdac	21.01cebd	303.41bdac	55.60b	23.37jlk	35.04fdec	45.48dc	3.91feihdg	83.66a	3.47gfe	31.73cb	451.17b	11.80cd
24	KNE 814 X Ex Alupe (P) P8-1-1-1-1	1.00c	12.58ba	86.00a	3.94hg	8.61f	11.03bac	0.157a	0.49a	36.28a	282.66ebdagcf	59.60ba	27.18hgf	34.16fdeg	41.72gdfeh	3.02lk	82.33a	3.98dce	25.42fcedg	369.33cfed	9.62fhg
25	P224- check	1.00c	11.81ba	77.41bac	5.43edf	9.88ebdacf	10.06bac	0.142bac	0.48ba	19.62fcedg	278.01edhgcf	54.17b	27.83hegdf	33.32hfdegi	51.69ba	3.02jlk	84.00a	3.64dfe	23.09fedg	360.67cfed	7.55jkil
		0.36	3.1	17.27	0.87	1.33	2.83	0.02	0.11	3.54	36.02	8.65	2.71	4.55	4.7	0.59	4.49	0.67	8.43	3.54	2.009

SV is the average seedling vigour, PL is the average peduncle length (cm), PH is the average plant height (cm), NPT is the average number of productive tillers, NF is the average number of fingers, FL is the average finger length (cm) and HI is the Harvest index. Site 1and 2 represents ATC Koibatek and ATC Soin trials respectively.

Appendix D: Mean separation of root traits performance of the 25 finger millet genotypes.

Entry no.	Genotype	SV	RDW	SDW	RSR	TDW	RL	RSA	SRL	RLD	RV	TIPS	FORKS	CROSS	AD
1	EX Alupe(G) × KNE 814 P1-1-2-3-1	2.33ab	0.025c-e	0.118ab	0.167ml	0.190c-e	181.23bc	48.92a-d	3348.4b-g	0.020e-j	0.219g-j	83d-h	239fg	23f-j	0.569a
2	EX Alupe (G) X KNE 814 P4-2-1-4-1	2.00ab	0.025c-e	0.196ab	0.201i-m	0.232a-e	163.70bc	47.80a-d	3085.1c-h	0.033c-e	0.462c-f	56gh	504c-e	23f-i	0.650a
3	ICFX 1420311-3-6-1-2	1.33b	0.029a-e	0.202ab	0.232f-k	0.256a-e	218.28ab	57.76ab	2483.3g-i	0.025d-h	0.309e-h	91d-g	885b	19h-k	0.799a
4	ICFX 1420312-3-2-1-1	2.00ab	0.039ab	0.235a	0.281e-h	0.290a-c	201.71a-c	49.03a-d	2166.0i	0.043bc	0.236g-i	120cd	369ef	12i-k	0.715a
5	ICFX 1420313-1-2-3-1	2.00ab	0.024c-e	0.169ab	0.167ml	0.212b-e	168.50bc	41.54a-d	3498.5b-f	0.014h-j	0.027k	50h	240fg	40de	0.594a
6	ICFX 1420313-3-2-1-1	2.66a	0.026c-e	0.181ab	0.232g-l	0.235a-e	179.66bc	47.49a-d	4734.7a	0.028c-g	0.031jk	84d-h	562cd	37de	0.611a
7	ICFX 1420314-2-1-1-1	2.66a	0.037a-c	0.213ab	0.296d-f	0.275a-d	195.74bc	49.26a-d	3259.5c-g	0.038bd	0.278g-h	98.33c-f	111gh	14i-k	0.652a
8	ICFX 1420314-6-2-1-1	2.00ab	0.027a-e	0.185ab	0.299d-f	0.247a-e	171.42bc	54.91a-c	2946.2c-1	0.053ab	0.020k	61f-h	472c-e	10jk	0.747a
9	ICFX 1420315-2-2-1-2	2.33ab	0.018e	0.152ab	0.127m	0.185de	116.91bc	25.64d	3592.4b-d	0.025d-h	0.015k	67e-h	468c-	44cd	0.535a
10	ICFX 1420342-3-1-2-2	2.66a	0.031a-e	0.142ab	0.854a	0.223b-d	209.31a-c	49.44a-d	3556.0b-d	0.028c-h	0.395d-g	257a	444de	35d-f	0.648a
11	ICFX 1420396-5-5-1-1	2.33ab	0.027c-e	0.150ab	0.324c-e	0.197c-e	146.59bc	32.64b-d	3510.2b-e	0.012h-j	0.032jk	90d-h	583cd	43cd	0.674a
12	ICFX 1420414-7-12-1-1	2.00ab	0.027c-e	0.162ab	0.216h-l	0.204c-e	159.19bc	33.67b-c	2596.2e-i	0.014g-j	0.174h-k	62g-h	177gh	10jk	0.611a
13	ICFX 1420414-7-4-1-1	2.33ab	0.020de	0.156ab	0.157ml	0.191c-e	144.81bc	30.02cd	3865.4a-c	0.022d-h	0.476c-e	83d-h	493c-e	34d-g	0.526a
14	ICFX 1420415-3-1-1-2	2.00ab	0.031a-e	0.199ab	0.269e-j	0.241a-e	197.97a-c	45.53a-d	2702.2d-i	0.004j	0.275f-h	209b	644c	55c	0.631a
15	ICFX 1420419-3-2-1-1	2.00ab	0.032a-d	0.2137ab	0.251e-j	0.310ab	176.15bc	45.36a-d	2872.2d-i	0.031c-f	0.634bc	73e-h	38h	16i-k	0.694a
16	ICFX 1420420-9-6-3-1	2.00ab	0.027b-e	0.170ab	0.202i-m	0.216b-e	165.55c	37.20b-d	3128.5c-h	0.011ij	0.451c-f	71e-h	69gh	7k	0.645a
17	ICFX 1420424-2-1-1-1	2.00ab	0.028a-e	0.181ab	0.302d-f	0.277a-d	232.82ab	54.48a-c	2837.9d-1	0.027d-h	0.819b	63g-h	502c-e	22g-j	0.632a
18	ICFX 1420431-1-3-1-2	2.66a	0.041a	0.216ab	0.284e-h	0.329a	273.42ab	56.92ab	4151.5ab	0.027c-h	0.794b	82d-h	539c-e	35d-g	0.624a
19	ICFX 1420431-2-5-1-1	2.00ab	0.032a-d	0.192ab	0.362c-d	0.313ab	213.42a-c	57.61ab	3412.0b-g	0.063a	1.189a	84d-h	449de	29e-h	0.695a
20	ICFX 142036-3-3-1-1	2.00ab	0.030a-e	0.155ab	0.272e-i	0.203c-e	159.58bc	33.06b-d	3239.6c-h	0.016f-i	0.064i-k	135c	224f-h	37de	0.668a
21	ICFX 1420437-1-4-1-1	2.00ab	0.033a-d	0.208ab	0.192j-m	0.227a-e	194.05bc	42.01a-d	2302.5hi	0.014g-j	0.549cd	108.3c-e	431de	19h-k	0.712a
22	ICFX 1420448-1-1-1-1	2.00ab	0.025c-e	0.130ab	0.430b	0.171e	228.08ab	37.59b-d	3442.7b-f	0.014g-j	0.190h-k	59f-h	100gh	73b	0.601a
23	KNE 814 × Ex Alupe (P) P7-9-3-2-2	2.66a	0.027a-e	0.164ab	0.262e-j	0.211b-e	153.34bc	34.74b-d	3528.0b-e	0.014g-i	0.130h-k	64f-h	51gh	13i-k	0.675a
24	KNE 814 X Ex Alupe (P) P8-1-1-1-1	2.00ab	0.030a-e	0.183ab	0.391bc	0.240a-e	162.86bc	39.93b-d	2557.4g-i	0.034c-e	0.022k	70e-h	90gh	14i-k	0.640a
25	P 224- check	2.00ab	0.024c-e	0.183ab	0.219k-l	0.287a-d	306.41a	68.28a	4762.6a	0.033c-e	0.024k	79d-h	1165a	87a	0.569a
LSD		1.114	0.013	0.105	0.077	0.103	108.91	26.89	951.52	0.016	0.19	41.073	190.32	12.79	0.333
CV (%)		16.29	15.27	18.62	8.67	13.73	18.35	18.94	9.2	19.73	19.16	14.06	15.24	13.28	16.32

TREAT- Genotypes, SV- seedling vigour, RDW-Root dry weight, SDW- Shoot dry weight, RSR- Root to shoot ratio, TDW- Total dry weight, RL- Rooting length, RSA- Root surface area, SRL- specific rooting length, RLD- Root length density, RV- Root volume, AD- average diameter, LSD – least significant difference and CV- coefficient of variation.