REPUBLIC OF TURKEY
BINGOL UNIVERSITY
INSTITUTE OF SCIENCE

THE EFFECT OF DIFFERENT IRRIGATION FREQUENCY AND LEVEL ON YIELD AND QUALITY CHARACTERISTICS OF SILAGE SORGHUM

MASTER'S THESIS

ABDUL MUMEEN IDDRISU

FIELD CROPS DEPARTMENT

THESIS SUPERVISIOR
Prof. Dr. Kağan KÖKTEN

BİNGÖL-2023

REPUBLIC OF TURKEY
BINGOL UNIVERSITY
INSTITUTE OF SCIENCE

THE EFFECT OF DIFFERENT IRRIGATION FREQUENCY AND LEVEL ON YIELD AND QUALITY CHARACTERISTICS OF SILAGE SORGHUM

MASTER'S THESIS

ABDUL MUMEEN IDDRISU

FIELD CROPS DEPARTMENT

THESIS SUPERVISIOR
Prof. Dr. Kağan KÖKTEN

BİNGÖL-2023

REPUBLIC OF TURKEY

BINGOL UNIVERSITY

INSTITUTE OF SCIENCE

THE EFFECT OF DIFFERENT IRRIGATION FREQUENCY AND LEVEL ON YIELD AND QUALITY CHARACTERISTICS OF SILAGE SORGHUM

This dissertation, created by Abdul Mumeen IDDRISU under supervision of Prof. Dr. Kağan KÖKTEN, was accepted as a Master thesis in Department of Field Crops by the following committee on 31/ 03/ 2023 with the vote unity.

Head of exam. commit.:	Prof. Dr. Kağan KÖKTEN	*Signature*:
Member	: Assoc. Prof. Dr.	*Signature*:
Member	: Assoc. Prof. Dr.	*Signature*:

This result has been approved on ..... / …… /....… with the decision of ………./………… by Board of Directors of the Science Institute.

Prof. Dr. Zafer ŞİAR
Director of the Institute

ACKNOWLEDGEMENT

Alhamdulillahi the Obvious. Peace and blessings of Allah be upon the manifestation of beauty, awe and perfection. I give thanks to my Supervisors Prof. Dr. Kağan KÖKTEN and Assoc. Prof. Dr. Erdal ÇAÇAN. Secondly, my thanks go to Dr. Selim ÖZDEMIR, Dr. Rıdvan UÇAR, Mr. Mehmet EKMEKÇİ, Mr. Serdal YAVUZ and Dr. Halit TUTAR.

My thanks further go to Omer and his family, my family in Elazig and Mr. Yusuf. To the pride of my supplications, Malama Khansaa, I say Allah razı olsun.

Finally, to all my friends in this cause of study, I say thank you.

Abdul Mumeen IDDRISU

Bingöl 2023

TABLE OF CONTENTS

ABBREVIATIONS

ADF	:Acid Detergent Fibre
CP	:Crude Protein Ratio
CPY	:Crude Protein Yield
DDM	:Digestible Dry Matter
DMI	:Dry Matter Intake
NDF	:Neutral Detergent Fibre
RFV	:Relative Feed Value

LIST OF TABLES

LIST OF FIGURES

SİLAJLIK SORGUMDA FARKLI SULAMA SIKLIĞI VE SEVİYESİNİN VERİM VE VERİM ÖZELLİKLERİNE ETKİSİ

ÖZET

Bu çalışma, silajlık sorgum bitkisine uygulanan farklı sulama sıklığı ve seviyelerinin, verim ve kalite üzerindeki etkisini belirlemek amacıyla yapılmıştır. Çalışma, 2022 yılında Bingöl Üniversitesi Tarımsal Araştırma ve Uygulama Arazisi'nde yürütülmüş ve bitkisel materyal olarak sorgum-sudan otu melezi olan Master BMR çeşidi kullanılmıştır. Çalışma, tesadüf bloklarında bölünmüş parseller deneme desenine göre üç tekerrürlü olarak yürütülmüş ve dört sulama seviyesi (%25, %50, %75 ve %100) ile dört sulama sıklığı (5, 10, 15 ve 20 gün) çalışma konusu olarak ele alınmıştır. Çalışmada; yeşil ot verimi, kuru ot verimi, ham protein oranı, ham protein verimi, asit deterjanda çözünmeyen lif (ADF), nötr deterjanda çözünmeyen lif (NDF), sindirilebilir kuru madde, kuru madde tüketimi ve nispi yem değeri ile ilgili özellikler incelenmiştir. İncelenen tüm özellikler arasında istatistiksel olarak önemli farklılıklar olduğu belirlenmiştir.

Çalışmada; en yüksek yeşil ot verimi, kuru ot verimi ve ham protein verimi 5 günlük sulama sıklığı ve %100 sulama seviyesinden elde edilmiştir. En yüksek ham protein oranı 5 günlük sulama sıklığı ve %25 sulama seviyesinden, en düşük ADF oranı ile en yüksek sindirilebilir kuru madde oranı 20 günlük sulama sıklığı ve %25 sulama seviyesinden, en düşük NDF oranı ile en yüksek kuru madde tüketimi ve nispi yem değeri de 10 ve 20 günlük sulama sıklıkları ile %25 sulama seviyesinden alınmıştır.

Sonuç olarak; silajlık sorgumdan yüksek oranda verim elde etmek için 5 günlük sulama sıklığında ve %100 sulama seviyesinde sulama yapmak gerektiği anlaşılmıştır. Ancak, bir miktar verim düşüklüğüne rağmen 10 günlük sulama sıklığı ve %25 sulama seviyesi ile kaliteli ürün elde edilebileceği anlaşılmıştır.

Anahtar Kelimeler: Sulama, yem kalitesi, BMR silajlık sorgum.

EFFECT OF IRRIGATION FREQUENCY AND LEVEL OF YIELD AND QUALITY CHARACTERISTICS OF SILAGE SORGHUM

ABSTRACT

This study was carried out to determine the effect of different irrigation frequency and levels applied to the silage sorghum plant on yield and quality. The study was carried out at the Bingöl University Agricultural Research and Application Field in 2022 and Master BMR variety, which is a Sorghum-Sudan grass hybrid, was used as planting material. The study was carried out in randomized blocks according to the split-plots experimental design with three replications; four irrigation levels (25%, 50%, 75% and 100%) and four irrigation frequencies (5, 10, 15 and 20 days) were considered as the treatments of the study. In the study; The properties related to green forage yield, dry matter yield, crude protein ratio, crude protein yield, acid detergent insoluble fibre (ADF), neutral detergent insoluble fibre (NDF), digestible dry matter, dry matter consumption and relative feed value were investigated. It was determined that there were statistically significant differences between all the examined features.

In the study; the highest green forage yield, dry matter yield and crude protein yield were obtained from 5-day irrigation frequency and 100% irrigation level. Highest crude protein ratio from 5-day irrigation frequency and 25% irrigation level, lowest ADF rate and highest digestible dry matter rate from 20-day irrigation frequency and 25% irrigation level, highest dry matter intake (DMI) and relative feed value (RFV) with the lowest NDF rate were observed from 25% irrigation level with 10 and 20-day irrigation frequencies.

In conclusion; it can be stated that, to obtain high yield from silage sorghum, it is necessary to irrigate at a frequency of 5 days and at 100% irrigation level. However, despite recording low yield, it has been observed that, a high-quality product can be obtained with a 10-day irrigation frequency and a 25% irrigation level.

Keywords: Irrigation, feed quality, BMR silage sorghum.

1. INTRODUCTION

Sorghum (*Sorghum bicolor* (L.) Moench), referred to as the crop of the future in animal nutrition, has had myriad of research conducted on it to determine its suitability as a replacement crop for maize/corn (McCary et al. 2020). De Morais et al. (2017) identified sorghum as the fifth most cultivated cereal in the world after its domestication some 3000 years ago. Sorghum, with its multiple application, has been preferred due to its tolerance and adaptive capacity over a large geographical area on different continents (Hossain et al. 2022). On a marginal land, sorghum is relatively productive compared to the other popular cereals. Its complete replacement of maize is still limited due to several reasons mostly having to do with digestibility and nutrients availability (De Morais Cardoso et al. 2017; Hossain et al. 2022; McCary et al. 2020). Variety, developmental stage, nutritional content, feed processing among other factors have been identified to affect the suitability of sorghum as a replacement for maize in animal nutrition. Fermentation processes such as silage has been proposed by de Morais et al. (2017) as a means to increase digestibility twice the current level. If the digestibility and nutritional content of the sorghum crop are improved through genetic manipulations, cultural practices or postharvest treatments, sorghum could become a food security crop now and moving into the future amidst the increasing climatic impacts. The Sudangrass-Sorghum hybrid was bred for its medium tillering, regrowth capacities, and nutritive values as an alternative to maize/corn in the production of silage and other forage resources (Bhat, 2019). The discovery of the BMR trait also improved its usability as a forage crop under water stress conditions.

There exists a plethora of evidence to the fact that the climatic situation of the earth is changing (IPCC, 2014). Reports of growing desertification and reduction of the amount and frequency of rainfall in various parts of the earth have been published by seasoned climate scientists (IPCC, 2007). Akin to this observed impact of the changing climate and the fact that the situation will be getting worse, is the imperativeness to develop a system to salvage the food production process of the world. Animal feed is an important part of the food chain since more than 15% of human food is derived from animal sources (FAO, 2018), a more reason supporting the significance of researching into effective production process aimed at building climate adaptive capacity. Sorghum, as stated above, possesses the additional advantage suitable for climate stress production. According to the IPCC (2014) report, there will be significant variability in the global precipitation system, which brings to bare the need to develop efficient irrigation measures for crop with minimum demands, which may result in the optimal use of water resources.

1.1. Irrigation of Sorghum in Limiting Condition

Sorghum is a crop with limited demand for agronomic resources such as moisture, nutrition and protection. However, it must be understood that the information is based on its relative performance with crops of similar production demand or post-harvest usage. For optimum yield, sorghum thus demand some level of inputs from the farmer. The BMR sorghum varieties are more resources demanding than their male parent, the Sudangrass.

Irrigation is the artificial technique of supplying crops with water in the event of moisture deficit, to enable crops grow productively (Reddy, 2010). There are many aspects to irrigation ranging from methods to water management. Frequency and amount (level of irrigation) contribute significantly to the effectiveness of the irrigation process. These factors are influenced by crop, soil and environmental factors (Ali, 2010). Different crops have different water requirements at different levels of their development as a result of physiological, botanical and biochemical differences. Soil type and profile also determines the amount and frequency of irrigation. Clay minerals such as Kaolinites and Montmorillonites for instance, swell during the irrigation process and thus limit the amount of water which could be supplied (Uddin, 2018). Sandy soils on the other hand will require frequent irrigation due to their high number of pores. A soil profile with high water table will require less amount of water per unit time compared to one with deeper table. Temperature, wind speed, precipitation among other weather factors affect soil moisture availability, thus, the frequency and amount of irrigation (Ali, 2010).

Moisture demands up to the booting stage of a sorghum plant is very crucial (New, 2021). Any drought during this stage significantly affects the yield of the crop. During the early growing stages, the crop produces leaves in response to moisture availability. The number of leaves produced by a plant affect the aggregate amount of photosynthates produced, which further influences the crop yield (Stichler and Fipps, 2021). Any additional moisture after the developmental stage will not offset the losses incurred during the growth stage. It is thus very prudent to manage the availability of moisture to sorghum crops up until the booting stage. Irrigation during dry seasons has been observed to produce corresponding higher yields as compared to wet seasons (Currie and Kisekka, 2014). This places sorghum as a crop of choice for production in a climate variant scenario. The challenge, when it comes to forage production, is to have an appropriate timing for harvesting so as not to trigger lignification; which is a common occurrence in high temperature seasons.

Sorghum has been identified by researchers as an alternative for maize in the animal production system with the additional advantage of tolerance to low nutrition and moisture availability (Neto et al. 2017). Neto et al. (2017) unlike Hossain et al. (2022) concluded that sorghum silages have high dry matter digestibility in their *in vitro* studies. The evidence in practical feed usage supports the opinion of Hossain et al. (2022), to the fact that digestibility of conventional sorghum is lower compared to maize (De Morais et al. 2017; McCary et al. 2020). Higher digestibility is an important quality component of animal feed. Energy supplying components of animal feed (ruminants in particular) make up more than 80%, a greater portion being of grass derivative (Hanapi et al. 2012). Sorghum, having the advantage of low nutrients requirement during production, and with the looming climatic impacts expected, becomes an important crop for sustainable animal production if its nutritional characteristics are improved.

1.2. Sorghum Domestication and Cultivation

Sorghum, of the family *Poaceae*, is reported to have been domesticate somewhere 3000 BP in the Sudan region of Sub-Saharan Africa though its cultivation is distributed over all continents especially arid and semiarid regions of the world (Jardim et al. 2020; Taylor and Duodu 2019). According to Taylor and Duodu (2019), there is a disagreement on the region of domestication, with most of the observed evidence pointing the Sudan region. This notion was agreed with by Assefa et al. (2014) in a prior publication. Cultivation of sorghum, thus, diffused from the horn of Africa to other parts of the globe, making it the first point of domestication. Due to its richness in carbohydrate, identified as the fifth most important cereal (Hossain et al. 2022) and the second in the *Poaceae* family (Assefa et al. 2014), sorghum received wide acceptance for cultivation to supply the energy needs of humans, animals and industry. Taylor and Duodu (2019) indicated that, the *bicolor* race is probably the primary race for the diversity of the species of the sorghum crop. This diversity, as expressed by them, arose from the point of domestication in the Sudan-Ethiopian region to India and then to Indonesia and China.

Though several sorghum species exist in natural reserves, most of the cultivated ones are of the *bicolor* race. Based on the end usage, the sorghum crop can be divided into four groups; grain sorghum, forage sorghum, sweet sorghum and biomass sorghum. Diversities of such nature resulted from the continuous interaction with other races (wild species and weeds included) and breeding programs (Taylor and Duodu, 2019). Cultivation of sorghum is dominantly concentrated in arid regions of the globe due to it adaptive superiority in such regions compared to its competitor, maize (Assefa et al. 2014). It has been reported to do better in water-stressed and saline soils compared to other carbohydrate rich cereals (Jardim et al. 2020).

Sorghum crops can grow to the height of almost 3 m in some varieties (Keskin et al. 2018) with yield of more than 8 tonnes green matter and 3 tonnes dry matter on a hectare, and up to 13 leaves per plant. Some varieties have been reported to possess up to 30 leaves per plant (Jardim et al. 2020). With a root system like that of maize i.e., a fibrous primary root system brunched by finer secondary roots, sorghum root system can penetrate up to 3 m in the soil (Assefa et al. 2014). Of course, this is influenced by soil characteristics, tillage practices and moisture availability. As a crop with a perfect flower, sorghum is seen as a self-pollinated crop though depending on the variety, crossing can be observed (Assefa et al. 2014). Self-pollination is a characteristic which increases the chances of pollination in drought conditions when pollen viability is reduced but can be a hurdle in a crossbreeding program. Due to its ability to draw water deep into the soil and higher number of stomata, sorghum can maintain relatively stable rate of photosynthesis in a water and CO_2 stressed environment.

Under CO_2 stress condition with increasing temperatures, a favourable condition for photorespiration, sorghum, being a C4 photosynthetic pathway crop does excellently well (Wasilewska-Dębowska et al. 2022) in as much as the intensity of light is not compromised even if moisture stress exist. It is due to this characteristic coupled with its ability to thrive under saline soils with significant reduction in productivity which made sorghum a crop of choice. Sorghum is standing as an alternative not only for maize but also for sugarcane in the production of ethanol, syrup and sugars (Jardim et al. 2020). The potential of the crop affords it the wide adoption for cultivation to feed the growing population in developing countries and to produce silage, hay and other forms of animal feed (De Morais Cardoso et al. 2017).

The production of Sorghum has dropped by almost 10 million tonnes from the data in 2014 (> 68 million tons) as published by the FAO (Taylor and Duodu, 2019). Cultivated area has also dropped by about 5 million ha over same period. The factors accounting for the decrease are not yet clear but probably due to lack of farmer interest in the crop or preference of the market for other crops. Compared to maize, wheat and barley, sorghum is still a minor crop in terms of production, research and consumption globally. Marsalis (2011) in prior research concluded that, adoption of sorghum for cultivation will not see significant increment now or the near future except in areas of aridity or when irrigation establishments are unable to supply the needed moisture for especially maize production. A similar conclusion was arrived at by Keskin et al. (2018). Production in Africa, especially in Nigeria, continuous to be a main source for food whilst the over 10 million tonnes produced in North America are mainly used in the feed industry. Recent research, mostly focused on building adaptive capacities towards climate change or finding alternatives for healthy human nutrition, have considered the potential of sorghum to be of great importance (De Morais Cardoso et al. 2017; Jardim et al. 2020; Hossain et al. 2022). It is on this background that sorghum will regain attention in terms of it usage with the expected climate impacts.

1.3. Usage and Nutritional Characteristics of Sorghum

As stated above, sorghum has been usage in human nutrition, animal feed and energy production. Different parts of the sorghum plant from various varieties are applied not only in nutrition and medicine, but also in research as alternatives for environmentally unsustainable chemical products. Syrup produced from sweet-sorghum, waxes on various part of the sorghum plant, pigments from sorghum leaves and seed, fibre from the stalk among others are some of the products currently being studied as the Sorghum crop is portrayed to be a crop of the future (Meena et al. 2022).

New cultivars of sorghum are genetically bred to rival the performance of popular cereals in animal nutrition. An example can be given of the Brown Midrib (BMR) varieties which have so far rival the performance of maize silage in terms of NDF (McCary et al. 2020). Sorghum is widely employed in the feeding of dairy cows and animal of low energy requirement in areas where maize-silage yield is below the productivity belt. Its low resource demand alongside suitability for adjustment of planting dates, make sorghum ideal for feeding of animals (Pupo et al. 2022). This position was previously shared by Bhattarai et al. (2020) in research in Texas, indicating that under limited irrigation, sorghum has the capacity to produce higher yield. Sorghum is fed to animals as green feed, hay or silage mostly depending on the season and the geographical area. In some part of Africa, crop waste is left on the field for nomadic herds to feed on (Erramouspe, 2021). This type of feed has very low nutritive value, however, more research must be done to ascertain how animals utilise them to produce energy. In other studies, the selection between silage and hay can be determined with consideration to the final product in mind (Serrapica et al. 2020). Generally, cold climate farmers prefer silage while warmer climate farmers produce hay. In the production season and after harvesting the forage, animals can be fed green forage or grazed on the field; this is mostly in late spring to early autumn/fall. The disadvantage of using Sorghum compared to other forage crops such as maize is the fact that it possesses higher NDF and lower DNDF (McCary et al. 2020) which lowers its nutritive value and animal intake for that matter (Pupo et al. 2022). Lower DNDF content of sorghum forages are attributed to lignification which kicks in as the plant matures. Lignin is an NDF which resists digestion by rumen microbes. Another problem encountered while feeding animals with sorghum forage is the low protein digestibility, a problem attributed to the levels of *kafirin* proteins it contains. These problems are, however, been solved using feed treatment methods and on the genetic scale, release of lysine-rich cultivars. The BMR cultivars among others are by far showing promising traits considering DNDF and protein digestibility.

Sorghum has been used as food since time immemorial from the point of domestication and it still serves as a security crop for some regions within African (Erramouspe, 2021). In West Africa, a popular beer, *Pito*, is brewed using sorghum. This beer has significance in nutrition, tradition and belief systems of the region (Zaukuu et al. 2016). According to Erramouspe (2021), researchers are working on developing varieties which can replace popular ingredients in the urban food market of East Africa. Recent studies are also focused not only on the nutritive qualities of the crop, but also on the health properties. Sorghum is reported to aid in the management of non-communicable diseases such as diabetes, obesity, hypertension, oxidative stress, inflammation and cancer (de Morais Cardoso et al. 2017). This property has been attributed to the ability of sorghum crops of all variety to produce immense levels of phenolic compounds such as tannin and 3-deoxyanthocyanidins, high starch content, unsaturated fat among others compared to other crops (Meena et al. 2022). *Kafirins*, unlike *glaidin*, secalin and hordein which are *prolamines* capable of triggering allergic response, make sorghum-based foods safe for consumers with celiac disease conditions (De Morais Cardoso et al. 2017). Over the years however, cultivation and consumption of sorghum have shifted to other high yielding palatable crops rendering it less popular (Meena et al. 2022). Consumption in areas with marginal condition has not been affected much. Sorghum is the crop which ensures food security in those areas Erramouspe (2021). Kunun-Zaki, sorghum-ogi and sorghum-pastries are currently being widely consumed and promoted as probiotic foods (Rashwan et al. 2021).

Research into sorghum is not limited to its use as food or source of nutrients. Its application in the field of energy production and laboratory chemicals among others have been studied. Comparing sorghum to maize in ethanol production, Szambelan et al. (2020) concluded that sorghum is a good alternative for maize in the production of ethanol. In another research, up to 89% of the theoretical maximum in terms of ethanol production was recorded using milling waste (El-Imam el al. 2019). Ethanol is not only a source of energy for machine usage, but also important in laboratory sanitation and other scientific usages.

Recent studies are focused on improving technologies for the optimum production of ethanol from sorghum (Joy and Krishnan, 2022). It is obvious that these studies are focused on the use of sorghum as an efficient alternative to the current crops to produce bioethanol envisaging the impacts of the changing climate. Another industry worth mentioning is the dye industry. Synthetic production and utilization do pose a climate mitigation problem, propelling the search for alternatives which are environmentally safe. It has been established that, extracts from sorghum can be used in cytoplasmic counter staining (Krampah et al. 2021). Results from the studies indicated no significant difference with the synthetic stains. Sorghum leaves application as dyes have been reported in the food industry as well. The use of sorghum as a food dye was found to increase the polyphenol and antioxidants content of the final dish (Tugli et al. 2019). A similar finding was reported earlier by Kayodé et al. (2012), indicating that sorghum leaf extracts contain high amounts of antioxidants.

Studies were also carried out testing the effect of sorghum in weed management. According to Raza et al. (2021), sorghum extracts combined with *allelopathic rhizobacteria* was effective in the control of some selected weeds on a wheat field. The research further indicated a relative boost in the yield of the wheat crop, concluding that the use of sorghum extract could be an alternative to the use of synthetic herbicides. As the crop of the future, sorghum has received a lot of attention in recent times. A lot of research has been carried out to test its uses in other fields including the production of Nano-fibre and adhesives (Li et al. 2020; Pennells et al. 2021). These and many other potentials of sorghum avails it for further research.

1.4. Statement of Problem

Global food resources will be significantly affected by the envisaged climatic impacts as well as increasing global population which will further increase the demand for food. The current production systems are not robust in absolute terms to withstand the impacts, calling for alternative to production, more so in the feed industry. Sorghum comes up as an alternative to current forage crops due to its low demand on agronomic resources. It is important to note that, low demand does not imply lack of demand. Thus, optimum levels need to be established for the efficient production of feed even with a low demanding crop.

1.5. Objectives of the study

The main objective of this study was to evaluate the yield characteristics of sorghum silage in response to frequency and levels (amount) of irrigation. The specific objectives were to:

1. Determine the most effect irrigation frequency for silage sorghum crop.
2. Determine the optimum irrigation level demand of silage sorghum crop.
3. Assess the quality of silage sorghum produced under irrigation.

1.6. Scope of Studies

The scope of this study was limited to the climatic condition in Bingol, using the BMR Sudangrass-Sorghum hybrid as a plant material.

2. LITERATURE REVIEW

This chapter will try to collate information from published previous relevant studies to highlight the knowledge gap as it establishes a map to blend the findings of this research into climate adaptation measure generally and improve forage production system specifically.

2.1. BMR Trait in Sorghum Cultivars

Cultivation and improvement of sorghum varieties for forage production were common in the 20th century. Most of these programs then were focused on the agronomic characteristics of the forage crop as compared to its nutritional differentiation (Sanderson et al. 1995). Sudan-grass variety of sorghum was known for multi-tillering, resistances to environmental stress and fast growing (Armah-Agyeman et al. 2002). Later assessments consider it less nutritive due to its high content of lignin and ADF. The discovery of Brown Midrib traits of some cultivars, an indication of less lignification or less resistant lignin, issued in a new line of breeding program (USDA, 2000). While some cultivars with the BMR trait were reported not to express any significant improvement (Ledgerwood et al. 2009), others had undesirable agronomic traits (Bhat, 2019) and yet other cultivars resulted in superior improvements (Pupo et al. 2022). Early breeding of the BMR trait face challenges including reduced yield, lower resistance to diseases and lodging. These challenges were smoothed following identification of new loci and comprehensive understanding the mechanism of action of the genes responsible for the trait.

In sorghum, two (BMR6 and BMR12) of the four BMR (the other two are BMR2 and BMR19) loci identified are receiving significant attention. BMR6 codes for the enzyme *cinnamyl alcohol dehydrogenase 2* (CAD 2), capable of blocking the synthesis of all three lignin forms while BMR12 encodes *caffeic O-methyltransferases* (COMT) capable of limiting the synthesis of basically S-lignin, produced as the plant ages (Sattler et al. 2010). Introduction of the BMR trait in forage sorghum has been reported to have superior forage quality in all fronts, especially digestibility, intake and resulting animal product (Ledgerwood et al. 2009). This agrees with report of Bean et al. (2013) that, the BMR trait reduces lignin content and resulting in higher digestibility in all tested cultivars. Reduced lignin content has earlier been attributed to unfitness of plants for agronomic traits as stated above (reduced yield, lodging and reduced resistance to pathogens). Absence of lignin were understood to affect the integrity of cell walls of resulting plant, which are sensitive to gene background and location (Pedersen et al. 2005). According to Sattler et al. (2010), new hybrids of the BMR cultivars competed with the wild sorghum types in terms of yield, disease resistance and resistance to lodging, with the dual-purpose varieties even doing great. Furthermore, existence of certain lignin precursors was reported to inhibit fungal growth but agreed however with the environmental sensitivity of the cultivars. Generally, BMR cultivar trials reported diverse results. However, it is apparent that, the trait, especially BMR6 and BMR12, have significantly improved sorghum cultivars (Miller and Stroup, 2003), making them cultivars of choice with regards to high quality forage production.

2.2. Feed Quality Measure

Research into forage sorghum tend to focus on forage quality compared with maize, a more favourable alternative. The proposition is that similar forage quality parameters result in similar productivity, with the Sorghum having an added advantage of less production cost (Li et al. 2020). Forage quality is thus, an important factor to consider for researchers, farmers and animal producers. According to Ball et al. (2001), forage quality is the capacity of the forage to support the production of the animal product in question. Palatability, intake, digestibility, nutrient content, anti-nutrient factors and animal performance are the factors they considered to influence quality of a forage material. Forage quality has also been defined as the expression of the features affecting intake, nutrient content and performance of the animal (Fulgueira et al. 2007). Accordingly, crop species, soil characteristics, maturity stage, harvest and post-harvest technologies, and environment were recognised as the factors influencing the quality of forage. Stated definitions above are partly consistent with the practical understanding of forage quality i.e., “milk in the bucket”, “pounds on the scale” or “calves on the ground” (Newman et al. 2013). Thus, if the proposition of Li et al. (2020) holds right, nutritional value and quality of forages, which are the other aspect of the previous definition, are indicated for in the resulting animal performance. This agrees with the understanding of (Newman et al. 2013).

Several factors influence forage quality of its suitability for use as stated above. While some are as a result genetic makeup of the forage material, other factors are due to environment or techniques in production. Soil characteristics and climate factors are the environmental factors affecting final forage quality, and maturity, harvest and post-harvest techniques are farmer-dependent factors which influence the resulting quality of the forage. Soil characteristics primarily influence the yield of crops. However, presence/absence and quantities of certain soil components may change the forage quality. This is very pronounced when carbohydrate/protein relationship is considered for silage production (Fulgueira et al., 2007). Soil factors can also affect the levels of anti-quality factors. When plants take up undesirable element from the soil with potential to poison animals, the resulting forage quality reduces (Ball et al. 2001).

Environment and stage of maturity, as stated above, influence forage quality in several ways. Temperature is probably the aspect of the climate with the most significant impact on forage quality. It has the capacity to bleach forage parts, ending in reduced protein content (Moore et al. 2020) as well as increase lignification (Fulgueira et al. 2007). Lignification, which is generally undesirable in forages, is also increased as a plant matures. Studies on specific forages crops often recommend stages for harvesting so as to balance yield and forage nutritional quality. It is recommended to harvest forage sorghum at the dough stage (DS) to minimise lignification and make it adequate to ensilage (Atis et al. 2012). This stage is around 55 days after planting (Philp and Harris, 2010). Digestibility at this stage is a little above 50%. Depending on type of feed to produce (silage or hay), harvesting can be done earlier to keep higher digestibility and protein content. Postharvest handling of forage affects quality. Exposure to rainfall especially depreciates forage quality significantly in a short time (Ball et al. 2001). Continuous respiration, exposure to light and heat, microbial activities are some postharvest factors which must be taken care of. Both silage and hay forages require a certain dry matter content for processing or storage. Harvesting time can be adjusted to meet this stage so as to limit deterioration of forage.

Finally, and important to this study is the genetic makeup of a forage crop. Clear difference exists between legumes and grasses. While legumes are rich in crude protein (CP), grasses have high fibre contents (Fulgueira et al. 2007). Differences in species, varieties and cultivars also exhibit significant difference regarding forage quality. In sorghum, marketed BMR cultivars have been reported to possess superior fibre content with increased intake and digestibility compared to non-BMR varieties (Wedig et al. 1987; Miller and Stroup, 2003; Reich, 2005; Ledgerwood et al. 2009; Sattler et al. 2010; Bean et al. 2013). Very few reports in this regard showed no significant difference (Ledgerwood et al. 2009). Sattler et al. (2010) explained that observation to be a result of breeding with different allele not the BMR6 or BMR12. The science behind the BMR trait clearly predicts superiority with regards to digestibility and intake since it demotivates the progress of lignification. BMR sorghum varieties have also been reported to compete favourably with maize in terms of yield and digestibility (Marsalis, 2011). Generally, current data shows that maize forage is superior in quality characteristics compared to sorghum of all types. However, sorghum has an advantage of low resource requirement and adaptable for a climate stress condition.

Quality characteristics of forages are mainly assessed based on dry matter (DM) parameters i.e., Crude Protein (CP), Crude Fibre (NDF, ADF), Mineral content, and other derivative parameters such as Relative Feed Value (RFV), Dry Matter Digestibility (DMD) and Dry Matter Intake (DMI).

2.2.1. Forage Fibre Characteristics

Forage fibre is basically the structural carbohydrate component of cells building up the feed material. Their relevance in animal nutrition is basically concerned with their digestibility to contribute to the nutritional component of the forage as well as their bulking effect which correlates negatively with the amount of feed intake. Digestibility can be measure in vivo, however, common in recent times is the *in-situ* method of acid and neutral detergent fibre determination (Mertens and Grant, 2020). The choice could be attributed to convenience and accuracy of results, though chemical characteristics may influence the quality of results. Neutral Detergent Fibre (NDF), which constitute all the structural carbohydrates; cellulose, hemicellulose and lignin, is positively correlated with the bulk density of the forage, thus, used in the determination of feed intake. Acid Detergent Fibre (ADF) constitute the indigestible components of the forage material including ash, thus, used in the calculation of dry matter digestibility (Morrison et al. 2009). The quality and characteristic of forage fibre is influence by season and agronomic practices such as tillage, seeding rates and pest and weed treatment (Diepersloot et al. 2021). The article further discussed the effect of irrigation on improvement of DM yield which subsequently influenced the fibre characteristics.

Lignin, a major component of ADF can make other nutritional structural-fibres unavailable thereby reducing the value of the feed (Stokes and Prostko, 1998). This notion was agreed with by an earlier work where low content of lignin in BMR hybrid varieties reported increase digestibility (Wedig et al. 1987). It is important thus, to limit the lignin content of a forage material using production methods necessary. According to Diepersloot et al. (2021), reducing time taken to reach relative maturity for harvest can increase the digestibility of a forage material. This goes to confirm the fact that, as plants develop, more lignin is produced to keep the upright structure of the plant, also, increased production time increases exposure to stress factors thereby increasing the production of structural molecules, such as lignin, which are indigestible to the rumen ecosystem. Depending on the quality of NDF and ADF, the value of forage is determined using a full bloomed Alfalfa as the yardstick (Morrison et al. 2009). NDF range of 10-80% and ADF range of 3-50% have been reported with the higher values recorded by warm season/climate crops (Newman et al. 2013). Temperature and moisture are the main factors influencing climatic or seasonal variations in forage yield and quality. The literature is very clear with regards to effect of temperature on grass forage quality and yield due to its influence on biochemical and physiological development of the crop (Pupo et al. 2022). Due to its efficient water utilisation capacity, Sorghum has been reported to do better than maize under water stressed condition (Bhattarai et al. 2020). Furthermore, BMR trait containing varieties performed better than non-BMRs under similar conditions with regards to yield and fibre digestibility and intake. Research on sorghum as a forage crop with season as a factor often recommended spring season for cultivation rather than summer due to the milder stress conditions (Pupo et al. 2022). With increasing variability in global precipitation patterns, choice of a crop such as Sudangrass-Sorghum with efficient water utilisation is eminent (Bhattarai et al. 2020).

2.2.2. Forage Crude Protein Characteristics

Proteins are very important in the animal diet as they contribute to the healthy activity of rumen microbes, overall animal development and productivity. Crude protein in forage is measured by determining the total nitrogen in the forage material (Newman et al. 2013). It is understood that nitrogen makes about 16% of total tissue protein. Multiplying the result by a factor of 6.25 results in the determination of forage crude protein content. Crude protein content differs depending on species, season and production factors. Generally, leguminous crops and crops at the early development stages possess higher crude protein contents (Ball et al. 2001). With regards to effect of season, Pupo et al. (2022) indicated that, warmer conditions yielded higher crude proteins, which they attribute to the plant response to increasing stress factors. The BMR trait in sorghum cultivars has been reported to yield high CP content than the non-BMR varieties (Reich, 2005; Sattler et al. 2010). Earlier research however reported a non-BMR variety yielding slightly higher CP compared to their BMR counterpart (Wedig et al. 1987). This observation was also reported by Bean et al. (2013) on photoperiod sensitive cultivars. However, same reported that the Sudangrass-Sorghum hybrid yielded higher CP on a similar cultivation condition. Unlike Pupo et al. (2022)'s report, Bean et al. (2013) observed that, moisture stress yielded less CP as they compare the yields of four consecutive years with climatic variability. Knowing the effect of moisture deficit is prudent in production of forage crops for a variable climate where optimization is a necessity.

Fibre characteristics as well as protein content are very significant in determining the suitability of a forage material for feeding animals and ration regime (Serrapica et al. 2020). Relative Feed Value (RFV), DMI and DMD, as important as they are in determining the quality of forage material, depend on the characteristics of the fibre characteristics. Since moisture availability affect the quality of forage quality, it is hence eminent to determine the optimum demand of moisture for important crop which can serve as food security sources (Hossain et al. 2022).

2.3. Choice of irrigation method

Irrigation, which in simple terms mean the application water to crops to facilitate their effective growth, is very important with the advent of sustainable and precision agriculture. Optimal application of water ensures that crops are efficiently productive. Sorghum crops have severally been reported to do better under water stress condition than other crops in their class such as maize (Currie and Kisekka, 2014). It is however important to note that tolerance to stress offsets some yield factors and product quality. Aydinsakir et al. (2021) presented the fact several studies have been undertaken in regards Sorghum irrigation with the finding stating that 100% irrigation yielded significantly higher compared to other levels. Hossain et al. (2022) postulated that, moisture stress in sorghum crops reduces leaf and tiller size and counts, a response feature capable of reducing forage yield and quality. Vigorous leaf growth begins immediately after the seedling development stage which is about four weeks into the production duration. Demand for moisture is very critical at this stage as productivity is chiefly determined at this stage (Stichler and Fipps, 2021). New (2021) agrees with this observation, stating that water demand is the highest just before the booting stage, about 35 days after emergence. In a three-year irrigation field trial, Garofalo and Rinaldi (2013) using four levels of irrigation in the Mediterranean region concluded that, sorghum does well when provided with above 300 mm of water over the growth period which falls between 50 and 75% Evapotranspiration replacement. At 100% drip irrigation, Gultekin et al. (2022) reported an increase in greenhouse emission. Instead of building adaptive capacity, irrigation may thus increase the amount of emission. The choice of a suitable irrigation method at this point is very crucial in a minimum irrigation regime, to build adaptive capacity as well as offset any mitigation problems which may arise.

Depending on several factors such as water availability, soil type, crop type and available resources, a suitable method can be adopted to optimize irrigation returns. Among the four fundamental methods of irrigation (Surface, Subsurface, sprinkler and drip irrigations), drip irrigation is the most economical in terms of water use efficiency. Reddy (2010) stated an efficiency of more than 90% of applied water. Drip irrigation is most suitable for orchards crop; however, its application can be employed in trying to determine optimum water use efficiency of arable crops such as sorghum. According to Ali (2010) identifying a method capable of efficiently using water under diminishing/deficit supply is the first step towards conservation. The arguments which will arise from this selection are that sorghum is not a high value crop, drip irrigation may impede agronomic practices and the cost of establishment. Morden agriculture has applied drip irrigation technologies with promising results. In a comparative study between surface and drip irrigation, Moursy et al. (2022) reported that drip irrigation, despite yielding lower that surface irrigation, is more economical for barley production. They further quoted a result which recorded higher yield in a previous trial. On an aerobic rice field trial, Samoy-pascual et al. (2022) reported no difference in crop yield. However, water use efficiency and economic value was higher than the surface irrigation. On a wheat field however, an inhibition in leaf development was reported though grain production increased by more than 10% over a four-year trial (Yang et al. 2022). With the water use efficiency of sorghum as a crop, different results may be recorded. Drip irrigation was used on a sorghum trial with an observed increment in yield on a saline soil (El-mageed et al. 2022). Recent studies have established the suitability and economic viability of the use of drip irrigation for not only high value crops, but arable crops including sorghum.

In trying to determine the optimum water demand under deficit/limited irrigation, soil and plant factors are important to consider. El-mageed et al. (2022) determined water replacement levels using evapotranspiration. According to Ali (2010), soil field capacity can be used in determining the amount of water to replace. This was applied by Liu et al. (2022) in determining the amount of water to apply on a six-replication deficit irrigation trial. The use of evapotranspiration is particularly easier due to the availability of daily meteorological data on a specific site. Furthermore, a special tool is necessary for calculating soil moisture content for each field several times in the trail season as compared to the evapotranspiration data which can easily be summed up to obtain the needed water to replace lost moisture in the soil. According to Patias et al. (2022), the use of field capacity to determine the irrigation demand over the growing season can be flawed because plant root systems grow and may go beyond the level measured for field capacity in the initial recordings. Furthermore, estimation using field capacity could be complex and expensive for a resource poor farmer (Phogat et al. 2023). Recent research is however trying to simplify methods used for the estimation of irrigation requirement using field capacity (Robertson et al. 2021). Owning to the fact that sorghum roots could penetrate up to 3 m below surface (Assefa et al. 2014), it is obvious to conclude that accurate moisture uptake may not be accounted for if only the first few centimetres are used in the calculation of soil field capacity. The formula used by Aydinsakir et al. (2021) in calculating captures losses accrued due to deep percolation and runoff of moisture. Evapotranspiration measures the amount of moisture lost from both the soil and plant thereby giving an almost accurate quantity to be replaced (Ali, 2010) without regards to the weather, stage of growth or management practices. With deeper roots as recorded in sorghum crops, most of the infiltrated moisture could be accounted for in determining the amount of moisture to replace. Furthermore, the fact that drip irrigation encourages the development of lateral roots may favour the use of soil field capacity for the determination of moisture requirement.

It is clear from the literature that drip irrigation is the best irrigation methods for water-use efficiency. Taking records of evapotranspiration gives a near accurate result for determining the amount of water to replace especially for a deficit irrigation program. In addition, crop moisture demand variation over the growth stage makes it necessary to apply the evapotranspiration method in determining soil water requirement for an irrigation program whose sole aim is to determine the optimum irrigation level and frequency for deficit irrigation. Aydinsakir et al. (2021) stated that most of the previous research on sorghum irrigation were concentrated on finding an alternative for maize in ethanol production. Studying the forage characteristics of irrigated sorghum thus, presents novelty in the field of adaptation building.

2.4. Sorghum in Climate Adaptation Strategies

Climate variability is real and the aspect of this variation which will significantly affect the agricultural industry is erratic precipitation patterns (Chadalavada et al. 2022). This is in line with the most recent IPCC report, stating with high confidence that drought has played a role in food unavailability in the past decade (Bezner Kerr et al. 2022). The report further indicated that developing water conservation strategies in crop production possess with high confidence the ability to stabilize productivity and yield. Over the past decades, studies assessing water use efficiency and climate tolerance have seen light in the potential of sorghum (Pennells et al. 2021; Hossain et al. 2022). Genome sequencing for drought tolerance showed that Sorghum is superior to its counterpart cereal crops in terms of resistance to changes in climate variables (George et al. 2022). Sorghum presents a continuum of drought and heat tolerance which are among the chief impact of the changing climate. To build adaptive capacity especially for resource poor farmers, it is prudent to consider the performance of climate-tolerant crops, more so in the production of animal feed.

Chen and Gong (2021) stated in their review studies that adaptation measures in the past have influenced yield sustainability in current production and as such recent developments will have significant impact in the future. Adaptation is viewed as a process of adjusting to obvious or envisaged climate and its impacts. In human systems, adaptation seeks to moderate or avoid harm or exploit beneficial opportunities. In some natural systems, human intervention may facilitate adjustment to expected climate and its effects (IPCC, 2014). Adaptation measures are thus not only limited to developing impact mitigation strategies but may also seek to take advantage of developing situations. Adaptation measures are currently at play in various agricultural niches. These measures are sometimes limited in distribution and adoption due to lack of access, which can be set off if farmers workers of different walks of life interact (Dun et al. 2022). That notwithstanding, studies need to be undertaken to tailor adaptation strategies to specific cultivation programs.

Using the CSM-CERES-Sorghum model, Singh et al. (2014) predicted that incorporating drought and heat tolerant sorghum in the production process could increase yield by about 17%; a simulation of India and Mali farm fields. In a review report, Motsi et al. (2022) presented Sorghum as a crop with efficient use of water under stress condition, and thus could be used in building adaptive capacity especially for small holder farmers. With an irrigation system in place, sorghum has been forecasted to have a yield increase towards the end of this century when climate impacts may be severe (Arumugam et al. 2022). In Ethiopia, models showed that irrigation as an adaptation strategy increased yield by an average of a tonne per hectare (Getachew et al. 2021). Kothari et al. (2020) concluded that improved sorghum varieties cultivated under irrigation have the potential to increase in yield when drought impacts increase. They further indicated that, higher root density provides effective potential for moisture utilization in sorghum. Improved production practices need to be researched and implemented to build and improve adaptive capacity for all agricultural ecosystems especially that of resources poor farmers (Araya et al., 2022). This agrees with the assessment of Srivastava et al. (2020), when they stated that more economical adaptation strategies should be researched into to support sorghum production over the coming years with envisaged climatic impacts. For forage sorghum, the strategies may differ from grain sorghum since sorghum respond to moisture stress by altering its leaf structure which is the main source of nutrition in the forage (Choudhary et al. 2020). Irrigation has been identified as one of the strategies to improve forage sorghum production in an arid or drought condition (Paye et al. 2022).

It is clear from the literature that measures are being taken to build adaptive capacity by researchers, policy makers and producers alike. The BMR Sudangrass-Sorghum hybrid, bred to take advantages of the forage characteristics of the parent plants, if provided with less moisture stress could play well in the animal feed production industry. The quality of the BMR trait cannot be over emphasized in terms of competitive performance for fibre, protein and other feed quality parameters. It is therefore in time to evaluate for the optimum irrigation needs of this cultivar so as to add to the body of knowledge for climate change adaptation.

3. MATERIAL AND METHOD

3.1. Research Site

This thesis was carried out in 2022 in Bingöl University Agricultural Research and Application land, which is approximately 15 km away from the city centre of Bingöl. Master BMR variety of Sorghum-Sudan grass hybrid was used as plant material in the thesis study. According to the data of the General Directorate of Meteorology, the annual average temperature in Bingöl is 12.1 degrees. Annual precipitation amount is 873.7 mm. The number of days with snow is 24.5 days and the number of days with frost is 94.1 days (Bingöl Valiliği, 2018). In general, the experimental soils have clay-loam texture, neutral or near neutral in reaction (pH), without salt, low and moderate level calcareous, low organic matter. Most analysed soils were found to be deficient in terms of phosphorus and sufficient in terms of potassium (Ateş and Turan, 2015).

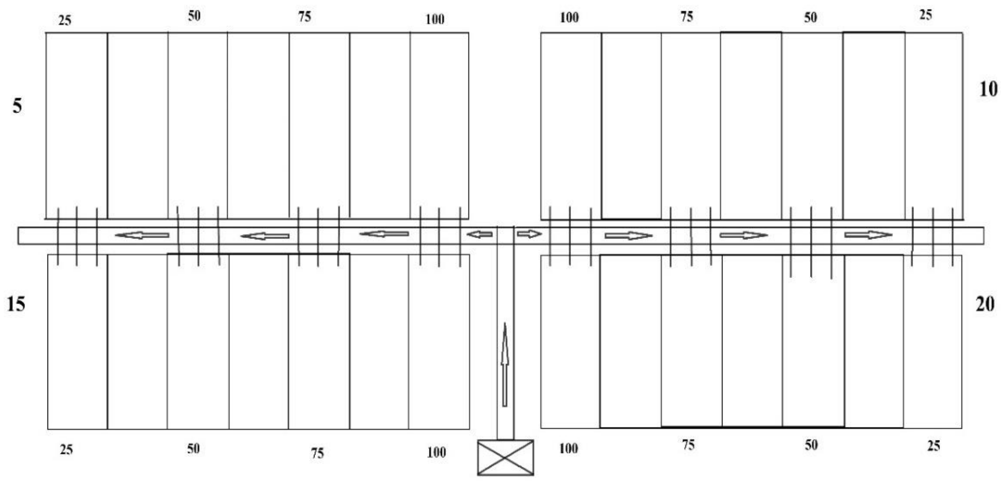

Figure 3.1. Design of the field experiment. Main plots serving as irrigation frequency and sub-plot serving as irrigation level. The arrow shows the movement of water

3.2. Experimental Design

The research was carried out in the field of Agricultural Application and Research Centre in the summer season of 2022 according to the Randomized Complete Block Design (RCBD) split-plot experimental design with 3 replications. In the experiment, 4 different irrigation frequencies (5-, 10-, 15- and 20-day intervals) were applied as main plots and 4 different irrigation levels (25%, 50%, 75% and 100%) were applied as sub plots (Figure 3.1).

3.3. Crop Establishment

The experimental plots were planted in 4 rows by hand in rows of 5 m in length with 70 cm intervals and sowing was done by hand. In the trial, the width of the area was determined as 19 m x 56 m = 1064 m^2, and the block width was 5 m x 56 m = 280 m^2. Sowing was done at the rate of 4 kg of seeds per decare (Figure 3.2).

3.4.Agronomic Practices

Weed control was carried out with hoe during the growth periods of the plants in the trial plots. With the planting, 15-15-15 compound fertilizer was applied as base fertilizer at a rate of 10 kg per decare and 22 kg of Urea (46% N) per decare was applied as top fertilizer later in the season.

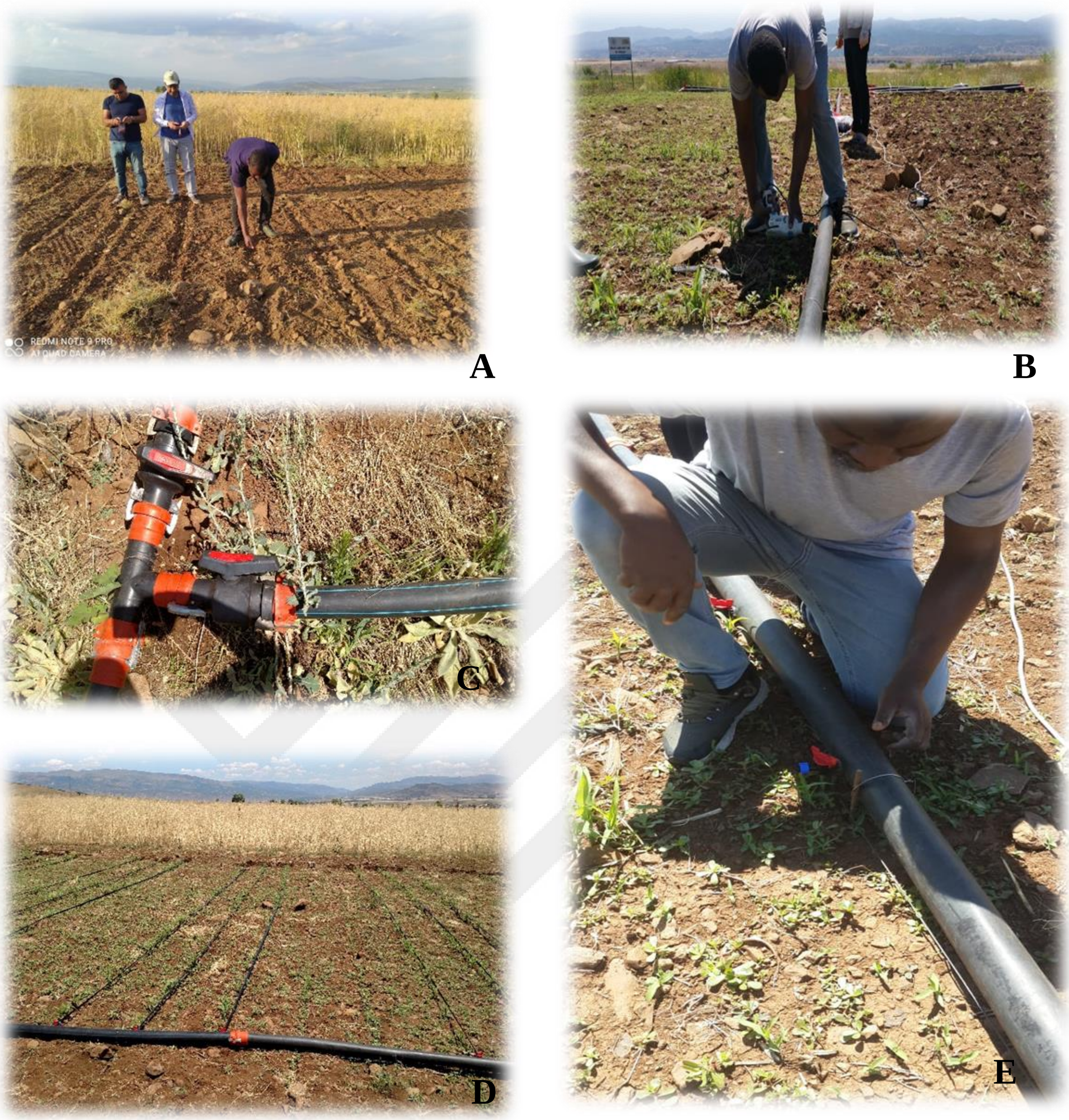

Figure 3.2. A=Row broadcasting of seeds; B=Perforating holes for irrigation line; C=Main irrigation valve; D=Plot layout; E=Row valve installation

Figure 3.3. F=Green forage weight measurement; G=Dry matter weight measurement; H=Forage grinding; I=Packaged and labelled grinded dried forage ready for quality analysis

3.5. Data Collection

In the plots, after the edge effects were removed when the vegetative features mentioned below are at the harvest maturity period, observations and measurements were made on 10 randomly selected plants from each row in order to determine the yield characteristics, and according to the method specified by Steel & Torrie (1960) and Düzgüneş et al. (1983) as stated below. In addition, quality analyses were carried out on dried and ground herbage samples (Figure 3.3).

3.5.1. Green Forage Yield (kg/da)

After removing the edge effect from each plot, the green parts of the plants harvested from the remaining area were weighed and the values obtained were converted to yield in kg per decares.

Figure 3.4Pictorial view of the field. Top-left = 20 days irrigation; top-right = 15 days irrigation; bottom-left = 10 days irrigation; bottom-right = 5 days irrigation

3.5.2. Dry Matter Yield (kg/da)

0.5 kg of the grass cut from each plot were taken as samples and dried in the drying cabinet at 70 °C for 48 hours. Then, they were kept for 24 hours, weighed, and the dry matter weights were obtained. The obtained dried matter values were then converted to dry matter yield per decare.

3.5.3. Crude Protein Ratio (%)

Nitrogen content of the grounded dried matter samples were determined using the Near Infrared Reflectance Spectroscopy (NIRS) as described by Corson et al. (1999).

3.5.4. Crude Protein Yield (kg/da)

Crude protein yields per decare were found by multiplying crude protein ratios in dried matter by dried matter yields per decare.

3.5.5. ADF (Acid Detergent Fibre) Ratio (%)

Acid detergent insoluble fibre (ADF) ratios was determined using the Near Infrared Reflectance Spectroscopy (NIRS) as described by Corson et al. (1999).

3.5.6. NDF (Neutral Detergent Fibre) Ratio (%)

Neutral detergent insoluble fibre (NDF) ratios were determined using the Near Infrared Reflectance Spectroscopy (NIRS) as described by Corson et al. (1999).

3.5.7. Digestible Dry Matter (DDM) Ratio (%)

Digestible dry matter was calculated using the formula: **DDM** = 88.9 - (0.779 x ADF%) (Morrison et al. 2009).

3.5.8. Dry Matter Intake (DMI) Ratio (%)

Dry matter consumption was calculated using the formula: **DMI** = 120 / NDF% (Morrison et al. 2009).

3.5.9. Relative Feed Value (RFV)

Relative feed values were calculated using the formula: **RFV** = (SKM x KMT) / 1.29 (Morrison et al. 2009).

3.6. Statistical Evaluation of Data

The experiment was set up in an RCBD split plot design with 3 replications. The obtained data were analysed with the help of the JMP statistical package program, and the differences and similarities were compared with the LSD test.

4. RESULTS AND DISCUSSION

This aspect of the thesis presents the results of the field work in a summary and considering other previous studies. Questions raised from the objectives of the study will be address within the context of the findings of the studies and as much as practically viable, the scientific foundations of the observations will be highlighted.

4.1. Green Forage Yield

The results of Table 4.1 show that, at ($P \leq 0.01$), irrigation frequencies, levels and interactions between various irrigation levels and frequencies yielded significantly different outputs with regards to green herbage yield. The reported CV of 3.126% indicate that data collection was very precise, showing that variability can be attributed to treatments as against attribution to data collection. From Table 4.2, it can be observed that, average treatment means are significantly different at ($P \leq 0.01$). Highest green forage yield of 3062 kg/da was recoded with 5 days irrigation frequency as compared to the lowest 2281 kg/da for 20 days irrigation interval. For the irrigation levels, 100% irrigation level recorded the highest green herbage yield of 3112 kg/da compared to 2234 kg/da for 25% irrigation level.

Table 4.1. The result of variance analysis of green herbage as influenced by irrigation frequency and level

Source of variation	DF	Sum of squares	Mean square	F value
Replication	2	17803.1	8901.6	1.2932
Irrigation frequency (IrrF)	3	4466134.9	1488711.6	216.2810**
Irrigation level (IrrL)	3	4840834.9	1613611.6	234.4265**
IrrF * IrrL	9	417288.0	46365.3	6.7360**
Error	30	206496.9	6883	
C. Total	47	9948557.8		
CV	3.126			

F values with ** are statistically significant at 1% ($P \leq 0.01$).

With regards to the interaction between irrigation levels and frequencies, the highest green forage yield was recorded from 100% irrigation at 5 days interval. This was followed by 75% irrigation level at 5-day frequency and 100% irrigation level at 10-day frequency, which are not significantly different at ($P \leq 0.01$). The lowest green forage yield was recorded with 25% irrigation level at 20-day frequency, with 25% irrigation level at 15-day frequency slightly above it with significant difference. It can be observed from Table 4.2 that irrespective of the irrigation frequency, 100% irrigation levels produced appreciable green herbage yield.

Table 4.2. Average values of sorghum green forage yields (kg/da) at different irrigation frequency and irrigation levels

Irrigation Frequency (days)	Irrigation Levels (%)				
	25	50	75	100	**Mean**
5	2683 d	2850 c	3260 b	3455 a	**3062 A**
10	2502 e	2800 cd	2832 c	3133 b	**2817 B**
15	2030 g	2312 f	2542 e	2933 c	**2454 C**
20	1722 h	2207 f	2270 f	2925 c	**2281 D**
Mean	**2234 D**	**2542 C**	**2726 B**	**3112 A**	

Values shown with the same letter(s) are statistically not different from each other according to LSD test within 1% ($P \leq 0.01$) error limits.

A maximum sorghum yield of 3860 kg/da was reported by El-mageed et al. (2022) at full irrigation over the cropping season. This is more than 400 kg/da compared to what was observed at 100% irrigation with 5 days irrigation frequency. In another study, Atis et al. (2012) reported an average of 6087 kg/da. With lower irrigation level, an average of 2392 kg/da green forage yield was reported by Bhattarai et al. (2020). This report is similar to the average yield observed for 15 days irrigation frequency in this study. At 75% irrigation, the yield in this study surpasses that reported by Bhattarai et al. (2020). As irrigation level increase with increasing irrigation frequency, green forage yield is reported to increase. The evidence in this study agrees with this assertion, considering that observed yields increased significantly above 15 days irrigation frequency.

4.2. Dry Matter Yield

The results as shown on Table 4.3 indicated significant difference for dry matter yield in terms of irrigation level, irrigation frequency and the interactions between irrigation levels and frequencies at ($P \leq 0.01$). Furthermore, a lower CV of 6.495% indicates that the data was less variable in term of collection method, showing that differences observed were largely as a result of variability in treatment outcomes. Table 4.4 shows the mean values for dry matter yield as affected by irrigation levels, frequencies and the interactions between irrigation levels and frequencies. Just as recorded for dry matter yield, 5 day irrigation frequency yielded the highest of 1067 kg/da with significant difference compared to the other frequencies, and the lowest yield of 821 kg/da was recorded with the 20 days irrigation frequency. With regards to levels of irrigation, 100% irrigation level yielded the highest dry matter yield of 1110 kg/da, which is significantly different from the other irrigation levels. Irrigating at 25% produced the lowest dry matter yield of 674 kg/da, in consistence with the observation in green forage yield. 50% and 75% irrigation levels followed a similar trend, falling between 25% and 100% irrigation levels with significant difference observed between them.

Table 4.3. The result of variance analysis of dry matter as influenced by irrigation frequency and level

Source of variation	DF	Sum of squares	Mean square	F value
Replication	2	940.1	470.05	0.1326
Irrigation frequency (IrrF)	3	420956.2	140318.7	39.5909**
Irrigation level (IrrL)	3	1269209.1	423069.7	119.3691**
IrrF * IrrL	9	123263.8	13695.98	3.8643**
Error	30	106326.5	3544.217	
C. Total	47	1920695.7		
CV	6.495319			

F values with ** are statistically significant at 1% ($P \leq 0.01$).

In terms of the interactions between treatment levels and frequencies, 100% irrigation level for 5 days, 10 days and 75% irrigation level at 5 days irrigation frequency are the highest with no significant difference at ($P \leq 0.01$) LSD. The lowest dry matter yield was recorded for 25% irrigation level at 20 days irrigation frequency. With the exception of irrigation at

5 days frequency, all the 75% irrigation levels showed similarity in term of dry matter yield as can be observed on Table 4.4.

Table 4.3. Average values of sorghum dry matter yields (kg/da) at different irrigation frequency and irrigation levels

Irrigation Frequency (days)	Irrigation Levels (%)				
	25	50	75	100	**Mean**
5	897 def	1010 bc	1177 a	1183 a	**1067 A**
10	696 g	868 ef	978 cd	1137 a	**920 B**
15	653 g	824 f	930 cde	1025 bc	**858 C**
20	448 h	810 f	933 cde	1095 ab	**821 D**
Mean	**674 D**	**878 C**	**1005 B**	**1110 A**	

Values shown with the same letter(s) are statistically not different from each other according to LSD test within 1% ($P \leq 0.01$) error limits.

Dry matter yield is a very important yield parameter especially for farmers. It is used to determine most nutrition quality. From the work of Kir and Şahan (2019), a maximum and minimum yield of 2896 kg/da and 878 kg/da, which are higher than the maximum and minimum values of this study (1183 and 448 kg/da respectively), were reported. Another report stated a varied dry matter yield of 2052 kg/da and 744 kg/da maximum and minimum respectively for no water stress and high stress level (Aydinsakir et al. 2021). At 50% ET irrigation, Garofalo & Rinaldi (2013) reported 1800 kg/da dry matter yield. The above yield difference can be attributed to the differences in harvest time. At the booting stage, Lyons et al. (2019) reported 1110 kg/da dry matter yield similar to the yield recorded in this study at 100% irrigation level. Both irrigation level and frequency determine the stress level a crop is subjected to, thus, affect dry matter yield (Garofalo and Rinaldi, 2013; Aydinsakir et al. 2021). The result of this study agrees with conclusion, observing that, with increasing frequency and level of irrigation, consistent and significant increment of dry matter yield has been recorded.

4.3. Crude Protein Ratio

From Table 4.5, we observe that significant differences existed for crude protein ratios based on irrigation levels and irrigation frequencies. Furthermore, interaction between levels and frequencies of irrigation produced variation which from Table 4.5 can be observed to be significant at (P ≤ 0.01). Precision in data collection was high based on the observed low CV value (3.070%) indicating that variation in data collected was low. Table 4.6 shows the means of crude protein ratios as affected by irrigation levels and frequencies. No significant difference was observed for irrigation levels 25% and 75%. 50% irrigation level however showed a lower crude protein ratio which is significantly different from the other lower irrigation levels. With regards to irrigation frequencies, it can be observed from Table 4.6 that, 5 days irrigation frequency, recoding 7.83% crude protein ratio, is the highest and significantly different from other treatments, followed by 10 days irrigation frequency (P ≤ 0.01).

Based on the interactions between levels and frequencies of irrigation, the highest observed crude protein ratio was observed with 25% irrigation level at 20 days frequency followed by 100% at 5 days irrigation frequency as can be observed on Table 4.6 at (P ≤ 0.01). The lowest crude protein ratio was recorded with 50% irrigation level at 20 days irrigation frequency. Significant differences were recorded in almost all treatment combinations.

Table 4.5. The result of variance analysis of crude protein ratio as influenced by irrigation frequency and level

Source of variation	**DF**	**Sum of squares**	**Mean square**	**F value**
Replication	2	0.078079	0.03904	0.7959
Irrigation frequency (IrrF)	3	10.796540	3.598847	73.3733**
Irrigation level (IrrL)	3	3.962123	1.320708	26.9266**
IrrF * IrrL	9	19.528502	2.169834	44.2386**
Error	30	1.471454	0.049048	
C. Total	47	35.836698		
CV (%)	3.07			

F values with ** are statistically significant at 1% (P≤0.01).

Kir and Şahan (2019) reported in a cultivar trials, minimum and maximum crude protein ratios (CP) of 7.8 and 10.5%, respectively. The results of this study recorded 5.99 and 9.2% minimum and maximum CP, respectively. At the booting stage, Lyons et al. (2019) reported CP of 12.9 and 7.6% maximum and minimum CP similar to that reported by Kir & Şahan (2019). Moisture and heat stress have been reported to positive affect CP content;

increasing stress increases CP content (Pupo et al. 2022). Result from this study however have different response between irrigation level and frequency. While irrigation level agrees with the previous studies, irrigation frequency from this study recorded the opposite. In effect, the result on irrigation frequency from this study agrees with the findings of Bean et al. (2013). The hypothesis behind the assertion of Pupo et al. (2022) is that, with increasing heat and water stress, photosynthetic apparatus tends to synthesize certain proteins to help in the survival of the plant. The BMR possessing varieties may respond differently (Reich, 2005; Sattler et al. 2010). Furthermore, though the differences are significant, what was observed, in terms of level and frequency of irrigation interaction, was about 3% between the highest and the lowest CP content.

Table 4.4. Average values of sorghum crude protein ratio at different irrigation frequency and irrigation levels

Irrigation Frequency (days)	**Irrigation Levels (%)**				
	25	50	75	100	**Mean**
5	7.16 e	7.81 cd	8.1 bc	8.23 b	**7.83 A**
10	6.11 hi	6.98 ef	6.63 fg	7.32 e	**7.52 B**
15	7.34 e	6.14 hi	7.13 e	6.36 gh	**6.76 C**
20	9.2 a	5.99 i	7.73 d	7.17 e	**6.74 D**
Mean	**7.45 A**	**6.73 C**	**7.40 A**	**7.27 B**	

Values shown with the same letter(s) are statistically not different from each other according to LSD test within 1% ($P \leq 0.01$) error limits.

4.4. Crude Protein Yield

As can be observed from Table 4.7, variations of significant levels have been recorded for crude protein yield for irrigation levels, irrigation frequencies and the interaction between levels and frequencies of irrigation at ($P \leq 0.01$). 6.91% CV shows a high precision with regards to data variability. Table 4.8 shows the mean of crude protein yields for the irrigation treatments.

Table 4.7. The result of variance analysis of crude protein yield as influenced by irrigation frequency and level

Source of variation	**DF**	**Sum of squares**	**Mean square**	**F value**
Replication	2	7.4901	3.74505	0.1797
Irrigation frequency (IrrF)	3	5276.4541	1758.818	84.372**
Irrigation level (IrrL)	3	7583.3365	2527.779	121.2597**
IrrF * IrrL	9	831.9806	92.44229	4.4345**
Error	30	625.3800	20.846	
C. Total	47	14324.6410		
CV	6.90			

F values with ** are statistically significant at 1% (P≤0.01).

The highest crude protein yield was recorded with 100% irrigation level, followed by 75%, 50% and 25% recording 81.06, 74.71, 59.61 and 49.02 kg/da, respectively, all showing significant differences at (P ≤ 0.01). No significant difference was observed between 15- and 20-days irrigation frequencies with regards to crude protein yield.

The highest crude protein yield was observed with 5 days irrigation frequency followed by 10 days irrigation frequency with significant difference between them. 5 days irrigation frequency at 100% and 75% irrigation levels showed no significant difference, producing the highest crude protein yield with interaction between level and frequency of irrigation at (P ≤ 0.01) as can be observed on Table 4.8. The lowest observed crude protein yield for interaction between irrigation levels and frequencies is recorded with 25% level at 10-, 15- and 20-days irrigation frequencies.

Table 4.8. Average values of sorghum crude protein yield at different irrigation frequency and irrigation levels

Irrigation Frequency (days)	**Irrigation Levels (%)**				
	25	50	75	100	**Mean**
5	64.26 e	78.83 bc	95.35 a	97.41 a	**83.97 A**
10	42.71 g	60.59 e	64.93 de	83.1 b	**62.83 B**
15	47.84 fg	50.57 f	66.34 de	65.27 de	**57.51 C**
20	41.26 g	48.45 fg	72.21 cd	78.47 bc	**60.10 BC**
Mean	**49.02 D**	**59.61 C**	**74.71 B**	**81.06 A**	

Values shown with the same letter(s) are statistically not different from each other according to LSD test within 1% (P≤0.01) error limits.

Crude protein yield (CPY) is affected positively by DM and CP (Kir and Şahan, 2019). It therefore follows that, increasing levels and frequencies as affected DM will affect CPY. Interestingly, though Gonulal (2020) used similar cultivars as done in this study, far less CPY was recorded in this study. Crude protein is very important in animal nutrition and forage quality and pricing. The highest yield in this study was 97.41 kg/da whereas that reported by (Kir and Şahan, 2019) and (Gonulal, 2020) are 280 kg/da and 253 kg/da, respectively. At the booting stage, higher CPY is expected (Ball et al. 2001) compared to the studies above. It thus follows that; some physiological factors are in play which are affected by the irrigation treatments.

4.5. Acid Detergent Fibre (ADF)

Table 4.9 shows that significant variations were observed in ADF value at ($P \leq 0.01$) for irrigation levels, frequencies and the interaction between levels and frequencies of irrigation. A lower CV (2.188%) further strengthens the precision of the data, indicating that little variability existed between recorded data, and thus, the differences observed can be attributed to effects of irrigation treatment. On Table 4.10, the means of ADF values as affected by irrigation treatments and their interactions have been presented. With regards to irrigation levels, the highest ADF value was observed with the 100% and 75% (35.37 and 35.32%, respectively) without any significant difference between them. The lowest ADF value was recorded by the 25% irrigation treatment which is significantly different compared to all other treatments at ($P \leq 0.01$). At 5 days irrigation frequency, the highest ADF yield was recorded (37.96%); a value which is significantly different from the other irrigation frequencies at ($P \leq 0.01$). The lowest observed ADF value was recorded with the 20 days irrigation frequency (32.91%). There exists no significant difference between the 10- and 15-days irrigation frequencies for ADF value at ($P \leq 0.01$).

Table 4.9. The result of variance analysis of ADF as influenced by irrigation frequency and level

Source of variation	DF	Sum of squares	Mean square	F value
Replication	2	0.81714	0.40857	0.7125
Irrigation frequency (IrrF)	3	185.54550	61.8485	107.8548**
Irrigation level (IrrL)	3	37.69637	12.56546	21.9123**
IrrF * IrrL	9	16.43373	1.82597	3.1842**
Error	30	17.20326	0.573442	
C. Total	47	257.69600		
CV	2.18			

F values with ** are statistically significant at 1% (P≤0.01).

Irrigating with the 100% level for at 5 days frequency yielded the highest ADF value which is significantly different compared to other treatment at ($P \leq 0.01$). The three other irrigation levels at 5 days irrigation frequency were not significantly different from each other. At 25% irrigation level for 20 days interval, the lowest ADF value was recorded; a value which is significantly different from all other treatments with regard to ADF value at ($P \leq 0.01$).

Table 4.10. Average values of sorghum ADF at different irrigation frequency and irrigation levels

Irrigation Frequency (days)	Irrigation Levels (%)				
	25	50	75	100	**Mean**
5	37.24 b	37.82 ab	37.92 ab	38.86 a	**37.96 A**
10	32.87 ef	33.51 def	33.81 cdef	34.43 cd	**33.65 B**
15	32.59 f	33.91 cde	34.78 c	34.48 cd	**33.94 B**
20	30.01 g	33.14 ef	34.77 cd	33.72 cdef	**32.91 C**
Mean	**33.18 C**	**34.59 B**	**35.32 A**	**35.37 A**	

Values shown with the same letter(s) are statistically not different from each other according to LSD test within 1% (P≤0.01) error limits.

At the booting stage, Lyons et al. (2019) reported a maximum ADF of 32.9% falls within 10 days frequency at 25% level and 20 days frequency at 100% level. In the work of Kir & Şahan (2019), a maximum of 37.5% similar to the value recorded in this study with 5 days frequency at 75% level. In an earlier study, Bean et al. (2013) reported 36.7% for non-

BMR variety and 26.9% for a BMR variety. With increasing moisture stress, ADF values are expected to increase (Bean et al., 2013), however, the results of this study agrees with the theory which states that, robust growth leads to increase in ADF, which is a structural carbohydrate needed to support stem erection (Diepersloot et al. 2021). The work of Pupo et al. (2022) is in line with this observation. The stress factors in this study have not had any effect on ADF content. This observation can be attributed to the fact that, experimental plants under increasing stress have slow growth rate at the early stage, resulting in less demand for structural carbohydrates. Due to the fact that ADF is a complex of lignin (Bean et al., 2013), which is almost indigestible, lower levels of ADF is required for a higher quality feed to release higher energy levels.

4.6. Neutral Detergent Fibre (NDF)

Table 4.11 shows the NDF value variation for the treatments of irrigation levels, frequencies and their interaction. At ($P \leq 0.01$), significant difference was recorded for irrigation levels and frequencies, such however cannot be said for the interaction between irrigation levels and frequencies at ($P \leq 0.01$). CV percentage shows a high precision in data values, indicating that the means did not deviate far from the standard deviation. On Table 4.12, the means for NDF value of the irrigation treatments can be observed. At 75% and 100% irrigation levels, the highest NDF values were recorded.

These values were significantly different from the other treatments at ($P \leq 0.01$). The lowest NDF value was recorded with the 25% irrigation level; with 61.26% NDF, irrigating at 25% level is significantly different from the other higher treatments at ($P \leq 0.01$). Irrigating at 5 days frequency yielded the highest NDF value of 66.95% which is significantly different from the other treatments. Interestingly, the mean NDF values for 10- and 20-days irrigation frequencies show no significant difference at ($P \leq 0.01$). Irrigating at 15 days frequency yielded the second significantly higher mean value of NDF.

Table 4.11. The result of variance analysis of NDF as influenced by irrigation frequency and level

Source of variation	**DF**	**Sum of squares**	**Mean square**	**F value**
Replication	2	6.76489	3.382445	1.9194
Irrigation frequency (IrrF)	3	289.76356	96.58785	54.8110**
Irrigation level (IrrL)	3	78.24251	26.08084	14.8002**
IrrF * IrrL	9	38.20437	4.24493	2.4089
Error	30	52.86591	1.762197	
C. Total	47	465.84123		
CV (%)	2.10			

F values with ** are statistically significant at 1% (P≤0.01).

NDF value of 57% was reported by Lyons et al. (2019) at the booting stage. This agrees with the report of Kir and Şahan (2019) when their highest reported NDF was 57.5%. These reports are similar to the lowest value recorded in this study. With normal sorghum varieties, increasing moisture stress increases NDF levels. In the BMR varieties however, less stress conditions led to increased NDF levels (Pupo et al., 2022). This conclusion agrees with the observations in this study. Increasing levels of irrigation increased NDF values. However, a mixed result was observed with regards to irrigation frequency in this study. Bulk of a forage fibre is NDF which consequently determines the amount of feed an animal can consume at a time (Bean et al., 2013). Higher NDF generally implies that less energy will be taken by the animal. This can be different with the BMR gene in play (Pupo et al., 2022). As a result, higher NDF values with the BMR variety does not directly result in poor quality feed.

Table 4.12. Average values of sorghum NDF at different irrigation frequency and irrigation levels

Irrigation Frequency (days)	**Irrigation Levels (%)**				
	25	50	75	100	**Mean**
5	65.08	65.55	67.53	69.65	**66.95 A**
10	59.7	60.92	62.4	62.38	**61.35 C**
15	62.45	63.07	64.79	62.34	**63.17 B**
20	57.81	60.09	63.54 e	60.95	**60.60 C**
Mean	**61.26 C**	**62.41 B**	**64.57 A**	**63.83 A**	

Values shown with the same letter(s) are statistically not different from each other according to LSD test within 1% (P≤0.01) error limits.

4.7. Digestible Dry Matter (DDM) Ratio

Table 4.13 shows variations of digestible dry matter (DDM) ratio as affected by irrigation levels and frequencies and their interactions. Significant differences were observed at ($P \leq 0.01$) for irrigation levels, irrigation frequencies and the interaction between irrigation levels and frequencies. With a CV value of less than 1%, the precision of the data can be said to be very high. On Table 4.14, the averages of DDM ratio are presented with their statistical differences as affected by irrigation levels, frequencies and their interactions. The highest DDM was recorded with 20 days irrigation frequency (63.26%) and the least was recorded with 5 days irrigation frequency (59.33%). 10- and 15-days irrigation frequencies exhibited no significant differences at ($P \leq 0.01$).

With regards to irrigation levels, 25% recorded the highest DDM followed by 50%. No statistical differences were recorded between 75% and 100%. DDMs of 63.06, 61.95, 61.39 and 61.34% were recorded in order of increasing irrigation levels.

Table 4.13. The result of variance analysis of DDM as influenced by irrigation frequency and level

Source of variation	DF	Sum of squares	Mean square	F value
Replication	2	0.49587	0.247935	0.7125
Irrigation frequency (IrrF)	3	112.59662	37.53221	107.8548**
Irrigation level (IrrL)	3	22.87570	7.625233	21.9123**
IrrF * IrrL	9	9.97266	1.108073	3.1842**
Error	30	10.43965	0.347988	
C. Total	47	156.38050		
CV	0.95			

F values with ** are statistically significant at 1% ($P \leq 0.01$).

The interaction of 5 days irrigation frequency at 100% irrigation level yielded the lowest DDM value, which compared to the other interactions is significantly different. The highest DDM value is recorded with the 20 days irrigation frequency at 25% irrigation level. Higher DDMs were observed along lower irrigation levels as well as higher irrigation frequencies.

Table 4.14. Average values of sorghum DDM at different irrigation frequency and irrigation levels

Irrigation Frequency (days)	Irrigation Levels (%)				
	25	50	75	100	**Mean**
5	59.89 f	59.44 fg	59.36 fg	58.63 g	**59.33 C**
10	63.29 bc	62.8 bcd	62.56 bcde	62.08 de	**62.68 B**
15	63.51 b	62.49 cde	61.8 e	62.04 de	**62.46 B**
20	65.52 a	63.09 bc	61.81 de	62.63 bcde	**63.26 A**
Mean	**63.06 A**	**61.95 B**	**61.39 C**	**61.34 C**	

Values shown with the same letter(s) are statistically not different from each other according to LSD test within 1% ($P \leq 0.01$) error limits.

At the highest stress level, this study recorded DDM (65.52%) content similar that reported by Kir and Şahan (2019), the lowest stress levels in this study recorded the lowest DDM (58.63%) which is slightly lower than that reported by Kir and Şahan (2019). These observations were expected following the increasing ADF content with decreasing stress of irrigation. It was established that, ADF is the main variable for determining DDM as presented in the function employed by Morrison et al. (2009). With increasing ADF content, DDM content reduces as ADF is inversely proportional to DDM. This assertion is counter the observation reported by Pupo et al. (2022). The difference in reported results may be attributed to the differences in method of calculating digestibility or digestible dry matter. Pupo et al. (2022) presented their data as a percentage of NDF_{30h} whereas, in this study, the results are presented as a percentage of dry matter. Higher DDM is expected with the BMR trait. This is evident in this study compared with the results recorded by (Bean et al. 2013; Pupo et al. 2022) when the yield of other cultivars was reported.

4.8. Dry Matter Intake (DMI) Ratio

The variance analysis of dry matter intake (DMI), as affected by irrigation levels and frequencies and their interactions, presented on Table 4.15 shows significant difference with irrigation levels and irrigation frequencies, however, no significant difference was observed with their interactions at ($P \leq 0.01$). Higher precision was as well recorded in terms of data variation when the CV value (2.14%) was considered. On Table 4.16, the means of DMI as influenced by irrigation treatment are presented, showing statistical differences produced as result of the treatments. A decreasing can be observed as irrigation levels increases. DMI of 1.963, 1.926, 1.861 and 1.886% were recorded in increasing order of irrigation levels. No significant differences were observed with 75% and 100% irrigation levels. Considering irrigation frequencies, the least DMI was recorded when 5 days intervals were applied. 10- and 20-days irrigation frequencies have no significant difference statistically. 15 days irrigation frequency averaged with the second DMI value which is statistically different from other treatments.

Table 4.15. The result of variance analysis of DMI as influenced by irrigation frequency and level

Source of variation	**DF**	**Sum of squares**	**Mean square**	**F value**
Replication	2	0.005848	0.002924	1.7487
Irrigation frequency (IrrF)	3	0.253319	0.08444	50.5034**
Irrigation level (IrrL)	3	0.073506	0.024502	14.6545**
IrrF * IrrL	9	0.033922	0.003769	2.2543
Error	30	0.050159	0.001672	
C. Total	47	0.416753		
CV	2.14			

F values with ** are statistically significant at 1% ($P \leq 0.01$).

An average of 2% DMI is expected of good quality forage (Government of South Australia, 2022). This helps to ensure that, the animal fed ration of such quality gains enough energy and nutrients to support maintenance and production. In a study, Aydin et al. (1999) reported 3.7 and 4.2% DMI for the BMR variety. This is higher than that reported in this study. Due to the fact that DMI is affected by NDF content, and that slow development of the plants in this experiment affected the NDF content with increasing moisture stress, the highest DMI was recorded by the treatment with the highest stress values (20 days frequency at 25% irrigation level). Pupo et al. (2022) reported DMI values similar to that reported by Aydin et al. (1999). The observed lower DMI values in this study compared to previous studies may be attributed to the higher values of NDF; as NDF content directly affects DMI according to the formula used by (Morrison et al. 2009). Above 50% irrigation levels of this study, approximately 2% DMI was recorded, which agrees with the optimum values published by the Government of South Australia (2022). As such, forage crops produced under this study can be effectively used in the feeding of animals. The exception may be with dairy cattle which require higher DMI values due to their higher energy requirement.

Table 4.16. Average values of sorghum DMI at different irrigation frequency and irrigation levels

Irrigation Frequency (days)	**Irrigation Levels (%)**				
	25	50	75	100	**Mean**
5	1.845	1.832	1.777	1.723	**1.794 C**
10	2.012	1.971	1.924	1.925	**1.958 A**
15	1.921	1.903	1.853	1.925	**1.901 B**
20	2.076	1.998	1.889	1.969	**1.983 A**
Mean	**1.963 A**	**1.926 B**	**1.861 C**	**1.886 C**	

Values shown with the same letter(s) are statistically not different from each other according to LSD test within 1% ($P \leq 0.01$) error limits.

4.9. Relative Feed Value (RFV)

On Table 4.17, the variance analysis is presented for relative feed value of the sorghum crop as influenced by irrigation levels and frequencies. Independently, irrigation levels and irrigation frequencies treatments varied significantly statistically at ($P \leq 0.01$). No significant difference was however observed when the interactions between levels and frequencies of irrigation treatments were considered at ($P \leq 0.01$). Considering the CV value, it can be said that precision was high owning to the fact that data points were not too far from the standard deviation.

From Table 4.18, we observe that RFV increases with decreasing irrigation levels and frequencies. The highest RFV was recorded with 25% irrigation level (96.1), followed by 50% (92.56). Irrigating at 75% and 100% levels averaged in no significant difference at ($P \leq 0.01$). On irrigation frequency, no significant difference was observed between 10- and 20-days frequencies, which produced the highest RFVs of 95.17 and 97.32 respectively.

Table 4.17. The result of variance analysis of RFV as influenced by irrigation frequency and level

Source of variation	DF	Sum of squares	Mean square	F value
Replication	2	21.6618	10.8309	1.5324
Irrigation frequency (IrrF)	3	1533.6996	511.2332	72.3305**
Irrigation level (IrrL)	3	399.9440	133.3147	18.8617**
IrrF * IrrL	9	161.8617	17.98463	2.5446
Error	30	212.0405	7.068017	
C. Total	47	2329.2149		
CV	2.89			

F values with ** are statistically significant at 1% (P≤0.01).

RFV is about the ultimate parameter used in the evaluation of forage quality. A 100% RFV is the *in vitro* analysis result of a full-bloom Alfalfa hay; an interaction of DMI and DDM of a given forage (Morrison et al. 2009). Results from this study fall within the third grade of hay quality scale as reported by Cherney and Parsons (2020), which results in it being a degree lower than what was reported by Ball et al. (2001) for forage of similar growth stage. The difference in RFV of this study compared to that reported by Ball et al. (2001) may be attributed to the differences in adaptation of the crops to seasons.

Table 4.18. Average values of sorghum RFV at different irrigation frequency and irrigation levels

Irrigation Frequency (days)	**Irrigation Levels (%)**				
	25	50	75	100	**Mean**
5	85.63	84.40	81.78	78.32	**82.53 C**
10	98.72	95.94	93.32	92.70	**95.17 A**
15	94.60	92.19	88.76	92.59	**92.04 B**
20	105.45	97.73	90.51	95.60	**97.32 A**
Mean	**96.10 A**	**92.56 B**	**88.59 C**	**89.80 C**	

Values shown with the same letter(s) are statistically not different from each other according to LSD test within 1% (P≤0.01) error limits.

Whereas sorghum is a warm season crop, grasses reported by Ball et al. (2001) are cool-season crops. Furthermore, owning to the fact that ADF and NDF play significant role in determining RFV per the formula applied in its calculation (Morrison et al. 2009), and that this study recorded higher ADF and NDF values with decreasing moisture stress, lower RFV were expected for reducing moisture stress treatment. With the BMR trait, true RFV may be different from what was reported using in vitro methods due to the observation that, BMR varieties have higher digestible NDF as compared to non-BMR varieties (Cherney and Parsons, 2020). Wedig et al. (1987) in an earlier study reported an observation similar to this assertion. Hence, it can be said that forage produced from this study are all of good quality and differentiation for selection may be based on individual parameters rather than RFV.

5. CONCLUSION AND RECOMMENDATION

This section of the study will try to answer the research questions posed in the introduction as derived from the research objectives. Furthermore, recommendations will be deduced with regards to the results of the analysis of data.

5.1. Conclusion

This thesis was carried out to answer three fundamental questions; what the most effective irrigation frequency of silage sorghum is; what the optimum irrigation level is; and what the quality of silage sorghum produced under drip irrigation is. Ultimately, the thesis sort to evaluate the yield characteristics of sorghum silage in response to frequency and levels (amount) of irrigation. This is to help build adaptive capacity for the changing climate especially for regions of high expected impacts. With the climate tolerance of the sorghum crop (Hossain et al. 2022) along with the superiority of the BMR trait in terms of forage quality (Bean et al., 2013; Ledgerwood et al., 2009; Miller and Stroup, 2003; Sattler et al., 2010), an irrigation program may add significantly to the feed production industry and science of field crops management.

Irrigation frequency has been observed to affect sorghum yield and quality across all parameters. 10 days irrigation frequency yielded the highest RFV, DMI and the second highest DDM, being significantly different from other treatments. The 10 days irrigation frequency also consistently recorded on average the second highest values with regards to green forage yield, dry matter yield, crude protein ratio, crude protein yield, ADF and NDF contents. The 5 days irrigation frequency yielded about 147 kg/da on average more dry matter than the 10 days irrigation frequency. However, this led to a relatively lower forage quality compared to lower frequencies, a difference with statistical significance. Fibre characteristics were affected by the growth rates of plants as affected by changes in moisture stress due to difference in irrigation frequency. With increasing stress, sorghum plants were observed to decrease robustness, which further limited the production of structural carbohydrates, as a result, higher quality parameters were observed.

This study therefore concludes that, after observing the effect of moisture stress on yield and forage characteristics, 10 days irrigation frequency is the most effective. This is due to the observation that, superior forage characteristics were recorded amidst a lower yield loss. Furthermore, lower frequencies were unsuitable, though with higher forage quality, since dry matter yields were significantly affected.

The highest yields, both green and dry matter content, were recorded by 100% irrigation level followed by 75% irrigation level on average, with differences of statistical significance. Juxtaposing green-herbage with dry matter content, relatively lower difference was observed. As such, though the highest yields were recorded by the 100% irrigation level, it can be concluded that, the optimum irrigation level demand for silage sorghum is at 75%. With regards to forage quality characteristics, irrigating at 75% recorded a significantly higher CP and similar average results as 100% for ADF, NDF and their derivatives. Generally, irrigation levels affected the yield and quality characteristics of sorghum plants. However, at the lowest stress level, relatively lower forage characteristics were recorded due to increase in ADF and NDF. Further studies may be needed to confirm the DDM at higher irrigation levels since the BMR cultivars are reported to have higher DNDF.

Irrigation has been observed to influence fibre characteristics, protein content and yield, and ultimately the value of forage. Lower irrigation levels resulted in higher forage characteristics based on the method used for computing quality parameters, but with very low yield parameter. Sorghum crop under slight moisture stress yielded a higher forage characteristic with a slight decrease in yield parameters. Interaction between irrigation frequencies and irrigation levels have consistently been observed to yield statistically different outcomes as affected by the treatments.

Finally, after evaluating the results of the yield and forage quality characteristics parameters from this study, it can be concluded that, both irrigation frequency and level have effect on the yield and forage quality characteristics. Furthermore, slight moisture stress yielded the optimum outcome, balancing yield and quality characteristics.

5.2. Recommendations

As a way of recommendation after considering the results of this study;

- Green herbage yields and dry herbage yields were highest at max irrigation both in terms of irrigation amount and irrigation interval. Reducing irrigation interval increased green and dry herbage yields under all irrigation water amounts (levels). This result shows that the crop may respond better under more luxury conditions untested in this study such as %125 irrigation level under 5 days interval with more nitrogen fertilizer. Future studies in Southeast Anatolia conditions of Turkey might include higher amounts of water and nitrogen fertilizer applications.

- Also, protein yield per decare was highest under max irrigation (under 100% level and under 5-day intervals). This was probably due to more nitrogen scavenging by roots from deep soil levels as water penetrated more with high irrigation levels and frequency.

- More irrigation water with more nitrogen under deep ploughed soil (1-1.5 m depth) may increase both yields and quality of sorghum under Bingöl conditions.

- Irrigating at 25% level with 10 days frequency will produce a high-quality forage though there will be significant loss in yield.

- Further studies should be conducted to ascertain the true digestibility of the BMR trait *in vivo*.

REFERENCES

Ahmed El-Imam, A. M., Greetham, D., Du, C., and Dyer, P. S. (2019). The development of a biorefining strategy for the production of biofuel from sorghum milling waste. *Biochemical Engineering Journal*, *150* (February), 107288. https://doi.org/10.1016/j.bej.2019.107288.

Ali, M. N. (2010). *Fundamentals of Irrigation and On-farm Water Management*. London: Springer Science and Business Media, LLC.

Araya, A., Jha, P. K., Zambreski, Z., Faye, A., Ciampitti, I. A., Min, D., … Prasad, P. V. V. (2022). Evaluating crop management options for sorghum , pearl millet and peanut to minimize risk under the projected midcentury climate scenario for different locations in Senegal. *Climate Risk Management*, *36* (May 2021), 1–17. https://doi.org/10.1016/j.crm.2022.100436.

Armah-Agyeman, G., Loiland, J., Karow, R., & Bean, B. (2002). *Sudangrass*, p. 1–6. Oregon State University Extension Service.

Arumugam, P., Chemura, A., Aschenbrenner, P., Schauberger, B., and Gornott, C. (2022). Climate change impacts and adaptation strategies : An assessment on sorghum for Burkina Faso. *European Journal of Agronomy*, *142*(October), 1–26. https://doi.org/10.1016/j.eja.2022.126655.

Assefa, Y., Roozeboom, K., Thompson, C., Schlegel, A., Stone, L., and Lingenfelser, J. E. (2014). *Corn and Grain Sorghum Comparison: All Things Considered*. Elsevier Inc.

Atis, I., Konuskan, O., Duru, M., Gozubenli, H., and Yilmaz, S. (2012). Effect of harvesting time on yield, composition and forage quality of some forage sorghum cultivars. *International Journal of Agriculture and Biology*, *14* (6), 879–886.

Aydin, G., Grant, R. J., and O'Rear, J. (1999). Brown midrib sorghum in diets for lactating dairy cows. *Journal of Dairy Science*, *82* (10), 2127–2135. https://doi.org/10.3168/jds.S0022-0302(99)75456-1.

Aydinsakir, K., Buyuktas, D., Dinç, N., Erdurmus, C., and Bayram, E. (2021). Yield and bioethanol productivity of sorghum under surface and subsurface drip irrigation. *Agricultural Water Management, 243* (August), 1–13. https://doi.org/10.1016/j.agwat.2020.106452.

Ball, D., Collins, M., Lacefield, G., Martin, N., Mertens, D., Olson, K., … Wolf, M. (2001). *Understanding forage quality*.

Bean, B. W., Baumhardt, R. L., McCollum, F. T., and McCuistion, K. C. (2013). Comparison of sorghum classes for grain and forage yield and forage nutritive value. *Field Crops Research*, *142*, 20–26. https://doi.org/10.1016/j.fcr.2012.11.014.

Bezner Kerr, R., Hasegawa, T., Lasco, R., Bhatt, I., Deryng, D., Farrell, A., … Thornton, P. (2022). Food, Fibre and Other Ecosystem Products. In H.-O. Pörtner, D. C. Roberts, M. Tignor, E. S. Poloczanska, K. Mintenbeck, A. Alegría, … B. Rama (Eds.), *Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*, p. 713–906. https://doi.org/10.1017/9781009325844.007.714.

Bhat, B. V. (2019). Breeding forage sorghum. In *Breeding Sorghum for Diverse End Uses* (pp. 175–191). https://doi.org/10.1016/B978-0-08-101879-8.00011-5.

Bhattarai, B., Singh, S., West, C. P., Ritchie, G. L., and Trostle, C. L. (2020). Water Depletion Pattern and Water Use Efficiency of Forage Sorghum, Pearl millet, and Corn Under Water Limiting Condition. *Agricultural Water Management*, *238* (November 2019), 106206. https://doi.org/10.1016/j.agwat.2020.106206.

Bingöl Valiliği. (2018). Coğrafi Durumu. Retrieved from https://bingol.csb.gov.tr/cografi-durumu-i-1393#:~:text=İKLİM%3A Kuzeyden sokulan nemli-serin,ortalama sıcaklık 12%2C1 derecedir.

Chadalavada, K., Guna, K., Kumari, B. D. R., and Kumar, T. S. (2022). Drought stress in sorghum: impact on grain quality. In *Climate Change and Crop Stress*, p. 113–134. https://doi.org/10.1016/B978-0-12-816091-6.00003-1.

Chen, S., and Gong, B. (2021). Response and adaptation of agriculture to climate change : Evidence. *Journal of Development Economics*, *148*, 1–17. https://doi.org/10.1016/j.jdeveco.2020.102557.

Cherney, D. J., and Parsons, D. (2020). Predicting Forage Quality. In *FORAGES: The Science of Grassland Agriculture*, 7th ed., p. 687–699.

Choudhary, S., Guha, A., Kholova, J., Pandravada, A., Messina, C. D., Cooper, M., and Vadez, V. (2020). Maize , sorghum , and pearl millet have highly contrasting species strategies to adapt to water stress and climate change-like conditions. *Plant Science*, *295*(October), 1–14. https://doi.org/10.1016/j.plantsci.2019.110297.

Corson, D. C., Waghorn, G. C., Ulyatt, M. J., and Lee, J. (1999). NIRS: Forage analysis and livestock feeding. *Proceedings of the New Zealand Grassland Association*, *61*, 127–132. https://doi.org/10.33584/jnzg.1999.61.2340.

Currie, R. S., and Kisekka, I. (2014). Corn and grain sorghum response to limited irrigation, drought, and hail. *Applied Engineering in Agriculture*, *30*(6), 915–924. https://doi.org/10.13031/aea.30.10810.

de Morais Cardoso, L., Pinheiro, S. S., Martino, H. S. D., and Pinheiro-Sant'Ana, H. M. (2017). Sorghum (Sorghum bicolor L.): Nutrients, bioactive compounds, and potential impact on human health. *Critical Reviews in Food Science and Nutrition*, *57*(2), 372–390. https://doi.org/10.1080/10408398.2014.887057.

Diepersloot, E. C., Paula, E. M., Sultana, H., van Santen, E., Wallau, M. O., and Ferraretto, L. F. (2021). Effects of seeding rate and hybrid relative maturity on yield, nutrient composition, ruminal in vitro neutral detergent fiber digestibility, and predicted milk yield of dairy cows in whole-plant corn forage in subtropical conditions. *Applied Animal Science*, *37*(2), 106–114. https://doi.org/10.15232/aas.2020-02082.

Dun, O., Klocker, N., Farbotko, C., and Mcmichael, C. (2022). Climate change adaptation in agriculture : Learning from an international labour mobility programme in Australia and the Pacific Islands region. *Environmental Science and Policy*, *139*(November), 250–273. https://doi.org/10.1016/j.envsci.2022.10.017.

Düzgüneş, O., Kesici, T., and Gürbüz, F. (1983). *İstatistik Metodları*. Ankara Üniversitesi.

El-mageed, T. A. A., Rady, M. O. A., El-wahed, M. H. A., El-mageed, S. A. A., Omran, W. M., Aljuaid, B. S., … Abdou, N. M. (2022). Consecutive seasonal effect on yield and water productivity of drip deficit irrigated sorghum in saline soils. *Saudi Journal of Biological Sciences*, *29*(4), 2683–2690. https://doi.org/10.1016/j.sjbs.2021.12.045.

Erramouspe, H. (2021). The Global Significance Of Sorghum – Africa. *Summer 2021 Issue of Sorghum Grower Magazine*, 1–4.

FAO. (2018). World Food and Agriculture: Statistical Pocketbook. In *The Lancet*. https://doi.org/10.1016/S0140-6736(59)91820-3.

Fulgueira, C. L., Amigot, S. L., Gaggiotti, M., Romero, L. A., and Basílico, J. C. (2007). Forage Quality : Techniques for Testing. *Global Science Books*, *1*(2), 121–131.

Garofalo, P., and Rinaldi, M. (2013). Water-use efficiency of irrigated biomass sorghum in a Mediterranean environment. *Spanish Journal of Agricultural Research*, *11*(4), 1153–1169.

George, T. T., Obilana, A. O., Oyenihi, A. B., Obilana, A. B., Akamo, D. O., and Awika, J. M. (2022). Trends and progress in sorghum research over two decades , and implications for global food security. *South African Journal of Botany*, *151*, 960–969. https://doi.org/10.1016/j.sajb.2022.11.025.

Getachew, F., Bayabil, H. K., Hoogenboom, G., and Teshome, F. T. (2021). Irrigation and shifting planting date as climate change adaptation strategies for sorghum. *Agricultural Water Management*, *255*(June), 1–18. https://doi.org/10.1016/j.agwat.2021.106988.

Gonulal, E. (2020). PERFORMANCE OF SORGHUM - SUDAN GRASS HYBRID (Sorghum bicolor L. - Sorhgum sudanense) CULTIVARS UNDER WATER STRESS CONDITIONS OF ARID AND SEMI-ARID REGIONS. *Journal of Global Innovations in Agricultural and Social Sciences*, *8*(2), 78–82. https://doi.org/10.22194/jgiass/8.908.

Government of South Australia. (2022). *Calculating Dry Matter Intakes for Various Classes of Stock*. Retrieved from https://pir.sa.gov.au/__data/assets/pdf_file/0007/272869/Calculating_dry_matter_intakes.pdf.

GULTEKIN, R., AVAĞ, K., GÖRGİŞEN, C., ÖZTÜRK, Ö., YETER, T., and ALSAN, P. B. (2022). Effect of deficit irrigation practices on greenhouse gas emissions in drip irrigation. *Scientia Horticulturae*, *310*(December), 1–12. https://doi.org/10.1016/j.scienta.2022.111757.

Hanapi, S. Z., Awad, H., Mat sarip, S. hajar, Aziz, R., Sarmidi, M., and Ali, S. (2012). *Animal Feed*.

Hossain, M. S., Islam, M. N., Rahman, M. M., Mostofa, M. G., and Khan, M. A. R. (2022). Sorghum: A prospective crop for climatic vulnerability, food and nutritional security. *Journal of Agriculture and Food Research*, *8*(April), 1–9. https://doi.org/10.1016/j.jafr.2022.100300.

IPCC. (2007). Climate Change 2007: impacts, adaptation and vulnerability. In M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. E. Hanson (Eds.), *contribution of Working Group II to the fourth assessment report of the Intergovernmental Panel on Climate Change*. https://doi.org/10.1256/004316502320517344.

IPCC. (2014). *Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* (C. B. Field, V. R. Barros, D. J. Dokken, K. J. Mach, M. D. Mastrandrea, T. E. Bilir, … L. L. White, Eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Jardim, A. M. da R. F., Silva, G. Í. N. da, Biesdorf, E. M., Pinheiro, A. G., Silva, M. V. da, Araújo Júnior, G. do N., … Silva, T. G. F. da. (2020). Production potential of Sorghum bicolor (L.) Moench crop in the Brazilian semiarid: review. *Pubvet*, *14*(4), 1–13. https://doi.org/10.31533/pubvet.v14n4a550.1-13.

Joy, S. P., and Krishnan, C. (2022). Modified organosolv pretreatment for improved cellulosic ethanol production from sorghum biomass. *Industrial Crops and Products*, *177*(December 2021), 114409. https://doi.org/10.1016/j.indcrop.2021.114409.

Kayodé, A. P. P., Bara, C. A., Dalodé-Vieira, G., Linnemann, A. R., and Nout, M. J. R. (2012). Extraction of antioxidant pigments from dye sorghum leaf sheaths. *Lwt*, *46*(1), 49–55. https://doi.org/10.1016/j.lwt.2011.11.003.

Keskin, B., Akdeniz, H., Temel, S., and Eren, B. (2018). Determination of agricultural characteristics of some silage sorghum and Sudan Grass varieties grown as second product. *Yuzuncu Yil University Journal of Agricultural Sciences*, *28*(4), 412–418. https://doi.org/10.29133/yyutbd.358318.

Kir, H., and Şahan, B. D. (2019). Yield and Quality Feature of Some Silage Sorghum and Sorghum-Sudangrass Hybrid Cultivars in Ecological Conditions of Kırşehir Province Kırşehir. *TURKISH JOURNAL of AGRICULTURAL and NATURAL SCIENCES*, *6*(3), 388–395.

Kothari, K., Ale, S., Bordovsky, J. P., Porter, D. O., Munster, C. L., and Hoogenboom, G. (2020). Potential bene fi ts of genotype-based adaptation strategies for grain sorghum production in the Texas High Plains under climate change. *European Journal of Agronomy*, *117*(May), 1–15. https://doi.org/10.1016/j.eja.2020.126037.

Krampah, C., Nyanzu, F., Quaye, A., Adu, P., Asiamah, E. A., Aboagye, B., and Simpong, D. L. (2021). Crude extracts from Allium cepa skin and Sorghum bicolor seed can provide as non-toxic and eco-friendly cytoplasmic stains. *Practical Laboratory Medicine*, *26*(June), 1–6. https://doi.org/10.1016/j.plabm.2021.e00239.

Ledgerwood, D. N., DePeters, E. J., Robinson, P. H., Taylor, S. J., and Heguy, J. M. (2009). Assessment of a brown midrib (BMR) mutant gene on the nutritive value of sudangrass using in vitro and in vivo techniques. *Animal Feed Science and Technology*, *150*(3–4), 207–222. https://doi.org/10.1016/j.anifeedsci.2008.10.001.

Li, J., Lin, H., Bean, S. R., Sun, X. S., and Wang, D. (2020). Evaluation of adhesive performance of a mixture of soy, sorghum and canola proteins. *Industrial Crops and Products*, *157*(August), 112898. https://doi.org/10.1016/j.indcrop.2020.112898.

Li, S. S., Zhang, J. J., Bai, Y. F., Degen, A. A., Wang, T., Shang, Z. H., … Long, R. J. (2020). Sorghum silage substituted for corn silage in diets for dairy cows: Effects on feed intake, milk yield and quality, and serum metabolites. *Applied Animal Science*, *36*(2), 228–236. https://doi.org/10.15232/aas.2019-01923.

Liu, M., Wu, X., and Yang, H. (2022). Evapotranspiration characteristics and soil water balance of alfalfa grasslands under regulated deficit irrigation in the inland arid area of Midwestern China. *Agricultural Water Management*, *260*(July), 1–12. https://doi.org/10.1016/j.agwat.2021.107316.

Lyons, S. E., Ketterings, Q. M., Godwin, G. S., Cherney, D. J., Cherney, J. H., Van Amburgh, M. E., … Kilcer, T. F. (2019). Optimal harvest timing for brown midrib forage sorghum yield, nutritive value, and ration performance. *Journal of Dairy Science*, *102*(8), 7134–7149. https://doi.org/10.3168/jds.2019-16516.

Marsalis, M. A. (2011). ADVANTAGES OF FORAGE SORGHUM FOR SILAGE IN LIMITED INPUT SYSTEMS. *Proceedings, 2011 Western Alfalfa & Forage Conference, Las Vegas*, 11–13.

McCary, C. L., Vyas, D., Faciola, A. P., and Ferraretto, L. F. (2020). Graduate Student Literature Review: Current perspectives on whole-plant sorghum silage production and utilization by lactating dairy cows. *Journal of Dairy Science*, *103*(6), 5783–5790. https://doi.org/10.3168/jds.2019-18122.

Meena, K., Visarada, K., and Meena, D. K. (2022). Sorghum bicolor (L.) Moench a multifarious crop -fodder to therapeutic potential and biotechnological applications: A future food for the millennium. *Future Foods*, *6*(May), 100188. https://doi.org/10.1016/j.fufo.2022.100188.

Mertens, D. R., and Grant, R. J. (2020). Digestibility and Intake. In *Forages: The Science of Grassland Agriculture*, p. 609–632.

Miller, F. R., and Stroup, J. A. (2003). *BROWN MIDRIB FORAGE SORGHUM, SUDANGRASS, AND CORN: WHAT IS THE POTENTIAL?*, p. 1–9.

Moore, K. J., Curtiss, C. F., Lenssen, A. W., and Fales, S. L. (2020). Factors Affecting Forage Quality. In *Forages: The Science of Grassland Agriculture*, Vol. 2, p. 701–717. https://doi.org/10.2307/3899429.

Morrison, J., Barnhart, S., and Johnson, K. (2009). Hay and Pasture. In *Illinois Agronomy Handbook*, p. 65–81. Retrieved from http://extension.cropsciences.illinois.edu/handbook/pdfs/chapter06.pdf.

Motsi, H., Molapo, M., and Phiri, E. E. (2022). A review of the adaptive capacity of sweet sorghum to improve food security and poverty alleviation in sub-Saharan Africa. *South African Journal of Botany*, *150*, 323–329. https://doi.org/10.1016/j.sajb.2022.07.040.

Moursy, M. A. M., Elfetyany, M., Meleha, A. M. I., and El-bialy, M. A. (2022). Productivity and profitability of modern irrigation methods through the application of on-farm drip irrigation on some crops in the Northern Nile Delta of Egypt. *Alexandria Engineering Journal*, *62*, 349–356. https://doi.org/10.1016/j.aej.2022.06.063.

Neto, A. B., Reis, R. H. P. dos, Cabral, L. da S., Abreu, J. G. de, Sousa, D. D. P., and de Sousa, F. G. (2017). Nutritional value of sorghum silage of different purposes. *Ciência e Agrotecnologia*, *41*(3), 288–299.

New, L. (2021). *Grain Sorghum Irrigation*.

Newman, Y. C., Lambert, B., and Muir, J. P. (2013). *Forage Quality*.

Patias, B., Bondesan, L., Alves, E., Pinheiro, R., Ortiz, B. V, Trimer, G., and Kumar, H. (2022). Determination of irrigation scheduling thresholds based on HYDRUS-1D simulations of field capacity for multilayered agronomic soils in Alabama, USA. *Agricultural Water Management*, *259*(May 2021), 1–15. https://doi.org/10.1016/j.agwat.2021.107234.

Paye, W. S., Acharya, P., and Ghimire, R. (2022). Water productivity of forage sorghum in response to winter cover crops in semi-arid irrigated conditions. *Field Crops Research*, *283*(April), 1–9. https://doi.org/10.1016/j.fcr.2022.108552.

Pedersen, J. F., Vogel, K. P., and Funnell, D. L. (2005). Impact of reduced lignin on plant fitness. *Crop Science*, *45*(3), 812–819. https://doi.org/10.2135/cropsci2004.0155.

Pennells, J., Cruickshank, A., Chaléat, C., Godwin, I. D., and Martin, D. J. (2021). Sorghum as a novel biomass for the sustainable production of cellulose nanofibers. *Industrial Crops and Products*, *171*(August). https://doi.org/10.1016/j.indcrop.2021.113917.

Philp, T., and Harris, G. (2010). Irrigated sorghum – best practice guide Key point. In *Irrigation management of grain crops* (pp. 298–304). Retrieved from http://www.insidecotton.com/jspui/bitstream/1/555/28/4_2 Irrigated Sorghum best practice Cotton WATERpak.pdf.

Phogat, V., Petrie, P. R., Collins, C., and Bonada, M. (2023). Plant available water capacity of soils at regional scale : Analysis of fixed and dynamic field capacity. *Pedosphere*. https://doi.org/10.1016/j.pedsph.2022.11.003.

Pupo, M. R., Wallau, M. O., and Ferraretto, L. F. (2022). Effects of season, variety type, and trait on dry matter yield, nutrient composition, and predicted intake and milk yield of whole-plant sorghum forage. *Journal of Dairy Science*, *105*(7), 5776–5785. https://doi.org/10.3168/jds.2021-21706.

Rashwan, A. K., Yones, H. A., Karim, N., Taha, E. M., and Chen, W. (2021). Potential processing technologies for developing sorghum-based food products: An update and comprehensive review. *Trends in Food Science and Technology*, *110*(February), 168–182. https://doi.org/10.1016/j.tifs.2021.01.087.

Raza, T., Yahya Khan, M., Mahmood Nadeem, S., Imran, S., Nazir Qureshi, K., Naeem Mushtaq, M., … Samuel Eash, N. (2021). Biological management of selected weeds of wheat through co-application of allelopathic rhizobacteria and sorghum extract. *Biological Control*, *164*(October), 104775. https://doi.org/10.1016/j.biocontrol.2021.104775.

Reddy, R. N. (2010). *Irrigation Engineering*. New Delhi: Gene-Tech Books.

Reich, J. M. (2005). UTILIZING THE BMR TRAIT IN SUDANGRASS AND SORGHUMS. *California Alfalfa and Forage Symposium*, p. 12–14.

Robertson, B. B., Carrick, S. T., Almond, P. C., Mcneill, S., Penny, V., Chau, H. W., and Smith, C. M. S. (2021). Predicting field capacity in undisturbed stony soils. *Geoderma*, *401*, 1–11. https://doi.org/10.1016/j.geoderma.2021.115346.

Samoy-pascual, K., Lampayan, R. M., Remocal, A. T., Orge, R. F., Tokida, T., and Mizoguchi, M. (2022). Optimizing the lateral dripline spacing of drip-irrigated aerobic rice to increase water productivity and profitability under the water-limited condition. *Field Crops Research*, *287*(August), 1–11. https://doi.org/10.1016/j.fcr.2022.108669.

Sanderson, M. A., Miller, F. R., and Jones, R. M. (1995). Forage quality and agronomic traits of experimental forage sorghum hybrids. *Texas Agricultural Experiment Station*, (January).

Sattler, S. E., Funnell-Harris, D. L., and Pedersen, J. F. (2010). Brown midrib mutations and their importance to the utilization of maize, sorghum, and pearl millet lignocellulosic tissues. *Plant Science*, *178*(3), 229–238. https://doi.org/10.1016/j.plantsci.2010.01.001.

Serrapica, F., Uzun, P., Masucci, F., Napolitano, F., Braghieri, A., Genovese, A., … Di Francia, A. (2020). Hay or silage? How the forage preservation method changes the volatile compounds and sensory properties of Caciocavallo cheese. *Journal of Dairy Science*, *103*(2), 1391–1403. https://doi.org/10.3168/jds.2019-17155.

Singh, P., Nedumaran, S., Traore, P. C. S., Boote, K. J., Rattunde, H. F. W., Prasad, P. V. V., … Bantilan, M. C. S. (2014). Quantifying potential benefits of drought and heat tolerance in rainy season sorghum for adapting to climate change. *Agricultural and Forest Meteorology*, *185*, 37–48. https://doi.org/10.1016/j.agrformet.2013.10.012.

Srivastava, A., Kumar, S. N., and Aggarwal, P. K. (2020). Assessment on vulnerability of sorghum to climate change in India. *"Agriculture, Ecosystems and Environment," 138*(3–4), 160–169. https://doi.org/10.1016/j.agee.2010.04.012.

Steel, R. G. D., and Torrie, J. H. (1960). *Principles and Procedures of Statistics With Special Reference to The Biological Sciences*. New York, Toronto, London: Mc. Graw Hill Book Company, Inc,.

Stichler, C., and Fipps, G. (2021). *Irrigating Sorghum in South and South Central Texas*, p. 6. Agricultural Communications, The Texas A&M University System Extension publications.

Stokes, S. R., & Prostko, E. P. (1998). *Understanding Forage Quality Analysis*. Texas Agricultural Exten- sion Services.

Szambelan, K., Nowak, J., Szwengiel, A., and Jeleń, H. (2020). Comparison of sorghum and maize raw distillates: Factors affecting ethanol efficiency and volatile by-product profile. *Journal of Cereal Science*, *91*, 1–8. https://doi.org/10.1016/j.jcs.2019.102863.

Taylor, J. R. N., and Duodu, K. G. (2019). *SORGHUM AND MILLETS: Chemistry, Technology and Nutritional Attributes*. Elsevier Inc. in cooperation with AACC International.

Ateş, K., and Turan, V. (2015). Bingöl İli Merkez İlçesi Tarım Topraklarının Bazı Özellikleri ve Verimlilik Düzeyleri. *Türkiye Tarımsal Araştırmalar Dergisi*, *2*, 108–113. Retrieved from https://www.researchgate.net/publication/284765814_Bingol_Ili_Merkez_Ilcesi_Tarim_Topraklarinin_Bazi_Ozellikleri_ve_Verimlilik_Duzeyleri.

Tugli, L. S., Essuman, E. K., Kortei, N. K., Nsor-Atindana, J., Nartey, E. B., and Ofori-Amoah, J. (2019). Bioactive constituents of waakye; a local Ghanaian dish prepared with Sorghum bicolor (L.)Moench leaf sheaths. *Scientific African*, *3*, 1–7. https://doi.org/10.1016/j.sciaf.2019.e00049.

Uddin, F. (2018). Montmorillonite: An Introduction to Properties and Utilization. *Current Topics in the Utilization of Clay in Industrial and Medical Applications*, (September). https://doi.org/10.5772/intechopen.77987.

USDA. (2000). *Brown Midrib Sorghum-Sudangrass*.

Wasilewska-Dębowska, W., Zienkiewicz, M., and Drozak, A. (2022). How Light Reactions of Photosynthesis in C4 Plants Are Optimized and Protected under High Light Conditions. *International Journal of Molecular Sciences*, *23*(7). https://doi.org/10.3390/ijms23073626.

Wedig, C. L., Jaster, E. H., Moore, K. J., and Merchen, N. R. (1987). Rumen Turnover and Digestion of Normal and Brown Midrib Sorghum × Sudangrass Hybrid Silages in Dairy Cattle. *Journal of Dairy Science*, *70*(6), 1220–1227. https://doi.org/10.3168/jds.S0022-0302(87)80134-0.

Yang, D., Li, S., Wu, M., Yang, H., Zhang, W., Chen, J., … Zhang, Y. (2022). Drip irrigation improves spring wheat water productivity by reducing leaf area while increasing yield. *European Journal of Agronomy*, *143*(February), 1–12. https://doi.org/10.1016/j.eja.2022.126710.

Zaukuu, J. L. Z., Oduro, I., and Ellis, W. O. (2016). Processing methods and microbial assessment of pito (an African indigenous beer), at selected production sites in Ghana. *Journal of the Institute of Brewing*, *122*(4), 736–744. https://doi.org/10.1002/jib.373.