RESPONSE OF CHIA (*Salvia hispanica*) TO WATER STRESS, PLANT DENSITY AND NITROGEN FERTILIZER IN TWO AGRO-ECOLOGICAL ZONES OF KENYA

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This thesis is my original work and has not been submitted for award of a degree in any other University.

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To my dear husband, our children and parents for their continued support and motivation throughout the course of my study. God bless you all.

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LIST OF ABBREVIATIONS

ANOVA	Analysis of variance
CGR	Crop growth rate
DAS	Days after sowing
FAO	Food and Agriculture Organization of the United Nations
FC	Field capacity
IPAR	Photosynthetically active radiation
LSD	Least significance difference
RUE	Radiation use efficiency

GENERAL ABSTRACT

Chia (*Salvia hispanica*) is gaining popularity worldwide due to its nutritional and health benefits. In Kenya, production of chia seed is relatively new, and the crop has gained attention hence prompting the possibility of its production within diverse agro ecological zones. Optimal production practices of the crop are partially understood. This study involved three main objectives. The first objective was to determine the effect of varying soil moisture regimes on the growth and yield of chia. The second objective determined the effect inter-row spacing on growth and yield of chia in contrasting agro-ecological zones of Kenya. The third objective evaluated the effect of different rates of nitrogen fertilizer rates on growth and yield of chia two agro-ecological zones of Kenya. The first objective of the study was carried out in the greenhouse for two experimental cycles, while the second and third objectives were carried out in open fields for two growing seasons. In the first objective, treatments comprised four moisture regimes, 40%, 60%, 80% and 100% field capacity in a randomized complete block design with three replications. A potting media of soil, sand and well- decomposed cow manure was prepared in the ratio of 2:1:1 w/w, respectively. Plastic potting bags of 8 kg capacity were filled with media, and five chia seeds sown and later thinned to three plants per pot. In a random sample of five pots per treatment plot, five chia plants were tagged for data collection. Significant variations were observed, with higher plant height, leaf traits, and yield componentsobserved in moisture regimes of 80% and 100% field capacity. Chia plants were significantly ($p<0.05$) taller under 80% and 100% FC compared with 40% and 60%. Highest grain yields greater than 20 g/plant were observed upon an increase of field capacity from 60% to 100%. Field experiments were conducted in Nyeri and Kabete for two seasons in a randomized complete block design in three replications. The influence of different row spacing on chia growth and yield was assessed. It comprised of three rows spacing of 30 cm x 10 cm, 60 cm x 10 cm and 90 cm x 10 cm. In each plot, 5 plants were randomly selected and tagged for data collection. No significant found among the evaluated row spacing treatments. For the third objective, treatments comprised of five nitrogen rates namely; 0 kg N/ha, 25 kg N/ha, 50 kg N/ha, 75 kg N/ha, and 100 kg N/ha. Urea was applied in two splits of 2 and 6 weeks using the drill method 5cm close to the crop rows then covered with soil lightly. In each plot, 5 plants were randomly selected and data on crop phenology growth and yield were assessed, recorded and analyzed. Plant height for both sites was highest at the treatments subjected to 50 kg N/ha. Yield components including grain yield, biomass, test weight defined as a measure of how much a specific volume of harvested crop weighs, and harvest index were highest at N-application rate of 50 kg N/ha. Application of N-fertilizer of 100kgN/ha resulted in more vegetative growth at the cost of seed setting during reproductive phase thus affecting grain yield. The results revealed that chia performed better in well irrigated soils. However, remarkable yield was realized in treatments under 40% FC and thus the crop can be grown in regions experiencing low rainfall. It is important to note that while row spacing may not have a significant direct impact on the growth and yield of chia, other factors such as nutrient availability, water management, pest and disease control, and overall agronomic practices canstill play crucial roles in maximizing chia crop. While varying nitrogen fertilizer application rates showed limited impact on chia growth and yield, it's crucial to exercise caution to prevent over application. This not only leads to excessive vegetative growth and reduced seed formation but also contributes to resource wastage, making it economically unsustainable in agricultural practices. Overall, these findings contribute to a better understanding of chia cultivation practices and provide insights for optimizing chia production in different environments.

CHAPTER ONE: GENERAL INTRODUCTION

1.1 Background information

Chia (*Salvia hispanica*) is a monocarpic annual herbaceous plant, which belongs to the family *Lamiaceae*. It has more names such as the Spanish sage, Mexican chia, and black chia (Cahill, 2003). It grows to approximately one meter tall, and has petiolate and serrated leaves that are on average 6cm long and 3-5 wide. It possesses flowers with both the male and female parts together that grow in clusters within a spike and are usually protected by bracts with long pointed tips. The seeds are usually oval, smooth, and shiny (Ayerza, 2005). Chia is a summer crop and therefore blooms during summer months. It originates from North-Central Mexico and Guatemala (Cahill, 2004).

Chia is grown for its rich nutritional composition comprising high fatty acids content, dietary fibre, antioxidants, minerals and vitamins (Lovelli et al., 2019).The high nutritional profile has resulted in the crop gaining popularity worldwide and its cultivation has spread significantly. It is mainly cultivated in Peru, Bolivia, Argentina, Guatemala, Mexico, Australia, and Colombia (Busilacchi et al., 2013). The increasing global demand for health-conscious food choices has further propelled the cultivation of chia, prompting exploration into its adaptability and agronomic potential beyond its traditional cultivation regions.

Kenya continues to experience frequent episodes of climatic change such as low and unreliable rainfall and this has been our present and the past challenge of production not only chia but also other crops in the country. The frequency of the dry spells in the country has been long over the decades resulting in poor and sometimes failure of production (Mwendwa et al., 2019).
Therefore, determining the effect of varying soil moisture regimes on chia is essential for devising strategies to mitigate the negative impacts of water stress on crop production.

Inter-row spacing, a key component of crop density, plays a pivotal role in crop architecture and resource utilization. Optimal plant density and spacing can affect light interception, water and nutrient uptake, and overall crop development (Grimes et al., 2019). This study aimed to determine the effect of inter-row spacing on chia growth and yield in two agro-ecological zones of Kenya, recognizing that different zones require tailored recommendations for maximizing chia production.

Other constraints to chia growth include low soil productivity due to over exhaustion of soil nutrients without replenishing it. Chia's response to nitrogen fertilization can significantly influence its productivity. Different agro-ecological zones require distinct approaches to nitrogen management due to variations in soil properties, climate conditions, and crop requirements (Njoka et al., 2022). This research sought to evaluate the effect of different rates of nitrogen fertilizer on chia growth and yield, with the ultimate goal of optimizing nitrogen management practices for chia cultivation.

This study encompasses a multidimensional approach, integrating water management, plant density, and nitrogen fertilizer. This will enhance understanding of chia cultivation in diverse agro-ecological settings. The insights gained from this research are expected to provide practical recommendations for chia farmers in Kenya, enabling them to harness the crop's economic and nutritional benefits while addressing the challenges posed by water stress, plant density, and nutrient management.

1.2 Statement of the problem

Chia is a high-nutrient crop with significant economic potential in Kenya. Studies have been concentrated on the nutritional composition of the seed. There are limited studies on the agronomic aspects especially regarding water requirement, spacing and optimal nitrogen fertilization, of this species outside its centres of origin. Bridging this knowledge gap will not only enhance the understanding of chia's adaptability to diverse environments but also pave the way for more sustainable and optimized agricultural practices in the country.

Whereas chia is relatively a drought tolerant crop, evidences allude significant yield increases when grown in well-watered environments (Gopal, 2009). Severe water stress of less than 50% field capacity (FC), resulted in a decline in the number of spikes per plant, seed yield per plant, test weight of seeds, drought tolerance index, and seed protein content (Gopal, 2009). On the other hand, moderate water stress, equivalent to 75% of FC, led to a reduced time to fifty percent flowering and promoted higher protein content in the seeds. Adequate soil moisture promotes reproductive development, enhances drought resistance, and ensures optimal plant health, ultimately contributing to improved biomass accumulation and seed production (Muriithi et al., 2022). However, understanding of chia response to moisture stress remains partially understood.

In addition to moisture related constraints, the impact of plant density on chia growth and yield is not well documented. Reduced row spacing while maintaining same plant densities results in a more uniform distribution of plants. This leads to decreased competition among individual plants for water, nutrients and light resulting in increased radiation interception and biomass production (Flenet et al., 1996). This ultimately determines the crop growth rate, seed set thus influencing the crop yields (Andrade, et al., 2002). There is limited information on chia response to row spacing and how plant density influences crop growth and yield.

The decline in soil fertility has significantly contributed to decreased crop productivity. This is contributed by farmers practicing continuous cropping without replenishing the required nutrients by the soil. The majority of soils in Kenya suffer from severe nitrogen (N) depletion which is a crucial nutrient required for optimal plant growth. In areas where chia is been grown, farmers do not use nitrogen fertilizer (Muriithi et al., 2022). Chia has a high degree of plasticityin traits as leaf morphology, plant height and architecture, flowering period and root morphology thus having a high adaptability and ability to thrive in low-input systems and hasled to the assumption that it has low fertilizer requirements (Baldivia, 2018). Literature has shown that highest seed yield of 1133.33 kg/ha was realized at 100kg N/ha while a rate of 40kgN/ha had the lowest seed yield of 496.67 kg/ha (Chil, 2021).

The knowledge gap in chia production across diverse agroecological zones lies in the limited understanding of how chia plants respond to nitrogen (N) fertilizer application. Inadequate research on varying N application rates hinders the ability to determine the most effective and sustainable approach to maximize chia yield while ensuring profitable crop production.Bridging this gap through scientifically designed experiments is essential for developing region-specific fertilizer recommendations and promoting environment friendly and economically viable chia production practices.

1.3 Justification of the study

The crop is gaining popularity in Kenya due to its economic and nutritional benefits. Kenya faces specific challenges related to resource availability, soil fertility, water scarcity, and climate change. Investigating these challenges in chia cultivation is crucial for developing targeted solutions and sustainable practices that can mitigate the negative effects of these constraints on chia productivity. Agronomic management is an essential factor for successful production of chia. Establishing a chia management system that is profitable and sustainable isthe key motive of this study. Environmental factors such as soil condition, climate, and rainfallplay a vital role in chia yield production and have a high effect on final yield.

Chia, being a water-efficient crop, has the potential to thrive under diverse soil moisture conditions. Investigating the effects of varying soil moisture regimes is essential for developing precise irrigation strategies that optimize chia growth and yield. This knowledge will not only contribute to water conservation but also empower farmers to adapt their cultivation practices to the specific moisture constraints in different regions, ensuring sustainable chia production.

Inter-row spacing is a pivotal agronomic factor influencing light penetration, air circulation, and nutrient distribution among chia plants. By exploring the effects of inter-row spacing in diverse agro-ecological zones, this study aims to provide tailored recommendations for optimizing plant density. Adequate spacing can enhance sunlight exposure and reduce competition, directly impacting chia growth and yield. The outcomes of this investigation will enable farmers to fine-tune their planting practices, ensuring optimal yields across varying landscapes and contributing to the overall sustainability of chia cultivation.

Nitrogen represents the most essential nutrient involved in various metabolic processes strongly influencing plant growth and yield. Like any other plant, chia seed yield increases proportionally with increased fertilizer rates. Field trials have to be carried out to determine theoptimal peak nitrogen economically and environmentally efficient, minimizing nutrient losses due to competition brought about by main crop and weeds or other crops, while maximizing seed yield (Rathke et al., 2005).

Chia production presents economic opportunities for farmers and the agricultural sector in Kenya. The global demand for chia seed and its by-products is increasing, and Kenya has the potential to become a significant player in the chia market. However, to achieve the yield potential of chia, it is essential to address constraints that limit chia production and develop strategies to improve its management practices. This knowledge can support farmers, extension services, and policymakers in making informed decisions, implementing effective interventions, and fostering sustainable chia production practices, improved yields, and sustainable agricultural development in Kenya.

1.4 Objectives

1.4.1 Broad objective

The main objective of the study is to enhance chia production by gaining a deeper understanding of the crop's responses to varying soil moisture regimes, optimizing plant density, and employing different fertilizer nitrogen management regimes.

1.4.2 Specific objectives

(i) To determine the effect of varying soil moisture regimes on growth and yield of chia.

(ii) To determine the effect of inter-row spacing on growth and yield of chia in contrasting agro-ecological zones of Kenya.

(iii) To evaluate the effect of different rates of nitrogen fertilizer on growth and yield of chia in contrasting agro-ecological zones of Kenya.

1.5 Hypotheses

(i) Varying soil moisture regimes does not affect growth and yield of chia.

(ii) Growth and yield of chia is not affected by row spacing, irrespective of agro-ecological zone.

(iii) Increasing fertilizer N rate does not affect chia growth and yield irrespective of agro-ecological zone.

CHAPTER TWO: LITERATURE REVIEW

2.1 Origin and botany of chia plant

Chia (*Salvia hispanica*) is classified in the Lamiaceae family. It is an annual herb that usually blooms during the summer months. Chia is originally from the valley of Mexico and northern Guatemala. It has an upright growth, petiolate and serrated leaves, and distinctive flowers containing both male and female parts. Chia seeds are oval-shaped and nutritionally rich, comprising fatty acids, fiber, antioxidants, minerals, and vitamins. It began to be used as food in the ancient time where it acquired the importance of being a staple food crop in Mexico (Ayerza and Coates, 2005).

2.2 Ecology of chia plant

Optimal elevations for chia production range from 500m and 2500m above sea level. Chia does not tolerate freezing in all its developmental stages (Turck et al., 2020). Although chia is drought tolerant, it performs well in rainfall ranging from 300 to 1000 mm annually (Yeboah et al., 2014; Coates and Ayerza, 1996). The crop can be grown under irrigation or rainfed conditions (Coates and Ayerza, 1996). However, there is limited information on crop water requirements.

Optimal temperatures for chia production ranges from 16 °C to 26 °C, but the crop can tolerate lows of 11°C and highs of 36 °C (Ayerza and Coates, 2009). The plant is known to mature wellin tropical and subtropical environments. Chia exhibits a relatively short growing season and is categorized as a summer crop. Its pollination is mainly facilitated by insects, ensuring seed set and subsequent crop yield.

2.3 Importance of chia

Chia seeds are abundant in omega-3 fatty acids and dietary fibre. The human consumption of omega-six fatty acid is usually high but is essential to maintain the ratio of omega-three and omega-six fatty acids in the body. Chia seed is the source of these elements and provides protein content that is usually almost equal to an egg protein, (Peiretti et al., 2009). Many studies have been conducted and all haveprovided shreds of evidence of the antioxidant and antimicrobial activity of chia seeds.

2.4 Status of chia production in Kenya

Chia production is practiced in several counties in Kenya, including Nakuru, Meru, Nanyuki, and Busia. In these regions, farmers follow a cooperative model and aggregate their chia produce to sell collectively in the export market, primarily to Europe. Among these counties, Busia stands out as the most dominant chia seed growing region. Busia County's geographical climate resembles that of Eastern Uganda, which is a significant chia seed producer in the country, accounting for over 90% of all chia seeds cultivated in Uganda. In the counties of Homabay, Busia and Bungoma, more than 2000 farmers collectively harvest over 8 tons of chia per season, selling it to a Danish organization (Ikumi et al., 2019). During a chia crop forecast, the production of the seeds was projected to rise to 5.7%, with the new farmers changing their farming patterns to adapt to the production of this lucrative crop.

2.5 Constraints to chia production in Kenya

Chia is a recently introduced crop in the country, and there is a lack of comprehensive agronomic data on its optimal production practices, as well as market dynamics. This hinders farmers' ability to make informed decisions and adopt best practices for chia cultivation (Njokaet al., 2022). Soil degradation and nutrient depletion have led to reduced agricultural productivity, affecting not only chia but also other crops in Kenya. (Kwena et al., 2019).

Farmers are reluctant in shifting from traditional crops like maize, which provide a stable but low income, to chia cultivation. This is due to uncertainties associated with a new crop, lack of awareness about the potential benefits of chia, or concerns about market access and profitability. Moreover, in regions with arid and semi-arid climates, water scarcity poses a significant challenge for chia production. While chia is known for its drought tolerance, more research is required to understand its specific moisture stress tolerance under varying climaticconditions (Singh et al., 2021).

Insufficient infrastructure such as storage and processing facilities can hinder post-harvest handling and storage of chia seeds. Farmers might face difficulties in accessing appropriate facilities to ensure the quality and value addition of their produce. Market access and linkages for chia are limited, affecting farmers' profitability and motivation to adopt chia cultivation.

2.5.1 Drought tolerance in chia

Chia is adapted to arid conditions and soils of low fertility (Lovelli et al., 2019). Adequate moisture supply is however necessary for seedling establishment. Once established chia will tolerate low moisture levels during the growing periods. At maturity, the crop does not tolerate waterlogging or very wet soils. It has been recommended as a choice crop in the semi-arid environment (Ayerza and Coates, 2009). Optimal rainfall distribution of this crop is critical during the first phenological phases corresponding to vegetative growth while the drier conditions are required during subsequent phases especially during seed maturation (Yeboah et al., 2014).

2.5.2 Traits conferring tolerance to drought in chia

Water stress is an environmental factor that significantly affects agricultural productivity leading to substantially low yields in crops (Tuberosa, 2012). Chia adapts well to arid and semi-arid regions (Silva et al., 2016*)*. The crop escapes drought by having the ability to accurately sense the seasons with moisture availability and restrict their major growth and their reproductive stages to the wet seasons (Valerio et al., 2017).

Chia responds to moisture stress by employing diverse adaptive mechanisms, broadly classified as escape, avoidance and tolerance mechanisms. Escape mechanisms entail adjusting phenological stages to circumvent critical periods of moisture stress. Chia, which is an annual plant, the escape response mainly refers to early flowering and seed set. This allows the plant to produce viable seeds before the onset of prolonged moisture stress conditions. Avoidance mechanisms involve regulating stomatal behavior to minimize water loss through transpiration,leaf modification. This can include changes in leaf size, shape, thickness, and orientation (Imadi et al., 2016).

Tolerance mechanisms encompass physiological and biochemical adaptations that enable plants to endure and recover from moisture stress. Chia plants can develop adaptive root traits to improve water uptake under moisture stress. This includes root system proliferation,increased root length, and enhanced root hairs, which help explore a larger soil volume for water extraction (Gaur and Sharma, 2014). By employing these mechanisms, chia plants can enhance their chances of survival and maintain productivity under moisture stress conditions.

2.6 Agronomic practices to maximize chia yield

Crop management practices influence growth and yield of chia. They influence radiation interception, and crop growth rate and allocation of dry matter to reproductive structures during critical stages that influence grain yield. These management practices include, optimal planting, proper seed selection, use of appropriate planting density and row spacing, soil moisture and nutrient management as well as weed control (Ahmad et al., 2010).

It is essential to choose the optimal planting time based on the specific agro-climatic region to ensure that the crop establishes and develops during the most favorable growth conditions. Using high quality chia seeds obtained from reliable sources is crucial to achieve uniform andhealthy plant establishment. Proper seed rate and plant spacing are vital to attain an ideal plant population, which can maximize light interception and reduce competition for resources among chia plants (Chil, 2021).

Water and nutrient availability greatly affect the crop’s light capture system and physiological status during critical periods that directly impact yield. Efficient irrigation practices should be implemented to meet the crop's water requirements during critical growth stages, particularly flowering and seed development. Effective weed control strategies are essential to minimize resource competition and prevent yield losses due to weed interference. Monitoring and prompt management of pests and diseases are critical to safeguarding crop health and preventing potential yield reductions (Grimes et al., 2019).

Timing the harvest correctly is essential to ensure that chia plants have reached maturity and that the seeds are fully developed and dried. Timely harvesting guarantees maximum seed yield and quality. Proper post-harvest handling practices, including cleaning, drying, and storage, are also vital to preserve the quality of chia seeds.

2.6.1 Optimal plant density

Plant density has been studied to have a direct impact on yield of crops. Sunflower exhibited the most substantial increase in grain weight with decreasing plant density (Andrade et al., 2005). In maize, increase in plant density beyond the optimum level resulted in significant yield reduction (Vega and Andrade, 2002). Crops response to plant density is determined by the agro ecological zone and management practices (Andrade et al., 2005).

The spacing between rows has a direct influence on various aspects of chia cultivation, including plant density, light interception, water availability, nutrient uptake, and overall crop performance. Intraspecific competition, as well as resource use efficiency, plays an important role in determining the growth and yield of chia. When plants are placed closely together, competition for resources such as light, water, and nutrients intensifies, leading to decreased individual plant performance and overall crop productivity. Dense planting can result in reduced light interception, limited water availability, and inefficient nutrient uptake, ultimately affecting the chia crop's overall health and yield potential (Chil, 2021).

2.7 Nitrogen nutrition in chia

Nitrogen is an essential nutrient for crops as it is a fundamental component of amino acids, proteins, enzymes, pigments, and various by-product molecules (Baldivia, 2018). In agricultural production, insufficient nitrogen can limit crop growth, whereas excessive nitrogen use often results in environmental pollution due to nitrogen loss. The difference between nitrogen supply and demand in farming systems highlights the need for efficient nitrogen utilization to improve crop productivity and profitability while minimizing environmental impact.

The uptake and assimilation of nitrogen during the reproductive stage significantly contribute to nitrogen accumulation in the grain (Maheswari et al., 2017). By optimizing nitrogen management practices, farmers can enhance crop yields, economic returns, and environmental sustainability. It helps in plant growth and development. In soils with good levels of nutrients, chia performs quite well and can therefore be cultivated under low fertilizer input.

However, low soil nitrate contents reduce plant growth and crop productivity (Coates, 2011). It is important to carry out studies to determine optimal nitrogen fertilization to evaluate the direct effects on plant maturity, seed yield, and protein content.

2.8 Yield physiology of chia

Seed yield is a key parameter in chia productivity. Potential yield is an estimate of the upper limit of yield increase that can be obtained from a crop plant (Thiago et al., 2016).Yield in chia is influenced by crop growth rate. During the critical periods of growth, such as flowering and seed development, crop growth rate becomes crucial in determining final yield.

A higher crop growth rate (CGR) during flowering and seed development leads to increased biomass production,which, in turn, contributes to higher grain yield. The number of panicles per plant significantly influences seed yield, as each panicle represents an inflorescence cluster that eventually develops into seeds. A higher number of panicles leads to increased seed production, resultingin enhanced yield potential (El- Serafy et al., 2020).

Achieving optimal seed yield requires a balanced approach between the number of branches and panicles. While increased branching and panicle formation generally promote higher yield potential, excessive branching may lead to resource competition, negatively impacting individual seed development (Grimes et al., 2019).

Understanding the mechanisms that influence crop growth and yield is crucial for efficient and sustainable agricultural production. This knowledge aids in designing and selecting the most suitable management practices for optimal crop performance, provides valuable information for the efficient and judicious use of agricultural inputs, ensuring resource utilization is optimized, equips breeders with conceptual and screening tools to enhance the selection of genotypes with high yield potential and adaptability to specific environments and forms the basis for developing crop simulation models, facilitating better understanding and prediction of crop behavior under varying conditions (Andrade et al., 2005).

2.9 Phenology of chia

Chia undergoes eight principal growth stages during its life cycle. These stages include germination, marked by the appearance of side shoots, and leaf appearance, which is characterized by the unfolding of cotyledons until the final leaf count is determined. Shoot appearance and verticillaster growth occur during the vegetative stage when the fruit transitions from a milky to a doughy texture. The flowering stage precedes grain filling, fruit changes, ripening, and senescence, followed by the period of leaf turning yellow, drying, and dying off, indicating that the crop is ready for harvesting (Baginsky et al., 2016). The flowering stage lasts for about 15 to 25 days, with each flower remaining open for 5 to 7 days. Among these growth stages, flowering and seed development period is crucial for yield formation in chia (Gomez et al., 2008).

The unequal ripening of chia seeds poses a major challenge as the seeds do not mature all at once. The risk of waiting for all the seeds to mature can result in bird's invasion, shattering and abiotic factors such as rain and wind and this can result in low or no yield during harvesting (Jamboonsri, 2012).

2.10 Biomass accumulation

Crops utilize solar radiation to convert carbon dioxide into plant biomass, and the portion of this biomass that is harvested represents the grain yield. The accumulation of biomass during a specific period depends on the amount of photosynthetically active radiation intercepted by the crop (IPAR) and the crop's efficiency in using this radiation to produce biomass known as radiation use efficiency (RUE) (Andrade et al., 2005). During the growth and development of chia, the intercepted solar radiation fuels the process of photosynthesis, where carbon dioxide is converted into organic compounds and plant biomass.

The crop's ability to efficiently capture and utilize solar radiation, coupled with favorable environmental conditions, such as adequate water and nutrient availability, influences the rate of biomass accumulation (Baginsky et al., 2016). Optimization of the interplay between intercepted radiation and the crop's radiation-use efficiency can promote healthy plant growth and maximize biomass production, ultimately leading to higher chia seed yield.

2.11 Quality attributes of chia

Important quality traits of chia include omega-3-fatty acids, protein content, antioxidants, fiber content and mineral composition (Ayerza & Coates, 2011). One of the quality determinants of chia is sowing date. Climatic conditions, such as air humidity, photoperiod, and air temperature, which vary with the changing seasons, also have a significant impact on plant health and the crop cycle. Selecting appropriate sowing dates for chia cultivation aims to minimize potential risks, such as exposure to frosts during the flowering period and avoiding excessive rainfall during harvest, ensuring better crop outcomes.

Crop production and seed quality can be influenced by irregular flowering and maturation of inflorescences. This lack of uniformity poses challenges for mechanized harvesting since the main stem's inflorescence may mature and dry at a different rate than those on lateral branches. Waiting for all inflorescences to dry uniformly can lead to losses due to rainfall, bird attacks, and wind damage (Jamboonsri, 2010). Row spacing significantly impacts the mucilage and crude oil content in chia, with an increase in row spacing causing a decrease in oil and mucilage content this is according to Ayerza and Coates (2001). Moisture stress also influences protein content. Chia planted in adequate soil moisture yields high protein content (Gopal, 2009).

CHAPTER THREE: DETERMINATION OF EFFECT OF VARYING SOIL MOISTURE REGIMES ON GROWTH AND YIELD OF CHIA

3.1 Abstract

Moisture stress is one of the most limiting factors to crop growth. Although chia is thought tobe drought tolerant, considerable yield losses have been reported under moisture stress. However, it is not known which traits regulate adaptation to moisture stress in this crop. In this regard, a study was designed to explore the effect of varying soil moisture regimes on the growth and yield of chia in Kenya under greenhouse conditions. Two experiment cycles comprising four moisture regimes at 40%, 60%, 80% and 100% FC were carried out in Kabetein a randomized complete block design with three replications. Data on growth parameters such as plant height, number of branches, leaf traits, stem and root girth were collected 15, 45, 80 and 100 days after sowing (DAS). Yield components including number of panicles, grain yield, biomass, test weight and harvest index were recorded upon harvesting. Data was subjected to analysis of variance using GenStat version 14 at 5% probability level. Height of chia increased by 13cm for crops grown under 80% FC compared with 40% FC. No significant variations were noted in number of branches across the four moisture regimes. Yield components showed a similar trend as that of height whereby chia plants under 40% FC recorded the lowest values of number of panicles, yield, test weight and harvest index. A 209% increase in yield was reported in plants under 100% FC when compared to the stressed plants under 40 % FC. Positive associations between growth traits were observed. Yield components showed positive correlations between biomass and grain yield, grain yield and harvest index. However, no significant associations were reported between stem and root girth with other yield components. There were no differences in measured traits between 80% and 100% field capacity. This therefore demonstrates that optimized chia production can be realized at 80% field capacity as this would help in sustainably conserving the natural resources such as water. Water stress impacts growth and yield of chia and thus the importance of soil moisture management practices for successful adoption of chia production in various agro ecological zones of Kenya. Additional research should be carried to determine the most effective water management practices in open field agriculture.

Key words: Yield, traits, resilient, field capacity

3.2 Introduction

Chia (*Salvia hispanica L.*) is an annual herbaceous plant of the family Lamiaceae. Although it is native to Central America, chia has gained popularity worldwide due to its nutritional value and potential health benefits (Cahill, 2004). The seeds of chia are rich in omega-3 fatty acids, dietary fiber, protein, and various micronutrients. As a result, chia has emerged as a promising crop (Kibuiet al., 2018).

Chia is a relatively new crop in Kenya where it is grown in different agro ecological zones of Nyeri, Busia, Nakuru, Meru and Nanyuki. While there is limited data on chia yield in the country,farmers often report low yield. Key constraints to chia yield include stress factors such as droughtwhich is an environmental stress which hinders crops productivity (Mishra and Singh 2010; Farooqet al., 2012). Agriculture plays a pivotal role in supporting around 75% of the Kenyan population and fulfilling nearly all of the country's food demands. Nevertheless, rain-fed agricultural production encounters substantial challenges due to drought, particularly in the arid and semi-aridlands (ASALs) that cover approximately 88% of Kenya's geographical area (Huho & Mugalavai,2010).

Insufficient soil moisture, often associated with water stress, can impede the physiological processes critical for chia growth. Reduced water availability affects photosynthesis, nutrient uptake, and overall plant metabolism. This results in stunted growth, fewer branches, and a decline in the number of flowers and seeds. The reproductive stages, such as flowering and seed formation, are particularly sensitive to water scarcity, leading to poor seed set and diminished yields (Taha et al., 2001).

Waterlogged conditions can hinder root development and oxygen uptake, negatively influencing nutrient absorption. Furthermore, prolonged exposure to excessive moisture may lead to nutrient leaching, depriving chia plants of essential elements required for growth and development. This imbalance in soil moisture levels across a field can result in uneven plant growth, affecting the overall uniformity and productivity of the chia crop (Erdem et al., 2006). Optimal soil moisture management, considering the specific water needs of chia at different growth stages, is crucial for achieving maximum yield.

Addressing moisture stress in chia cultivation is of paramount importance for ensuring sustainable production and maximizing crop yield. By optimizing soil moisture management practices, farmers can minimize yield losses, improve water-use efficiency, and enhance profitability of chia cultivation. Additionally, mitigating the impact of moisture stress on chia can contribute to food security, especially in regions prone to drought and water scarcity (Singh and Sandhu, 2020). The objective of this study was to investigate the effect of different soil moisture regimes on the growth and yield of chia.

3.3 Materials and Methods

3.3.1 Study site and planting media preparation

A greenhouse experiment was carried out at the University of Nairobi in Kabete field station located 1^o 15′ 25″ S, 36^o 44′06″ E and 1865 m elevation. A potting media of soil, sand and well-decomposed cow manure was prepared in the ratio of 2:1:1 *w/w*, respectively. Plastic potting bags of 8 kg capacity were filled with the media, and five chia germplasm seeds sown. A total of 8 pots per treatment plot were used. After emergence, thinning was done to three evenly spaced plants per pot.

3.3.2 Treatments and experiment design

Treatments comprised four moisture regimes of 40% field capacity FC, 60% FC, 80% FC and 100% FC as the control. Treatments were laid out in a randomized complete block design in the greenhouse in three replications. Ideally, greenhouse experiments use complete randomized design but due to significant shady effects in the greenhouse a randomized complete block design was used to reduce experimental error.

3.3.3 Calibration of moisture regimes, water supply scheduling and experiment management

A potting media of soil, sand and well decomposed cow manure was prepared in the ratio of 2:1:1 w/w respectively. A random sample of the media was collected for field capacity determination in the laboratory. Determination of soil field capacity was done using gravimetric analysis. The soil sample was mixed thoroughly to create a homogenous sample and each treatment labelled clearly.

Weight of the cores holding the soil was weighed using a weighing scale and recorded. The soil samples were then added into the cores and weight recorded. The mass of the soil was calculated by getting the difference between the mass of the core together with the soil and that of the core alone. The samples were oven dried a 105°c to remove all the moisture. After cooling, they were weighed. Moisture content was calculated using the equation below:

Mc (%) = M_2-M_3/M_3-M_1 *100; Where Mc = moisture content of the soil; M_1 = weight of core; M_2
= weight of core + soil sample, while M_3 = weight of core + oven dried soils.

This represented the percent water present in the soil at field capacity. Volumetric moisture was obtained by multiplying the gravimetric measurements with the soil bulk density. The moisture results were standardized to 100cm^3, and a formula was employed to determine the moisture content for each pot based on its standard volume. This provided the amount of water required totop up on each treatment plot.

3.3.4 Data collection

Data collection encompassed observations on crop phenology, growth traits, and yield components. Crops' growth was closely monitored from emergence to maturity. Growth parameters included plant height (cm), number of leaves and branches per plant, leaf area and leaf greenness which were assessed at 15, 45, 80 and 100 days after sowing (DAS). Upon harvesting, the number of panicles, length of panicles, grain yield (g/plant), test weight (g), total biomass (g) and harvest index (%) were determined.

In a random sample of five pots per treatment plot, five chia plants were tagged for data collection.Height of chia was measured from the soil surface up to the start of the inflorescence parts usinga meter ruler. After counting the number of leaves of chia, their leaf area was determined. Leaf area was determined similarly to a study by Goergen et al., (2019) by multiplying a constant, 0.642 with leaf length and leaf width as LA (cm^2) = 0.642 × leaf length × leaf width. Leaf greenness was determined using a SPAD meter.

Panicle length was measured as the central length from the distal to the proximal end. At physiological maturity, all the plants per plot were harvested and threshed to determine seeds yield(kg/plant), test weight (g) and harvest index (%). Total biomass was determined as the total weight of the harvested plants after drying. Test weight was determined by obtaining a representative sample of seeds in a standard size container. The weight of the seeds was measured and recorded. This provided an indication of seed density and quality. From the harvested seed yields, the harvest index was computed as the ratio between grain yield and total biomass.

3.4 Data analysis

Data were subjected to analysis of variance (ANOVA) to aid in assessing the experiment sources of variation using GenStat version 14. A two-way ANOVA routine was applied, with replicate and variety representing factors, and the variables were the recorded parameters. Data was tested for normality and conformed to requirements of ANOVA before carrying out the analysis. Transformations were not necessary after checking residuals for normal distribution. Treatment means were compared and separated using Fisher's least significant difference (LSD) at 5% probability level. Relationships between traits were explored using correlation analyses.

3.5 Results

3.5.1 Plant height and number of branches

Measurements for plant height during the two experimental cycles are presented in Table 3.1. Over the two experiment cycles, the effect of soil moisture regime was marginal during the early phase but differences increased as the crop matured. Generally, crops were significantly shorter ($P<0.05$)under 40% and 60% FC compared with those grown in 80% and 100% FC. On average at maturity,plants were 79 cm tall under the drier moisture regimes compared with 88 cm across 80% and 100% field capacity. Table 3.2 shows the number of branches increased steadily from 45 DAS to 100 DAS. However, at physiological maturity, no statistical differences were observed across the four moisture regimes for both experimental cycles.

Table 3.1. Plant height(cm) at 15, 45, 80 and 100 days after sowing (DAS) of chia grown under different moisture regimes of 40, 60, 80 and 100% field capacity (FC) during two experiment cycles.

Field capacity	Experiment cycle 1				Experiment cycle 2			
	15 DAS	45 DAS	80 DAS	100 DAS	15 DAS	45 DAS	80 DAS	100 DAS
40% FC	23ab	63a	71a	77a	28a	73a	76a	80a
60% FC	20a	65a	77ab	82ab	31a	90b	88ab	90bc
80% FC	24b	71a	84b	90b	31a	84ab	82ab	84ab
100% FC	22ab	66a	81b	87b	30a	91b	91b	94c
Mean	21.9	66.1	78.1	83.6	30	84.5	84.2	86.79
LSD	2.6	6.31	7.76	7.4	4.18	9.63	9.01	10.78
P value	0.033	0.142	0.011	0.005	0.609	0.003	0.013	0.022

Means in the same column not having a common letter are significantly different based on theTukeys LSD test at (P≤0.05).

Table 3.2. Number of branches at 15, 45, 80 and 100 days after sowing (DAS) of chia grown under different moisture regimes of 40, 60, 80 and 100% field capacity (FC) during two experiment cycles.

Field capacity (FC)	Experiment cycle 1			Experiment cycle 2		
	45 DAS	80 DAS	100 DAS	45 DAS	80 DAS	100 DAS
40% FC	8a	11a	12a	10a	12a	12a
60% FC	8a	12a	12a	11a	12a	12a
80% FC	9a	12a	13a	11a	12a	13a
100% FC	8a	11a	12a	11a	13a	13a
Mean	8.4	11.2	12.5	10.7	12.3	12.3
LSD	1.4	1.8	1.8	1.2	2.5	2.0
P value	0.081	0.49	0.17	0.25	0.56	0.42

Means in the same column not having a common letter are significantly different based on theTukeys LSD test (P≤ 0.05).

3.5.2 Number of leaves, leaf area and leaf greenness

Leaf traits included count per plant, (Table 3.3), leaf area (Table 3.4) and greenness (Table 3.5) which varied across the four moisture regimes. Crops grown under 80% and 100% field capacities produced significantly more leaves per plant compared with counterparts under 40% and 60% field capacity. However, these differences only appeared as the crop matured. No differences were measured between drier soils(40% and 60% FC) as well as between 80% and 100% FC.

Leaf expansion followed a similar trend as number of leaves per plant, where this trait did not show differences early in the season but differences were recorded as the crop aged (Table 3.4). Significantly ($P<0.05$) large leaves were measured under 80% and 100% moisture regimes compared with the drier regimes Similarly, there were differences in leaf size between the two low moisture regimes (40% and 60%) as well as between the well-watered treatments.

Results from Table 3.5 showed that during the early developmental stages of between 15-45 DAS,moisture regimes did not modify leaf greenness of chia plant. However, as the crop approached physiological maturity, significant differences were observed with the treatment at 40% FC having the lowest level of leaf greenness. The moistest soils,100% FC recorded the highest level of leaf greenness at an average of 42.93 during the first experiment cycle.

Table 3.3. Number of leaves at 15, 45, 80 and 100 days after sowing (DAS) of chia grown underdifferent moisture regimes of 40, 60, 80 and 100% field capacity (FC) during two experiment cycles.

Field capacity	Experiment cycle 1				Experiment cycle 2			
	15 DAS	45 DAS	80 DAS	100 DAS	15 DAS	45 DAS	80 DAS	100 DAS
40% FC	4a	42a	79a	81a	17a	60a	78a	83a
60% FC	4a	51b	82b	88b	15a	73a	86ab	89a
80% FC	4a	51b	85b	89b	18a	85a	99b	106b
100% FC	4a	60c	93c	104c	20a	77a	83ab	86a
Mean	4.3	51	84.6	90.5	17.3	73.9	86.2	90.8
LSD	1.0	7.3	2.9	5.3	5.3	27.7	18.6	7.9
P value	0.133	0.003	<0.001	0.025	0.750	0.540	0.034	<0.001

Means in the same column not having a common letter are significantly different based on theTukeys LSD test ($P\leq 0.05$).

Table 3.4. Leaf area (cm^2) at 15, 45, 80 and 100 days after sowing (DAS) of chia grown under different moisture regimes of 40, 60, 80 and 100% field capacity (FC) during two experiment cycles.

Field capacity	Experiment cycle 1				Experiment cycle 2			
	15 DAS	45 DAS	80 DAS	100 DAS	15 DAS	45 DAS	80 DAS	100 DAS
40% FC	25.5ab	59.8ab	53.7a	56.5a	30.4a	65.8a	68.3a	70.3a
60% FC	21.3ab	64.5ab	65.1a	55.0a	39.0a	60.2a	65.6a	67.4a
80% FC	17.5a	71.7b	57.2a	67.8a	34.4a	70.3a	74.7a	77.6a
100% FC	25.9b	48.0a	52.0a	50.6a	45.7a	68.4a	71.4a	73.7a
Mean	22.5	61	57	57.5	37.4	66.2	70	72.2
LSD	6.1	12.6	12.1	15.3	12.8	14.4	12.7	15
P value	0.025	0.004	0.148	0.149	0.109	0.25	0.87	0.73

Means in the same column not having a common letter are significantly different based on theTukeys LSD test ($P\leq 0.05$).

Table 3.5. Leaf greenness (SPAD units) at 15, 45, 80 and 100 days after sowing (DAS) of chia grown under different moisture regimes of 40, 60, 80 and 100% field capacity (FC) during two experiment cycles.

Field capacity	Experiment cycle 1				Experiment cycle 2			
	15 DAS	45 DAS	80 DAS	100 DAS	15 DAS	45 DAS	80 DAS	100 DAS
40% FC	40.3a	38.6 a	36.9a	35.5ab	45.2a	33.2a	28.9a	26.8b
60% FC	39.7a	38.9a	39.2ab	34.9a	41.9a	29.2a	24.2a	24.0ab
80% FC	41.4a	40.1a	39.8b	39.0bc	43.3a	31.9a	23.8a	23.0ab
100% FC	46.9b	42.6b	41.4b	41.1c	44.0a	31.9a	20.4a	20.0a
Mean	42	40	39.3	37.6	43.6	31.6	24.3	23.5
LSD	6.3	2.3	2.3	3.5	6.5	5.8	10	5.2
P value	0.032	0.041	0.032	0.044	0.55	0.45	0.63	0.04

Means in the same column not having a common letter are significantly different based on theTukeys LSD test (P≤0.05).

3.5.3 Stem and root girth of chia at physiological maturity

Data from Table 3.6 shows that stem and root girth of chia at physiological maturity did not differ statistically across the four moisture regimes.

Table 3.6. Stem (mm) and root girth (mm) under different moisture regimes of 40, 60, 80 and 100% field capacity (FC) at physiological maturity of chia grown during two experiment cycles.

Field Capacity	Experiment cycle 1		Experiment cycle 2	
	Stem girth	Root girth	Stem girth	Root girth
40% FC	7.5a	1.0a	6.1a	0.8a
60% FC	7.7a	0.7a	6.7a	0.9a
80% FC	8.0a	0.9a	6.9a	1.1a
100%FC	8.1a	0.8a	7.0a	1.1a
Mean	7.8	0.8	6.7	1
LSD	1.0	0.5	1.1	0.6
P value	0.34	0.21	0.377	0.12

Means in the same column not having a common letter are significantly different based on theTukeys LSD test (P≤0.05).

3.5.4 Yield components of chia

Number of panicles were significantly few under 40% FC compared with the other moisture regimes (Table 3.7). The panicles increased with increasing field capacity but in the first experiment cycle, panicle numbers reduced with 100% FC. On the contrary, yield components of chia including number of panicles and test weight were highest at 100% FC in the second experiment cycle.

While total biomass was not significantly different across the four moisture regimes in both experiment cycles, the drier soils of 40% FC recorded the lowest quantity at an average of 105.95g(Table 3.7). There was a positive correlation between number of panicles and grain yield and testweight whereby yield increased with an increase in the number of panicles, while highest test weight was realized in treatments that recorded the highest grain yield. The highest grain yield wasrealized at the highest soil moisture regime of 100% FC in experimental cycle 1.

Table 3.7. Yield components of chia including number of panicles per plant, total biomass(g), grain yield(g/plant), test weight (g) and harvest index % (HI) under different moisture regimes of40, 60, 80 and 100% field capacity FC

Field capacity	Experiment cycle 1					Experiment cycle 2				
	Panicles	Biomass	Grain yield	Test weight	HI	Panicles	Biomass	Grain yield	Test weight	HI
40%	19a	154.3a	15.3a	6.7a	9.6a	14a	57.6a	8.8a	6.5a	15.3a
60%	24ab	215.7a	28.0ab	6.8b	13.0ab	20ab	73.3a	13.9a	6.8b	18.4a
80%	33c	222.7a	41.0bc	6.9c	18.2bc	24ab	88.9a	14.8a	6.8bc	17.1a
100%	31bc	216.7a	47.3c	7.0c	21.4c	27b	104.4a	23.2a	7.0c	21.0a
Mean	26.9	202.4	32.9	6.9	15.5	21.4	81	15.2	6.8	18
LSD	6.8	73.6	17.4	0.1	6.0	12.5	49.6	16.9	0.1	14.6
P value	<0.001	0.72	<0.001	<0.001	0.011	<0.001	0.35	0.75	<0.001	0.81

Means in the same column not having a common letter are significantly different based on the Tukeys LSD test ($P \leq 0.05$).

3.5.5 Relationship between traits

Results from (Table 3.8) show a correlation analysis of plant traits in chia, revealing strong positive associations between the number of branches, number of leaves, and leaf area, while leaf greenness exhibited weak or no significant correlations with other traits. Correlation analysis of growth and yield components of chia under varying moisture regimes, showed positive associations between biomass and grain yield, and a consistent positive relationship between grain yield and harvest index (Table 3.9). Stem girth and root girth exhibited no significant correlations with other yield components.

Table 3.8. Correlation between plant growth parameters of chia including height, number of branches, number of leaves and leaf area grown in two experiment cycles.

Plant traits	Plant height	Number of branches	Number of leaves	Leaf area
Experiment cycle 1				
Number of branches	0.8**			
Number of leaves	0.7*	0.8*		
Leaf area	0.9**	0.8*	0.9*	
Leaf greenness	-0.3^{ns}	0.2^{ns}	0.3^{ns}	0.7*
Experiment cycle 2				
Number of branches	0.6**			
Number of leaves	0.8*	0.9*		
Leaf area	0.7**	0.9*	0.9*	
Leaf greenness	-0.5^{ns}	0.3^{ns}	0.4^{ns}	0.7*

ns = no significant difference; * significant at 1% probability level and ** significance at 5%probability level.

Table 3.9. Relationship between growth and yield components of chia including stem and root girth(mm), number of panicles, biomass (g), grain yield(g/plant) and harvest index % (HI) under different moisture regimes of 40, 60, 80 and 100% field capacity (FC) at physiological maturity of chia in two experiment cycles.

Plant traits	Stem girth	Root girth	Panicles	Biomass
Experiment cycle 1				
Root girth	0.4^{ns}			
Panicles	0.2^{ns}	0.2^{ns}		
Biomass	0.3^{ns}	0.5^{ns}	0.7*	
Grain yield	0.5^{ns}	0.3^{ns}	0.7*	0.9*
HI	0.4^{ns}	0.3^{ns}	0.6*	0.8*
Experiment cycle 2				
Root girth	0.36^{ns}			
Panicles	0.1^{ns}	0.2^{ns}		
Biomass	0.2^{ns}	0.4^{ns}	0.7*	
Grain yield	0.5^{ns}	0.1^{ns}	0.8*	0.9*
HI	0.2^{ns}	0.3^{ns}	0.6*	0.9*

ns=no significant difference, * significant at 1% probability level and ** significance at 5%probability level.

3.6 Discussion

Understanding the response of chia to moisture stress will guide the deployment of this crop in drylands. The findings of this study showed that chia produced yields even in moisture stress conditions. However, significantly higher yields were observed in treatments with less stressed soils of 80% and 100% field capacities.

3.6.1 Effect of moisture regimes on chia growth

Through the analysis of growth parameters and yield components, the results revealed that increasing soil moisture regimes positively influenced chia growth, with plants subjected to higher moisture levels displaying improved plant height, branch number, and stem and root girth. This is attributed to sufficient soil moisture which increases nutrient absorption and root development. This also increases the rate of photosynthesis in well-watered plants which improves the rate of growth parameters as compared to water stressed plants. Similar findings were reported by (Muriithi et al., 2022).

Result in this current study indicated that SPAD values increased with the increase in soil moisture regimes in both seasons. This study is similar to Gong et al. (2005) in wheat where chlorophyll content in leaves reduced as a result of reduction in soil moisture content. The observed phenomenon can be ascribed to the detrimental impact of water stress on the photosynthetic apparatus. Leaf greenness and yield components are correlated and the loss of chlorophyll content can also be associated to the photo-oxidation (Kamble et al., 2015).

Reduced growth in stem and root girth in treatments under water stress including 40% and 60 % field capacities as indicated in the results findings as influenced by limited water availability that hinders cell division resulting to smaller and thinner roots and stem. Research on sunflower showed that the plants had thicker stems under irrigation compared to the non-irrigated plants with a maximum stem girth of 5.59cm and 4.94cm respectively (Gawankar et al., 2003).

Water stress can adversely affect the development of vascular tissues, such as xylem and phloem,which are responsible for water and nutrient transport within plants. Insufficient water supply limits the formation and functionality of these tissues, leading to reduced nutrient and water uptake. This, in turn, can result in narrower stems and shallower root systems (Imadi et al., 2016).

3.6.2 Effect of moisture regimes on yield of chia

Yield components of chia were significantly affected by moisture content of the soil with the highest number of panicles recorded in 80% FC. However, there was no significant differences between 80 and 100% FC moisture regimes. Grain yield increased with increase in soil moisture. 100% FC recorded the highest grain yield with 40% FC the lowest in experimental cycle 1. In a similar study, number of panicles per plant and grain yield reduced remarkably under water stressed conditions (Pallavolu et al., 2023).

The increase in total biomass correlated with a corresponding increase in yield. Chia plants that were grown under moisture stress decreased growth due to reduced photosynthetic activities and this therefore negatively affected foliar growth resulting to a decline in total biomass. Silva et al. (2018) reported that the deficit in moisture content reduced chia growth resulting to decline in drymatter as well as leaf area in comparison to plants growing under no moisture stress.

Water stress reduces the rate of transpiration affecting the allocation of resources within the plant,leading to a reduction in the harvest index. The plant redirects resources away from seed production to survival mechanisms, such as developing deeper roots to access water or reducing the size of its leaves to conserve water. This justifies the low harvest index in plants under 40% FC. In this study, whereby 40% FC had shorter plant height and fewer gain yield, also recorded a fewer number of panicles, which indicates reduced assimilates for grain production, hence lower harvest index.

Moisture stress reduces plants physiological processes such as photosynthesis and thus less energy production leading to compromised seed development and subsequently lower test weight. Similar findings on wheat showed that test weight declined significantly in water stress treatments by up to 25% (Kumari et al., 2014).

3.6.3 Relationship between traits

Significant associations were observed between the number of branches, number of leaves, and leaf area, indicating a positive relationship among these traits. The strong positive associations suggest that chia plants with more branches tend to have a higher number of leaves and larger leaf area. These relationships are attributed to the physiological and morphological adaptations of the plant to optimize light interception and photosynthesis.

Leaf greenness, which is an indicative of chlorophyll content and photosynthetic efficiency, did not exhibit strong associations with plant height, number of branches, number of leaves, or leaf area. This suggests that other factors may influence leaf greenness in chia, such as genetic variation, nutrient availability, or environmental conditions. The positive associations between the number of branches, number of leaves, and leaf area suggest that these traits collectively contributeto the overall growth and biomass production of chia plants.

While root girth exhibited positive associations with stem girth, panicles, biomass, and grain yield, the relationships between panicles and other components were generally weak. Biomass showed consistent positive correlations with panicles and grain yield, emphasizing its role as a major determinant of chia productivity. Additionally, the positive associations observed between harvestindex and other components highlight the importance of resource allocation efficiency in optimizing chia yield.

The strong positive correlation between growth and yield components can be contributed by the favorable conditions provided by adequate soil moisture. Optimal soil moisture content facilitatesefficient nutrient uptake and supports essential physiological processes in chia plants, resulting in improved growth and subsequent increases in grain yields. Furthermore, higher soil moisture availability can enhance photosynthetic efficiency, leading to increased biomass accumulation and ultimately higher grain yield (Imadi et al., 2016).

Maintaining adequate soil moisture levels, particularly during critical growth stages, is crucial to maximize the growth and yield potential of chia. These findings highlight the importance of implementing effective irrigation management strategies or utilizing soil moisture monitoring techniques to optimize chia production and improve resource-use efficiency (Silva et al., 2018).

Factors such as temperature variations, soil nutrient levels, or other environmental variables could have influenced the observed growth and yield outcomes. Although these factors were not explicitly controlled in this study, they should be considered in future research to gain a more comprehensive understanding of chia crop responses to soil moisture variations.

Further studies that focus on exploring the specific physiological mechanisms underlying the observed positive correlation between growth and yield components in response to soil moisture variations are recommended. Furthermore, conducting field trials encompassing a wider range ofsoil moisture levels and investigating the interaction between soil moisture and other environmental factors would provide valuable insights into optimizing chia crop production.

3.7 Conclusion

Water stress influences growth and yield of chia as crops grown under 80% and 100% FC had significantly higher yields as compared to the other counterparts. However, this study revealed that chia plants can still give some yield in water stress conditions. It is important for farmers to note that excess application of water to the crop does not translate to more yields, as the results of this study did not show significant differences between plants grown under 80% and 100% FC. Moisture management strategies can lead to improved crop growth and productivity. It is important to acknowledge the limitations of this study. The research was conducted under controlled greenhouse conditions, which may not fully replicate field conditions.

CHAPTER FOUR: DETERMINATION OF EFFECT OF ROW SPACING ON GROWTH AND YIELD OF CHIA IN CONTRASTING AGRO ECOLOGICAL ZONES IN KENYA

4.1 Abstract

Optimal spacing is a critical aspect of crop management systems in modern agricultural practices,particularly with the continuous improvement of mechanization. It plays a crucial role in determining the potential of land to sustain reasonable yields and influences subsequent agronomic activities. Chia (*Salvia hispanica L.*) is a recent crop in Kenya, understanding the influence of row spacing on its growth and yield is essential for optimizing production practices. This study explored the potential of different row spacing on the growth and yield of chia in Kenya. This followed an establishment of chia in two study sites, Kabete and Nyeri in a randomized complete block design with three replications during two growing seasons. The treatments were three rows spacing including 30cm x 10 cm, 60cm x 10cm, and 90cm x 10cm. Data on growth parameters such as plant height, number of branches and leaf traitswere periodically collected 15, 45, 80 and 100 days after sowing (DAS). Yield components including number and length of panicles, grain yield, biomass, test weight and harvest index were recorded upon harvesting. Data was subjected to analysis of variance using GenStat version 14 at 5% significant level. In this study, all the assessed row spacing did not show any significant differences in growth and yields of chia in open fields. Further research to investigate how interactions between row spacing, soil moisture and fertilization regimes influence growth and yield of chia in different agro- ecological zones of Kenya.

4.2 Introduction

Chia cultivation is influenced by different agroecological zones, which encompass variations in climatic conditions, soil types, andother environmental factors. The cultivation of the crop in Kenya is currently limited by lack of comprehensive information on its growth, phenology, nutritional requirements, and effective management strategies. This knowledge gap hinders the ability to fully unlock the potential of chiacrops farming in the country (Ikumi et al., 2019). One of the management strategies in yield maximization is inter row spacing.

Spacing between rows directly impacts plant density, light interception, water availability, nutrientuptake, and overall crop performance. Intraspecific competition and resource use efficiency significantly impact the growth and yield of chia. When plants are closely spaced, competition for light, water, and nutrients intensifies, leading to reduced individual plant performance and overall crop productivity.

Dense planting can result in reduced light interception, limited water availability, and inefficient nutrient uptake (Thiago et al., 2016). Drawing on the example of cassava, it's evident that nutrient efficiency alone does not guarantee improved yield quality. Rather, an optimal balance in plant density is crucial (Rebecca et al., 2022). It's imperative to underscore that the population should not surpass the optimum level for quality optimization. This delicate equilibrium ensures that the benefits of enhanced nutrient acquisition are harmonized with the overall growth and yield goals for chia cultivation.

Row spacing influences the canopy architecture, affecting light interception and distribution withinthe crop, which subsequently influences photosynthesis and biomass accumulation (Tao et al., 2019). When chia plants are grown under conditions of high plant density or narrow spacing, they respond by elongating their stems to reach for more light and reduce shading effects. This elongation allows them to access greater light resources and maintain optimal photosynthesis levels.

Soil characteristics such as fertility and texture also influence row spacing effects on chia growth and yield. In nutrient-rich soils, wider row spacing is suitable to prevent excessive competition for nutrients, ensuring optimal nutrient uptake by individual plants. However, in soils with low nutrient availability, closer row spacing can enhance nutrient acquisition efficiency through intensified competition, resulting in improved chia growth and yield (Chil, 2021).

Although extensive research has been conducted on management practices in chia production, there is a notable research gap concerning the specific influence of row spacing on chia growth and yield to help unlock its full potential as a sustainable crop. Understanding the specific characteristics of different agroecological zones is crucial for determining the most appropriate row spacing for chia cultivation, thereby optimizing resource utilization and maximizing chia productivity. The objective of this study is to determine the effect of different row spacing on growth and yield of chia in two agro ecological zones of Kenya.

4.3 Materials and methods

4.3.1 Study sites

This study was conducted in Kabete field station of the University of Nairobi and Dedan Kimathi University field plots. Two experiment seasons were conducted concurrently from April 2021 to February 2022. Upper Kabete field station is located 1^{o} 15′ 25″ S, 36^{o} 44′06″ E and 1865 m elevation. It is characterized by a sub-humid climate with an average annual rainfall of 1000 mm and a mean monthly maximum temperature of 23°C and a minimum of 12°C. Its soils acidic and with medium to low nitrogen percentages. On the other hand, field plots in Dedan Kimathi University are in Kieni West, Nyeri County and are located 0^{o} 23′ 51″ S, 36^{o} 57′33″ E within an elevation of 1786 m. The average rainfall is 800 mm, well-drained soils, with a mean monthly maximum temperature of 24°C and a minimum of 18°C.

Table 4.1. Chemical characteristics of the experimental sites at Kabete and Nyeri.

Parameters	Kabete	Nyeri	Nutrient Status
pH (H_2O)	6.34	6.55	Neutral
% Organic carbon	1.2	0.7	Adequate
Total nitrogen (%)	0.25	0.13	Adequate
Potassium (cmol kg^{-1})	2.67	2.27	Adequate
Sodium (cmol kg^{-1})	0.5	0.4	Adequate
Calcium (cmol kg^{-1})	7.6	4.2	Adequate
Magnesium (cmol kg^{-1})	3.73	1.96	Adequate
Phosporus (ppm)	52.5	59	Adequate
% Sand	73	45	Adequate
% Silt	4	12	Adequate
% Clay	23	43	Adequate
Texture	Sandy clay loam	Clay	Adequate

4.3.2 Treatments and experiment design

In Kabete and Nyeri, treatment plot measuring 19.6 m^2 was demarcated to accommodate 9 treatment plots of chia in a randomized complete block design. The respective treatments were replicated three times. Each experimental plot was 4.2 m^2 and was 1m apart whereas the plots were 2m towards either side of the guard row. In each plot, chia seeds were drilled along the inter-row. In the experimental layout, there were three treatments of chia planting densities of 30cm x 10 cm,60cm x 10cm, and 90cm x 10cm.

4.3.3 Crop husbandry

Thinning was carried out 15 days after sowing when 50% of chia plants per treatment had attained a height of 15cm. Nitrogen fertilization with 46% N (Urea) was applied at 50 Kg N/ha in two splits 8 and 20 days after sowing. Weeding was carried out regularly to keep the plots weeds free. Introduction of chia to a new ecological zone poses challenges, particularly with bird infestation. Birds heavily feed on the matured chia seeds, leading to reduced yields. A strategic approach was implemented by sowing sunflower as a guard row crop to attract the birds' attention away from thechia seeds.

4.3.4 Data collection

Weather data for the two growing seasons was obtained from the Kenya meteorological department headquarters, collected monthly and comprised of relative humidity, evapotranspiration, precipitation and maximum and minimum temperatures.

Five chia plants per treatment plot were randomly sampled and tagged for data collection. Data on main stem length, number of leaves, leaf area, number and length of the developed panicles, number of branches developing from the main stem and leaf greenness were collected. Elaboratively, the main stem length was determined from the soil surface up to the start of the inflorescence parts. Leaf area was determined by measuring leaf length and leaf width using a meter ruler on the tagged plants then following an equation by Goergen *et al.* (2019) that defines leaf area as;

LA (cm^2) = 0.642 × leaf length × leaf width, where 0.642 is a constant.

The length of the developed inflorescence was determined as the central length from the distal to the proximal end of inflorescence this was measured using a meter rule. Upon physiological maturity, all chia plants per plot were harvested to determine seeds yield (g/plant), test weight (g)and harvest index (%). Harvest index was computed as ratio between grain yield and total biomass.Test weight determination was done by obtaining a representative sample of seeds, weighing in aclean and dry measuring container, with the weight of the empty container subtracted from the weight of the container with seeds to calculate the net weight, providing an indication of seed density and quality.

Table 4.2. Maximum and minimum temperature (°C), rainfall (mm), relative humidity (%), and evaporation (mm) at Kabete field station and Nyeri between April 2021 and February 2022 planting season.

Month	Kabete					Nyeri			
	T (°C)		R (mm)	RH (%)	E (mm)	T (°C)		R (mm)	RH (%)
	Max	Min	Total	Mean	Total	Max	Min	Total	Mean
Year 2021									
April	24	15.2	272.1	91	4.6	25.6	14.8	58.6	88
May	23	14.6	118.1	90	3	23.8	14.8	101.7	88
June	21	12.4	3.1	84	2.3	21.8	13.2	50.1	90
July	21	12.1	7	85	2	19.5	12.7	24.6	93
August	22	11.9	20.3	81	2.8	22.7	12.5	18.2	87
September	23	13.5	12.8	83	3.3	23.8	13.4	6	89
October	25	14	59.9	76	4.4	26.3	13.9	71.1	80
November	25	14.6	114.1	78	4.7	25.9	13.3	92.2	78
December	22	14.7	104.6	89	3.5	23.6	13.8	91	84
Year 2022									
January	24	13.9	66.7	71	5.1	26.6	11.1	33.9	78
February	25	14.4	77.1	73	5.1	28.5	11.8	33.9	78

Source: Kenya meteorological department headquarters. T-temperature, R- rainfall, RH- relativehumidity, E- evapotranspiration

4.4 Data analysis

Data were subjected to analysis of variance (ANOVA) to aid assessing the experiment sources of variation using GenStat version 14. A two-way ANOVA routine was applied, with replicate and variety representing factors, and the variables were the recorded parameters. Data was tested for normality and conformed to requirements of ANOVA before carrying out the analysis. Transformations were not necessary after checking residuals for normal distribution. Treatment means were compared and separated using Fisher’s least significant difference (LSD) at 5% probability level.

4.5 Results

4.5.1 Plant height

Height of chia was not significantly different in Kabete for both seasons across the three-row spacing as reported in Table 4.3. In Nyeri, spacing of 30cm x 10cm had the tallest plants at an average of 70cm and 102cm in season 1 and season 2 respectively. The row spacing of 90cm x 10cm recorded the shortest plants in both sites for the two seasons. The mean values for the other row spacing treatments in Nyeri were slightly lower, but the differences were not statistically different. (Table 4.3)

Table 4.3. Height (cm) of chia in open fields at Kabete and Nyeri 15,45 and 80 days after sowing (DAS)for two growing seasons under three row spacings

	Kabete						Nyeri					
	Season 1			Season 2			Season 1			Season 2		
Row spacing	15	45	80	15	45	80	15	45	80	15	45	80
30 x 10	32b	72b	84a	41a	95a	94a	38b	63a	71b	31a	66b	102b
60 x 10	28a	63a	83a	45a	94a	94a	29a	64a	60a	30a	60b	99ab
90 x 10	27a	62a	75a	48a	89a	88a	33ab	59a	59a	31a	50a	90a
Mean	29	66	81	45	93	92	33.2	62	63.4	30.9	58.7	96.8
LSD	3.2	5.6	8.1	6.2	5.9	6.2	4.4	8.3	8.2	2.3	6.5	7.8
P value	0	<0.01	0.07	0.09	0.12	0.1	0.001	0.37	0.012	0.72	<0.001	0.006

Means in the same column not having a common letter are significantly different based on the Tukeys LSD test ($P \leq 0.05$).

4.5.2 Number of leaves and leaf area

For the two growing seasons in Kabete and Nyeri, leaf traits including number of leaves and leaf area varied across the three rows spacing (Table 4.4). Results showed that the number of leaves progressively increased as the crop matured. For instance, in Kabete, a spacing of 60cm x 10cm had the highest number of leaves with season 1 recording an average of 83. In Nyeri, a spacing of30cm x 10cm had the lowest number of leaves, however, there were no significant differences between a row spacing of 60cm x 10cm and 90cm x 10cm in season1.

Table 4.5 shows that leaf area increased significantly over time in two seasons across the three rows spacing with the row spacing of 30cm x 10cm having the lowest values when compared to 60cm x 10 and 90cm x 10cm spacings in Kabete. In Nyeri however, there was no significance difference in row spacing in both seasons.

Table 4.4. Number of leaves of chia in open fields at Kabete and Nyeri 15, 45 and 80 days after sowing (DAS) for two growing seasons under three row spacings

Row spacing	Kabete						Nyeri					
	Season 1			Season 2			Season 1			Season 2		
	15	45	80	15	45	80	15	45	80	15	45	80
30 x 10	16a	29a	59a	13a	36a	56a	19a	27a	63a	12b	29a	59a
60 x 10	21a	39a	83b	18a	36a	76b	22a	40a	80b	11ab	32a	68a
90 x 10	19a	40a	77b	16a	35a	65ab	20a	43a	78b	9a	33a	70a
Mean	18.3	36.1	72.9	15.6	35.7	65.5	20.38	36.57	73.67	10.8	31.32	65.4
LSD	7.8	13.7	15.5	7	7.2	11.9	5	21.5	12.5	2.4	6.2	12.6
P value	0.07	0.24	0.03	0.45	0.9	0	0.17	0.09	0.01	0.04	0.24	0.07

Means in the same column not having a common letter are significantly different based on the Tukeys LSD test (P≤0.05).

Table 4.5. Leaf area (cm^2) in open fields at Kabete and Nyeri 15, 45, and 80 days after sowing (DAS) for two growing seasons under three row spacings

Row spacing	Kabete						Nyeri					
	Season 1			Season 2			Season 1			Season 2		
	15	45	80	15	45	80	15	45	80	15	45	80
30 x 10	21.3a	30.0a	31.5a	24.5a	31.0a	33.1a	43.a	50.2a	58.a	45.a	50.a	57.a
60 x 10	23.3a	35.9b	28.4a	25.9a	47.b	42.2b	40.a	48.3a	54.a	48.a	50.a	62.a
90 x 10	31.6b	44.8b	34.4a	32.5b	45.b	39.2b	40.a	46.3a	52.a	45.a	44.a	56.a
Mean	25.4	36.9	31.6	27.6	41.3	38.1	41.3	48.3	55.3	46.3	48.3	58.7
LSD	4.8	7.8	6.5	5.3	10.3	7.3	4.5	5.5	9	6.2	7.3	9.7
P value	<0.01	0	0.2	<0.01	0	0.04	0.06	0.07	0.38	0.47	0.14	0.42

Means in the same column not having a common letter are significantly different based on the Tukeys LSD test (P≤0.05).

4.5.3 Leaf greenness and number of branches

As the crop approached physiological maturity, the plants recorded a decline in the level of leaf greenness as shown in Table 4.6. There was a slight variation in leaf greenness in Kabete in season two whereby a spacing of 30cm x 10cm, had the lowest levels. Row spacing of 60cm x 10cm and 90cm x 10cm showed no statistical differences.

Table 4.7 showed that the number of branches were significantly different in Kabete for both seasons with the row spacing of 90cm x10cm having more branches than spacing of 60cm x 10cmand 30cm x 10cm in season 1 while in season 2 a spacing 60cm x10cm had the highest number of branches of 12cm on average.

Table 4.6. Leaf greenness (SPAD units) in open fields at Kabete and Nyeri 15, 45, and 80 days after sowing(DAS) for two growing seasons under three rows spacings

Row spacing	Kabete						Nyeri					
	Season 1			Season 2			Season 1			Season 2		
	15	45	80	15	45	80	15	45	80	15	45	80
30 x 10	35.9a	26.3a	20.5a	34.4a	28.4a	23.9a	39.7a	27.6a	22.5a	43.5a	39.5a	28.5a
60 x 10	36.6a	30.0a	26.7a	35.2a	29.2a	28.6b	39.5a	28.3a	20.3a	45.3a	40.2a	30.2a
90 x 10	37.0a	30.6a	28.8a	35.7a	30.6a	29.9b	38.1a	27.8a	21.0a	46.1a	40.3a	30.8a
Mean	36.47	28.97	25.33	35.09	36.7	27.51	45.8	27.87	21.23	44.97	39.99	29.83
LSD	10	12	9	4.6	31.1	6.6	25.2	20.2	18.0.0	24.8	18	10.5
P value	0.09	0.1	0.07	0.51	0.29	<0.001	0.36	0.25	0.09	0.47	0.09	0.06

Means in the same column not having a common letter are significantly different based on theTukeys LSD test (P≤0.05).

Table 4.7. Number of branches of chia greenness in open fields at Kabete and Nyeri 15, 45, and 80 days after sowing (DAS) for two growing seasons under three rows spacings.

Row spacing	Kabete						Nyeri					
	Season 1			Season 2			Season 1			Season 2		
	15	45	80	15	45	80	15	45	80	15	45	80
30 x 10	9a	10a	12a	6a	9a	10a	9a	12a	12a	9a	12a	14a
60 x 10	9a	11a	12a	8a	10a	12b	8a	12a	12a	9a	12a	14a
90 x 10	10b	11a	13b	8a	10a	11ab	9a	11a	12a	8a	12a	13a
Mean	9.3	10.8	12.1	7.3	9.6	10.8	8.4	11.7	11.9	8.8	12.1	13.5
LSD	0.8	1	0.7	2.4	1.3	1.2	0.8	1.4	0.9	2.3	1.8	1.8
P value	<0.001	0.1	0.01	0.08	0.11	0.001	0.13	0.62	0.35	0.09	0.47	0.69

Means in the same column not having a common letter are significantly different based on theTukeys LSD test (P≤0.05).

4.5.4 Yield components of chia

Results from Table 4.8 and 4.9 indicate that yield components of chia including number of panicles, panicle length, grain yield, test weight and harvest index showed no significant differences across the three row spacings in both sites for the two seasons

Table 4.8. Number of panicles and panicle length in open fields at Kabete and Nyeri at physiological maturity for two growing seasons under three rows spacings.

Row spacing	Kabete				Nyeri			
	Season 1		Season 2		Season 1		Season 2	
	Panicles	Length	Panicles	Length	Panicles	Length	Panicles	Length
30 x 10	28a	22a	13a	18a	32a	20a	20a	25a
60 x 10	29a	23a	18a	20a	29a	22a	24a	28a
90 x 10	40b	23a	18a	20a	31a	21a	21a	26a
Mean	32.2	22.62	16.5	19.42	30.6	21.08	21.8	26.62
LSD	7.1	3.2	4.8	4.3	8.6	4.3	13.4	3.8
P value	0.002	0.71	0.09	0.1	0.7	0.06	0.83	0.08

Means in the same column not having a common letter are significantly different based on theTukeys LSD test (P≤0.05).

Table 4.9. Yield components of chia including grain yield (g/plant), test weight (g) and harvest index % (HI) in open fields at Kabete and Nyeri at physiological maturity for two growing seasons under three rows spacings.

Row spacing	Kabete						Nyeri					
	Season 1			Season 2			Season 1			Season 2		
	Grain yield	Test weight	HI	Grain yield	Test weight	HI	Grain yield	Test weight	HI	Grain yield	Test weight	HI
30 x 10	173.3a	16.7a	46.3a	2300a	21.1a	27.8a	783.3a	20.4a	47.9a	702.5a	19.8ab	49.3a
60 x10	172.0a	16.9a	46.3a	2360a	21.5a	28.9a	600.0a	21.0a	50.2a	643.0a	20.9b	53.2a
90 x 10	175.30a	17.5a	44.6a	2320a	22.4a	28.4a	846.7a	20.7a	60.2a	894.5a	19.1a	57.2a
Mean	173.6	17.0	45.8	2327.0	21.7	28.3	743.0	20.7	52.7	746.7	20.0	53.3
LSD	21.7	1.5	2.7	1017.1	1.2	8.3	442.3	1.5	46.0	288.3	1.2	8.5
P value	0.9	0.5	0.3	1.0	0.1	1.0	0.4	0.7	0.8	0.34	0.0	0.12

Means in the same column not having a common letter are significantly different based on theTukeys LSD test (P≤0.05).

4.6 Discussion

4.6.1 Effect of row spacing on chia growth

Growth, as assessed in terms of height, increased in narrow crop density. A row spacing of 30cm and 35cm had the tallest plants of 50 cm and 49 cm respectively (Khan et al., 2010). Similar results reported that the increase in the plant population in the narrow crop spacing of 30cm x 10cm enhanced the increase in the internodal lengths (Mary et al., 2018). In high plant density areas, plants tend to actively compete for light leading to suppression of lateral growth, thus increasing apical dominance (Inamullah et al., 2012).

Its phenotypic plasticity, enables chia plants to exhibit different physical traits in response to environmental factors such as changes in plant height, leaf size, branching patterns, and flowering time. Chia plants modify their morphology and development in order to better suit prevailing environmental conditions, such as light availability, water availability, and nutrient availability (Thiago et al., 2016). Production of new leaves in chia is driven by the activity of apical meristems.These are regions of actively dividing cells at the growing tips of stems and branches. As the plant grows, these meristems generate new leaves, leading to an increase in leaf number over time (Khanet al., 2010).

The variation in leaf area across different row spacing is as a result of intraspecific competition. In closer spacing, such as 30cm x 10cm, chia plants are in close proximity to each other, resulting in intense competition for resources such as light, water, and nutrients. This competition can limitthe availability of resources for individual plants, leading to smaller leaf sizes. On the other hand, wider row spacing, like 60 cm x 10cm and 90 cm x 10cm, allows for more space between plants, reducing the intensity of competition and providing better access to resources. This enables individual plants to allocate more resources to leaf growth, resulting in larger leaf areas (Grimes et al., 2019).

The decline in leaf greenness as the crop approaches maturity is associated with leaf senescence. The slight difference in leaf greenness between row spacing can be influenced by factors such as nutrient availability, light interception, and plant density (El-Serafy et al., 2020). Closer spacing may result in more intense competition for nutrients, leading to accelerated senescence and a faster decline in leaf greenness.

Wider row spacing facilitated the development of more lateral branches in chia plants. This can be attributed to the principle of intraspecific competition. In narrower row spacing, chia plants experience higher resource competition, particularly light. As a result, the plants tend to invest more in vertical growth to access adequate sunlight, which restricts lateral branching. On the other hand, wider row spacing allows for reduced competition and greater availability of light, enablingthe plants to allocate more resources towards lateral branching (Grimes et al., 2019).

4.6.2 Effect of row spacing on yield of chia

Chia exhibits compensatory mechanisms and efficient resource use efficiency whereby they modify their reproductive strategies to ensure efficient resource utilization and seed production. In conditions where resources are limited, chia plants allocate more resources towards seed production by reducing the number of panicles and increasing panicle length. In favorable growing conditions with ample resources, chia plants may produce more panicles with shorter lengths. This flexibility in resource allocation allows chia plants to maintain a relatively stable grain yield across different row spacing treatments (Thiago et al., 2016).

4.7 Conclusion

This study demonstrates that row spacing has a limited impact on the yield components of chia in the studied agro-ecological zones. The findings emphasize the plasticity and resource use efficiency of chia plants, which contribute to their ability to thrive under varying growingconditions. Further research is recommended to explore other agronomic practices and environmental factors that may influence chia's growth and yield, ultimately enhancing its cultivation and utilization in different agro-ecological zones of Kenya.

CHAPTER FIVE: DETERMINATION OF THE EFFECT OF NITROGEN FERTILIZER APPLICATION ON GROWTH AND YIELD OF CHIA

5.1 Abstract

Despite the growing popularity of Chia (*Salvia hispanica* L.) due to its rich nutritional profile across the world, data on agronomic practices on this crop is still scarce. Essentially, mineral nitrogen (N) is an important nutrient in driving crop growth, yield and quality of crops, in addition to its inter-relations with other nutrients. This study examined the effect of rate of N fertilizer supply on crop growth and yield of chia in open field conditions. Experiments were carried out inKabete and Nyeri over two growing seasons using a randomized complete block design with three replications. The studied N rates were 25 kg N/ha, 50 kg N/ha, 75 kg N/ha, 100 kg N/ha and 0 kg N/ha as negative control. Nitrogen was sourced from urea with 46% N, and applied in two equal splits at two and six weeks after planting. Crop growth traits including plant height, number of branches, leaf area and biomass were tracked over time, and upon physiological maturity, yield components such as number of panicles, panicle length, grain yield, test weight and harvest index were recorded. Data was subjected to analysis of variance using GenStat, version 14 at 5% significant level. An increase in nitrogen fertilizer concentration led to an increase in the growth parameters as opposed to yield parameters such as grain yield (g/plant), test weight (g) and harvest index (%). Significant differences were observed in Nyeri in season 1 with highest grain yield of 1333g realized in treatments under 50kgN/ha. These findings imply that the nitrogen levels present in the soil were satisfactory for optimal chia production. Specifically, the soil nitrogen percentages of 0.25% in the clay-loam soil of Kabete and 0.13% in the clay soil of the Dedan Kimathi field station were deemed sufficient for effective chia cultivation. Notably, the study underscores a crucial observation that the application of excessive nitrogen fertilizer at a rate of 100 kg N/ha led to increased vegetative growth at the expense of reproductive growth. Conducting comprehensive soil analysis is essential to identify precise soil nutrient requirements. This analytical approach enables the customization of nutrient management practices, ensuring the targeted supplementation of nutrients based on specific deficiencies or excesses identified in each agro-ecological zone. Such tailored practices not only enhance chia production efficiency but also contribute to sustainable agricultural practices.

Key words Nutrients, urea, yield, crop growth, panicles

5.2 Introduction

Chia (*Salvia hispanica* L.) production has gained interest in other tropical regions beyond its centres of origin, Guatemala and Mexico (Cahill, 2004). Its adaptability to other regions especiallyin sub-Saharan Africa seemed prioritized owing to its associated nutrition and health benefits (Kibui et al., 2018; Ashura et al., 2021). High concentration of beneficial components such as polyunsaturated fatty acids omega 3 and omega 6, essential fatty acids and mucilaginous fiber content (Peiretti and Gai, 2009) are among the beneficial components making chia exceptionally cultivated in most tropical and subtropical areas (Orozco et al., 2014).

Chia is considered an emerging crop in the country, with increasing interest from farmers and entrepreneurs due to its nutritional properties and market demand. Kenya's favorable climate, especially in regions with well-distributed rainfall, provides suitable conditions for chia cultivation. The main chia-growing areas in Kenya include parts of Rift Valley, Nyanza, Western,and Eastern regions. Chia cultivation in Kenya is primarily carried out by small-scale farmers, whooften grow the crop alongside other traditional crops such as maize, beans, or vegetables. Farmers are gradually adopting improved agricultural practices and modern technologies to enhance crop production (Kwena et al., 2019).

The decline in soil fertility has significantly contributed to decreased crop productivity. This is contributed by farmers practicing continuous cropping without replenishing the required nutrients by the soil. The majority of soils in Kenya suffer from severe nitrogen (N) depletion which is a crucial nutrient required for optimal plant growth. It is estimated that nitrogen loss rate in the central Kenyan highlands is more than 30kgN/ha. This significantly reduces the yield of cereals and legumes in the region. The arid and semi-arid lands (ASALs) in Kenya, comprising more than 80% of the country's land area, experience an even more severe situation with regards to nitrogen (N) depletion in the soils (Kwena et al., 2019).

Nitrogen (N) is a fundamental nutrient that plays an important role in plant growth, development,and productivity. It is particularly essential for driving vegetative growth, yield formation, and quality of crops. Adequate nitrogen supply is crucial for maximizing crop performance, while nitrogen deficiency can lead to stunted growth and reduced yields. According to Rathke et al. (2005), nitrogen fertilizer was reported to play a vital role in enhancing crop yields.

A study by Qayyum et al. (1998) showed that nitrogen fertilization increased the growth and development of branches and pods, seeds and 1000 seed weight. Top dressing chia with N fertilizer negatively affected the yield in chia (Bochicchio et al.,2015). On the contrary, Bilalis et al. (2016) studied that the growth of chia was not influenced by fertilization.The fertilization effects on growth and yield of chia mentioned in these studies are derived from research conducted in regions with diverse climatic conditions and varying soils, they may not be directly applicable to Kenya. Proper nitrogen management, considering crop-specific requirements and environmental considerations, is critical for sustainable and productive crop cultivation.

This study addressed the limited information available on nitrogen management practices in chia cultivation by investigating the impact of different rates of nitrogen supply on crop growth and yield in two contrasting agro-ecological zones of Kenya. The research hypothesized that varying N fertilizer rates is not competitive with the recommended N-fertilizer application rate on growth and yield of chia in two contrasting agro-ecological zones of Kenya. The study aimed to contributeto the development of sustainable agronomic practices for chia production. The knowledge gained from this study would support farmers, researchers, and agronomists in optimizing nitrogen fertilizer use and maximizing the productivity and quality of chia crops.

5.3 Materials and Methods

5.3.1 Description of study sites

This study was conducted in Kabete, University of Nairobi and Dedan Kimathi University Field plots. In each study site, two growing seasons were conducted concurrently from April 2021 to February 2022. Kabete is located 1° 15′S, 36° 44′E and 1930 m above sea level and receives bimodal rainfall (Sambroek et al., 1982). The mean temperatures and humidity are 26^0 C and 69%, respectively. Dedan Kimathi University is located 0°23′52″S, 36°57′ 39″E and 1781m above sea level, characterized by bimodal rainfall patterns of between 800 to1400mm. It is characterized with well-drained soils, and have a mean monthly maximum temperature of 24 °C and a minimumof 18 °C.

5.3.2 Chia crop establishment and nitrogen fertilizer application

On a 29m × 18.6m well cultivated piece of land, chia seeds were sown within the 15 accommodated plots. In each plot, enough chia seeds were drilled along the 60cm apart inter-row.Thinning was carried out 14 days after planting. Other subsequent agronomic practices such as weeding was done manually using a hoe.

5.3.3 Treatments and experiment design

The treatments comprised of five nitrogen fertilizer (Urea 46%) rates including 0 kg N/ha, 25 kg N/ha, 50 kg N/ha, 75 kg N/ha, and 100 kg N/ha. Nitrogen fertilizer was applied in two splits-after2 and 6 weeks using the drill method 5cm close to the crop rows then covered with soil lightly. Allthe treatments were arranged in a randomized complete block design with three replications. To accommodate spatial variations in the field, the five nitrogen fertilizer rates were randomly allocated within the field.

5.3.4 Data collection

Weather data for the two growing seasons was acquired from the Kenya meteorological department headquarters, collected monthly and comprised of relative humidity, evapotranspiration, rainfall and maximum and minimum temperatures. Crop growth parameters were scored periodically as the crop matured 45, 80 and 100 days after sowing (DAS). Yield components were recorded when the crop attained physiological maturity which was identified as when 80% leaves of chia dried up followed by chia panicles becoming hard and brittle and shattering of the seeds.

Five chia plants were randomly sampled and tagged for data collection. Growth parameters included plant height (cm), leaf area (cm^2), number of branches developing from the main stem, leaf greenness, and biomass accumulation (g). Yield components comprised of number of panicles,panicle length (cm), grain yield (g/plant), test weight (g) and harvest index (%). Elaboratively, the main stem length was determined from the soil surface up to the start of the inflorescence parts using a meter ruler. Leaf area was determined by measuring leaf length and leaf width using a meter rule then following an equation by Goergen *et al.* (2019) that defines leaf area as;

$$LA\ (cm^2) = 0.642 \times \text{leaf length} \times \text{leaf width}.$$

The length of the developed inflorescence was determined as the central length from the distal to the proximal end of inflorescence this was measured using a meter rule. Upon physiological maturity, all chia plants per plot were harvested to determine seeds yield (g/plant), test weight (g)and harvest index (%). Harvest index was determined as ratio between grain yield and total biomass. Test weight was determined by obtaining a representative sample of seeds, weighing in a clean and dry measuring container, with the weight of the empty container subtracted from the weight of the container with seeds to calculate the net weight, providing an indication of seed density and quality.

5.4 Data analysis

All the research data was statistically analyzed using the GenStat software, 14th edition. An analysis of variance (ANOVA) was used to determine significant differences in means of the experimental treatments against all assessed variables the growth and development of chia at P<0.05% significance level using Tukeys Least Significance Difference multiple comparisons.

5.5 Results

5.5.1 Plant height and leaf area

The growth traits of chia, such as height, leaf area, number of branches, and biomass, exhibited some variations across different nitrogen fertilizer rates and growing seasons in Kabete and Nyeri. The effect of nitrogen fertilizer on height of chia was significant in the last stage of crop maturityin Kabete for both seasons (Table 5.1). In season 1, plants with no nitrogen treatment as well as with 100kg N/ha were the tallest at 79cm. In season 2, the N- rate of 100kg N/ha increased in height to 90cm recording the tallest plants across the five N fertilizer rates. No statistical differences were observed in Nyeri for both seasons as shown in table 5.1.

Table 5.1. Height of chia (cm) in open fields at Kabete and Nyeri 15,45 and 80 days after sowing(DAS) for two growing seasons under different nitrogen fertilizer rates

	Kabete						Nyeri					
Nitrogen rate	Season 1			Season 2			Season 1			Season 2		
	15	45	80	15	45	80	15	45	80	15	45	80
0	24a	58ab	79b	32a	72a	81ab	44a	69a	74a	55ab	68a	72a
25	25a	52a	75ab	37a	76a	80a	41a	69a	75a	53ab	66a	68a
50	27a	62b	70a	37a	76a	84ab	40a	75ab	79a	61b	70a	74a
75	24a	59ab	73ab	36a	77a	83ab	43a	72ab	76a	51a	66a	68a
100	23a	60ab	79ab	39a	80a	90b	43a	78b	81a	54ab	64a	68a
Mean	24.43	58	75.1	36.15	76.2	83.7	42	72.49	77	55	66.8	69.7
LSD	3.28	6.66	6.31	5.24	6.82	6.6	3.8	6.01	6.1	5.6	6.64	6.33
P value	0.25	0.05	<0.01	0.13	0.17	0.04	0.23	0.01	0.12	0.01	0.38	0.22

Means in the same column not having a common letter are significantly different based on the Tukeys LSD test (P≤0.05).

As recorded in Table 5.2, no differences were observed in the five nitrogen fertilizer treatments early in the season. However, as the crop matured, significant variations were observed between nitrogen fertilizer rates and leaf area in season two in Kabete with N rate of 100kg N/ha having the largest leaf area. In Nyeri however, both seasons showed statistical differences across the five N fertilizer rates, with an N rate of 75kg N/ha recording the lowest leaf area in both seasons.

Table 5.2. Leaf area (cm^2) of chia in open fields at Kabete and Nyeri 15,45 and 80 days after sowing (DAS) for two growing seasons under five nitrogen fertilizer rates of 0,25,50,75 and 100 kg N/ha.

	Kabete						Nyeri					
Nitrogen	Season 1			Season 2			Season 1			Season 2		
rate	15	45	80	15	45	80	15	45	80	15	45	80
0	22a	31a	37a	19a	28a	33ab	45a	70a	79c	44a	62a	73c
25	22a	33ab	36a	20a	25a	28a	48a	65a	76c	42a	62a	71bc
50	26a	38ab	29a	23a	31a	33ab	43a	69a	61ab	42a	63a	58a
75	23a	39ab	31a	23a	40b	34ab	43a	59a	50a	45a	64a	56a
100	28a	43b	33a	25a	45b	41b	44a	66a	63b	42a	69a	63ab
Mean	24.3	36.6	33.1	21.71	33.68	33.7	44.7	65.93	65.6	43.09	63.87	64.12
LSD	6.01	8.21	8.02	7.22	6.1	8.48	6.5	9.06	10.5	6.23	9.63	8.5
P value	0.22	0.04	0.31	0.15	<0.001	0.08	0.45	0.11	0.03	0.81	0.61	<0.001

Means in the same column not having a common letter are significantly different based on the Tukeys LSD test ($P \leq 0.05$).

5.5.2 Number of branches and biomass accumulation

Table 5.3 Shows that the number of branches were not significantly different across the 5 nitrogen treatments of 0, 25, 50, 75 and 100kg N/ha in season 1 in Kabete. On the contrary, the treatment of 75kg N/ha recorded the highest number of 12 branches in season 2. In Nyeri nitrogen rates of 100kg N/ha had more branches in comparison to other treatments in season 1 while no differences were observed in season 2. In both Kabete and Nyeri, there were no significant differences in biomass among the nitrogen rates. (Table 5.4)

Table 5.3. Number of branches of chia in open fields at Kabete and Nyeri 15,45 and 80 days after sowing (DAS) for two growing seasons under five nitrogen fertilizer rates

	Kabete				Nyeri			
	Season 1		Season 2		Season 1		Season 2	
Nitrogen rate	45 DAS	80 DAS	45 DAS	80 DAS	45 DAS	80 DAS	45 DAS	80 DAS
0	12a	13a	9a	11ab	13a	14ab	11a	12a
25	11a	12a	8a	9a	12a	14ab	11a	12a
50	11a	12a	9a	10ab	12a	14a	11a	12a
75	10a	12a	9a	12b	12a	14ab	12a	12a
100	11a	12a	9a	11ab	13a	15b	11a	12a
Mean	10.81	12.37	8.83	10.44	12.49	14.08	10.99	11.9
LSD	1.14	0.98	1.56	1.50	1.16	1.03	1.10	1.00
P value	0.42	0.69	0.48	0.01	0.26	0.06	0.45	<0.35

Means in the same column not having a common letter are significantly different based on the Tukeys LSD test (P≤0.05).

Table 5.4. Shoot biomass (g/plant) of chia in Kabete and Nyeri 15, 45 and 80 days after sowing (DAS) for two growing seasons grown under five nitrogen fertilizer rates

	Kabete						Nyeri					
Nitrogen	Season 1			Season 2			Season 1			Season 2		
rate	45	80	100	45	80	100	45	80	100	45	80	100
0	122a	110a	965a	122a	110a	307a	12a	60a	126a	25a	55a	159a
25	82a	120a	1567a	82a	120a	251a	18a	43a	85a	18a	90a	106a
50	76a	161a	947a	76a	161a	262a	15a	46a	113a	37a	126a	169a
75	59a	78a	1105a	59a	78a	229a	17a	33a	101a	23a	139a	93a
100	55a	110a	993a	55a	110a	156a	23a	41a	109a	26a	123a	108a
Mean	78.9	116	1115	78.9	116	241	17	44.5	106.9	25.6	106.6	127
LSD	68.72	102.5	811	68.72	102.5	250	9.57	47	58.38	13.29	64.67	99.4
P value	0.26	0.51	0.42	0.26	0.51	0.72	0.16	0.77	0.61	0.1	0.09	0.35

Means in the same column not having a common letter are significantly different based on the Tukeys LSD test (P≤0.05).

5.5.3 Yield components of chia

Results in Table 5.5 presents the number of panicles and panicle length of chia plants in Kabete and Nyeri at physiological maturity, under different nitrogen fertilizer rates and across two growing seasons. The results show that there were no significant differences in the number of panicles and panicle length among the nitrogen rates in Kabete in both seasons. Significant ($P \leq 0.05$) differences were only noted in Nyeri in the second season whereby 25kg N/ha had 7 more panicles comparedto plants under 100 kg N/ha, with a panicle length of 10cm. Table 5.6 presents the yield components of chia, including grain yield (g/plant), test weight (g), and harvest index (%), in the open fields of Kabete and Nyeri across two growing seasons under different nitrogen fertilizer rates. Nitrogen fertilizer rates had varying effects on the yield components of chia in Kabete and Nyeri.

In Kabete, the grain yield showed no statistical differences across the nitrogen rates in both seasons. However, the test weight and harvest index exhibited some significant ($P \leq 0.05$) variations. In Kabete, higher test weight values were observed at 25 kg N/ha and 50 kg N/ha in Season 1 and 2 respectively. Significant differences ($P \leq 0.05$) in grain yield were only observed atNyeri, in the first season. The highest grain yield of 1333g, among the nitrogen rates was noted inplots under 50 kg N/ha. In Nyeri, the test weight significantly($P \leq 0.05$) differed among the differentN rates only in season 1. There was a 1.8g difference between the treatments with the highest testweight and the lowest test weight represented by 75kg N/ha and 25kg N/ha respectively. The harvest index did not exhibit significant differences across the nitrogen rates in both seasons (Table5.6).

Table 5.5. Number of panicles per plant and panicle length in Kabete and Nyeri at physiological maturity for two growing seasons under five nitrogen fertilizer rates.

Nitrogen rate	Kabete				Nyeri			
	Season 1		Season 2		Season 1		Season 2	
	Panicles	Length	Panicles	Length	Panicles	Length	Panicles	Length
0	34a	21a	37a	11a	50a	11a	17ab	9a
25	30a	22a	32a	11a	47a	11a	23b	10a
50	31a	24a	29a	11a	48a	11a	19ab	10a
75	29a	21a	29a	11a	48a	11a	20ab	9a
100	32a	24a	31a	12a	53a	12a	16a	9a
Mean	30.88	22.08	31.47	11.19	49.2	11.19	18.83	9.29
LSD	5.71	3.42	9.35	1.77	8.75	1.77	4.57	1.62
P value	0.43	0.26	0.56	0.36	0.6	0.36	0.03	0.45

Means in the same column not having a common letter are significantly different based on the Tukeys LSD test (P≤0.05).

Table 5.6. Yield components of chia including grain yield(g/plant), test weight (g) and harvest index % (HI) in open fields at Kabeteand Nyeri at physiological maturity for two growing seasons under five nitrogen fertilizer rates.

Nitrogen rate	Kabete						Nyeri					
	Season 1			Season 2			Season 1			Season 2		
	Grain yield	Test weight	HI	Grain yield	Test weight	HI	Grain yield	Test weight	HI	Grain yield	Test weight	HI
0	180.3a	17.6bc	45.5a	1025.0a	22.7a	25.5a	1250.0b	19.1a	34.6a	250.1a	20.2a	46.2a
25	206.3a	18.3c	39.6a	1100.0a	22.9ab	30.9a	950.0a	18.9a	36.1a	320.7a	20.2a	40.0a
50	238.7a	17.0b	37.1a	1520.0a	23.1b	28.8a	1333.0b	19.5ab	32.3a	277.3a	19.7a	43.6a
75	240.7a	17.3bc	37.6a	1500.0a	22.9ab	32.8a	1200.0ab	20.7b	32.0a	263.3a	19.6a	40.3a
100	226.0a	15.6a	37.9a	1300.0a	22.9ab	23.6a	1050.0ab	20.3ab	42.0a	346.3a	19.4a	39.8a
Mean	218	17.15	39.56	1289	22.89	28.3	1157	19.68	35.4	292	19.81	41.97
LSD	127.7	0.7	13.6	505	0.3	12.6	255.5	1.1	10.9	158.3	1.2	6.8
P value	0.79	<.001	0.62	0.43	0.039	0.48	0.04	0.005	0.3	0.62	0.607	0.25

Means in the same column not having a common letter are significantly different based on the Tukeys LSD test (P≤0.05)

5.6 Discussion

5.6.1 Effect of nitrogen fertilizer on chia growth

Plant height increased gradually as the crops matured. In Kabete, significant variations were observed across the five nitrogen rates during the second season. Treatments under 100kg N/ha had the tallest plants. Chil (2021) also noted that highest plant height was with treatments subjectedto 100kg N/ha. In Nyeri however, no significant differences were observed across the nitrogen rates in the two seasons. Similar findings were reported by Bilalis et al., (2016) who noted that fertilization did not influence height of chia. Higher nitrogen fertilization rates, such as 100 kg N/ha, provide an abundant supply of nitrogen to the plants. This increased nitrogen availability promotes vigorous cell growth and elongation, leading to taller plants.

The lack of significant differences in plant height across the nitrogen rates in both seasons suggests that nitrogen availability may not have been a limiting factor for plant height in that particular agro-ecological zone. It is possible that the natural soil fertility or nitrogen content in Nyeri was already sufficient to meet the nitrogen demands of the chia plants. In such cases, additional nitrogen fertilization may not have led to a noticeable increase in plant height.

Treatments subjected to 25 kg N/ha had significantly lower leaf area when compared to other treatments in Kabete in season 2. In Nyeri, a similar trend was observed during both seasons, with increasing leaf area as nitrogen rates increased in both seasons. Similar results reported that neither the sowing rates nor the fertilization had any influence on the growthof chia as well as no notable variations observed among the different fertilization treatments for dry weight and leaf area index (Bilalis et al., 2016). Nitrogen is a vital nutrient involved in chlorophyll synthesis, which is necessary for photosynthesis. Adequate nitrogen supply enhances the production of chlorophyll, resulting in increased photosynthetic capacity and overall leaf area.

Variations in the number of branches between the nitrogen rates in Kabete in season 2 were observed. Chia plants treated with 75 kg N/ha had more branches compared to the other treatments.This suggests that moderate nitrogen application rates promote branching in chia plants in Kabete.This indicates that the nitrogen fertilization did not have a substantial impact on the branching pattern of chia plants in Nyeri. The number of branches in chia plants can be influenced by various factors, such as environmental conditions and cultural practices.

Nitrogen availability can also play a role in regulating branching patterns. However, the lack of significant differences in Nyeri may suggest that other factors, such as genetic factors or environmental conditions, may have a stronger influence on the branching characteristics of chia in that specific agro-ecological zone. In both Kabete and Nyeri, there were no significant differences in biomass among the nitrogen rates, indicating that nitrogen levels did not have a substantial impact on overall biomass production of chia plants.

Having a thorough grasp of the mechanisms that control nitrogen (N) uptake and distribution in crops holds great significance concerning environmental considerations and the overall quality of crop outputs. As stated by Gastal and Lemaire (2002), nitrogen uptake and accumulation are two crucial elements within the nitrogen cycle in agricultural systems. Nevertheless, in the case of most crops, the interplay between nitrogen and biomass accumulation relies on the intricate regulation of various physiological processes within the crops themselves.

The findings highlight the importance of considering specific agro-ecological conditions and soilnutrient levels when determining the appropriate nitrogen fertilization rates. The response of chia plants to nitrogen fertilization can vary depending on the existing soil fertility, nutrient availability,and other environmental factors. It is essential to optimize nitrogen management practices by conducting site-specific soil analyses and considering the specific nutritional requirements of chia in different regions.

5.6.2 Effect of nitrogen fertilizer on yield of chia

The results from both Kabete and Nyeri showed no statistical differences in number of panicles and panicle length among the different nitrogen rates tested. This suggests that nitrogen levels did not have a substantial impact on the reproductive parameters of chia plants in these locations.

The number of panicles represents the reproductive capacity of the plants, while panicle length can indicate the potential for seed production. However, the lack of significant differences among the nitrogen rates suggests that nitrogen availability did not play a significant role in determining these reproductive parameters in chia. While nitrogen is important for plant growth and reproduction, other factors such as temperature, moisture, and light availability may have had a stronger influence on panicle development and length (Grimes etal., 2019). Though the recommended nitrogen application is 50 Kg N/ha, this study further indicated that 100Kg N/ha or 0 Kg N/ha, had similar total biomass, grain yield, and harvesting index and test weight in chia grown in open field. Contrary to these findings, a study by Njoka et al., (2022) noted that plants treated with a nitrogen application rate of 120 kg N/ha demonstrated significantly higher yields, ranging from 3.82 to 4.35 t/ha, compared to the control crops which yielded between 1.83 and 3.02t/ha. However, the study was conducted in a different agro-ecological zone of Meru County which falls under midland agro- ecological zone.

Grain yield represents the actual yield of chia seeds per plant, while test weight is an indicator of seed quality and density. Harvest index reflects the proportion of total dry biomass allocated to grain production. The lack of significant differences in grain yield and harvest index among the nitrogen rates in both locations indicates that nitrogen levels may not have been the primary limiting factor affecting yield and partitioning of biomass to grain production (Chil, 2021).

Application of nitrogen to crops such as maize was shown to remarkedly increase most of its growth parameters and yield (Vos et al., 2005). However, application of 20 Kg N/ha in chia had negative effect on the yield and resulting to lodging and lower rate of seed maturation (Bochicchioet al., 2015). Similarly, on rapeseed, a higher amount of nutrients and available N were shown to frequently limit seed yield (Hockings et al., 1997).

Chia, being a relatively low-demanding crop in terms of nitrogen, have the ability to effectively extract and utilize available nitrogen from the soil, even at lower levels. Chia plants might have been able to meet their nitrogen needs from the soil's existing nitrogen pool, thus minimizing the response to additional nitrogen fertilizer application. Overall, the lack of significant response to different nitrogen fertilizer rates in chia production can be attributed to sufficient nitrogenavailability in the soil, the ability of chia plants to efficiently utilize nitrogen, genetic factors, environmental conditions, and interactions with other nutrients (Grimes et al., 2019).

5.7 Conclusion

The study's findings revealed that varying rates of nitrogen fertilizer application had no significant influence on the growth and yield parameters of chia in the agro-ecological zones under investigation in Kenya. There were minimal variations regardless of the nitrogen rates applied on yield components of chia. These results suggest that the existing nitrogen levels in the soil were sufficient for effective chia production, with soil nitrogen percentages of 0.25% and 0.13% in the clay-loam and clay soils of Kabete and Dedan Kimathi field stations, respectively. The plant either utilized the available nitrogen optimally for its growth and development or only absorbed as much as it needed for its overall growth without responding to additional nitrogen application. However, important to note from the findings is that over application of N fertilizer at 100kgN/ha resulted to excessive vegetative growth over reproductive growth of the crop thus negatively affecting seed setting. Reproductive performance is a complex trait influenced by multiple interacting factors, and further research is needed to elucidate the underlying mechanisms and optimize nutrient management practices for enhancing chia seed production. It is crucial to conduct thorough soil analysis to determine specific soil nutrient requirements. This analysis will help tailor nutrient management practices and ensure appropriate nutrient supplementation based on the specific nutrient deficiencies or excesses foundin each agro-ecological zone, promoting sustainable and efficient chia production The study's limitations, included its limited scope of agro-ecological zones, short-term evaluation and sample size.

CHAPTER SIX: GENERAL DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

6.1 General discussion

This study revealed that moisture stress significantly affects the growth and yield of chia. Higher moisture regimes, specifically 80% and 100% field capacity, resulted in improved growth parameters and yield components. This suggests that chia exhibits a degree of drought tolerance but still requires adequate moisture for optimal productivity. Soil moisture is a critical factor that affects the physiological processes and overall performance of chia plants. The functions affected include, nutrient uptake, photosynthesis, and water transport within the plant. Insufficient soil moisture can negatively impact chia growth and yield. Importance of water was further shown by Lovelli et al. (2019), whereby a reduction of 25% of the photosynthetic rate was observed upon the shortage of water in chia.

The study on row spacing's impact on chia growth and yield revealed that varying row spacing treatments did not have a significant effect. This is likely due to chia's low water requirements, enabling it to thrive well in arid and semi-arid areas. Consequently, when chia is cultivated in nutrient-rich soils, its growth and yield remain unaffected by the chosen row spacing. The study on nitrogen (N) fertilization demonstrated that an increase in N supply led to improved growth parameters of chia. However, yield parameters such as grain yield, test weight, and harvest index did not consistently respond to increased nitrogen concentrations. This suggests that there might be an optimal threshold for nitrogen application beyond which excessive fertilization may not enhance chia yields.

Chia possesses inherent mechanisms to efficiently acquire and utilize nitrogen from the soil, making it a cost-effective and sustainable crop option for farmers. Moreover, the reduced relianceon nitrogen fertilizers not only reduces production costs but also minimizes the environmental impact associated with fertilizer application, such as nutrient runoff and pollution. The findings from this study support the notion that chia, a versatile and resilient crop, exhibits remarkable growth and yield potential without the need for substantial nitrogen fertilizer application in contrasting agro-ecological zones of Kenya.

Collectively, these findings provide a broader understanding of chia's growth and yield dynamics, highlighting its adaptability and resilience across varied environmental and agronomic conditions. The crop's inherent ability to efficiently utilize nitrogen, as evidenced in the nitrogen fertilization study, not only enhances economic viability for farmers by reducing production costs but also aligns with sustainable agricultural practices. Overall, these findings emphasize the importance of considering multiple factors in tailoring chia production strategies to diverse agro-ecological zones.

6.2 Conclusions

This study underscores the pivotal role of moisture stress in shaping the growth and yield of chia, emphasizing the crop's reliance on optimal soil moisture levels. While chia exhibits some drought tolerance, higher moisture regimes, particularly at 80% and 100% field capacity, significantly enhance both growth parameters and yield components. The study highlights the critical impact of soil moisture on essential physiological processes such as nutrient uptake, photosynthesis, and water transport within the plant.

Notably, the investigation into row spacing treatments reveals that variations in this factor do not exert a significant influence on chia growth and yield. This observation suggests that chia's low water requirements enable it to thrive in arid and semi-arid regions, particularly when cultivated in nutrient-rich soils. Moreover, the nitrogen fertilization study indicates that increased nitrogen supply positively affects chia's growth parameters, yet the response of yield components, such as grain yield, test weight, and harvest index, is not consistently proportional to higher nitrogen fertilizer rates. This implies the existence of an optimal threshold for nitrogen application, beyond which excessive fertilization may not consistently enhance chia yields.

Chia's inherent capacity to efficiently acquire and utilize nitrogen from the soil positions it as a cost-effective and sustainable crop choice for farmers. This mitigates the environmental impact associated with fertilizer application, such as nutrient runoff and pollution. Consequently, the study's findings support the notion that chia, characterized by versatility and resilience, demonstrates substantial growth and yield potential across diverse environmental and agronomic conditions in Kenyan agriculture, without necessitating significant nitrogen fertilizer input.

6.3 Recommendations

1. Implementing effective soil moisture management practices, especially maintaining soil moisture conditions close to 80 % field capacity. This contributes to resource conservation, particularly water, and ensures consistent and enhanced chia production.
2. Conduct further research to explore optimal water management strategies in open fields, considering the specific moisture requirements of chia at different growth stages and undervarying agroecological conditions.
3. Investigate the interactions between row spacing, fertilization regimes, and other agronomic practices to identify the most suitable combination for maximizing chia yields.
4. Study the nutrient dynamics in chia crops and develop tailored fertilization strategies that balance nutrient requirements with environmental sustainability.

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