

**FOLIAR SELENIUM INFLUENCE ON AGRONOMIC PERFORMANCE,  
GRAIN QUALITY AND WATER USE EFFICIENCY OF COMMON  
BEAN (*Phaseolus vulgaris* L.) UNDER WATER STRESS CONDITIONS**

**VICTORIA LIVINGSTONE GAMBA**

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Requirements for the Master of Science Degree in Water Resources and  
Environmental Management of Egerton University**

**EGERTON UNIVERSITY**

**OCTOBER, 2025**

## **DECLARATION AND RECOMMENDATION**

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Signature: .....

Date: .....

Name: Victoria Livingstone Gamba

Reg No: BM13/10020/23

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The thesis is the candidate's original work and has been prepared with our guidance and assistance. It is presented for examination with our approval as official University Supervisors.

Signature: .....

Date: .....

Dr Romulus O. Okwany, PhD

Department of Agricultural Engineering

Egerton University

Signature: .....

Date: .....

Dr Samwel Nyakach, PhD

Department of Agricultural Engineering

Egerton University

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## ABSTRACT

Water scarcity is a critical global issue, especially in arid and semi-arid regions where agricultural productivity heavily depends on irrigation. Common beans (*Phaseolus vulgaris* L.), a vital legume for food and nutrition security, is highly sensitive to water deficits. This study was conducted to evaluate the effects of foliar selenium (Se) application on the growth, yield and Water Use Efficiency (WUE) of common beans under Deficit Irrigation (DI). The experiment was carried out in a greenhouse at Egerton University using Surface Drip Irrigation (SDI). Treatments involved three irrigation levels (100%, 70% and 50% of crop evapotranspiration ( $ET_c$ )) combined with four selenium concentrations (0, 0.5, 1.0 and 1.5 mg/L), arranged in a factorial design with three replications. Selenium applications were done 23 days after sowing and during vegetative, flowering, pod formation stages. The growth parameters (plant height, leaf number, branches and leaf area index), yield components (pod length, pods per plant, seed number and yield), were monitored across various growth stages and after harvesting. The results demonstrated full irrigation 100%  $ET_c$  with 1.5 mg/L Se application resulted in highest vegetative growth parameters and yield parameters while moderate water stress (70%  $ET_c$ ) combined with 1.5 mg/L Se application significantly enhanced growth and yield of common beans and improved WUE. The highest selenium accumulation in the grains (0.445 mg/Kg) was observed at 50%  $ET_c$  together with application of 1.5 mg/L Se concentration, exceeding the daily consumption allowable limit. This implied that plants under water stress absorbed and retained more selenium compared to those under full irrigation. For optimal yield and WUE, the study indicated 70%  $ET_c$  irrigation level combined with 1.5 mg/L of foliar selenium concentration with the optimum yield (10348.1 Kg/Ha) while maintaining a high WUE (0.357 Kg/m<sup>3</sup>) as compared to the control (100  $ET_c$  with no selenium). This confirms the potential of integrating deficit irrigation with foliar Se application to optimize water use while improving bean productivity and nutritional quality. Notably, foliar Se enhanced the plants' physiological tolerance to water stress, particularly during flowering and pod formation. Therefore, Se application can help improve drought resilience, enhances physiological performance and supports sustainable agricultural limited water availability, contributing to SDG 2 (End hunger, achieve food security and improved sustainable agriculture), as well as ensuring safe food production under SDG 3.

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## **LIST OF ABBREVIATIONS AND ACRONYMS**

<b>AAS</b>	Atomic Absorption Spectroscopy
<b>ANOVA</b>	Analysis of Variance
<b>DI</b>	Deficit Irrigation
<b>DoE</b>	Design of Experiment
<b>DNA</b>	Deoxyribonucleic Acid
<b>ET<sub>c</sub></b>	Crop evapotranspiration in millimetres per day
<b>ET<sub>o</sub></b>	Reference crop evapotranspiration in millimetres per day
<b>FAO</b>	Food and Agricultural Organization of the United Nations
<b>GLP</b>	Genetically Local Population
<b>Ha</b>	Hectare
<b>K</b>	Potassium
<b>K<sub>c</sub></b>	Crop coefficient
<b>Mn</b>	Manganese
<b>P</b>	Phosphorus
<b>RDA</b>	Recommended Daily Allowance
<b>SDI</b>	Surface Drip Irrigation
<b>Se</b>	Selenium
<b>SDG</b>	Sustainable Development Goals
<b>SSA</b>	Sub Saharan Africa
<b>STs</b>	Sulphate Transporters
<b>TM</b>	Taguchi Method
<b>WHO</b>	World Health Organization
<b>WUE</b>	Water Use Efficiency

# CHAPTER ONE

## INTRODUCTION

### 1.1 Background Information

Water plays a vital role in sustaining biological and ecological functions, supporting food production, energy generation, and aquatic life. Oceans and inland saltwater bodies form 97.5% of water in the world. Of the remaining 2.5% that makes up freshwater, approximately 69% is trapped in glaciers and icebergs. Earth's surface and groundwater resources are vital for the needs of humans and the ecosystem. Rapid population increase and accelerated urbanization particularly in undeveloped countries have intensified global competition for limited freshwater resources leading to unsustainable utilization. The main use of freshwater is in agriculture where developed nations use about 70% of their available freshwater while in under-developed nations it accounts for over 90% (Alipour *et al.*, 2022).

Climate change has significantly disrupted rainfall patterns affecting its timing, distribution, and intensity thereby worsening global water shortages. Rising temperatures further influence precipitation patterns, increasing watershed runoff and reducing effective water availability for crop development and productivity (Trenberth *et al.*, 2014). Crop water use varies according to crop growth stages and their water requirements, as one of the most crucial elements in the agricultural production system. However, it has become a scarce natural resource for crop production since proper water management procedures are often not followed or have not been appropriately developed. The adoption of effective nature-based solutions like life-saving irrigation and supplemental irrigation during critical crop growth stages remains essential for enhancing water productivity, ensuring crop resilience and supporting sustainable agricultural systems. Water stress influences several crop functions including morphological, physiological, and biochemical processes depending on the species and growth stage which reduces yield. This effect is particularly severe in common beans (*Phaseolus vulgaris* L.) cultivated in the arid and semi-arid areas (Ravello *et al.*, 2022). The available water requires the adoption of drip irrigation systems as an irrigation technology that increases water productivity and ensure effective use of water for the crops.

Furthermore, deficit irrigation (DI) ensures maximum resource utilization and comes in as a strategic to optimize water use conservation measures and conserve the available water. Nutrients and vitamins are naturally found in food crops consumed by

humans but agronomic bio-fortification is an alternative technological method that increases the nutritional content of crops. This is true especially for selenium (Se) as it is not only necessary for plants but human beings too especially in areas with low Se content in the soil. Despite not being a key element for plants, Se may encourage the activation of their defence mechanisms to promote plant development and reduce losses in output due to external stressors like a water shortage (Ravello *et al.*, 2022).

Different studies have shown that selenium (Se) enhances photosynthetic performance by shielding chlorophyll and chloroplast ultrastructure from free radical damage. Furthermore, by increasing water intake and decreasing water loss from plant cells, Se aids in the maintenance of the plant's water content. The use of bio-fortification to increase the amount of Se in plant-based meals has become more popular recently, specifically in areas with selenium deficiency. Selenium is well acknowledged as a dietary trace element that is necessary for both humans and animals, has a significant impact on health promotion and illness prevention (Moussa & Hassen, 2018). Selenium is necessary for DNA synthesis, thyroid gland function, reproduction, and defence against infection and free radical damage. A widespread risk to human health has been noted in Se deficiency, which impacts over 50% of the global populace. Consumption of food products fortified with Se can enhance Se intake and eating a regular selenium enriched diet has become one possible method of obtaining Se (Bao *et al.*, 2023). Foliar selenium application for water stress resilience has been selected relative to other methods such as the use of mulch and super absorbent polymers which help to increase water holding capacity of soil and save water under drip irrigation system but do not protect the plants against abiotic stresses, increase the photosynthesis activity and supplement nutrients to the crop which is essential for humans and animals (Satriani *et al.*, 2018). Fertilizers supplemented with Se for crop production is not only an effective way to produce selenium-rich food but also a means to suppress water stress effects on the crop (Moulick *et al.*, 2024). Given the sensitivity of yield to water deficit, the information on the concentration of the applied foliar selenium in *Phaseolus vulgaris* L is crucial. Thus, there was a need to assess the effect of varied water stress levels on *Phaseolus vulgaris* L yield, quality and water productivity under varied applications rates of foliar selenium.

## **1.2 Statement of the Problem**

The production of common beans (*Phaseolus vulgaris* L.) in Kenya has declined due to unfavourable weather conditions, including water shortages in the growing regions (Duku *et al.*, 2020). To address water shortage, particularly in arid and semi-arid areas, deficit irrigation offers a practical strategy to conserve water while optimizing agricultural water consumption. Unfortunately, despite the noted improvements in water use efficiency the gross yield is usually lower with economic impact on the gross margins for production. It is thus necessary to not just improve water use efficiency but also sustain the yield levels. With combination-n of effective agronomic practices such as foliar Se fertilizer application, the technique which can mitigate water stress effects to the crop and save water without significantly compromising crop yield and/or quality. However, improper application can lead to bioaccumulation, causing toxicity in plant tissues (Bao *et al.*, 2023). The foliar Se application rate have not been extensively studied to be cautiously implemented for use. This research aimed to address the effects of DI and foliar Se application on the yield, quality and water productivity of *Phaseolus vulgaris* L. Addressing this problem provided practical solutions for farmers, ensuring improved *Phaseolus vulgaris* L production under water-stressed and irregular rainfall conditions while minimizing yield and quality losses.

## **1.3 Objectives**

### **1.3.1 Broad Objective**

The broad objective of this study was to determine how foliar selenium application influences the agronomic performance, grain quality and water use efficiency of common beans (*Phaseolus vulgaris* L.) subjected to deficit irrigation

### **1.3.2 Specific Objectives**

In this research the following were the specific objectives:

- i. To assess the effects of foliar Se application rates and deficit irrigation on growth parameters and yield parameters of *Phaseolus vulgaris* L.
- ii. To evaluate the effects of reduced water availability on the uptake levels of selenium by *Phaseolus vulgaris* L.
- iii. To identify the most effective rates of foliar Se application and water levels within the experimental conditions for optimal yield and water use efficiency of *Phaseolus vulgaris* L.

#### **1.4 Research Questions**

- i. How does foliar Se application rates and deficit irrigation affect the growth parameters and yield parameters of *Phaseolus vulgaris* L.?
- ii. What is the influence of foliar selenium application and deficit irrigation on selenium uptake in common bean tissues?
- iii. What combination of foliar Se application rates and water-stress conditions resulted in optimum yield and water use efficiency of *Phaseolus vulgaris* L.?

#### **1.5 Justification**

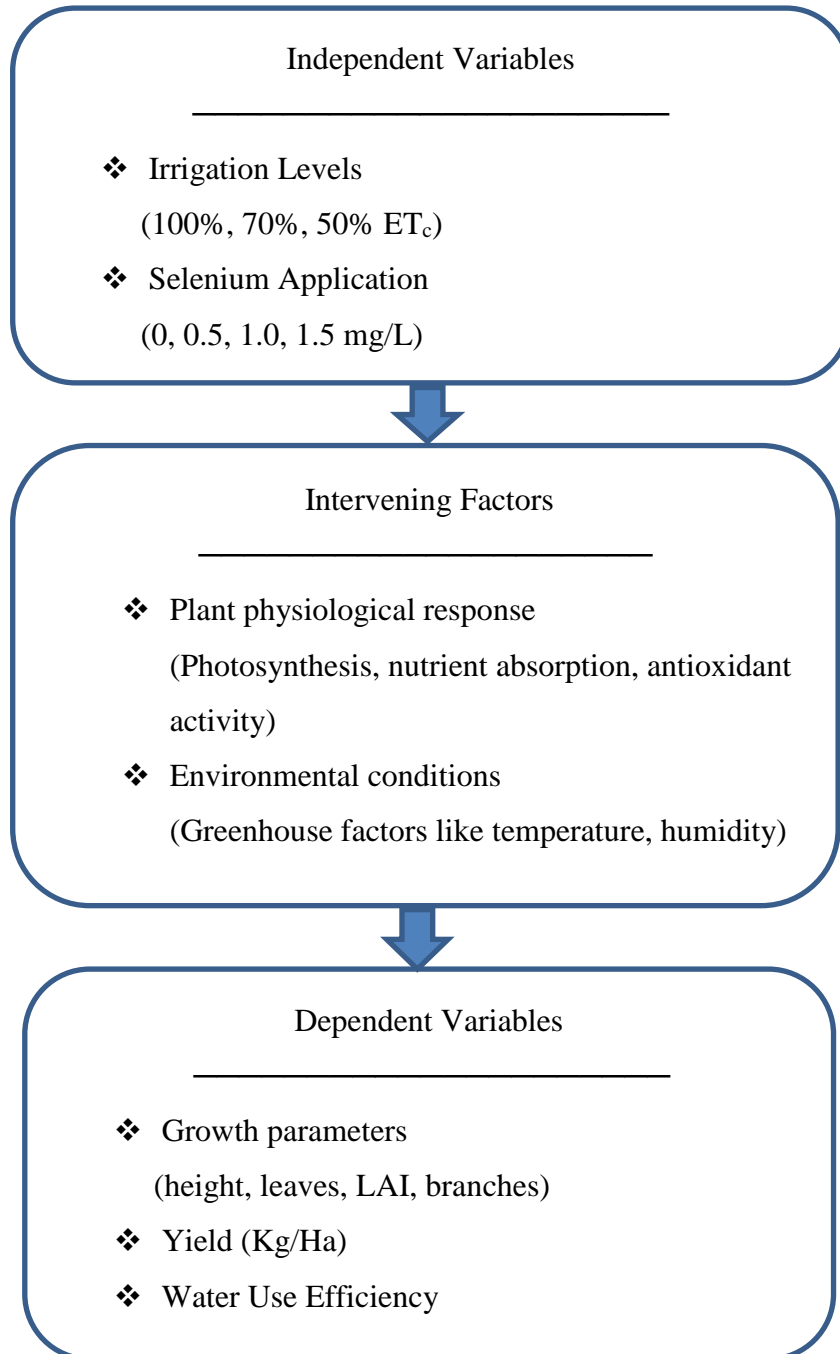
Water scarcity is a global challenge, especially in arid and semi-arid regions where agriculture relies heavily on irrigation. With increasing water demands from various sectors and the effects of climate change, there is a growing need to optimize water use in agricultural systems to improve crop productivity and quality. *Phaseolus vulgaris* L is an important legume crop cultivated worldwide and their yield and quality are sensitive to water stress. That is why, investigating strategies to mitigate the adverse effects of under-watering either by natural means (inadequate rainfall) or artificial water application through deficit irrigation on common bean production is crucial. Selenium is a micronutrient that can be added to plants for resistance to several abiotic stressors including drought, enhance plant growth and provide nutritional quality. Therefore, investigating the combined effects of reduced water application levels and different foliar Se application rates on *Phaseolus vulgaris* L growth parameters, yield, quality and water use efficiency is essential for developing a sustainable water management practice that enhance crop productivity and quality while addressing global, regional and local sustainability challenges.

#### **1.6 Scope and Limitations**

The study primarily focused on investigating the effects of reduced crop water availability through DI and response to foliar Se application by *Phaseolus vulgaris* L. The experiments were conducted at Egerton University in one growing season under controlled conditions to assess various parameters related to yield, quality and water use efficiency. Irrigation levels of 100%  $ET_c$ , 70%  $ET_c$  and 50%  $ET_c$  were adopted to imitate varying field water availability levels and foliar Se levels (0, 0.5 mg/L, 1.0 mg/L and 1.5 mg/L) were applied to determine the individual and combined effects on *Phaseolus vulgaris* L production. Water application was through a surface drip irrigation system to ensure efficient water distribution. Although the study's primary objective was to

examine the relationship between foliar selenium application and deficit irrigation, other influencing factors such as soil fertility, pests and diseases and management practices were also considered. These variables were appropriately managed using standardized agronomic practices across all treatment units to minimize bias in the results. The harvested crops were used for experimental purposes only and appropriately disposed after the tests completed.

### 1.7 Conceptual Framework



**Figure 1.1:** Conceptual Framework

## CHAPTER TWO

### LITERATURE REVIEW

#### 2.1 Water Management

Water management is the practice of planning, developing, distributing and managing the optimum use of water resources. It is essential in agriculture, industry, urban planning and environmental protection. Effective water management ensures the availability of water for various uses, prevents water scarcity, controls water pollution and helps in sustaining ecosystems. Water management in agriculture is concerned with techniques such as conservation of soil moisture, drainage and irrigation. Its goal is to maximize crop yield and reduce water waste by giving crops the appropriate amount of water at the correct time (Grafton & Hussey, 2011).

Agricultural water management is critical in ensuring the sustainability of agricultural systems, especially in areas with limited water resources. Implementing strategies to conserve, optimize and enhance water use efficiency like drip irrigation, which minimizes water loss by delivering it directly to plant roots and scheduling irrigation based on crop needs using data from soil moisture sensors or weather patterns to avoid overwatering. Additionally, the use of drought-resistant crops and precise fertigation techniques (combining fertilizers with irrigation) further enhances water use efficiency while maintaining productivity. These methods collectively help in maximizing the utility of available water, ensuring sustainable agricultural practices (Rastogi *et al.*, 2024).

Irrigation is the artificial application of water to soils for crop use. Irrigation water is applied to the fields by different methods such as surface irrigation methods (basin irrigation, border irrigation and furrow irrigation) and pressurized irrigation methods through drip irrigation or sprinkler irrigation (Anjum *et al.*, 2023). The selection of irrigation systems is influenced by several factors which can be categorized into environmental, economic, social and technical. These factors include water availability, soil type, crop type, climatic conditions, topography and labour availability.

A surface drip irrigation system involves a network of pipes placed on the ground surface to deliver water directly through emitters spaced along water distribution lines (often made of polyethylene tubing). It is designed to provide precise amounts of water at

or near the root zone of crops, improving water efficiency by minimizing evaporation and runoff. The system layout typically composed of a water source, water filter, mainline, sub mainline, laterals and emitters (Keshtgar, 2012). Compared to conventional irrigation methods such as furrow irrigation system and sprinkler irrigation system, drip irrigation system conserves more water and enhances uniformity of application making it suitable strategy for improving water use efficiency.

## **2.2 Common Beans (*Phaseolus vulgaris* L.)**

*Phaseolus vulgaris* L is one of the widely cultivated species, grown approximately over 85% of the total world production planted. Among the *Phaseolus* species (such as *P. Vulgaris*, *P. conscius*, *P. accutifolius*, *P. polyanthus* Greenman, *P. lunatus*), the common bean (*Phaseolus vulgaris* L) is the most widely used species for human consumption [Food and Agriculture Organization of the United Nations] (FAO, 2018). *Phaseolus vulgaris* L is a legume crop cultivated across a wide tropical and subtropical geographical areas of the world with temperature ranges of 21 °C -24°C and a soil pH between 6.3 and 6.7. They are either early or late maturing ranging from 60 to 300 day with a crop water requirement between 300 mm – 600 mm depending on soil, climate and cultivar (Karanja *et al.*, 2014). The largest *Phaseolus vulgaris* L producing region is Latin America, followed by Africa and the United States of America [Food and Agriculture Organization of the United Nations] (FAO, 2021). In Africa, *Phaseolus vulgaris* L production is majorly done in the eastern and southern highlands, with Kenya being the second largest producer after Ethiopia (Duku *et al.*, 2020; Teferi *et al.*, 2022). As the production of *Phaseolus vulgaris* L in Kenya has been decreasing, varieties such as KK 22, KK 8 and KK 15 have been developed for root-rot prone areas and KAT B1, KAT B9, KATX56 and KATX69 for drought tolerant, which has been widely promoted in the country (Karanja *et al.*, 2014).

### **2.2.1 Production, Uses and Economic Importance of Common Bean in Kenya**

Common bean (*Phaseolus vulgaris* L.) ranks among the most grown legumes worldwide and is particularly significant in Kenya and it is valued for their nutritional and health benefits. As a key source of protein and calories, they contribute significantly to food security, making up 50% of globally consumed grain legumes, 15% of dietary protein and 30% of caloric intake (Lone *et al.*, 2021; Semida *et al.*, 2023). Their high nutritional

profile includes phenols, resistant starch and fructooligosaccharides, which aid in preventing oxidative stress, diabetes, cardiovascular diseases and cancers. Global production averages over 776 kilograms per hectare, though yields are affected by abiotic stresses such as drought, extreme temperatures and salinity, impacting more than 60% of global dry beans output (Mohammed & Feleke, 2022).

In Sub-Saharan Africa (SSA), *Phaseolus vulgaris* L covers about 3.5 million hectares and contributes roughly 25% of world production. In East Africa, Kenya ranks as the second-largest producer and seventh globally (Karanja *et al.*, 2014). *Phaseolus vulgaris* L is essential to the region's agricultural economy, providing critical nutritional protein for both rural and urban communities. In addition, they offer substantial economic benefits, generating an estimated 13.18 billion Kenya shillings annually (Duku *et al.*, 2020). The legume is primarily cultivated by 1.5 million smallholder farmers on approximately one million hectares, with an average yield of 600 Kg/Ha. Key production zones include the Rift Valley, Eastern, Lake Victoria, Western and Central regions, contributing 33%, 24%, 18%, 13% and 20% of the national output, respectively (Karanja *et al.*, 2014).

The cultivation in Kenya is largely by women farmers, as such indicated as a reason for the slow/low productivity in addition to the agronomic settings characterized by marginal environment prone to drought and other unfavourable weather conditions such as extremes of temperature coupled with low adoption of improved technologies resulting in approximated 25% loss of the potential yield (Karanja *et al.*, 2014; Lone *et al.*, 2021). As highlighted by Katungi *et al.* (2010) the production of legumes in Eastern and Southern Africa is critical, serving as a key food security crop for over 100 million people and forming a daily dietary staple for many Kenyans due to its excellent nutritional value. Beans are rich in protein and rank as the third most important source of calories (Broughton *et al.*, 2003). In western Kenya, bean consumption can reach up to 66 Kg per person annually, compared to the national per capita average of 14 Kg per year (Duku *et al.*, 2020). *Phaseolus vulgaris* L is commonly consumed as cooked or boiled mature grains, while its immature grains, young pods, and leaves are also eaten as vegetables in many parts of the world. Beans often complement energy/starchy foods like maize, plantains or root crops. The high mineral (iron and zinc) content of beans is

advantageous in regions having high prevalence of iron deficiency as described by Broughton *et al.* (2003) such as western Kenya. *Phaseolus vulgaris* L also serves as a rotation crop with cereals, reducing the soil pathogen and supplying nitrogen to the cereal crop to enhance soil fertility (Broughton *et al.*, 2003; Mangole *et al.*, 2022). More so, intercropping of beans is also a common practice especially with maize, millet, sorghum, bananas and plantains or root and tuber crops. Beans like most legumes are considered as profitable crops compared to other options.

With their high nutrient content and commercial potential, *Phaseolus vulgaris* L potentially solves food security and generating income to smallholder farmers in most developing countries. The consumption of beans tends to reduce as the economic level rises, depicting the demand for beans as income-inelastic (Broughton *et al.*, 2003). Over the years, beans have been increasingly cultivated and offered in national, regional and international markets. In the African region, over 40% of common bean is marketed at USD 452 million (Mangole *et al.*, 2022). Kenya's bean production is a notable income generating crop grown by three million households mainly the small-scale farmers in rural and peri-urban areas of the regions with existing commercial possibilities to boost income (Katungi *et al.*, 2010).

The marketing of beans usually occurs within the country and across established trade routes to the neighbouring countries. With such a great potential, Kavoi *et al.* (2022) observed the increase in household income from certified bean seeds and showed a great potential for commercialization of bean production. In addition, the untapped potential of increasing production lies with irrigation to boost the low export rates in the country and the slightly higher national consumption thus at 800 million Kg against the production of 600 million Kg (Nzuma, 2020). However, with the annual population growth, the production trends of *Phaseolus vulgaris* L does not keep up due to numerous biotic, abiotic and socio-economic factors (Katungi *et al.*, 2010). A good example is the decline in Kenya's bean production in 2014 due to drought vulnerability noted by Duku *et al.* (2020) and Katungi *et al.* (2010) despite the projected increase of 4% and 5% in 2014 and 2015 respectively (Karanja *et al.*, 2014).

### 2.2.2 Production Constraints

Enlisted among the major constraints in Kenya's bean production is the reduced soil fertility resulting from over-cultivation and inadequate soil amendment along with climate change. Soils that are toxic and/or with nutritional deficiencies for such nutrients as Phosphorus (P), Nitrogen (N) and Manganese (Mn) limit productivity (Beebe *et al.*, 2010; Broughton *et al.*, 2003). As described by Beebe *et al.* (2010) soil constraints are the primary cause of the persistent gap between potential and actual bean yields. Beans are predominantly grown on acidic soils that are low in available phosphorus or have high phosphorus-fixing capacities and high in Aluminum (Al) which is toxic to beans (Broughton *et al.*, 2003). In Eastern Africa, over 23% of bean production occurs on soils with a pH  $\leq 5.0$  which also limits the availability of micronutrients (Beebe *et al.*, 2010). Nutrient deficiency or toxicity symptoms include poor emergence, slow growth, stunted plants, reduced biomass accumulation, and lower seed weight, deformed seeds and severe yield loss among others, often limiting in tropical soils. Beans contribute to N fixation in the soil, however low available P and increasing temperatures limits its potential Beebe *et al.* (2010) and Teferi *et al.* (2022) hindering sustainable crop production. This in return reduces the soil quality, inhibiting root growth and potential plant recovery from infection.

The production of *Phaseolus vulgaris* L is also constrained by drought, pests and diseases, low adaptation of improved technologies, poor agronomic practices, land shortages and hostile physical and chemical factors including high/low temperature, high salinity among others (Katungi *et al.*, 2010; Lone *et al.*, 2021) causing substantial crop yield losses. Biotic stressors, such as pests and fungus-related diseases can lead to considerable yield losses in the presence of favourable circumstances. This reportedly caused about 30% yield loss for 50% respondents in Kenya Katungi *et al.* (2010) which can be resolved by improved crop varieties and management.

In most African countries, bean production occurs under climatic areas with moderate to severe water deficit, with studies suggesting only 7% of the growing areas receiving adequate water (Broughton *et al.*, 2003; Mangole *et al.*, 2022). Severe water stress (abiotic stress) leads to yield reduction as identified by Kavoi *et al.* (2022) where over 50% of yield loss occurs due to unpredictable rainfall patterns in addition to other

constraints in Kenya's bean production. Similarly, most of the bean growing areas in Africa are hampered by drought induced stress in tropical and subtropical countries, limiting common beans growth, production and survival (Lone *et al.*, 2021). However, even with the adoption of drip irrigation, there is still need for improvement on production and Water Use Efficiency (WUE) by adoption of water management strategies such as deficit irrigation.

### **2.3 Effect of Deficit Irrigation (DI) on Growth Stages**

By definition, deficit irrigation (DI) is a management practice where water is applied at levels below the full crop water requirement. This practice aims at maintaining the soil water level without significantly limiting the crop yield. DI ensures water application over the full growing cycle, minimizing water stress at critical growth stages (Fereris & Rabanales, 2007). Among various solutions, DI has been growing to ensure optimal production per water unit with the minimum amount of water possible. As such DI potentially improves WUE as compared to full overhead sprinkler irrigation and subsurface drip irrigation (Shukr *et al.*, 2021). Deficit irrigation can either be planned as a sustained deficit, where the deficit is applied all across the growing season, or a regulated deficit where the growing season is divided based on the plant's physiological process and deficit irrigation is only applied in some certain stages (Chaves *et al.*, 2007).

Generally, increased deficit irrigation results in a decrease in the yield and most of its growing parameters. In a study by Priyanka *et al.* (2015) on tomatoes at 100%, 80%, 60% and 40% DI levels influenced the plant height, number of leaves per plant, early flower initiation, fruit weight and fruit yield. In this study the maximum averages were obtained at 80% saving up to 20% of water. A study by Hassan *et al.* (2020) made a report on green peas where the maximum average seed yield was obtained at 90%  $ET_c$  and lowest at 70%  $ET_c$  under semi-arid conditions. The highest water use efficiency was observed with a mild water deficit (90%  $ET_c$ ) with a minimal water consumption reduction of 10% and at 80%  $ET_c$  during the flowering stage. Similarly, under high water stress (50%  $ET_c$ ), substantial yield reduction and water use efficiency was observed unlike low water stress conditions (75%  $ET_c$ ). With the scarcity of natural resources and increased demand, the efficiency of on-farm water management practices is important to the increased crop production from a water drop. However, studies on how common

beans respond to comparable deficit irrigation levels remains limited particularly under drip irrigation system.

#### **2.4 Foliar Fertilizer Applications and their Effects on Agricultural Water Management**

Specific foliar fertilizer application can come in as an effective way that, improve water use efficiency by reducing reliance on soil moisture. Additionally, foliar fertilizers deliver nutrients directly to plant leaves and ensure faster uptake of nutrients (Alshaal & El-Ramady, 2017). For instance, foliar Potassium (K) regulates stomata function, which in turn reduces water loss through transpiration. As observed by Ramachandra & Viswanatha (2004) applying potassium foliar spray during dry periods conserved water and maintained plant growth. Similarly, Zare *et al.* (2014), observed a 2% increase in the plant Relative Water Content (RWC) under water stress conditions (irrigation per 9 and 12 days). This evidently resulted to increased grain yield of corn under foliar potassium against drought effects. Reduced plant RWC reduces plant growth. Foliar Zinc (Zn) improves root growth/elongation, allowing plants' access to deeper soil moisture in drought conditions and increases water absorption capacity (Hafeez *et al.*, 2013). Notably Mosa *et al.* (2013) attained an increased corn yield potentially from the 4% increase in RWC and chlorophyll with irrigation stopped at anthesis stage. This directly contributes to better water use efficiency. More so, Mahdy and Farghali (2022) concluded that foliar zinc alleviated drought stress (planting irrigation and one irrigation three weeks later) by increasing yield and yield component. In previous studies, it had been noted that a combination of zinc and bio-stimulants such as zeolite enhances the biochemical performance of canola cultivars especially in water stressed regions (Shahsavari *et al.*, 2014). Zeolite functions as a slow-release mechanism for water and minerals, improving soil water retention. It increases the root zone's ability to hold water, guaranteeing that plants have access to hydration even in dry situations. A study by Zahedi *et al.* (2009) reported that the application of Zeolite at 10 tonnes/Ha improved water retention capacity, plant growth and production.

Manganese inhibits oxidative damage, activates stress-related enzymes, maintains photosynthetic efficiency and promotes healthy root development to assist plants cope with water stress. It becomes an essential nutrient for plants in water-limited environments because of these combined benefits which also help the plant resist drought and preserve water. Water

absorption and use efficiency are indirectly enhanced by manganese, which also promotes root growth and helps with photosynthesis. According to Movahhedy-Dehnavy *et al.* (2009) the application of foliar Manganese improved seed yield and quality of safflower which were grown under water deficit stress.

## **2.5 Selenium (Se)**

Selenium is essential to the biological functions of both human and animal bodies. It can lead to health risks due to consumption in large concentrations but its absence can have disastrous effects on the health of both humans and animals. Selenium insufficiency is becoming a global problem even though selenium offers several significant benefits (Imran *et al.*, 2023). Selenium is a necessary component of over 25 enzymes in humans, it plays a crucial role in avoiding several chronic diseases, including cancer, neurological disorders and cardiovascular disease (Newman *et al.*, 2019). Overconsumption of Se however can cause neurological damage, paralysis, loss of hair and nails, tremors, kidney failure, heart attacks, heart failure and even death. This makes adherence to the daily dosage limits of selenium supplementation important. World Health Organization (WHO) commends a Recommended Daily Allowance (RDA) of 40 µg/day for Se because within this dosing range, it enhances the immune response and stimulates a more efficient production of proteins and enzymes (Imran *et al.*, 2023). When a man's consumption exceeds 60 µg/day and a woman's exceeds 53 µg/day, an overdose takes place (Imran *et al.*, 2023). Lack of Se in food animals can significantly affect productive efficiency and health. Se deficiency associated with decreased weight growth, decreased milk supply and decreased fertility, among other impacts. Immunosuppression and peroxide-induced cell membrane damage are the main causes of health issues in livestock (Pecoraro *et al.*, 2022).

### **2.5.1 Selenium Application and Utilization**

Selenium is a micronutrient present in soils and naturally occurring in water and some foods. It enhances the activity of antioxidant enzymes such as glutathione peroxidase and superoxide dismutase, which scavenge harmful Reactive Oxygen Species (ROS) generated during water deficit stress. These ROS can damage cellular structures, impair photosynthesis and inhibit plant growth. It also protects cells from damage by environmental conditions such as drought, salinity, high temperatures and heavy metals

as observed by Semida *et al.* (2023). This in turn improves plant development, yields, and availability of Se in fruit and grain for consumption. Other elements such as Calcium, Potassium, Zinc and Zeolite also protect the plants against water stress conditions by accessing deeper water reserves during drought conditions, reduce water loss through leaves; improving the ability of plants to absorb water and nutrients from deeper soil layers and water retention (Zahedi *et al.*, 2009). The availability of selenium in the soil is dependent on the soil's pH levels, electrical conductivity, ions (PO<sub>4</sub><sup>-</sup> and SO<sub>4</sub><sup>-</sup>), texture, organic matter and temperature. The Se forms in soils are usually found in aerobic soils with a neutral pH (Selenite), those useful in soils with a lower pH and lower oxidation-reduction potential (Selenate) and the dominant form (selenide) (Raza *et al.*, 2024). Selenate is taken up and transported from the roots throughout the plant in the greatest quantity and maintains its stability when thoroughly oxidized (Alltech, 2021; Imran *et al.*, 2023). Compared to selenite (Se<sup>4+</sup>), plants absorb selenate (Se<sup>6+</sup>) at a much higher rate.

In cultivated soils, selenite and selenate forms are commonly used forms and their mechanism of absorption, translocation and distribution by plants are related to Se concentration. Adding Se to the soil, seed and plant leaves, raises the concentration of Se in low-Se soils and plants as reported by Imran *et al.* (2023) as well as when applied as a foliar fertilizer (Hmood *et al.*, 2022). Because Se directly affects human and animal health via the food chain, plant uptake of Se is vital with some studies focusing on the amount of Se present in plants as an element that is potentially toxic. Conversely, the uptake or accumulation of Se in plants can be increased by Se-rich environments or seleniferous soils. Under seleniferous soils, plants can accumulate very high amounts of Se (Imran *et al.*, 2023; Ragályi *et al.*, 2021).

### **2.5.2 Selenium Uptake Levels**

Notably, Se is beneficial when supplied within its threshold limit, but toxic levels of Se accumulate inside plant cells, inhibit photosynthesis and lead to competitive inclusion in the biochemical structure components with sulphur and the overproduction of starch (Garousi *et al.*, 2017). In addition, the toxicity of Se means reduced growth, leaf chlorosis, reduced protein synthesis and prompt plant death (Corbo *et al.*, 2018). The ability of plants to absorb Se from a soil-specific area closely relates to the daily Se intake of

people and animals (Ragályi *et al.*, 2021). Enriching the irrigation water through fertigation ensures a high intake of certain elements to produce nutrient rich foods (Edelstein *et al.*, 2016). Selenium is applied in the form of sodium selenate ( $\text{Na}^2\text{SeO}_4$ ), as it easily transports to the plants from the soil (Ragályi *et al.*, 2021).

The absorption and accumulation of Se in edible plant parts depends on the concentration of selenium in the soil. According to Ragályi *et al.* (2021) irrigation water containing 100 and 500  $\mu\text{g/L}$  of Se on green beans in a greenhouse experiment resulted in 0.02 mg/Kg – 0.08 mg/Kg Se concentration in green beans. A study by Ravello *et al.* (2022) under DI observed a higher Se concentration in *Phaseolus vulgaris* L grains which increased with the Se rates to the soil at 1.0 mg/Kg and 2.0 mg/Kg but different DI were not defined. Similarly, translocation of Se to the grains of common bean at 50 and 500 g/Ha application rates increased yield and did not exceed the established Se concentration limit (Corbo *et al.*, 2018). Se uptake and translocation in plants take place through sulphate transporters (STs) and phosphate transporters (PiTs). After being absorbed from the soil, the inorganic Se is converted into a more bio-available organic form, selenomethionine (SeMet). The STs in the root cell membrane and PiTs uptake the selenite which is later incorporated through enzyme sulphate assimilation into selenocysteine (SeCys) and selenomethionine (SeMet). The levels of Se in the grain are mainly affected by the rate and application method (Ahmad *et al.*, 2016).

### **2.5.3 Selenium Concentration in Soils**

Selenium concentrations in soils vary widely across the globe, ranging from extremely low to hazardous levels even within a single nation. Its overall content in soil is comparatively modest, typically ranging from 0.01 mg/Kg to 2 mg/Kg with an average of 0.4 mg/Kg worldwide (Saha *et al.*, 2017). However, the availability of Se to plants is also a crucial factor that is significantly controlled by the element's chemical form, in addition to the soil's overall selenium level. After application, foliar Se can also reach the leaves by passing through the cuticle or through the stomata. It is subsequently moved to the edible portions of the plant; however, its new placement depends on the plant's phenological stage and nutritional state. The age of leaves in cereal crops, such as wheat, impacts whether the leaf may serve as a source or compete with the grain to transfer selenium or both. Mature leaves cannot import selenium they can only transfer Se directly

to grains through phloem. Consequently, the transportation of Se to the edible portions of plants may be improved by both soil and foliar Se treatment techniques (Wang *et al.*, 2022).

Soil physical and agrochemical parameters have a significant impact on soil Se content. Sandy soils have the lowest selenium concentrations (0.05 – 0.08 mg/Kg) due to a correlation between the soil clay particles and selenium content. The amount of Se in the soil varies depending on the type of soil (Luvisols 0.12 mg/Kg – 0.25 mg/Kg, Cambisols 0.25 mg/Kg – 0.34 mg/Kg, Leptosols 0.38 mg/Kg and Histosols 0.37 mg/Kg – 0.70 mg/Kg) that has been studied (Kabata *et al.*, 1998). Soil pH has a major impact on Se concentration where scientists have shown that acidic soils (pH 4.5) contain 0.183 mg/Kg of Se and slightly alkaline soils (pH 7.5) contain 0.878 mg/Kg. A study by Antanaitis *et al.* (2014) reported that Se concentration in soil depends on soil texture, pH, total and absorbed bases. Sandy loam soils had the lowest Se concentration, whereas light loam, medium loam, and clay loam soils had the next lowest concentrations. Sandy loam soils had an average Se content of 0.144 mg/Kg in the 0-20 cm soil layer when the pH range was 6.1-7.0. Light loam soils had an average Se content of 0.160 mg/Kg, and medium loam and clay loam soils had average Se contents of 0.228 mg/Kg. Soils containing 20–40 cm of dirt had an average selenium content of 0.224 mg/kg. The application of foliar Se with concentrations of 0.5 mg/L, 1.0 mg/L and 1.5 mg/L had no significant effect to the soil as reported by Saha *et al.* (2017) since this mode of application resulted in Se being more readily absorbed by the plants. The typical range of selenium concentrations in soil is 0.01 mg/L - 2 mg/Kg, with seleniferous soils having a concentration of 5 mg/Kg. Soil selenium concentrations have been categorized as deficient (<0.125 mg/Kg), marginal (0.125 mg/L - 0.175 mg/Kg), moderate to high (0.175 mg/L - 3 mg/Kg), and excessive (>3 mg/Kg) to meet human nutrition requirements.

#### **2.5.4 Selenium on Plant Growth**

Selenium application can positively influence plant growth under optimal irrigation conditions. As a micronutrient, Se plays a key role in enhancing plant physiological processes, including photosynthesis, antioxidant activity and nutrient uptake. When applied as a foliar Se is readily absorbed through the leaf surface, where it can mitigate oxidative stress, promote chlorophyll synthesis and improve metabolic

efficiency. According to Boghdady *et al.* (2017) foliar Se application of 5 mg/L and 10 mg/L gave positive effects on growth, yield and quality of Faba beans (*Vicia faba* L.) and no negative effects on humans and animals. A study by Azpilcueta-Perez *et al.* (2022) reported an improvement in the morphological, physical and yield characteristics of a bean seeds with foliar application of 10 mg/L sodium selenite ( $\text{Na}_2\text{SeO}_3$ ) and 5 mg/L selenium dioxide ( $\text{SeO}_2$ ), compared to sodium selenate ( $\text{Na}_2\text{SeO}_4$ ) of 20 mg/L. In addition, high concentrations up to 13 mL of phosphoric acid ( $\text{H}_3\text{PO}_4$ ), 55 g of MULTI-NPK (potassium nitrate  $\text{KNO}_3$  enriched with phosphorus), 61 g of Haifa MKP (monopotassium phosphate;  $\text{KH}_2\text{PO}_4$ ), 133 g of calcium nitrate [ $\text{Ca}(\text{NO}_3)_2$ ] and 9.4 g of Librel Mix-AL with micronutrients (Cu, Fe, Mn and Zn) pose negative effects on most morphological, physical and yields characteristics of *Phaseolus vulgaris* L.

In saline soils, the concentration of Se is required at moderate level in order to mitigate the effects of salinity as reported by Moussa & Hassen, (2018). Here, the foliar application of Se at concentration rate of 0.8 mg/L alleviated negative effects of salinity and improved photosynthetic capacity and antioxidant activities of *Phaseolus vulgaris* L. Also, a study by Farag *et al.* (2022) showed a positive impact of 0.5 mg/L foliar Se application rate in saline soil by minimizing the harmful effects of salinity in snap bean seedlings and improved growth, photosynthetic pigments and antioxidant activities.

#### **2.5.5 Selenium and Plant Growth Under Water Stress Conditions**

Selenium promotes plant growth and reduces production losses by boosting the activity of antioxidant enzymes and non-enzymatic antioxidants. This helps in reducing the amount of oxygen-reactive species (ROS), which is why crops experiencing a water deficit benefit from Se supplies (Aissa *et al.*, 2018; Farag *et al.*, 2022). The synergistic effects of Se and antioxidant enzymes have been documented in recent studies with rice Andrade *et al.* (2018) sweet potatoes Huang *et al.* (2020) potatoes grown in tropical soil de Lima Lessa *et al.* (2019) and increased growth of sugarcane plants (Araujo *et al.*, 2023).

As reported by Moulick *et al.* (2024) Se improves the growth characteristics (pod weight, leaf number and stem weight) of peas, increasing yield and increasing Se concentration in the plant. A study conducted by Sharma *et al.* (2015) observed a maximum average plant height (218.92 cm), an average of 22 leaves per plant, 41 flowers per plant, 35 fruits per plant, 84.72% fruit set, individual fruit weight (77.04 g) and fruit yield per

plant (2708.33 g/plant) of tomatoes under DI of 80%  $ET_c$ . Similarly, Semida *et al.* (2023) observed that Se concentration at 0, 25 and 50 mg/L grown under DI enhanced growth and pod yield in *Phaseolus vulgaris* L even under saline soils. Hmood *et al.* (2022) also reported a significant increase in pod yield/weight, seed weight and mineral content from selenium application in *Phaseolus vulgaris* L. Ravello *et al.* (2022) demonstrated that moderate foliar selenium application (0.25 mg/L and 0.5 mg/L) enhanced antioxidant activity in *Phaseolus vulgaris* L and producing Se-rich grains even under water deficit conditions. However, higher application rate 2 mg/L suppressed biomass production indicating toxicity at elevated doses. This finding highlights the narrow threshold between beneficial and toxic of selenium underscoring the need to determine safe foliar rates for common beans yield improvement under deficit irrigation.

#### **2.5.6 Optimization of Selenium Application Rates Under Water Stress Conditions**

Selenium optimization involves application methods, concentration and timing. Foliar application methods are more effective than soil-based methods, as it allows direct absorption, penetration and bioavailability of Se in plants. The foliar Se concentration ranges from moderate to high (0.175 - 3 mg/L) has no negative impact to human nutrition (Saha *et al.*, 2017). The application rates for optimal yields and water productivity typically range between 0.79 mg/L -3.95 mg/L with variations depending on specific crop requirements under water stress conditions. Atomic Absorption Spectrometry technique is used for analysis of low levels of Se as it allows direct measurement of sample dilution and it requires very low sample volume which make it to be cost effective compared to Inductively Coupled Plasma Mass Spectrometry (ICP/MS) (El Ati-Hellal *et al.*, 2014). Optimization is an engineering design that obtain the best solutions within predetermined factors and parameters. In this study, optimization is particularly important in evaluating the most effective combinations of deficit irrigation levels and foliar selenium (Se) application rates to improve the growth, yield and water use efficiency of common beans in water-limited conditions. As noted by Tsai *et al.* (2014) optimization provides practical challenges with efficient and effective solutions ensuring strength, durability, productivity, efficiency and resource utilization attributes that are critical when managing crop evapotranspiration ( $ET_c$ ) and selenium concentration. To facilitate robust experimental design, optimization techniques such as the Design of

Experimentation (DoE) play a key role by considering the experimental objectives, the number of variables involved and the cost-effectiveness of treatment combinations. Therefore, DoE provides the response's statistical accuracy at a reduced cost (Penteado *et al.*, 2010). Taguchi Method (TM) is an efficient experimental design that combines mathematical and statistical techniques. TM is mostly used for optimization compared to other methods such as response surface methodology and factorial because it uses tabulated arrays that allows maximum effects compared orthogonally, minimal bias, lessening the number of experimental run and reduce cost. For an optimal design in maximization, these orthogonal arrays are the best setting from a complete factorial experiment (Awty-Carroll *et al.*, 2020).

## **2.6 Summary of Literature Review**

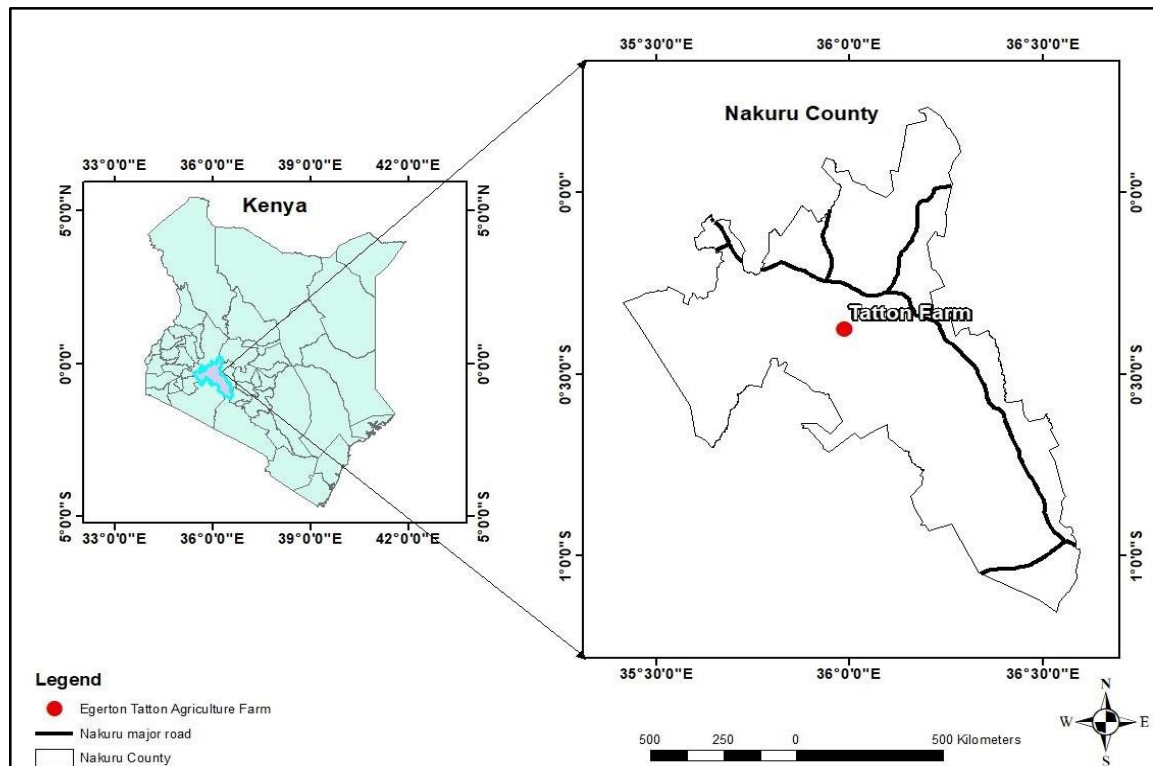
The reviewed literature emphasizes the need for sustainable water management strategies to address water scarcity and climate variability in agriculture sector. Common beans (*Phaseolus vulgaris* L) though vital for food and nutrition security but they are very sensitive to water stress make them suitable for studies on deficit irrigation. Deficit irrigation has been recognized as a strategy to conserve water and improve water use efficiency but it reduces yields if not complemented with other agronomic practices. Foliar fertilization especially with selenium has been shown to enhance plant stress tolerance, photosynthetic activity and nutritional quality but its benefits depend on application rates with the excessive application rate causing toxicity. Studies on deficit irrigation and selenium application has been addressed separately while few researches have been examined their combined effects in common beans especially under surface drip irrigation system which ensures precise water delivery to the crop. This gap justifies the present study which aimed to evaluates three irrigation water levels (100% ET<sub>c</sub>, 70% ET<sub>c</sub> and 50% ET<sub>c</sub>) and moderate foliar selenium application rates (0, 0.5, 1.0 and 1.5 mg/L) to determine optimal conditions for growth, yield, selenium uptake and water use efficiency in common beans.

## CHAPTER THREE

### MATERIALS AND METHODS

#### 3.1 Description of Study Area

The study was conducted inside the greenhouse at Tatton Farm located at Egerton University in Nakuru County, Kenya. The experimental site lies on a latitude of 0°22'11''N, a longitude of 35°55'58''E with an elevation of 2,238 meters above the sea level as shown in Figure 3.1.



**Figure 3.1:** Map Showing the Location of Tatton Agriculture Park at Egerton University

The soil at the study site is sandy loam characterized with good drainage and a pH ranging from 6.0 - 6.2. The area experiences warm temperate climate, with a mean annual rainfall of 1200 mm having bimodal distribution with long rains between April and August and short rains from October to December. The average temperature of the area is 22°C and relative humidity 64% (Ng'etich *et al.*, 2014).

### 3.2 Experimental Layout

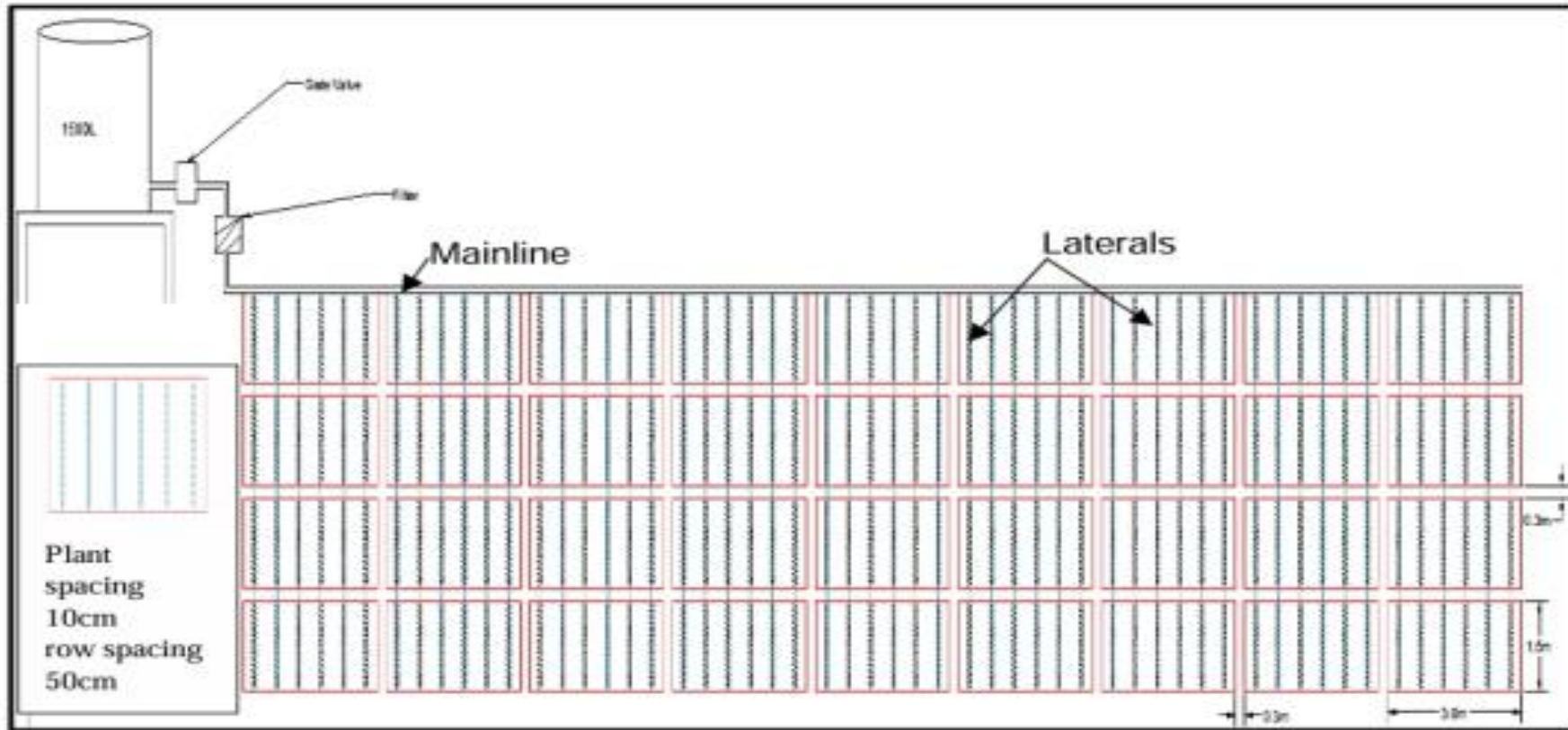


Figure 3.2: Experimental Layout of Drip Irrigation System and Plots

The drip irrigation system was installed and operated with a water from a tank raised at 2.0 meters to create a pressure head for gravity flow. The sub-main lines and laterals was laid on the soil surface to deliver water to the soil surface directly through the emitters. The main line was High-Density Polyethylene (HDPE) pipe with internal diameter of 50 mm and a lateral line of 25 mm diameter. The amount of water supplied to the plots was measured by using a water meter installed at the mainline and in order to ensure that the water supplied to the emitters was free from sediments or other materials that could cause clogging, a filter was installed to the main line. Discharge control valves were installed on each lateral to regulate the amount of water delivered to each plot. The irrigation water application of 100%  $ET_c$ , 70%  $ET_c$  and 50%  $ET_c$  were selected to represents full irrigation, moderate deficit irrigation and severe deficit irrigation respectively in order to evaluate crop response under different water availability, while the foliar Se fertilizer application rates at 0 mg/L, 0.5 mg/L 1.0 mg/L and 1.5 mg/L were chosen in order to ensure the doses are within the safe and effective for crop bio-fortification and stress tolerance. The foliar spray was prepared with distilled water and manually applied on the plant leaves as an aqueous solution using hand-held sprayer which was fitted with a fine hollow-cone nozzle in order to ensures uniform coverage of leaf surface while minimizing droplet size and runoff losses as described by (Garousi *et al.*, 2017). The layout of the experiment was as shown in Figure 3.2.

A factorial experimental design was adopted consisting of combinations of four foliar Se application rates and three irrigation levels administered in the plots. The main factors were foliar Se application with 3 levels (0.5 mg/L, 1.0 mg/L and 1.5 mg/L plus a control treatment with 0 mg/L of Se.) and water application levels of full irrigation (100%  $ET_c$ ) and DI at 70 and 50%  $ET_c$ . Each treatment was replicated three times, thus a total number of 36 experimental units as shown in Tables 3.1 and 3.2.

**Table 3.1:** Experimental Treatments and Selenium Concentration Levels

<b>Treatment Number</b>	<b>Irrigation Level (% ET<sub>c</sub>)</b>	<b>Se Concentration (mg/L)</b>
T1	100	0.5
T2	70	0.5
T3	50	0.5
T4	100	1.0
T5	70	1.0
T6	50	1.0
T7	100	1.5
T8	70	1.5
T9	50	1.5
T10	100	0
T11	70	0
T12	50	0

**Table 3.2:** Treatment Allocation of Plots

<b>Plot 1</b>	<b>Plot 2</b>	<b>Plot 3</b>	<b>Plot 4</b>
50% ET <sub>c</sub>	50% ET <sub>c</sub>	50% ET <sub>c</sub>	50% ET <sub>c</sub>
1.0 mg/L	1.5 mg/L	0 mg/L	0.5 mg/L
<b>Plot 5</b>	<b>Plot 6</b>	<b>Plot 7</b>	<b>Plot 8</b>
50% ET <sub>c</sub>	50% ET <sub>c</sub>	50% ET <sub>c</sub>	50% ET <sub>c</sub>
1.5 mg/L	0 mg/L	0.5 mg/L	1.0 mg/L
<b>Plot 9</b>	<b>Plot 10</b>	<b>Plot 11</b>	<b>Plot 12</b>
50% ET <sub>c</sub>	50% ET <sub>c</sub>	50% ET <sub>c</sub>	50% ET <sub>c</sub>
0 mg/L	0.5 mg/L	1.0 mg/L	1.5 mg/L
<b>Plot 13</b>	<b>Plot 14</b>	<b>Plot 15</b>	<b>Plot 16</b>
70% ET <sub>c</sub>	70% ET <sub>c</sub>	70% ET <sub>c</sub>	70% ET <sub>c</sub>
0.5 mg/L	1.0 mg/L	1.5 mg/L	0 mg/L
<b>Plot 17</b>	<b>Plot 18</b>	<b>Plot 19</b>	<b>Plot 20</b>
70% ET <sub>c</sub>	70% ET <sub>c</sub>	70% ET <sub>c</sub>	70% ET <sub>c</sub>
1.0 mg/L	1.5 mg/L	0 mg/L	0.5 mg/L
<b>Plot 21</b>	<b>Plot 22</b>	<b>Plot 23</b>	<b>Plot 24</b>
70% ET <sub>c</sub>	70% ET <sub>c</sub>	70% ET <sub>c</sub>	70% ET <sub>c</sub>
1.5 mg/L	0 mg/L	0.5 mg/L	1.0 mg/L
<b>Plot 25</b>	<b>Plot 26</b>	<b>Plot 27</b>	<b>Plot 28</b>
100% ET <sub>c</sub>	100% ET <sub>c</sub>	100% ET <sub>c</sub>	100% ET <sub>c</sub>
1.0 mg/L	1.5 mg/L	0 mg/L	0.5 mg/L
<b>Plot 29</b>	<b>Plot 30</b>	<b>Plot 31</b>	<b>Plot 32</b>
100% ET <sub>c</sub>	100% ET <sub>c</sub>	100% ET <sub>c</sub>	100% ET <sub>c</sub>
0.5 mg/L	1.0 mg/L	1.5 mg/L	0 mg/L
<b>Plot 33</b>	<b>Plot 34</b>	<b>Plot 35</b>	<b>Plot 36</b>
100% ET <sub>c</sub>	100% ET <sub>c</sub>	100% ET <sub>c</sub>	100% ET <sub>c</sub>
0 mg/L	0.5 mg/L	1.0 mg/L	1.5 mg/L

### 3.2.1 Land Preparation and Seedbed Preparation

Primary tillage was carried out in an area of 10 m by 30 m by using hoes and subsequently levelled using a scraper and a rake and then beds of 1.5 m by 3 m were prepared as shown in appendix A.1. This was followed by sowing *Phaseolus vulgaris* L

of the rose coco variety with row spaced 0.5 m apart and plants spaced 0.1 m apart as suggested by (Corbo *et al.*, 2018). The bean variety was chosen because of its high yield productivity, resistance to diseases and wide adaptation to the climate and soil conditions in the study area (Karanja *et al.*, 2014).

### 3.2.2 Fertilizer Application, Pest and Disease Control

Fertilization, weeding, pest and disease management, and other agronomic procedures used in common bean cultivation were carried out consistently across all treatments. Cutworms, white flies, and aphids were managed with 10 g of Actara in 40 liters of water. The inorganic fertilizer NPK (nitrogen, phosphorous and potassium) packaged in the ratio of 17- 17-17 was applied at a rate of 3 grams per planting hole which consists of N (ammonium sulfate), P<sup>2</sup>O<sup>5</sup> (triple superphosphate) and K<sup>2</sup>O (KCl) at sowing and N as a side dressing as recommended by Corbo *et al.* (2018) and Géant *et al.* (2020). The foliar Se rates (0 mg/L, 0.5 mg/L, 1.0 mg/L and 1.5 mg/L) based of the recommendations by (Ravello *et al.*, 2022). The treatments were replicated three times and Rose coco bean variety was used as the test crop. The selenium was mixed with distilled water forming sodium selenate (Na<sub>2</sub>SeO<sub>4</sub>) which was sprayed to the plant leaves, stem, branches, flowers and pods during vegetative stages (23 days after sowing), flowering stage (40 days after sowing) and pod formation stage (50 days after sowing) of the crop. This was performed in the morning (7:00 am) to minimize evaporation rates as plants' stomata are more open early in the morning, allowing better absorption of the Se through the leaves. Additionally, the strong sunlight later in the day increases the risk of leaf burn or damage when a foliar selenium is applied (Hmood *et al.*, 2022).

### 3.2.3 Estimation of Crop Water Requirement using FAO Penman - Monteith Method

The amount of water needed for common beans (*Phaseolus vulgaris* L.) was estimated based evapotranspiration at each crop development stage using equation 3.1 assuming no effective precipitation because of the polythene greenhouse cover.

$$ET_c = ET_o \times K_c \dots\dots\dots \text{Equation 3.1}$$

Where ET<sub>c</sub>, ET<sub>o</sub> and K<sub>c</sub> are the crop evapotranspiration in millimetres per day, reference crop evapotranspiration in millimetres per day and crop coefficient respectively. Reference crop evapotranspiration (ET<sub>o</sub>) was calculated by the FAO CROPWAT 8.0 software version 8.0.1.1 which implies the use of Penman-Monteith Equation (Allen *et al.*, 1998).

$$ET_0 = \frac{0.408\Delta(R_n - G) + \gamma \left(\frac{900}{T} + 273\right) U_2 (e_s - e_a)}{\Delta + \gamma(1 + 0.34U_2)} \dots\dots\dots \text{Equation 3.2}$$

Where:

$ET_0$  = Reference evapotranspiration (mm day<sup>-1</sup>)

$R_n$  = the net radiation (MJ m<sup>2</sup>/day)

$G$  = the soil heat flux density (MJ m<sup>2</sup>)

$$\Delta = \frac{4098 \left[ 0.6108 \exp\left(\frac{17.27T}{T+237.3}\right) \right]}{(T+237.3)^2} \dots\dots\dots \text{Equation 3.3}$$

Where:

$\Delta$  = the slope of the saturated vapor pressure curve (kPa/°C)

$T$  = daily mean air temperature (°C) at 2m based on the average of maximum and minimum temperature and  $T$  is calculated as:

$$T = \frac{(T_{\max} + T_{\min})}{2} \dots\dots\dots \text{Equation 3.4}$$

$U_2$  is the average wind speed at 2m height (ms<sup>-1</sup>) calculated as:

$$U_2 = U_z \frac{4.87}{\ln(67.8z - 5.42)} \dots\dots\dots \text{Equation 3.5}$$

Where:  $U_z$  is the measured wind speed at height  $z$  (m/s)

$z$  is the height of measurement above ground surface (m)

$\ln$  is the natural logarithm

$e_s$  is the saturation vapour pressure (kPa), calculated as;

$$e_s = \frac{e^o T_{\max} + e^o T_{\min}}{2} \dots\dots\dots \text{Equation 3.6}$$

$$e^o T_{\max} = 0.6108 \exp \left[ \frac{17.27 T_{\max}}{T_{\max} + 237.3} \right] \dots\dots\dots \text{Equation 3.7}$$

$$e^o T_{\min} = 0.6108 \exp \left[ \frac{17.27 T_{\min}}{T_{\min} + 237.3} \right] \dots\dots\dots \text{Equation 3.8}$$

$e_a$  is the actual vapour pressure (kPa)

The actual vapour pressure was determined using the actual vapour pressure calculator from the relative humidity and the saturated vapour pressure.

$(e_s - e_a)$  = The saturation vapour pressure deficit

$$\gamma = \frac{C_p P}{\epsilon \lambda} = 0.665 \times 10^{-3} P \dots\dots\dots \text{Equation 3.9}$$

Where:

$\gamma$  = Psychrometric constant (0.0677 kPa/°C)

$C_p$  = Specific heat at constant pressure  $1.013 \times 10^{-3}$  (MJ/kg/°C)

$P$  = Atmospheric pressure (kPa)

$\varepsilon$  = Ratio molecular weight of water vapour/dry air = 0.622

$\lambda$  = Latent heat of vaporization 2.45 (MJ/kg)

$$P=101.3 \left[ \frac{293-0.0065z}{293} \right]^{5.26} \dots\dots\dots\text{Equation 3.10}$$

Where:

P = Atmospheric pressure (kPa)

z = Elevation above sea level (m)

In order to get the crop coefficients for the various stages of common bean growth, we looked to the FAO  $K_c$  table appendix B.1.  $K_c$  ini,  $K_c$  dev,  $K_c$  mid, and  $K_c$  late are the available crop coefficients for the initial, development, mid, and late stages of growth, respectively. To find the crop evapotranspiration, we multiplied the predicted reference crop evapotranspiration by the values of the crop coefficients, as indicated in equation 3.1. As a result of equating the crop water need with the crop evapotranspiration determined during the different growth stages of common beans, the necessary amount of water was applied to the crop on the agricultural research field at Egerton University's Tatton Agricultural Park. Table 3.3 shows the annual mean values of relevant climatic data and the computed reference evapotranspiration ( $ET_0$ ).

**Table 3.3:** Experiment Site Meteorology Data

<b>Month</b>	<b>Min temp °C</b>	<b>Max temp °C</b>	<b>Humidity %</b>	<b>Wind Km/day</b>	<b>Sun Hours</b>	<b>Rad MJ/m<sup>2</sup>/day</b>	<b>ET<sub>o</sub> Mm/day</b>
January	9.2	27.7	55	86	7.5	20.4	4.12
February	9.4	28.3	49	95	7.9	21.7	4.50
March	9.7	29.2	55	86	6.9	20.4	4.32
April	9.6	28.7	67	78	6.0	18.4	3.84
May	9.1	27.4	72	69	6.5	18.1	3.55
June	8.8	26.5	68	69	7.5	18.8	3.53
July	8.5	25.6	70	69	7.2	18.6	3.41
August	8.7	26.2	68	69	6.7	18.9	3.60
September	8.8	26.4	65	69	7.0	20.2	3.88
October	8.8	26.5	66	69	6.2	19.0	3.73
November	8.8	26.3	70	69	5.5	17.4	3.88
December	9.0	26.9	63	86	7.2	19.6	3.82
<b>Average</b>	<b>9.0</b>	<b>27.1</b>	<b>64</b>	<b>76</b>	<b>6.9</b>	<b>19.3</b>	<b>3.82</b>

**Source:** FAO CLIMWAT 2.0

### **3.3 Effect of Foliar Se Application Rates and Deficit Irrigation on Growth Parameters, Yield and Water Use Efficiency on Common Bean**

Following germination, three plants of the common bean (*Phaseolus vulgaris* L.) were chosen at random from each experimental plot. These plants were then studied for their growth and yield characteristics, including plant height, leaf area index, branch count, pod length, pod count, seed yield, and pod yield. Bean growth parameters were measured at 14 days intervals from 5 to 95 days after seed sowing and yield parameters after harvest were measured and evaluated. Planting, germination, vegetative growth, flowering, pod formation, maturity and harvest stages took between 5-10, 10-20, 20-30, 30-50, 50-70 and 70-95 days respectively in agreement with observations by (Alipour *et al.*, 2022; Marques *et al.*, 2022). Plant height, number of leaves per plant and number of branches per plant were measured at two-week intervals whereas, leaf area index was determined 45 days after sowing. The pod length, number of pods per plant, number of seeds per plant and pod yield after harvesting time. The growing period had identical

irrigation frequency whilst maintaining the desired irrigation levels. The Leaf area index (LAI) was calculated based on the following equation 3.11.

$$LAI = A \times N \dots\dots\dots \text{Equation 3.11}$$

Where:

A = Leaf area per plant (cm<sup>2</sup>)

N = Number of plants/cm<sup>2</sup>

$$A = 0.75 \sum_{i=1}^n L_i \times W_i \dots\dots\dots \text{Equation 3.12}$$

Where:

n = Number of leaves per plant

L<sub>i</sub> = Leaf length (cm)

W<sub>i</sub> = Leaf width (cm)

The common bean water productivity and water use efficiency values were determined based on total grain yield obtained for different treatments of selenium after harvesting against the volume of applied irrigation water as Kg/m<sup>3</sup> using the following equation 3.13 adopted from (Semida *et al.*, 2016).

$$WP = \frac{Y_T}{I_w} \quad WUE = \frac{Y_T}{I_w} \dots\dots\dots \text{Equation 3.13}$$

Where:

WP = Water Productivity (Kg/m<sup>3</sup>)

WUE = Water Use Efficiency (Kg/m<sup>3</sup>)

Y<sub>T</sub> = Total grain yield (Kg/m<sup>2</sup>)

I<sub>w</sub> = Irrigation water use (m<sup>3</sup>/m<sup>2</sup>)

To determine the total grain yield, common beans were harvested after reaching maturity period and well dried. After each harvest, the weight of the common beans was recorded using a weigh scale in order to calculate the overall grain yields. In order to estimate the water productivity and water usage efficiency at every water level, we calculated the total grain yields from each treatment and compared them. The same method was used due to the fact that the experiment took place within the greenhouse environment where rainfall was not a contributing factor in the estimation of water use efficiency.

### 3.4 Effect of Water Stress on Common Bean Selenium Uptake Levels

According to Ravello *et al.* (2022) the uptake and accumulation of selenium (Se) in plants are influenced by the selenium content in the leaves, speciation, and the

metabolic processes of plant organs. At the end of the crop cycle the *Phaseolus vulgaris* L was harvested and their moisture content measured. The leaves, stems and grains were naturally dried inside the greenhouse for the three days and then crushed into powder using blender machine for analysis at the Safe Food laboratory at Egerton University.

Following the method described by Muchemi *et al.* (2015) was adopted where the dry mass of leaves and seeds were crushed into powder by using blender and then the crushed powder of 1 g per 72 samples was digested in 5 millilitres volume of nitric acid (HNO<sub>3</sub>) and hydrochloric acid (HCl) for oxidation and digestion. The digest was cooled and filtered using a Whatman number 42 filter paper to remove any particulate matter as shown in appendices A9, A10 and A11. Then 50 millilitres volume with distilled water was added to each sample to ensure proper dissolution and dilution for allowing accurate detection and quantification of selenium and a series of Se standard solutions was prepared to create a calibration curve. Calibration and measurement of Se concentration was done by using Atomic Absorption Spectroscopy (AAS) as shown in appendices A12, C1 and C2. According to Food and Agriculture Organization (FAO, 2019) the mean consumption of beans in the world is 100 g/person/day. Based on this information and considering Se contents in bean grains, Se intake was calculated using the equation 3.14 as follows (de Lima Lessa *et al.*, 2019).

$$Se_{Intake} = Se \times C \dots\dots\dots \text{Equation 3.14}$$

Where:

$Se_{Intake}$  (µg/person/day) = Daily Se intake estimation per person

Se (µg/g) = Se contents in bean grains obtained from the studied treatments

C (g/person/day) = Mean consumption of bean grains per person

### **3.5 Determination of Optimal Selenium Foliar Application Rate in Water-Stressed Environments for Optimum Yield and WUE**

The optimal yield and water use efficiency was determined using the Taguchi Design of Experiment method from the measured dry bean responses after harvesting. The controlled variables were selenium application rates 0.5 mg/L, 1.0 mg/L and 1.5 mg/L and water levels varied at three levels full irrigation 100% ET<sub>c</sub> and DI at 70% ET<sub>c</sub> and 50% ET<sub>c</sub>. The Orthogonal Array was adopted to determine the number of tests according to (Wysk *et al.*, 2000). The factors and their corresponding levels are shown Table 3.4.

**Table 3.4:** Operation Parameters and Levels

Parameters	Labels	Levels		
		L1	L2	L3
Water level (ET <sub>c</sub> %)	A	50	70	100
Se Concentration (mg/L)	B	0.5	1.0	1.5

An L9 orthogonal array was appropriate for this experimental design. The layout of the L9 experiments is presented in Table 3.5.

**Table 3.5:** Optimization Experimental Layout

Experimental Runs	Levels	
	A	B
1	1	1
2	2	1
3	3	1
4	1	2
5	2	2
6	3	2
7	1	3
8	2	3
9	3	3

This experimental design aimed to determine the parameters under which optimal yield and WUE was achieved. The statistical measure Signal-to-Noise ratio (S/N) given by equation 3.15 was performed to optimize yield and WUE under “the higher-the-better” characteristics.

$$SN_L = -10 \log \left( \frac{1}{n} \sum_i^n \frac{1}{y_i^2} \right) \dots \dots \dots \text{Equation 3.15}$$

Where:

y<sub>i</sub> = Response variable at each experiment

n = Total number of repetitions in a trial.

The S/N ratio is used in the optimization of process or product design. This analyses the influence of each factor on the response variable, showing the parameter with the greatest effect. A maximized S/N ratio reduces the “variability of the process against undesirable changes in noise (uncontrollable) factors” (Davis & John, 2018). This optimization process was used to determine the optimal balance between irrigation water level ( $ET_c$ ) and foliar selenium application for the optimum yield of common beans and WUE.

### **3.6 Statistical Analysis**

Data were collected and statistically analysed using the Data Analysis tool Pak in Microsoft Excel (2019) and Minitab software (Version 21). These tools were employed to identify sources of variation in the means and to assess the significance of the interactive effects of irrigation levels and foliar selenium application rates on the growth parameters and yield of common beans, using the Least Significant Difference (LSD) test at ( $p < 0.05$ ). Response plots and the Analysis of the Mean (ANOM) method were applied to determine the optimal selenium concentrations and irrigation levels for achieving maximum yield and water use efficiency (WUE). The contribution of each factor to percentage yield and WUE was evaluated using main effect signal-to-noise (S/N) ratios and Analysis of Variance (ANOVA).

## CHAPTER FOUR

### RESULTS AND DISCUSSIONS

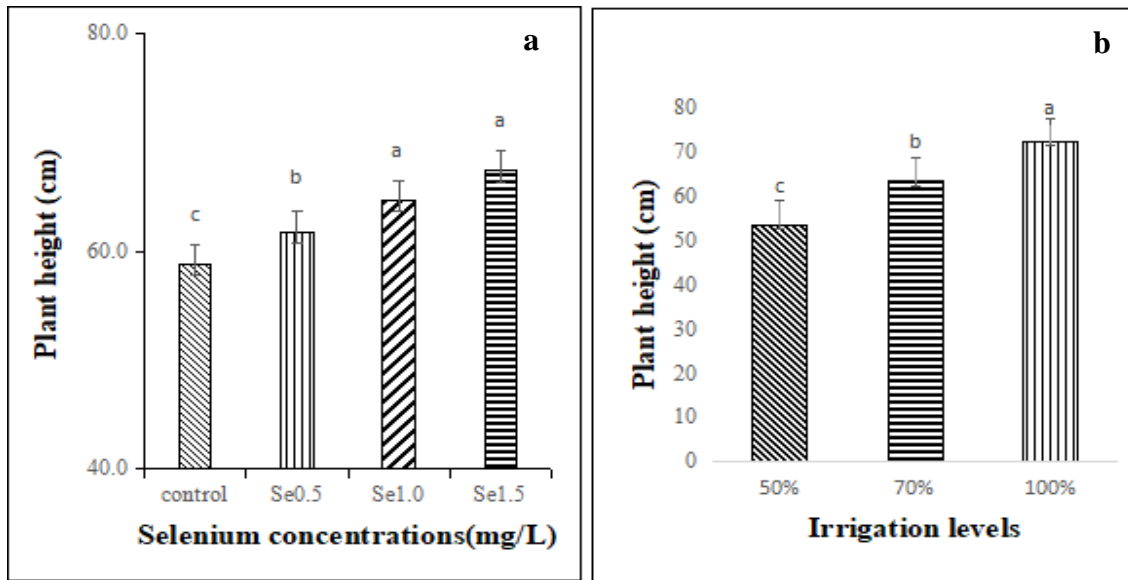
#### **4.1 Effect of Foliar Se and Deficit Irrigation on Growth Parameters, Yield and Water Use Efficiency on Common Bean**

Water scarcity remains a significant challenge to crop productivity and deficit irrigation is widely practiced a water saving approach, though it reduces yields. Foliar selenium application has been reported as a beneficial agronomic practice for enhancing plant stress tolerance and improving growth under limited water conditions. Evaluating their combined influence on common beans provide insights strategies for maintaining yield while improving agriculture water use. The study investigated the vegetative response of common beans by assessing growth parameters including plant height, number of leaves, number of branches, and leaf area index. Additionally, yield related traits such as pod length, number of pods, number of seeds, and grain yield were measured to evaluate overall productivity.

##### **4.1.1 Plant Height**

As demonstrated in appendix B2, there was a significant ( $p < 0.05$ ) impact on plant height when foliar selenium was applied in conjunction with sustained deficit irrigation to evaluate the impact of deficit irrigation on the agronomic traits of the bean crop. At maturity stage, plants with 100%  $ET_c$  had the largest plant height, with an average of 72.4 cm, followed by 70%  $ET_c$  at 63.5 cm, and 50%  $ET_c$  at 53.6 cm, as shown in (Figure 4.1b) when irrigation levels were considered. This indicates that adequate water application promotes vegetative growth by sustaining cell expansion and turgor, whereas water deficit limits plant elongation leading to reduced height. Relative to the 50%  $ET_c$ , the 100%  $ET_c$  elevated the average plant height by 35.1%, underscoring the susceptibility of bean development to water stress. The foliar spray rate of selenium significantly influenced plant height development ( $p < 0.05$ ) (Figure 4.1a). The plant height showed an increase with rising of foliar selenium application rates; the lowest plant height was 66.1 cm (no selenium) and the plot at highest application rate of foliar selenium giving the highest plant height of 75.4 cm. This indicates that foliar selenium application

mitigates negative effects of water stress by boosting antioxidant activities and physiological processes that sustain growth under limited water availability.



**Figure 4.1:** a) Selenium Concentration and b) Deficit Irrigation against Plant Height

Nevertheless, no discernible variation existed in the average value of the plant height of those plots treated with 1.0 and 1.5 mg/L of foliar selenium application rates as shown in Table 4.1 (a). This is because the bean plant had already attained an optimal growth response at 1.0 mg/L, so the additional application of 1.5 mg/L did not translate into further elongation. This finding concurs with those of (Andrade *et al.*, 2018; Chen *et al.*, 2022; Hashim & Mohammed 2023).

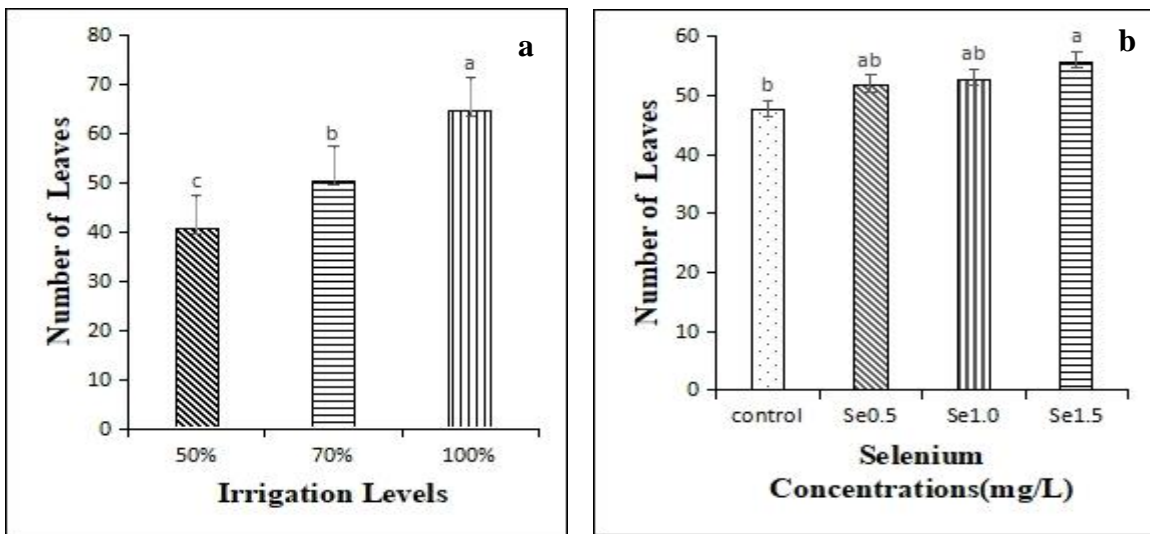
**Table 4.1(a):** Mean Comparison Between the Irrigation Level and Selenium Concentration on the Plant Height

Selenium Concentrations (mg/L)	Irrigation Levels		
	50%	70%	100%
0	50.84 <sup>c</sup>	59.40 <sup>b</sup>	66.22 <sup>b</sup>
0.5	52.67 <sup>bc</sup>	61.80 <sup>b</sup>	70.87 <sup>ab</sup>
1.0	54.30 <sup>ab</sup>	64.60 <sup>ab</sup>	75.22 <sup>a</sup>
1.5	56.72 <sup>a</sup>	68.23 <sup>a</sup>	77.18 <sup>a</sup>
LSD <sub>0.05</sub>	2.69	7.52	7.29

LSD=Least Significant Difference. Means of the same letter within the column are not significantly different at the 5% probability level using Tukey Significant Difference.

#### 4.1.2 Number of Leaves per Plant

Both foliar selenium and irrigation water levels produced statistically significant differences ( $p < 0.05$ ) as shown in appendix B2. Selenium concentration influenced leaf formation with the highest mean number of leaves recorded at 1.5 mg/L Se. In contrast, treatments with 0.5 mg/L and 1.0 mg/L selenium showed no significant difference at ( $p < 0.05$ ) as illustrated in Figure 4.2b. This is because at 1.5 mg/L application rate selenium sufficiently stimulate physiological processes such as photosynthesis efficiency, antioxidant activity and hormonal regulation that promote leaf initiation and expansion while, at lower rates the response may not be strong enough to cause measurable differences. Also, the number of leaves was found to increase whenever irrigation level was increased (Figure 4.2a). The highest number of leaves were observed with 100% ET<sub>c</sub> (68) followed by 70% ET<sub>c</sub> (52) and 50% ET<sub>c</sub> (46) respectively at ( $p < 0.05$ ) as shown in Table 4.1(b). Indicating that adequate water supply enhances photosynthesis process and nutrients uptake which contribute to greater leaf production. Abouelhamd *et al.* (2023) reported an increase in the number of leaves following selenium application compared to treatments without selenium. Similarly, Ali *et al.* (2020) observed that okra plants treated with 3 µg/L of selenium produced the highest number of leaves (25.33), whereas the lowest leaf count (19.44) occurred in plants grown without selenium supplementation.



**Figure 4.2:** a) Irrigation Water Levels and b) Selenium Concentration against Number of Leaves

**Table 4.1(b):** Mean Comparison Between the Irrigation Level and Selenium Concentration on the Number of Leaves

Selenium Concentrations (mg/L)	Irrigation Levels		
	50%	70%	100%
0	38.22 <sup>b</sup>	46.33 <sup>b</sup>	57.78 <sup>a</sup>
0.5	38.11 <sup>b</sup>	50.22 <sup>ab</sup>	66.67 <sup>a</sup>
1.0	40.33 <sup>ab</sup>	52.78 <sup>a</sup>	65.11 <sup>a</sup>
1.5	46.0 <sup>a</sup>	52.44 <sup>a</sup>	68.67 <sup>a</sup>
LSD <sub>0.05</sub>	6.26	5.29	12.9

**Note:** Means denoted by the same letter inside the column do not exhibit significant differences at the 5% probability level, as determined by Tukey's Significant Difference test.

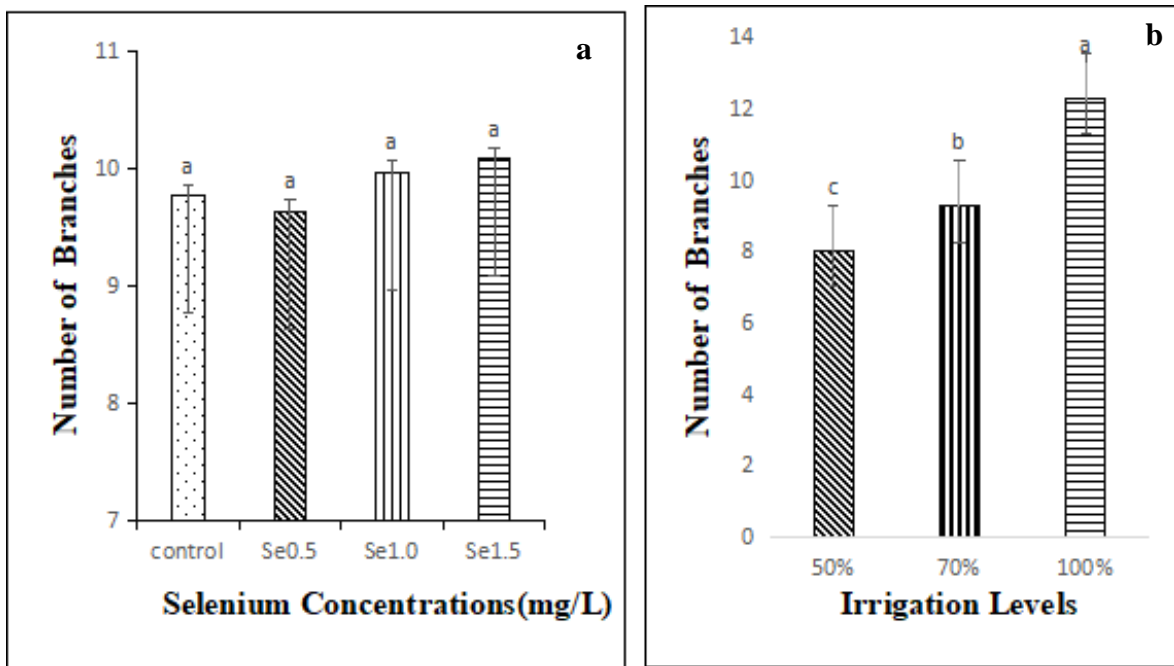
#### 4.1.3 Number of Branches

The mean number of branches per plant was significantly influenced by the irrigation water levels ( $p < 0.05$ ), as detailed in appendix B2. This study shown that 100% ET<sub>c</sub> resulted in the maximum number of branches (12.28) of common beans, but it was statistically comparable to 70% ET<sub>c</sub>. The application of 100% ET<sub>c</sub> resulted in a greater number of branches compared to the 50% ET<sub>c</sub> irrigation level (Figure 4.3b). The quantity of branches per plant rose as the stress level diminished. This may be attributed to water's critical role in nutrient absorption and transport, hence enhancing crop vegetative development. Similarly, Alipour *et al.* (2022) reported that increasing water application enhanced practically all plant development metrics including the number of branches per plant. From the mean comparisons and the analysis of variance, foliar selenium had no statistical effect on the formation of the number of branches of the common bean plant at ( $p < 0.05$ ) as shown in Table 4.1(c) and Figure 4.3 (a). Suggesting that branch initiation is largely controlled by genetic factors and hormonal balances particularly auxins and cytokinin which may not be strongly influenced by the tested selenium application rates. Additionally, selenium is primarily involved in enhancing physiological tolerance to water stress through antioxidant defence and metabolic regulation, functions that may not directly stimulate branches. This finding concurs with that of (Moloi & Khoza 2022); (Zahedi *et al.*, 2009).

**Table 4.1(c):** Mean Comparison Between the Irrigation Level and Selenium Concentration on the Number of Branches

Selenium Concentrations (mg/L)	Irrigation Levels		
	50%	70%	100%
0	8.11 <sup>a</sup>	9.39 <sup>a</sup>	11.78 <sup>a</sup>
0.5	8.33 <sup>a</sup>	9.00 <sup>a</sup>	11.56 <sup>a</sup>
1.0	8.00 <sup>a</sup>	9.78 <sup>a</sup>	12.11 <sup>a</sup>
1.5	7.67 <sup>a</sup>	8.89 <sup>a</sup>	13.67 <sup>a</sup>
LSD <sub>0.05</sub>	1.53	1.21	3.62

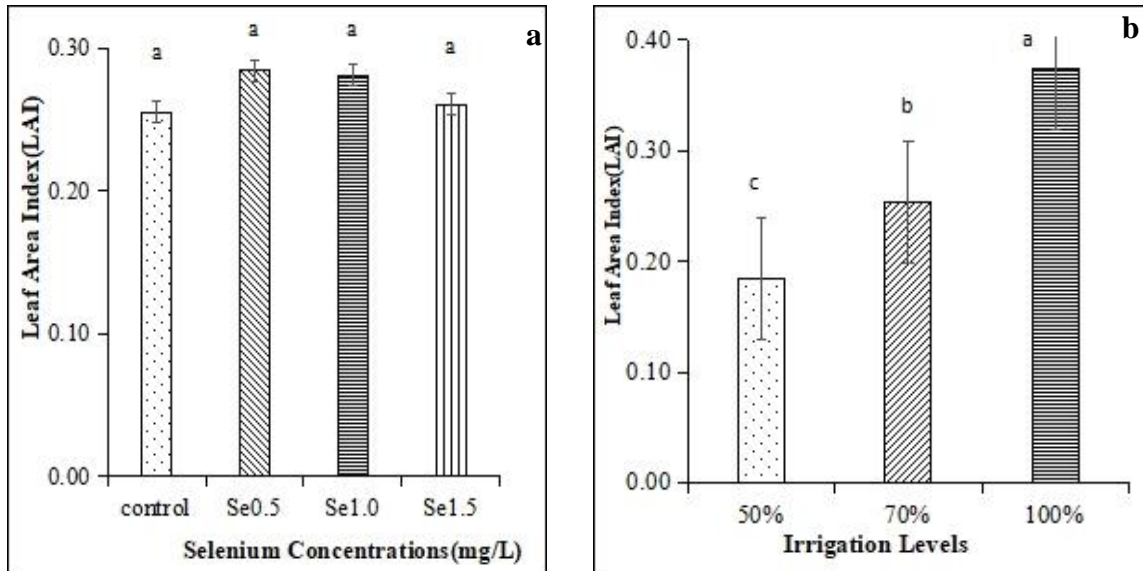
**Note:** Means of the same letter within the column are not significantly different at the 5% probability level using Tukey Significant Difference



**Figure 4.3:** a) Foliar Selenium and b) Deficit Irrigation against Number of Branches

#### 4.1.4 Leaf Area Index

As indicated in appendix B2, the analysis of variance showed that irrigation water levels had a significant impact on the leaf area index at  $p < 0.05$ . According to this investigation, the largest leaf area index (0.356) was achieved at 100%  $ET_c$ , while the lowest value (0.172) was found at 50%  $ET_c$ . The application of 100%  $ET_c$  resulted in a greater leaf area index of (0.356) than the 50%  $ET_c$  irrigation level (Figure 4.4b).



**Figure 4.4: a) Foliar Selenium and b) Deficit Irrigation against Leaf Area Index**

In general, leaf area index increased with lowering stress level. This could be due to the fact that full irrigation 100%  $ET_c$  provides sufficient water to support vegetative growth, cell expansion and leaf development. Adequate moisture ensures optimal photosynthesis and nutrient uptake, promoting the formation of larger and more numerous leaves, which directly increases LAI. In contrast, 50%  $ET_c$  imposes water stress that limits leaf expansion, accelerates leaf senescence and reduces overall canopy growth as the plant conserves water, resulting in a smaller leaf surface area and thus a lower LAI. Similar results were reported by Kalaydjieva *et al.* (2015) and Soureshjani *et al.* (2019) whereby, under optimal irrigated beans there was maximum development of leaf area compared to the water deficit plots which were highly affected in the process of leaf formation. From the mean comparisons and the analysis of variance, selenium spray produced no statistically significant impact on the common bean plant LAI at  $p < 0.05$  as shown in appendix B2 and Table 4.1(d).

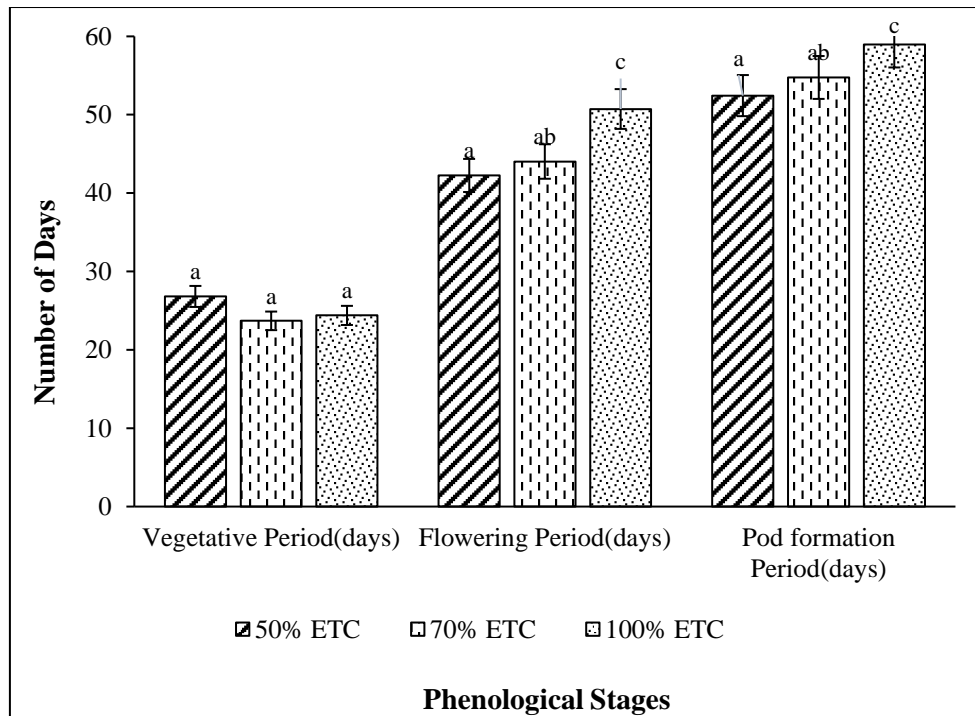
**Table 4.1(d):** Mean Comparison Between the Irrigation Level and Selenium Concentration on the Leaf Area Index

Selenium Concentrations (mg/L)	Irrigation Levels		
	50%	70%	100%
0	0.172 <sup>a</sup>	0.260 <sup>a</sup>	0.333 <sup>a</sup>
0.5	0.184 <sup>a</sup>	0.282 <sup>a</sup>	0.388 <sup>a</sup>
1.0	0.196 <sup>a</sup>	0.203 <sup>a</sup>	0.445 <sup>a</sup>
1.5	0.184 <sup>a</sup>	0.269 <sup>a</sup>	0.330 <sup>a</sup>
LSD <sub>0.05</sub>	0.141	0.188	0.273

**Note:** Means of the same letter within the column are not significantly different at the 5% probability level using Tukey Significant Difference.

#### 4.1.5 Phenological Stage of Common Bean Crop

The study finding revealed that deficit irrigation practices had significant effects on the duration of common beans phenological stages. Flowering is one of the essential stages for pod development which requires sufficient water. According to Alipour *et al.* (2022); Fathi & Tari, (2016) and Hirich *et al.* (2014) during the vegetative stage, common beans exhibit tolerance to water stress; however, they become highly sensitive to drought conditions during the flowering and pod formation stages. This was observed with the 30% less of pod development at 50 ET<sub>c</sub> compared to the 90% and 100% at 70 ET<sub>c</sub> and 100 ET<sub>c</sub> respectively. This could be attributed to the adequate water that prolongs reproductive growth, pod formation phase resulting to better pod development, seed filling, for better yield potential. In contrast with 50% ET<sub>c</sub> whose long vegetative stages delayed growth, shortening the flowering and pod formation periods, due to water stress which accelerated the plants to maturity. This is similar to the observation by (Alipour *et al.*, 2022). Overall, full irrigation (100% ET<sub>c</sub>) promoted optimal progression through phenological stages, while water deficit (50% ET<sub>c</sub>) disrupts normal development and shortens reproductive phases. Figure 4.5 shows that during the blooming and pod formation stages of the growth season, there was a substantial increase ( $p < 0.05$ ) in the 100% ET<sub>c</sub> and 70% ET<sub>c</sub> treatments.



**Figure 4.5:** Phenological Stages against Number of Days

This may be because agricultural drought resistance varies depending on weather, plant growth and development stages, drought accumulation and duration, and Genetically Local Population (GLP 2) genotype (Golezani *et al.*, 2010).

#### 4.1.6 Pod Length

Both irrigation and foliar selenium application rates had a significant impact on the average pod length of the common bean at  $p < 0.05$  as shown in appendix B3. At 100%  $ET_c$ , the mean pod length was the longest (14.6 cm), while at 50%  $ET_c$  irrigation water level, the smallest (11.5 cm). The mean pod length fell by 21.2%  $ET_c$  when comparing the 50% and 100%  $ET_c$ , suggesting that a lower degree of water stress corresponds to a longer mean pod length. This is due to the soils' adequate moisture availability. As selenium concentration increased, a notable rise in the number of pods was observed. The smallest mean pod length (13.1 cm) occurred in the fully irrigated control without selenium, while the maximum length (15.6 cm) was achieved in treatments receiving selenium supplementation with 1.0 and 1.5 mg/L application rates and full irrigation (Tables 4.2, 4.3 and 4.4 (a)). This is because selenium played a positive role in enhancing reproductive growth. According to a study by Kütük Dinçel *et al.* (2024) selenium application was found to enhance yield-related traits, including the number of pods and seeds per pod. These improvements indicate that selenium may positively influence pod development characteristics, such as pod length.

**Table 4.2:** Mean Comparison for Main Effect of Deficit Irrigation on Selected Yield Parameters

<b>Yield Parameters</b>				
<b>Irrigation Levels (%)</b>	<b>Pod Length (cm)</b>	<b>Number of Pods</b>	<b>Number of Seeds</b>	<b>Yield (Kg/Ha)</b>
50	11.50 <sup>c</sup>	15.50 <sup>c</sup>	63.62 <sup>c</sup>	4442.59 <sup>c</sup>
70	13.25 <sup>b</sup>	22.75 <sup>b</sup>	75.23 <sup>b</sup>	8629.63 <sup>b</sup>
100	15.08 <sup>a</sup>	27.58 <sup>a</sup>	109.88 <sup>a</sup>	11703.70 <sup>a</sup>
LSD <sub>0.05</sub>	0.75	3.27	10.35	560.72
CV (%)	6.5	20	15.5	20.2

**Table 4.3:** Mean Comparison for Main Effect Selenium Concentrations on Selected Yield Parameters

<b>Yield Parameters</b>				
<b>Selenium Concentrations (mg/L)</b>	<b>Pod Length (cm)</b>	<b>Number of Pods</b>	<b>Number of Seeds</b>	<b>Yield (Kg/Ha)</b>
Control	12.51 <sup>b</sup>	17.33 <sup>c</sup>	70.22 <sup>c</sup>	5953.09 <sup>d</sup>
0.5	13.30 <sup>ab</sup>	20.33 <sup>b</sup>	85.73 <sup>b</sup>	8241.98 <sup>c</sup>
1.0	13.78 <sup>a</sup>	24.67 <sup>a</sup>	84.42 <sup>b</sup>	8770.37 <sup>b</sup>
1.5	13.52 <sup>a</sup>	25.44 <sup>a</sup>	91.24 <sup>a</sup>	10069.14 <sup>a</sup>
LSD <sub>0.05</sub>	0.96	4.2	13.2	713.93
CV (%)	12.9	27.3	1.7	38

**Table 4.4(a):** Mean Comparison Between the Irrigation Level and Selenium Concentration on the Pod Length

Selenium Concentrations (mg/L)	Irrigation Levels		
	50%	70%	100%
0	11.04 <sup>a</sup>	11.89 <sup>a</sup>	14.61 <sup>a</sup>
0.5	11.28 <sup>a</sup>	13.78 <sup>a</sup>	14.83 <sup>a</sup>
1.0	12.23 <sup>a</sup>	13.52 <sup>a</sup>	15.56 <sup>a</sup>
1.5	11.46 <sup>a</sup>	13.78 <sup>a</sup>	15.33 <sup>a</sup>
LSD <sub>0.05</sub>	1.26	2.66	1.5

**Note:** Means of the same letter within the column are not significantly different at the 5% probability level using Tukey Significant Difference.

#### 4.1.7 Number of Pods

Appendix B3 shows that the number of pods with the deficit irrigation and foliar selenium treatment rates was significantly impacted ( $p < 0.05$ ) by the analysis of variance. Based on results from the study, a combination of 100% ET<sub>c</sub> and 1.5 mg/L of selenium concentration produced the most pods (31 per plant) which was statistically equivalent to the interaction between 70% ET<sub>c</sub> and 1.5 mg/L. Indicating that adequate water combined with selenium supplementation produced favourable conditions for reproductive growth. Sufficient irrigation ensures proper physiological functioning, while selenium enhance stress tolerance and nutrient use efficiency allowing the plants to allocate more resources to pod formation. On the other hand, the combination of 50% ET<sub>c</sub> and no foliar selenium application produced the fewest pods (12 per plant) as shown in Tables 4.2, 4.3 and 4.4(b). The reduction of pod number was due to undeveloped flowers and pods dropping down without reaching maturity because of severe water stress with no foliar selenium application. This finding aligns with the observations of Zahedi *et al.* (2009) who reported that water stress in agricultural systems significantly reduced the number of pods per plant, while selenium fertilizer application increased pod formation and alleviated the effects of water stress.

**Table 4.4(b):** Mean Comparison Between the Irrigation Level and Selenium Concentration on the Number of Pods

Selenium Concentrations (mg/L)	Irrigation Levels		
	50%	70%	100%
0	11.67 <sup>a</sup>	18.67 <sup>a</sup>	21.67 <sup>b</sup>
0.5	14.00 <sup>a</sup>	20.67 <sup>a</sup>	26.33 <sup>ab</sup>
1.0	17.00 <sup>a</sup>	25.67 <sup>a</sup>	31.33 <sup>a</sup>
1.5	19.33 <sup>a</sup>	26.00 <sup>a</sup>	31.00 <sup>a</sup>
LSD <sub>0.05</sub>	7.92	9.34	7.85

**Note:** Means of the same letter within the column are not significantly different at the 5% probability level using Tukey Significant Difference.

#### 4.1.8 Number of Seeds

The analysis of variance showed that the main effect of irrigation water levels and selenium rates at ( $p < 0.05$ ) substantially influenced number of seeds as shown in appendix B3. The combination of 100% ET<sub>c</sub> and 1.5 mg/L of selenium concentration produced the highest number of seeds (116 per plant) compared to the 100% ET<sub>c</sub> and no selenium application control treatment (88 number of seeds per plant), whereas the combination of 50% ET<sub>c</sub> and no foliar selenium application produced the fewest number of seeds (59 per plant) (Tables 4.2 and 4.3). More seeds per plant at 100% and 70% ET<sub>c</sub> with 1.5 mg/L foliar selenium application resulted from the balance between adequate to moderate water supply and the protective effects of selenium. These effects when combined supported strong vegetative growth, enhanced flower retention, pollination and improved seed development as shown in Table 4.4(c). Selenium boosts antioxidant activity and stress tolerance, maintaining reproductive processes even under moderate water stress (70% ET<sub>c</sub>).

Conversely, the low number of seeds per plant at 50% ET<sub>c</sub> with no selenium arose from severe water deficit impairing physiological functions and reproductive success, compounded by the lack of selenium's protective role, leading to flower abortion, poor fertilization and reduced seed set. This result is consistent with the findings of Zahedi *et al.* (2009) who reported that increased water stress significantly reduced the number of seeds per plant in canola. They further noted that the application of selenium fertilizer enhanced seed formation, resulting in higher overall yield.

**Table 4.4(c):** Mean Comparison Between the Irrigation Level and Selenium Concentration on the Number of Seeds per Plant

Selenium Concentrations (mg/L)	Irrigation Levels		
	50%	70%	100%
0	58.87 <sup>a</sup>	63.70 <sup>b</sup>	88.10 <sup>a</sup>
0.5	60.43 <sup>a</sup>	76.87 <sup>ab</sup>	119.93 <sup>a</sup>
1.0	61.33 <sup>a</sup>	76.70 <sup>ab</sup>	115.23 <sup>a</sup>
1.5	73.83 <sup>a</sup>	83.63 <sup>a</sup>	116.27 <sup>a</sup>
LSD <sub>0.05</sub>	23.69	16.7	35.73

**Note:** Means with the same letter within the column are not significantly different at the 5% probability level using Tukey Significant Difference.

#### 4.1.9 Pod Yield

The overall pod output was significantly impacted by the irrigation and foliar selenium application rates both individually and in combination at  $p < 0.05$  as shown in appendix B3. The highest total pod yield (13177.8 Kg/Ha) was obtained at 100% ET<sub>c</sub> combined with 1.5 mg/L of foliar selenium, but statistically on pair with 70% ET<sub>c</sub>; 1.5 mg/L of selenium concentration as compared to the control treatment 100% ET<sub>c</sub> with no foliar selenium application (8785.2 Kg/Ha), while the lowest pod yield (2288.9 Kg/Ha) was attained at 50% ET<sub>c</sub> combined with no foliar selenium application as shown in Tables 4.2, 4.3 and 4.4 (d). This is because optimal water availability ensuring full physiological function and nutrient transport, while the selenium enhances stress tolerance, antioxidant activity and metabolic efficiency in the plant. A study conducted by Moloji & Khoza (2022) at the controlled condition with Endamame plant found that total yield was not substantially affected by selenium application under drought stress conditions which does not concurs with the finding of this study, this may be because Endamame is naturally more tolerant to drought than common beans which are more sensitive to drought. So, selenium improves antioxidant defence, protecting cell membranes and photosynthesis in common beans making its effect on yield under water stress condition.

**Table 4.4(d):** Mean Comparison Between the Irrigation Level and Selenium Concentration on the Pod Yield

Selenium Concentrations (mg/L)	Irrigation Levels		
	50%	70%	100%
0	2288.9 <sup>c</sup>	6785.2 <sup>b</sup>	8785.2 <sup>c</sup>
0.5	4266.7 <sup>b</sup>	8392.6 <sup>ab</sup>	12066.7 <sup>b</sup>
1.0	4533.3 <sup>b</sup>	8992.6 <sup>a</sup>	12785.2 <sup>ab</sup>
1.5	6681.5 <sup>a</sup>	10348.1 <sup>a</sup>	13177.8 <sup>a</sup>
LSD <sub>0.05</sub>	833.84	2122.24	1003.59

**Note:** Means with the same letter within the column are not significantly different at the 5% probability level using Tukey Significant Difference.

Under full irrigation, plants are not limited by water, allowing them to fully utilize the benefits of selenium, which supports chlorophyll synthesis, delays senescence and boosts enzyme function. The synergy between adequate hydration and selenium-induced resilience results in improved growth, reproductive development and ultimately higher yield. Low yield under 50% ET<sub>c</sub> with no selenium application is primarily due to severe water stress, which limits critical physiological processes such as photosynthesis, nutrient uptake and cell expansion. The deficit irrigation reduces stomatal conductance and transpiration, leading to poor plant growth and reproductive development.

Without selenium, the plant lacks additional protection against oxidative stress and membrane damage caused by water scarcity. The current result is consistent with that of Ragályi *et al.* (2021), who proposed that using irrigation water enriched with selenium could be a viable approach for selenium bio-fortification without significantly lowering plant biomass production or altering the contents of other macro and microelements. The administration of greater amounts (25 mg/L or 50 mg/L) of Se enhances plant hydration status and the development and production of common beans grown in salty soil, according to a research by Semida *et al.* (2023).

**Table 4.5:** Correlation Coefficients of Yield Parameters under Deficit Irrigation and Selenium Foliar Application

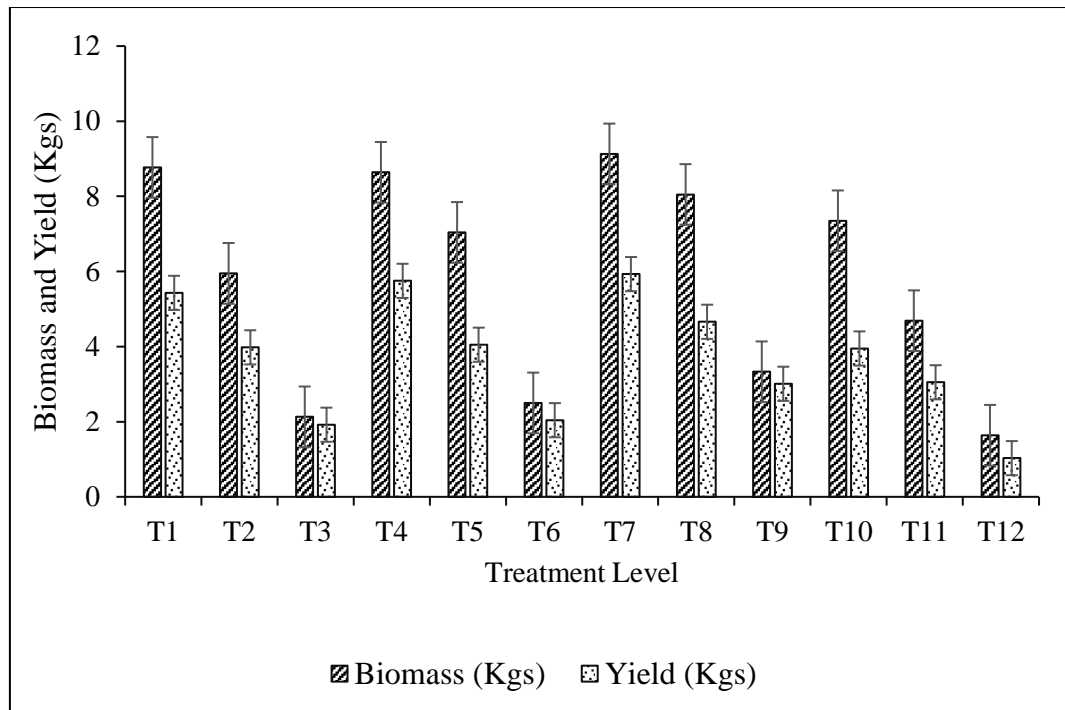
	Pod Length (cm)	Number of Seeds per Plant	Yield (Kg/Ha)
Number of pods per plant	0.791*	0.791*	0.901*
Pod length (cm)		0.82*	0.858*
Number of seeds per plant			0.863*

**Key:** \* means significant at  $p < 0.05$

A strong positive correlation was observed between seed yield and the number of pods per plant, as indicated by Pearson's correlation coefficient ( $R = 0.858$ ). This suggests that pod number could serve as a reliable selection criterion for identifying high yielding bean genotypes under water stress conditions. Similarly, a direct relationship was noted between the number of seeds per plant and pod yield ( $R = 0.791$ ), as presented in Table 4.5. Moreover, the number of seeds per plant showed a positive association with the number of pods per plant. All yield parameters (pod length, pod number, number of seeds and grain yield) were found to increase with an increase in the foliar selenium application rates and irrigation water levels ( $p < 0.05$ ). Those plants with higher number of pods and longer pod lengths were found to produce higher yield of bean grains with positive strong correlation of  $R = 0.901$  and  $R = 0.858$  respectively.

#### 4.1.10 Water Productivity

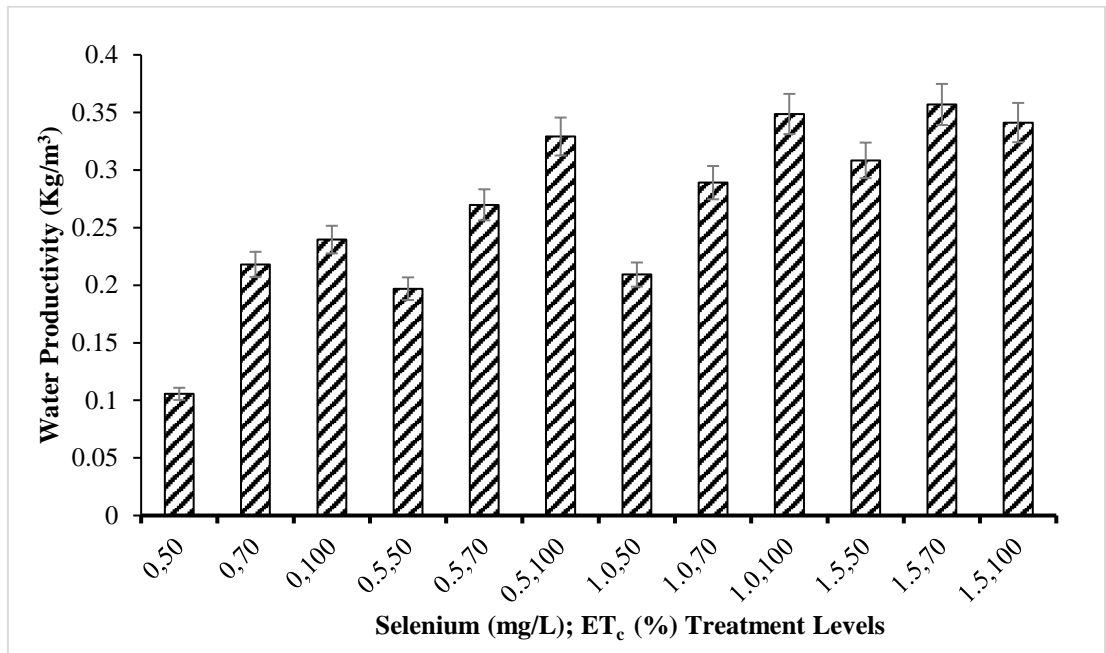
Water productivity was evaluated to determine how efficient common beans (*Phaseolus vulgaris* L.) utilized the applied irrigation water under different selenium application rates and water regimes. The water productivity of *Phaseolus vulgaris* L was calculated based on the total grain yield and the corresponding amount of water utilized, to provide deeper understanding of how the combined influence of foliar selenium application and deficit irrigation affected both yield performance and the efficient use of limited water resources. The total grain yield and biomass of *Phaseolus vulgaris* L obtained under the various treatment combinations are presented in Figure 4.6, with treatments T1 to T12 detailed in Table 3.1.



**Figure 4.6:** Biomass and Total Grain Yield against Treatment Levels

It can be seen that the highest and the lowest *Phaseolus vulgaris* L total grain yields were obtained at treatments T7 (100 % ET<sub>c</sub> with 1.5 mg/L of Se) and T12 (50 % ET<sub>c</sub> with no Se) respectively. The higher biomass and yield can be attributed to the synergistic effect of adequate irrigation and optimal selenium foliar application. Selenium likely enhanced the plants' antioxidant defence systems and improved physiological processes such as stomatal regulation and photosynthetic efficiency, enabling better tolerance to water stress and ultimately resulting in improved growth and productivity. Conversely, treatments with limited water and/or without selenium supplementation faced physiological stress, leading to reduced biomass and yield. Boghdady *et al.* (2017) carried out a study on faba beans and the results revealed that foliar selenium application of 2.5 ppm, 5 ppm, 10 ppm and 15 ppm concentration without water stress condition increased yield but the maximum significant increase in seed yield was observed with application of 10 ppm selenium in both studied seasons. Also, a study conducted by Ali *et al.* (2020) revealed that vegetative and yield parametric quality of okra plant were significantly alleviated by the foliar application of Se under drought stress and the highest yield was obtained at Se application of 3 mg/L. Semida *et al.* (2023) also revealed that the highest yield of *Phaseolus vulgaris* L was obtained at 100% ET<sub>c</sub> water application with selenium application of 25 and 50 mg/L under saline soil. The water productivity of the common bean was estimated from the bean yields and the total water use and the

highest water productivity obtained from 70% ET<sub>c</sub> and 1.5 mg/L selenium concentration whereas, the lowest water productivity was obtained from 50% ET<sub>c</sub> and 0 mg/L selenium concentration as shown in Figure 4.7.



**Figure 4.7:** Selenium Rates and ET<sub>c</sub> Treatment Levels against Water Productivity

This is because there was an optimal balance between water conservation and physiological plant performance. At 70% ET<sub>c</sub>, plants received sufficient moisture to maintain key metabolic functions without the high water use as in full irrigation 100% ET<sub>c</sub>, while the 1.5 mg/L selenium application likely enhanced stress tolerance by improving antioxidant activity, stomatal regulation and root growth. This synergy between moderate deficit irrigation and selenium-induced stress mitigation enabled the plants to produce more yield per unit of water used compared to the more stressed 50% ET<sub>c</sub> treatments. This observation aligns with the conclusion of Ravello *et al.* (2022) the selenium supplementation mitigated the adverse effects of water deficit through the stimulation of antioxidant enzyme activities and increasing water productivity. A study done by Semida *et al.* (2023) demonstrated that selenium concentration at 25 and 50 mg/L grown under DI 80% ET<sub>c</sub> enhanced growth and pod yield in *Phaseolus vulgaris* L even under saline soils and water deficit at 20% increased the water productivity.

## 4.2 Effect of Water Stress on Common Bean Selenium Uptake

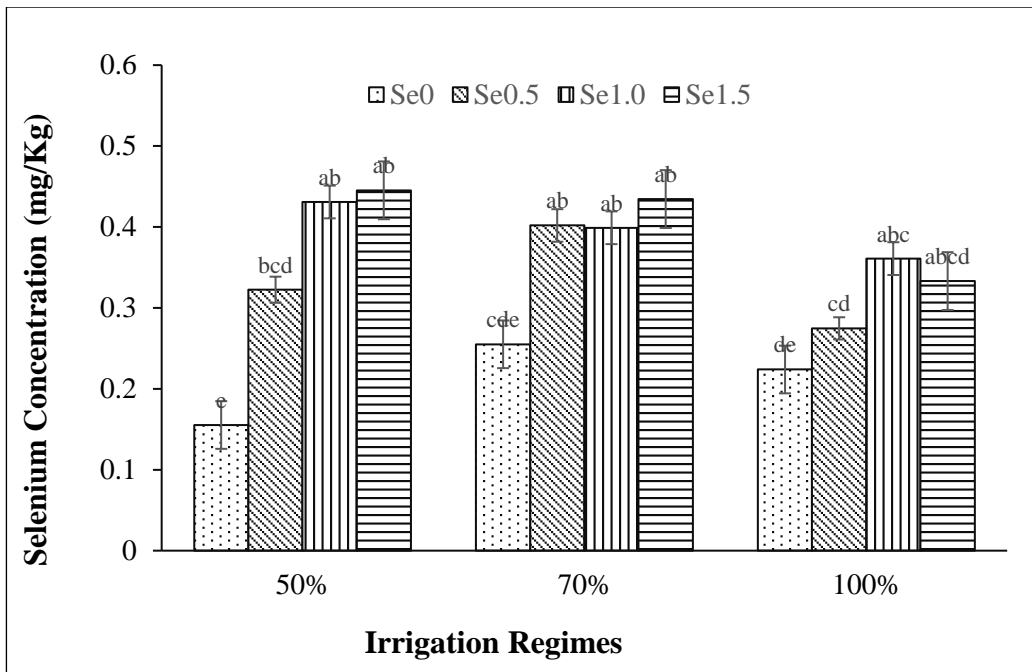
Water stress is among the major constraints to crop productivity, as it disrupts key physiological and biochemical processes that govern nutrient uptake and utilization. In common beans, insufficient water availability not only reduces growth and yield but also affects the absorption and movement of essential micronutrients such as selenium. Although required in small quantities, selenium is crucial for enhancing plant tolerance to stress by strengthening antioxidant defence systems and preserving cellular integrity under unfavourable conditions. Understanding how water stress affects selenium uptake in beans is important in determining strategies that can optimize micronutrient use efficiency while sustaining crop performance in water-limited conditions.

### 4.2.1 Irrigation Regimes and Foliar Selenium Application Rates on Selenium Concentration in Common Bean Grains

The analysis of variance (ANOVA) indicated that irrigation water levels, selenium application rates, and their interaction had a significant effect ( $p < 0.05$ ) on selenium concentration in bean grains, as presented in Table 4.6 and Figure 4.8.

**Table 4.6:** Analysis of Variance on Results for Concentration of Selenium on the Bean Grains

Sources of Variation	SS	Df	MS	F	P-value	F crit
Irrigation regimes	0.0333	2	0.0167	11.079	0.0003	3.43
Selenium concentrations	0.2153	3	0.0718	47.666	0.0007	3.01
Irrigation regimes*selenium conc.	0.0374	6	0.0062	4.14	0.0054	2.51
Error	0.0362	24	0.0015			
Total	0.3221	35				



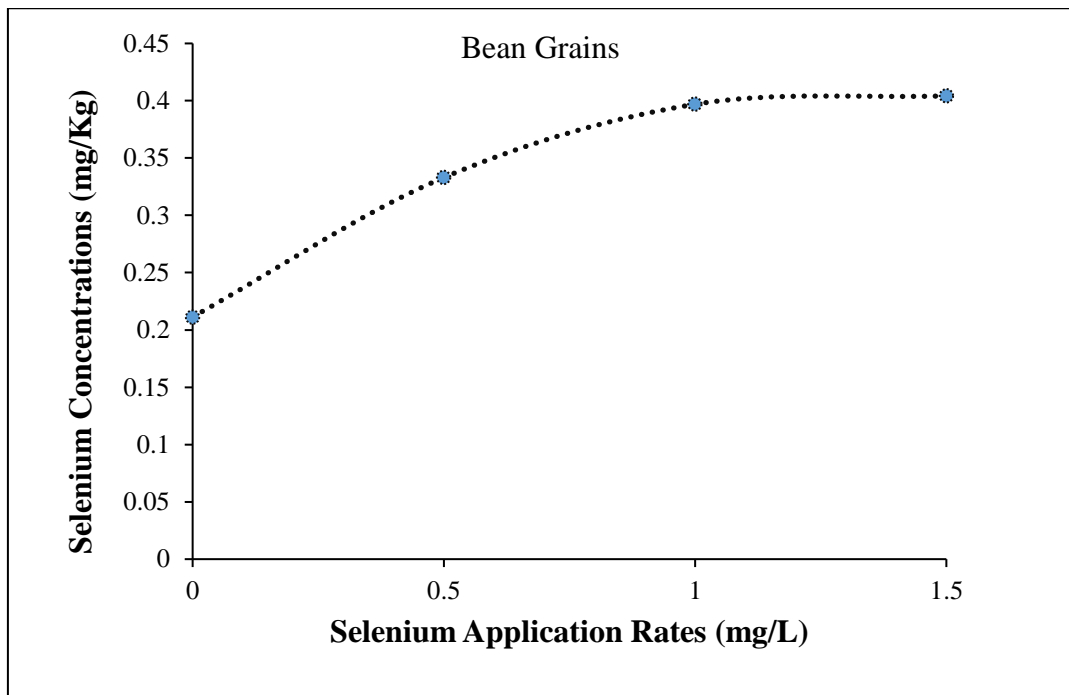
**Figure 4.8:** Interactive Effect of Foliar Selenium and Different Irrigation Regimes on Selenium Concentration of Common Bean Grains

**Note:** The vertical bar represents the standard error. Similar letters on the bars refer to insignificant differences among means based on Tukey's LSD test at the ( $p < 0.05$ )

Overall, selenium concentration increased with the application rate of selenium under all irrigation regimes. Notably, the highest selenium accumulation was observed at 50%  $ET_c$  with 1.5 mg/L selenium, suggesting that plants under severe water stress absorbed and retained more selenium compared to those under full irrigation. At 70%  $ET_c$ , selenium uptake remained relatively high across all Se application levels, with values comparable to those at 50%  $ET_c$ , especially at 1.5 mg/L. This indicates that slight water stress may enhance selenium bioavailability or uptake mechanisms. Conversely, under full irrigation (100%  $ET_c$ ), selenium concentrations were generally lower, possibly due to poor intake of applied selenium, dilution effects or reduced physiological demand under non-stress conditions. This suggests that both selenium application and irrigation practices significantly influence selenium accumulation in common bean tissues, agreeing with several other studies (Lyons *et al.*, 2005; Natasha *et al.*, 2018).

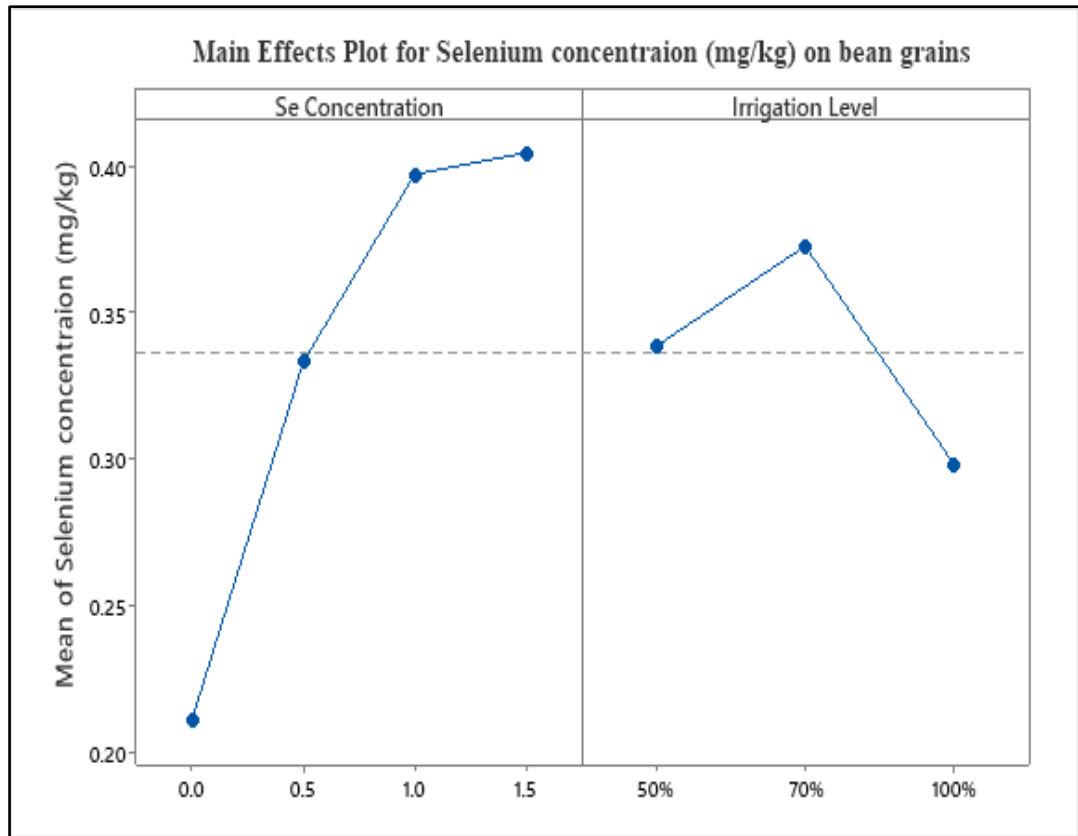
Selenium concentration in common bean grains increased linearly upon increasing foliar selenium application rates as shown in Figure 4.9. This is because plants were able to take in more selenium through their leaves and then transported into reproductive organs by phloem and then stored in grains. Notably grains without foliar selenium treatment (0 mg/L) had a Se concentration of 0.21 mg/Kg which could be attributed to

the soils parent materials and the irrigation water as described by (Malik *et al.*, 2012).



**Figure 4.9:** Selenium Concentration in Grains of Bean against Different Selenium Application Rates

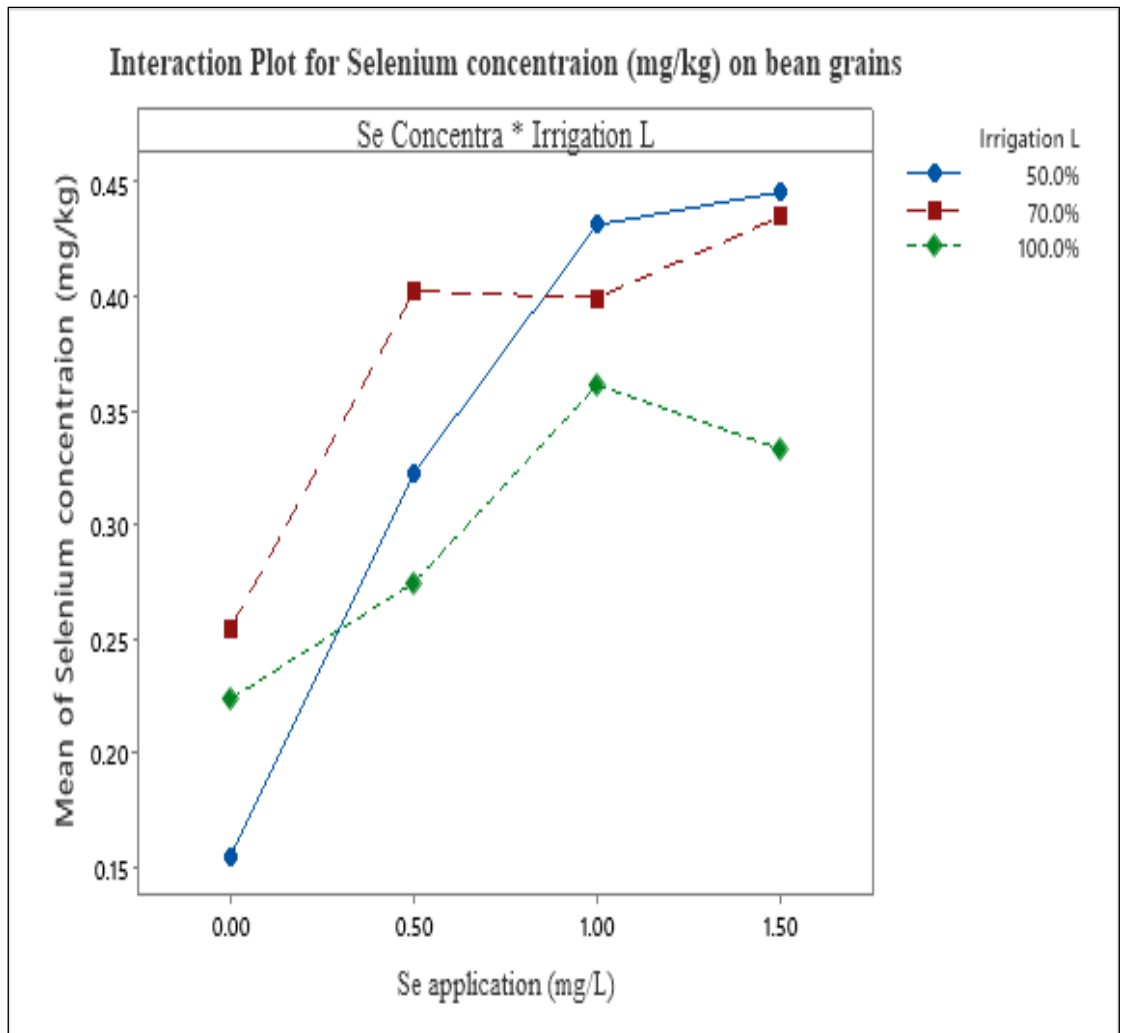
Foliar application allowed the selenium to be taken in directly without being lost in the soil, which helped improve its uptake. This result agrees with that of Ravello *et al.* (2022) which revealed that selenium content in both the grains and leaves of common beans increased proportionally with higher selenium application rates under both full irrigation and water deficit conditions. It can be seen from the means plot (Figure 4.10) that the selenium uptake concentrations increased with an in increased application rate regardless of irrigation water level. Here, it was observed that under full irrigation (control) the uptake of the common bean grains selenium concentrations was very low compared to deficit irrigation regimes. This may be because when the plant received its required water, it grows more leaves and stems, which can cause the selenium taken up to spread out across the larger plant parts resulting in less selenium being stored in the grains. On the other hand, under deficit irrigation the plant produces less overall growth, allowing more of the absorbed selenium to be concentrated and directed to the grains. The rate of uptake was highest at 70%  $ET_c$  which could be due to the fact this moderate water stress creates a balance between water availability and nutrient absorption efficiency. At this level, the plant experiences mild stress, which can stimulate root activity and enhance the uptake and movement of micronutrients.



**Figure 4.10:** Effect of Water Deficit on the Uptake of Selenium Concentration of Common Bean Grains

Unlike severe deficit irrigation (50%  $ET_c$ ), where stress may limit nutrient transport, or full irrigation (100%  $ET_c$ ), where uptake may be diluted due to excessive vegetative growth, the 70%  $ET_c$  condition provides an optimal environment for selenium absorption and effective translocation to the grains. Ravello *et al.* (2022) found that Se concentrations in grains at irrigated treatments tended to be lower than those at water deficiency plots.

The interaction plot shown in Figure 4.11, found that there was meaningful a statistically variation between the treatments. The selenium concentration on the common bean grains at full irrigation was very low across all application rates. At 50%  $ET_c$ , there was a significant increase in selenium content for each and every application rate with an approximate 21% increase in selenium concentrations. This is because under full irrigation (100%  $ET_c$ ) there was higher production of biomass as compared to deficit irrigation (70%  $ET_c$  and 50%  $ET_c$ ) which diluted selenium across bean tissues and lowering its concentration.



**Figure 4.11:** Interaction Plot for Water Levels on the Uptake of Selenium Concentration on Bean Grain

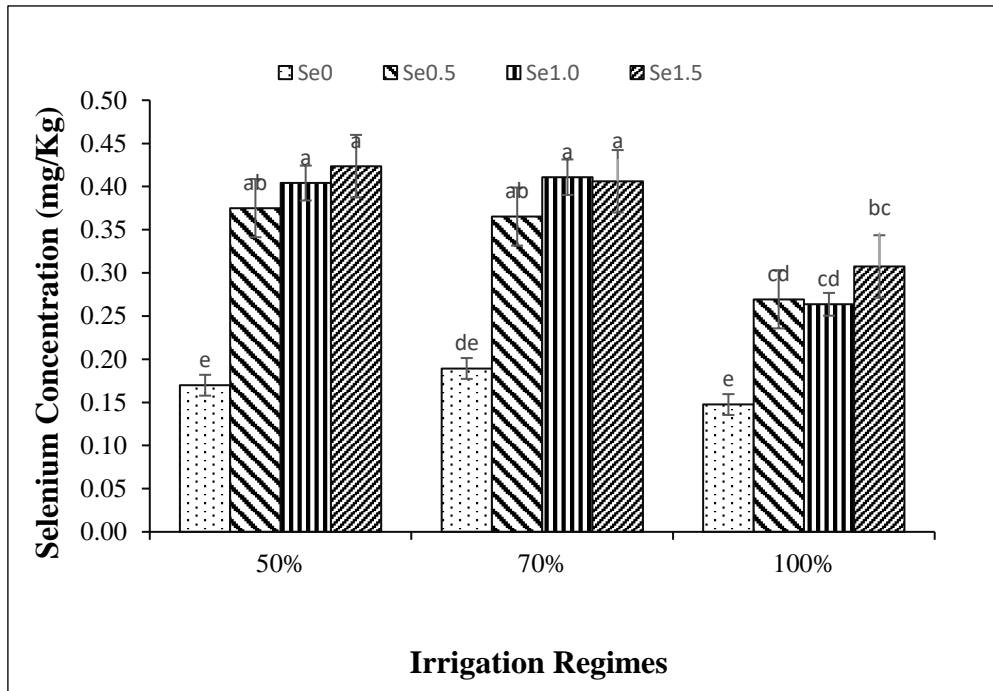
#### 4.2.2 Selenium Concentration in Common Bean Plant

The analysis of variance revealed that the main effect of irrigation water levels and foliar selenium application rates and their interaction ( $p < 0.05$ ) substantially affected the concentration of selenium in common bean plant as shown in (Table 4.7).

**Table 4.7:** Analysis of Variance on Results for Concentration of Selenium on the Common Bean Plant

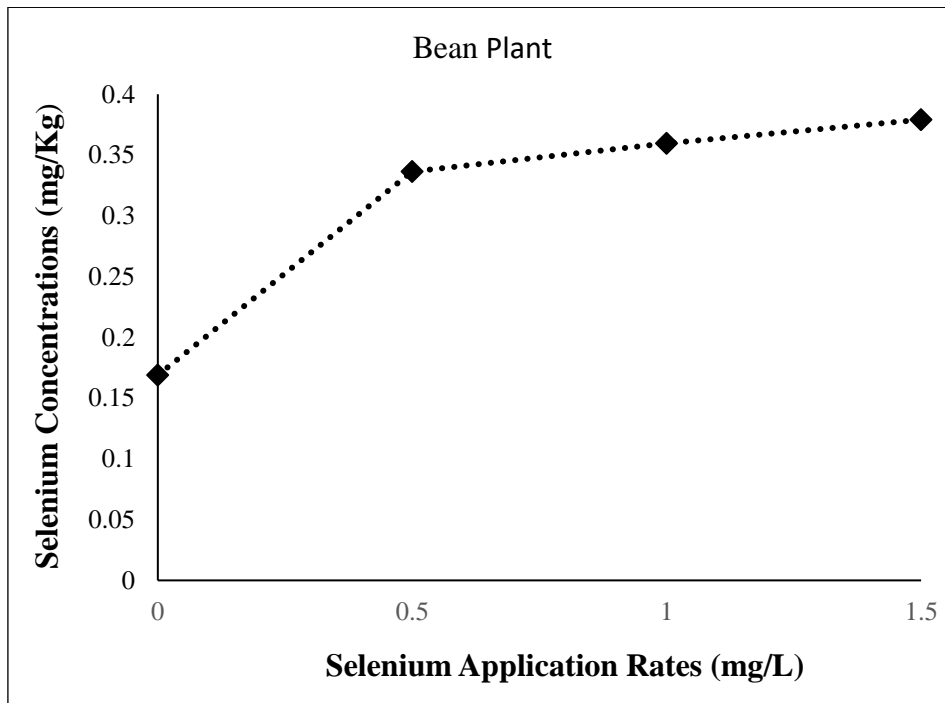
Sources of Variation	SS	df	MS	F	P-value	F critical
Irrigation regimes	0.0738	2	0.0369	47.9	0.0006	3.4
Selenium concentrations	0.2506	3	0.0835	108.4	0.0008	3.0
Irrigation regimes*selenium conc.	0.0143	6	0.0024	3.1	0.0221	2.5
Error	0.0185	24	0.0008			
Total	0.357136	35				

Figure 4.12 illustrates the selenium concentration (mg/Kg) in bean plant subjected to varying selenium treatments (0 mg/L, 0.5 mg/L, 1.0 mg/L and 1.5 mg/L) and irrigation regimes (50%, 70% and 100% ET<sub>c</sub>). The results show a clear trend where selenium concentration in plant tissues increases with higher selenium application rates, peaking at 1.5 mg/L. However, the response is not linear, as intermediate concentrations exhibit variability, possibly due to interactions with irrigation regimes or plant uptake efficiency.



**Figure 4.12:** Interactive Effect of Irrigation Regimes and Foliar Selenium Application on Selenium Concentration of Common Bean Plant

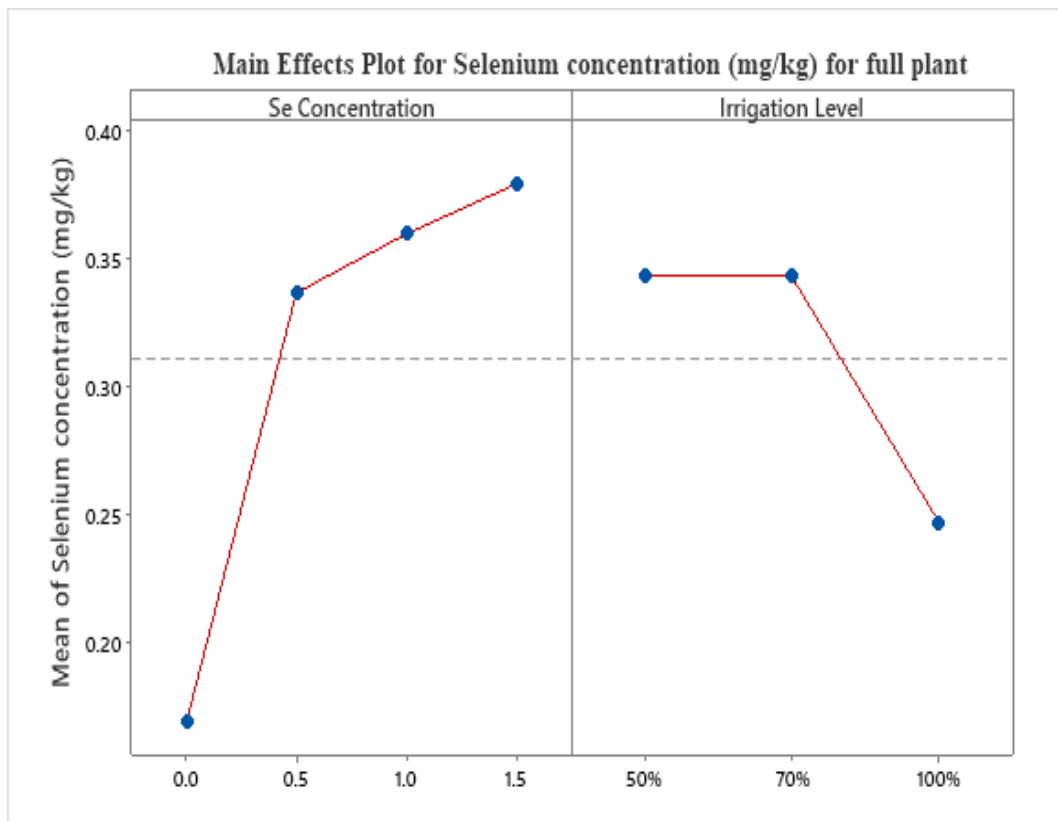
The letters ab, cd, and e suggest statistical groupings, indicating significant differences between treatments. For instance, control treatments (0 mg/L) consistently shows the lowest selenium levels at all irrigation regimes, while selenium application of 1.5 mg/L with 50% ET<sub>c</sub> differs significantly from other groups. Selenium concentration in common bean plant increased linearly upon increasing foliar selenium application rates as shown in Figure 4.13.



**Figure 4.13:** Selenium Concentration in Common Bean Plant against Different Selenium Application Rates

This can be attributed to the plant's efficient absorption and translocation of selenium through foliar pathways. Foliar application delivers nutrients directly to the leaf surface, allowing for rapid uptake and minimizing potential losses associated with soil interactions, such as leaching or fixation. The applied selenium in the form of sodium selenate, is easily absorbed by leaf tissues and transported throughout the plant, leading to a consistent accumulation pattern. Additionally, the gradual increase across application rates reflects the dose-responsive nature of selenium uptake, indicating that the applied rates were within the physiological limits of the plant and did not reach toxicity thresholds in align with Ravello *et al.* (2022). The findings are critical for agronomic practices aiming to enhance selenium content in crops, addressing dietary deficiencies while considering irrigation management to optimize uptake.

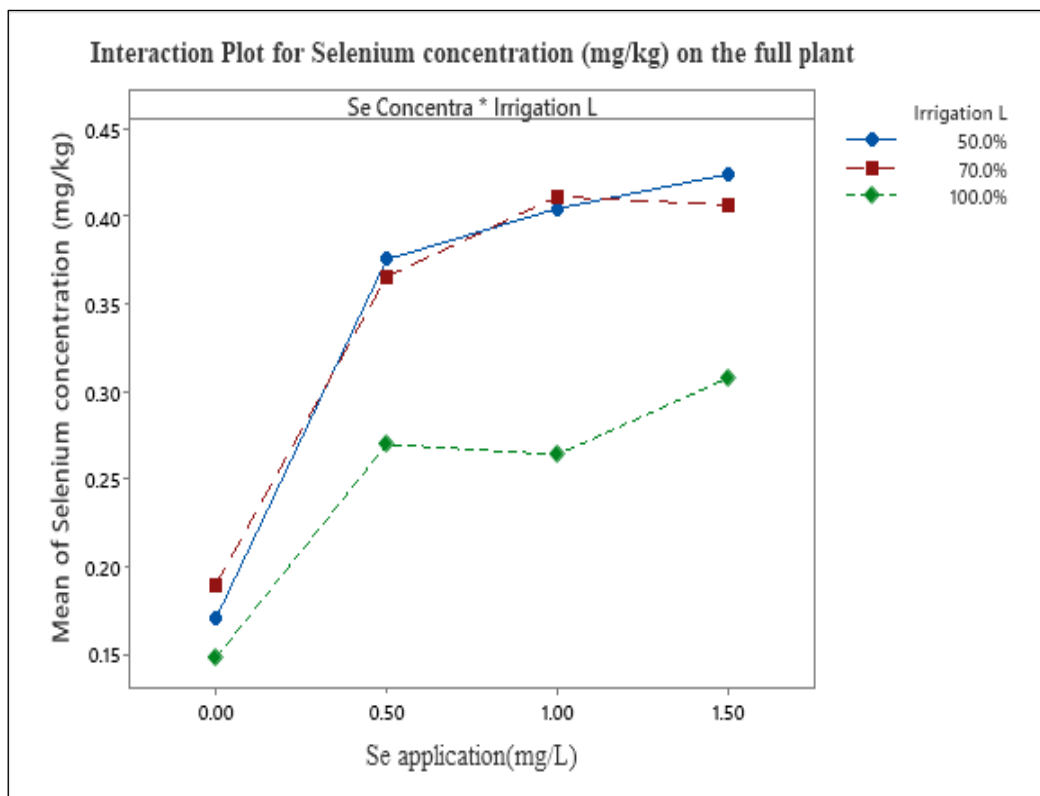
The main effects plot (Figure 4.14) revealed that selenium content in the common bean plant raised consistently with increasing of foliar selenium application rates. A notable increase was observed from 0.0 mg/L to 0.5 mg/L, followed by a gradual rise up to 1.5 mg/L, indicating a strong positive relationship between foliar selenium application and selenium accumulation in plant tissues. Additionally, irrigation level significantly influenced selenium concentration. Plants under deficit irrigation 50%  $ET_c$  and 70%  $ET_c$  exhibited higher selenium content compared to those under full irrigation (100%  $ET_c$ ), where a marked decline was observed. This suggests that moderate water stress conditions may enhance selenium uptake or reduce dilution within plant biomass, leading to higher selenium concentration under limited water supply agreeing with other studies (Dinh *et al.*, 2019; Hartikainen, 2005).



**Figure 4.14:** Main Effect Plot for Selenium Concentration

The interaction plot for selenium concentration in the bean plant (Figure 4.15) illustrates a significant interaction between selenium application rates and irrigation levels. Across all irrigation regimes, selenium content in the bean plant tissue increased with higher selenium application, with the steepest rise occurring between 0.0 and 0.5 mg/L. Notably, plants subjected to deficit irrigation (50%  $ET_c$  and 70%  $ET_c$ ) consistently accumulated higher selenium concentrations compared to those under full irrigation

(100% ET<sub>c</sub>) at corresponding selenium application levels. The interaction effect is especially evident at the 0.5 mg/L and 1.0 mg/L selenium treatments, where both 50% ET<sub>c</sub> and 70% ET<sub>c</sub> irrigation treatments achieved selenium concentrations above 0.35 mg/Kg, while the 100% ET<sub>c</sub> irrigation treatment lagged behind. This trend suggests that under water-limited conditions, the uptake and accumulation of selenium via foliar application is enhanced. This could possibly be due to altered stomatal conductance, reduced dilution from biomass expansion, or stress-induced increases in nutrient absorption efficiency. The results affirm that selenium bio-fortification is more efficient under moderate water deficit conditions, providing insights into integrated nutrient and water management strategies for improving micronutrient content in common beans.

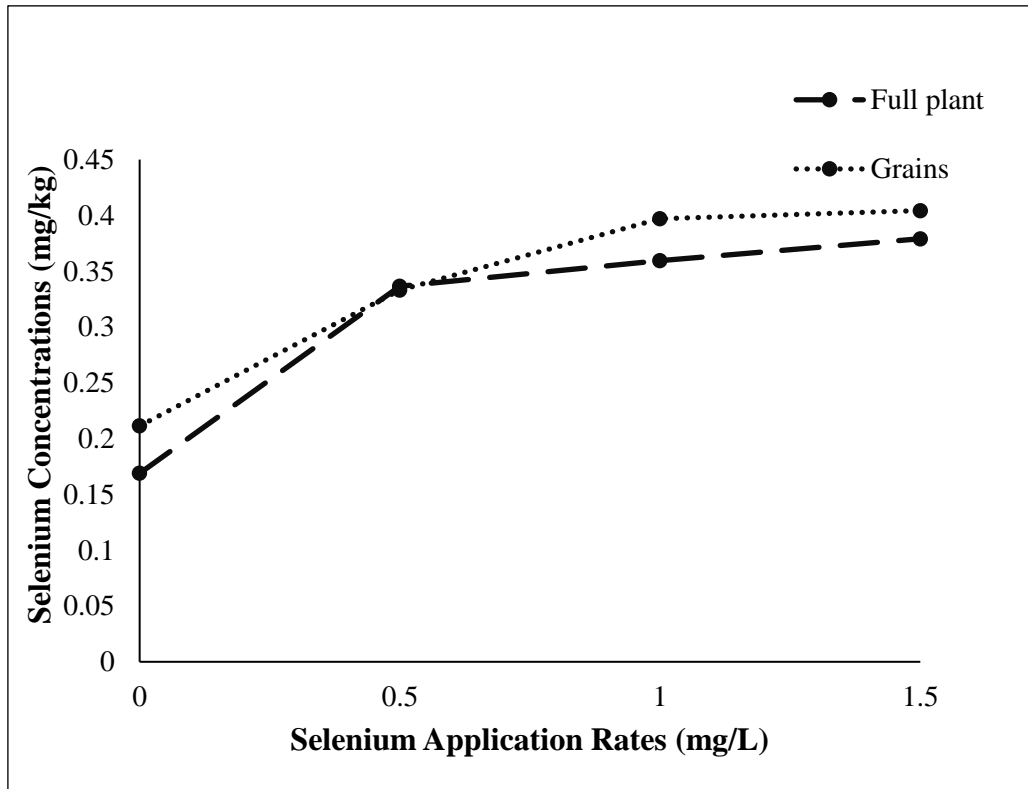


**Figure 4.15:** Interaction Plot for Water Levels on the Uptake of Selenium Concentration

#### 4.2.3 Reduced Water Availability and Foliar Selenium Application on Selenium Concentration in Plant and Grains of Common Bean

The effect of increasing Se application rates on selenium accumulation in both the entire plant and the grains of common bean is presented in Figure 4.16. As the foliar selenium application raised from 0 mg/L to 1.5 mg/L, there was a clear upward trend in selenium content in both tissues. This indicates that selenium uptake by the plant is responsive to external selenium supply through foliar application. At the control plot (0 mg/L), the whole plant and the grain showed relatively low selenium levels, but a sharp

increase was observed at 0.5 mg/L, showing that the plants responded quickly to even a small amount of added selenium. This result concurs with that of Boghdady *et al.* (2017) who reported that foliar selenium application in faba beans significantly increased mineral content in low level application.

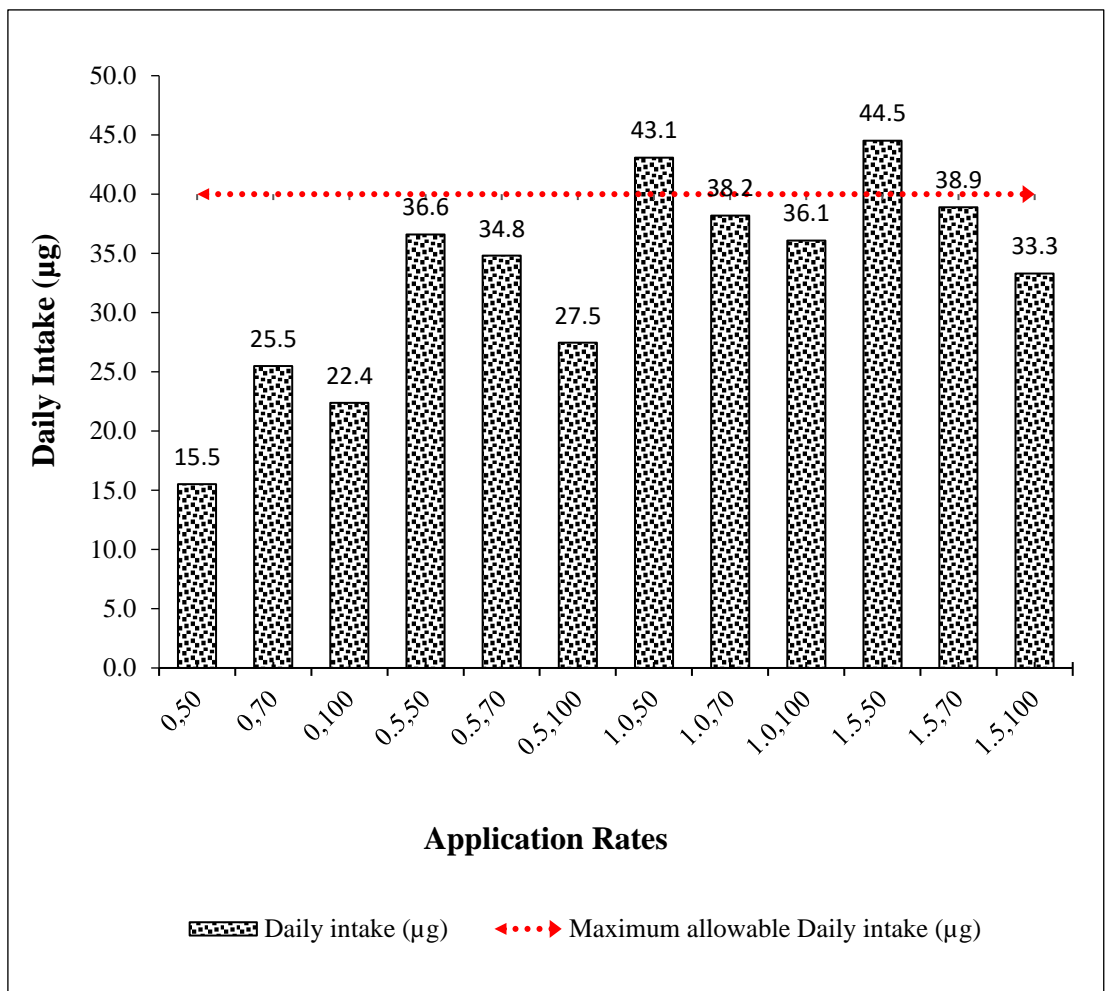


**Figure 4.16:** Selenium Uptake in Common Bean Plant and Grains under Different Selenium Application Rates

Grains consistently had higher selenium concentrations than the bean plant at all selenium application rates, suggesting that selenium is effectively mobilized and translocated from vegetative parts to reproductive organs in agreement with (Ravello *et al.*, 2022). This behaviour is beneficial for nutritional improvement because it increases selenium levels in the edible portion of the plant. The trend slightly flattened between 1.0 mg/L and 1.5 mg/L suggesting that plants may be approaching their capacity to absorb or store selenium, possibly due to physiological limits or homeostatic mechanisms. This result show that foliar selenium is a practical method to enrich common bean grains with selenium, helping improve the nutritional value of the crop, especially in areas where dietary selenium intake is low.

#### 4.2.4 Deficit Irrigation and Foliar Selenium Fertilization on Estimated Dietary Selenium Intake Relative to Safety Thresholds

Selenium is an essential micronutrient for human health but its intake must remain within safe limit. Crops such as common beans can serve as a dietary source of selenium and its content is influenced by both selenium application and irrigation. Evaluating how deficit irrigation and foliar selenium fertilization affect selenium accumulation in beans is important to estimate dietary intake and ensure it remains within established safety thresholds. Figure 4.17 illustrates the relationship between selenium application rates, irrigation levels and their combined effect on estimated daily dietary selenium intake.



**Figure 4.17:** Estimation of Daily Se Intake per Person against Irrigation Water Levels and Selenium Application Rates

As depicted, crops treated with higher selenium concentrations (1.0 mg/L and 1.5 mg/L) yielded substantially greater selenium levels in consumable portions with daily intake values ranging from 33.3 to 44.5  $\mu\text{g}$ . These values approach or surpass the recommended upper tolerance limits for selenium consumption in adults, which is typically set at 40  $\mu\text{g}$  per day to prevent potential toxicity as recommended by World Health Organization (WHO) (Imran *et al.*, 2023). The control treatment (100%  $\text{ET}_c$ , 0 mg/L) consistently demonstrated the lowest intake levels (22.4  $\mu\text{g}$ ), confirming baseline selenium content in untreated crops. A clear dose response trend is evident, where increased selenium fertilization correlates with elevated dietary intake.

However, irrigation intensity also plays a moderating role. For instance, the highest selenium application rate 1.5 mg/L and severe water stress condition 50%  $\text{ET}_c$  resulted in the peak intake value (44.5  $\mu\text{g}$ ). This can be due to the fact that under water stress conditions plants are more eager to take in any available moisture or nutrients and since selenium was applied as a liquid spray, the plants absorbed it through their leaves and used it to fight against water stress condition. Also, the prolonged retention of sprays on the leaf surface extended contact time and enhancing the absorption of applied foliar selenium. These findings align with Djanaguiraman *et al.* (2005) and Hasanuzzaman *et al.* (2010), indicating that agronomic practices and environmental factors affect selenium assimilation in plants.

#### **4.3 Optimization of Common Bean Yield and WUE in Water Stressed Environment under Foliar Selenium Application**

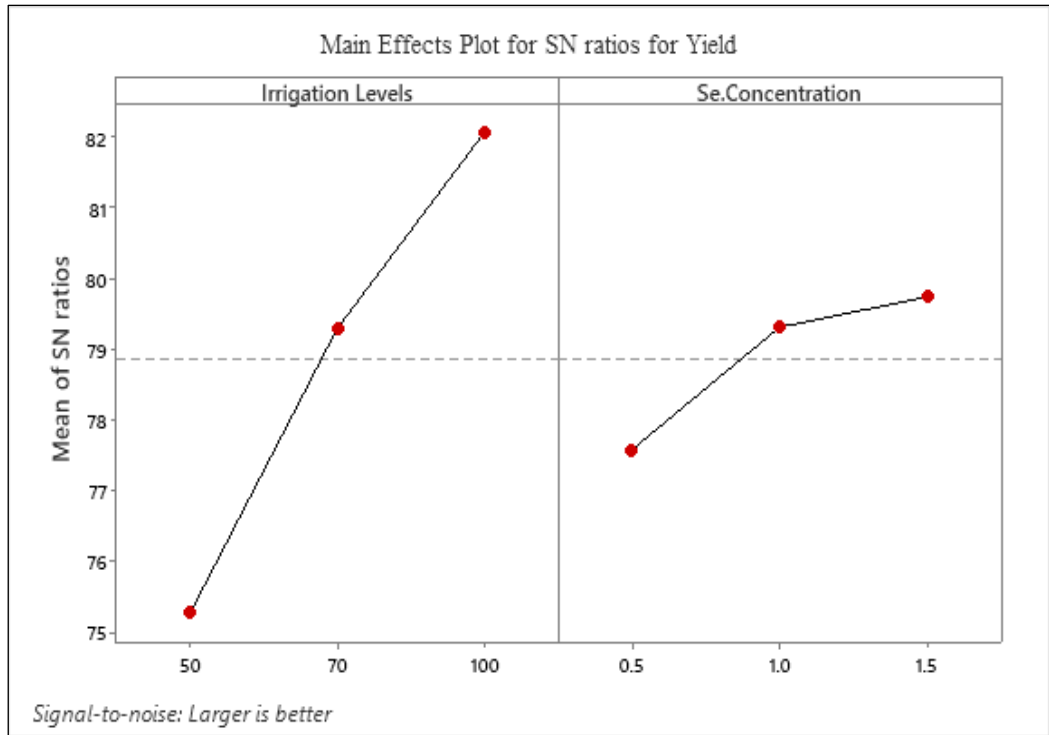
The optimization approach, Taguchi, was implemented to determine the optimal conditions of water level  $\text{ET}_c$  and foliar selenium application rate which produces optimal yield and effectiveness of water utilization common beans. Treatment levels of water and foliar selenium concentrations used for optimization of yield and water use efficiency is shown in the Table 4.8.

**Table 4.8:** Treatment Levels for Optimization of Yield and Water Use Efficiency

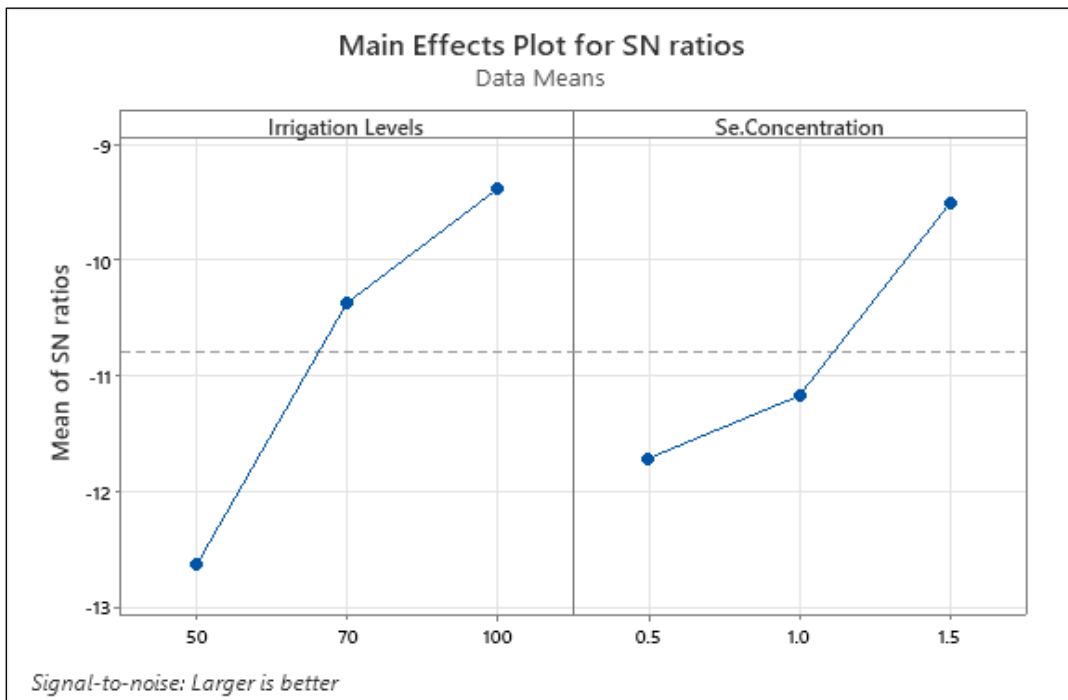
Treatments Levels		Yield (Kg/Ha)	WUE (Kg/m <sup>3</sup> )
50	0.5	42667	0.197
50	1.0	6837	0.209
50	1.5	6682	0.308
70	0.5	8393	0.270
70	1.0	89923	0.289
70	1.5	10348	0.357
100	0.5	12067	0.329
100	1.0	12785	0.349
100	1.5	13178	0.341

#### 4.3.1 Signal-to-Noise Ratio Function

The best setting for each controllable factor (irrigation water levels  $ET_c$  and foliar selenium concentrations) for a maximized S/N ratio is presented in Figures 4.18 and 4.19.



**Figure 4.18:** Main Effect Plot for S/N Ratios for Yield



**Figure 4.19:** Main effect Plot S/N Ratios Showing Optimal Setting for WUE

Figures 4.18 and 4.19, shows the main effect plot of signal to noise ratio, the maximum amount of bean yield was achieved at both higher concentrations of selenium spray and the plots that received full irrigation 100%  $ET_c$ . Taguchi analysis revealed water as the major factor affecting the yield of common bean production followed by

foliar selenium ( $R = 96.02\%$ ). The effect of water as a resource for bean growth and physiological development is seen to have much impact compared to selenium application.

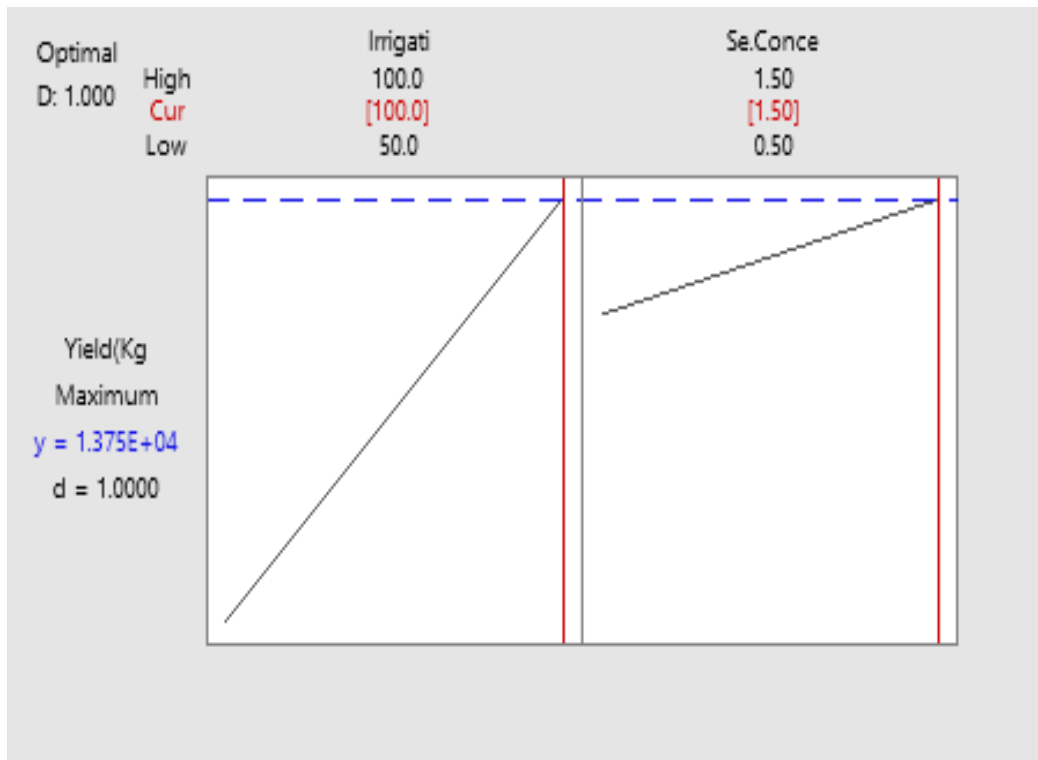
The optimization analysis revealed the relationship between water level and foliar selenium utilization in optimizing yield and water use efficiency (WUE). The finding indicates that the 70%  $ET_c$  irrigation level combined with 1.5 mg/L of foliar selenium concentration achieved the optimum yield (10348 Kg/Ha) while maintaining a relatively high WUE (0.357 Kg/m<sup>3</sup>), making it the most optimal treatment. The control treatment (100%  $ET_c$  0 mg/L) on the other hand, attained less WUE (0.329 Kg/m<sup>3</sup>). The trend shows that at 100%  $ET_c$  irrigation level with 1.5 mg/L selenium concentration yielded slightly higher yield, whereas 50%  $ET_c$  led to lower yields due to severe water stress. The finding further confirms that selenium enhances plant resilience under moderate water stress, improving both yield potential and water resource efficiency. The ability to achieve such a high yield and WUE under 70%  $ET_c$  indicates that plants efficiently utilized available water when supplemented with selenium, potentially improving stress tolerance and metabolic efficiency. These findings suggest that adopting a 70%  $ET_c$  irrigation strategy with 1.5 mg/L selenium application can optimize water productivity while sustaining high bean yields, making it a suitable approach for water-limited environments. Table 4.9 shows optimization conditions for yield and WUE.

**Table 4.9:** Optimization Results for Irrigation Level and Selenium Concentration

<b>Solution</b>	<b>Irrigation Level <math>ET_c</math></b>	<b>Selenium Concentration</b>	<b>Yield (Kg/Ha)</b>	<b>WUE (Kg/m<sup>3</sup>)</b>
1	70%	1.5 mg/L	10348	0.357

The desirability plot in Figure 4.20 illustrates the optimization of yield with corresponding to varying irrigation water and foliar selenium concentrations. The finding indicates that highest anticipated yield (13,750 Kgs) is achieved when irrigation is maintained at 100% and selenium concentration at 1.5 mg/L. The linear trends in both input factors indicate that yield increases with increasing levels of irrigation and selenium within the studied range. The individual and composite desirability values ( $d = 1.000$ ;  $D = 1.000$ ) confirm that the selected combination of input parameters is optimal for maximizing yield. These findings suggest that full irrigation combined with a selenium foliar application rate of 1.5 mg/L significantly enhances yield performance, highlighting

the beneficial interaction between water availability and selenium nutrition in common bean production.



**Figure 4.20:** Response Optimization of Yield

The level values of control factors for the WUE and maximum yield are given in Table 4.10 and 4.11. Optimal yielding parameters maximizing the yield can be easily determined. The best levels of each factor were found according to S/N ratio in the levels of the control factor.

**Table 4.10:** Response Table for Signal to Noise Ratios of WUE (Larger is Better)

Level	Irrigation Levels	Se Concentration
1	-12.640	-11.716
2	-10.370	-11.173
3	-9.381	-9.502
Delta	3.258	2.214
Rank	1	2

**Table 4.11:** Response Table for Signal to Noise Ratios of Yield (Larger is Better)

Level	Irrigation Levels	Se Concentration
1	75.27	77.57
2	79.28	79.30
3	82.05	79.73
Delta	6.79	2.16
Rank	1	2

Here, the ranks indicate that irrigation water levels ( $ET_c$ ) has the most influence on both the S/N ratio and the mean. This suggests that common bean yields were highly affected with amount of water applied, aligned with (Alipour *et al.*, 2022). For the S/N ratio, foliar selenium concentration ranking number two implies that the foliar has the positive impacts on mitigating the water stress effects in beans, leading to improving yield and water use efficiency. This can be due to the fact that foliar selenium protects the plants against oxidative damage in a water deficit condition by boosting antioxidant enzyme activities. A study conducted by Ali *et al.* (2020) revealed that supplementation of foliar selenium reduces drought stress through fighting against oxidative stresses which were developed during drought condition and boost the production of okra plant and improved the drought tolerance.

#### 4.3.2 Regression Equation for Yield Prediction

A regression equation was developed as;

$$Y = 9629x_1 + 1946x_2 \dots \dots \dots \text{Equation 4.0}$$

Where:

Y = Yield (Kg/Ha)

$x_1$  = Irrigation water level (%  $ET_c$ )

$x_2$  = Selenium application rates (mg/L),

The equation is valid within the experimental range of the independent variables

$$50 \leq x_1 \leq 100 \text{ (\% } ET_c) \text{ and } 0 \leq x_2 \leq 1.5 \text{ (mg/L Se)}$$

Under irrigation water level going above 100%  $ET_c$  could cause root rot due to waterlogging, poor soil aeration and nutrient leaching which can cause plant to die before reaching maturity and results in yield decline. Also, irrigation below 50%  $ET_c$  can cause severe water stress, reducing photosynthesis, leaf area expansion, and pod formations

application thereby decreasing of yield. Similarly, applying foliar selenium above 1.5 mg/L in common beans may result in selenium toxicity leading chlorosis, reduction of enzymatic activities, stunted growth to plants and cause yield reduction and could even harm human health through bioaccumulation. While, no selenium application may cause selenium deficiency, limiting its beneficial role in antioxidant defence and stress tolerance mechanisms.

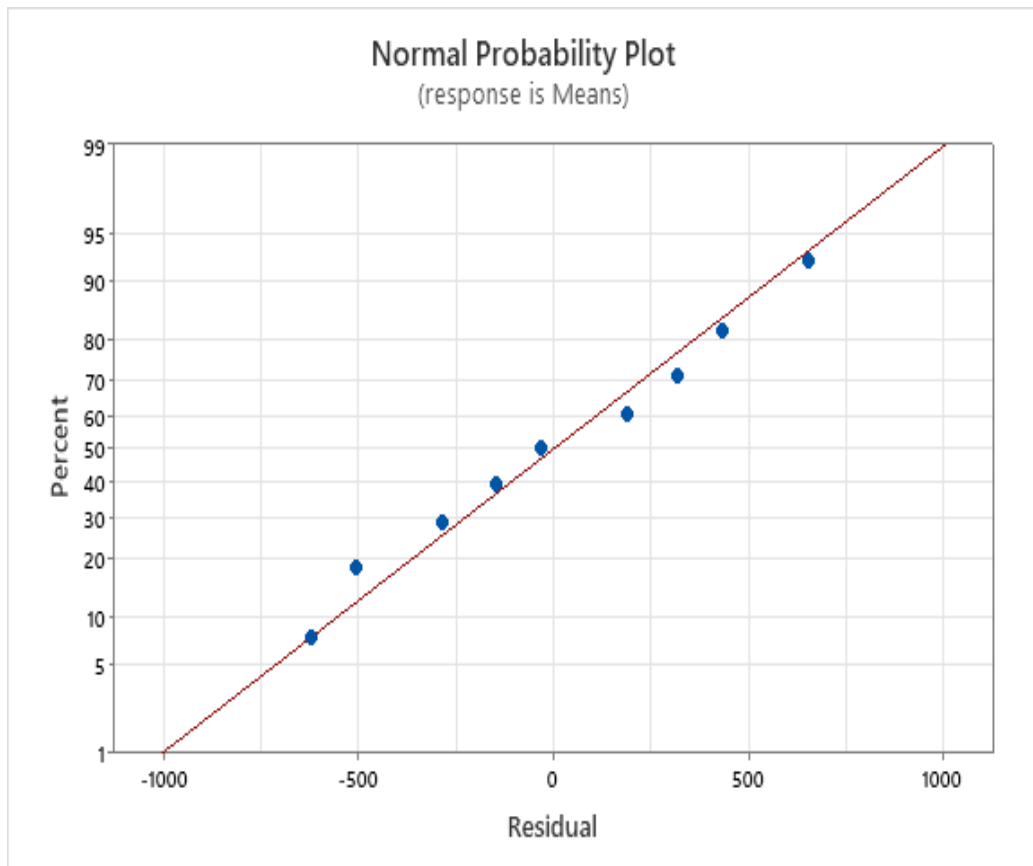
The regression model describing the influence of irrigation level and selenium concentration on common bean yield. The equation suggests that both increased irrigation levels and selenium concentrations contribute positively to yield with a coefficient of determination ( $R^2$ ) of 97.46%. The other factors such as temperature, relative humidity, soil fertility, pests and diseases were not taken into consideration because they were kept constant in the greenhouse environment and the main purpose of the model was to quantify the direct effects of irrigation water level and foliar selenium application rates on yield while assuming all other conditions remained uniform.

This high  $R^2$  value suggests that the model explains over 97% of the variation in yield, highlighting a strong predictive relationship between the two independent variables (irrigation water level and selenium concentration) and the dependent variable (yield). This level of accuracy indicates that the model is reliable for interpreting and predicting yield responses under different water and selenium treatment conditions. The positive coefficient of 9629 for irrigation water level implies that yield increases proportionally with increasing irrigation. This confirms that water availability is a critical determinant of yield, as water stress typically reduces photosynthesis, limits nutrient uptake and ultimately impairs reproductive development. Increasing irrigation enhances physiological processes, biomass accumulation and pod formation, especially in water-sensitive crops like common bean.

The coefficient for selenium concentration (1946) indicates a strong influence of selenium application on yield improvement. Selenium is essential for reducing oxidative stress, improving chlorophyll content, boosting enzymatic activities and enhancing overall plant vigour. In this study, the positive response of yield to increasing selenium concentration underlines selenium's beneficial role in promoting plant resilience, particularly under deficit irrigation conditions. The model confirms that both adequate irrigation water levels and optimal selenium supplementation significantly and positively contribute to maximizing common bean yield. Their combined application presents a

promising agronomic strategy for improving productivity, particularly under water-limited conditions.

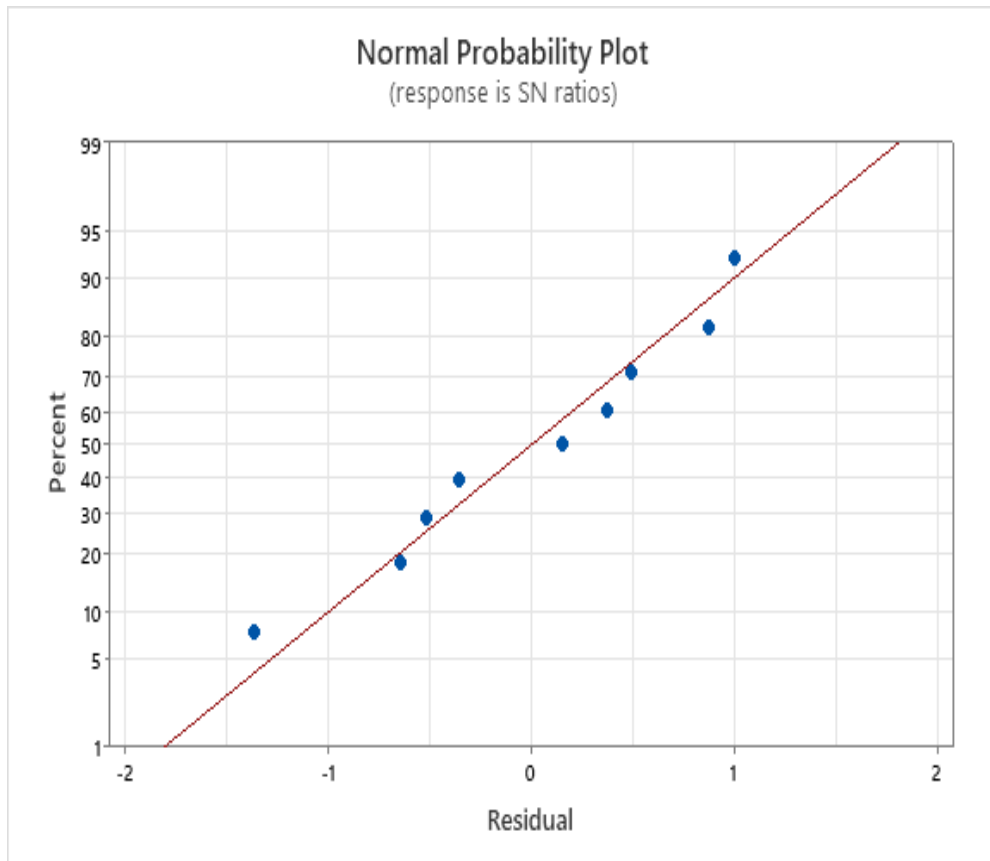
The normal probability plot shown in Figure 4.21, where the response is the mean values, demonstrates a generally linear pattern of residuals along the reference line. This linear alignment suggests that the residuals are approximately normally distributed, fulfilling a key assumption for the validity of the model. This supports the robustness of the model in explaining the variations in the mean response under different treatment combinations, such as irrigation water levels and foliar selenium applications. The normality of residuals implies the reliability of the model in predicting the yield.



**Figure 4.21:** Normal Probability Plot of Residuals for Mean Yield Response

The residuals for the signal-to-noise (S/N) ratios are roughly normally distributed, according to the normal probability plot of residuals, which shows that the data points closely match the reference line. This confirms that the variability in the S/N ratio data is randomly and normally distributed around the fitted model, satisfying a key assumption of analysis of variance (ANOVA) and regression modelling. Therefore, the statistical model used to evaluate SN ratios is valid and the inferences made regarding treatment effects (irrigation and selenium levels) for the common yield prediction can

be considered statistically reliable and accurate (Figure 4.22).



**Figure 4.22:** Normal Probability Plot of Residuals for Signal-to-Noise (S/N) Ratios

With a high  $R^2$  value of 97.46%, the regression analysis demonstrated a robust and favorable correlation between the parameters (foliar selenium treatment and irrigation water level) and common bean production. This indicates that over 97% of the variability in yield was accounted for by the combined effects of water availability and selenium application. The normal probability plots of residuals for both the S/N ratios and the mean responses validate the reliability of the model. In both graphs, the residuals aligned closely along the reference line, confirming that the assumptions of normality were met. These results provide strong statistical evidence that foliar selenium application, in conjunction with appropriate irrigation water levels, plays a significant role in enhancing yield performance of common bean, especially under deficit irrigation conditions. The model and residual analyses collectively confirm the robustness of the experimental findings and support the integration of selenium and water management strategies.

#### 4.4 Summary of Results and Contribution to Knowledge

Aspect	Summary of Results	Contribution to Knowledge
Growth parameters	Sustained deficit irrigation reduced plant height, number of leaves, number of branches and leaf area index. Foliar selenium application improved growth performance of common beans both under full irrigation and deficit irrigation	Selenium enhanced growth resilience of common beans under water-limited conditions
Yield components	Deficit irrigation without selenium reduced pod length, pods per plant and seed yield. Selenium application improved yield under water stress.	Established selenium as a micronutrient that mitigates yield losses under water deficit
Selenium uptake	Foliar selenium application increased selenium concentration in both bean plant and grains. Uptake was higher under deficit irrigation than full irrigation	Provided insights into how water stress influences selenium uptake dynamic
Water use efficiency	70% $ET_c$ irrigation water level and 1.5 mg/L of foliar selenium application rate optimized yield and WUE	Identified an effective strategy for balancing yield and water productivity of common beans
Overall finding	Foliar selenium application and irrigation water levels significantly influenced growth, yield and WUE	Expanded understanding of how foliar selenium application can improve crop tolerance to water stress

## CHAPTER FIVE

### CONCLUSIONS AND RECOMMENDATIONS

#### 5.1 Conclusions

This research examined how foliar selenium (Se) application and sustained deficit irrigation influence the growth, yield, selenium uptake and water use efficiency (WUE) of common beans (*Phaseolus vulgaris* L.) in a controlled greenhouse conditions over a single growing season. The findings demonstrated that both selenium application and irrigation water levels had significant individual and interactive effects on most agronomic and physiological parameters. In terms of growth performance, full irrigation (100% ET<sub>c</sub>) generally produced the tallest plants, highest number of leaves, number of branches, leaf area index (LAI) and high yield confirming sensitivity of common beans to water stress during vegetative development. However, plants treated with selenium under moderate water stress (70% ET<sub>c</sub>) also maintained good growth and yield performance, indicating the potential of selenium in reducing the negative effects of water shortage. However, 50% ET<sub>c</sub> without selenium there was reductions in growth parameters and yield showing that water stress alone, without Se supplementation, limits physiological development. Notably, foliar Se application significantly improved plant performance, particularly under water deficit conditions indicating its role in enhancing drought tolerance and crop productivity.

The study found that moderate water stress (70% ET<sub>c</sub>) combined with 1.5 mg/L foliar selenium application resulted in optimal selenium uptake in *Phaseolus vulgaris* L without exceeding the recommended dietary limits. Plants under severe stress (50% ET<sub>c</sub>) and high selenium (1.5 mg/L) accumulated more selenium which surpassed the safe intake thresholds. Consequently, a moderate water deficit combined with selenium dose provided an effective balance between enhanced plant uptake and food safety. These results suggest that selenium biofortification under controlled water stress can be a viable strategy to produce nutrient-rich beans while preserving human health.

The regression model developed in this study confirmed that the two factors irrigation water level and selenium concentration strongly influenced yield. Selenium played a key role in increasing yield even under limited water supply, likely due to its contribution to antioxidant defence systems and improved physiological efficiency. Furthermore, the use of Taguchi optimization revealed that 70% ET<sub>c</sub> irrigation combined with 1.5 mg/L Se concentration was the most effective treatment for balancing yield and

WUE, supporting the application of moderate deficit irrigation with micronutrient supplementation in water stress conditions. The research confirms that foliar selenium application is a promising strategy to enhance common bean productivity under water scarcity conditions. The integration of Se biofortification and deficit irrigation offers a sustainable, low-cost approach for balancing both yield and nutritive value in environments facing increasing water scarcity conditions.

## **5.2 Recommendations**

The foliar selenium application of 1.5 mg/L combined with moderate deficit irrigation at 70% ET<sub>c</sub> showed potential to enhance growth parameters and yield of common beans, suggesting it may be promising practice under water-limited conditions. Their combined application improves drought resilience, enhances physiological performance and supports sustainable agricultural under SDG 2. Furthermore, integrating water and nutrient management through sustained deficit irrigation and selenium supplementation should be promoted as a holistic strategy for improving drought resilience and sustaining safe production of common beans without exceeding daily intake of selenium. The combination of 70% ET<sub>c</sub> with 1.5 mg/L of foliar selenium application demonstrated relatively optimal yield and water use efficiency as compared to other treatments, indicating it's potential as an efficient strategy to conserve water in those regions with water-scarce conditions for better water use efficiency and plant productivity while saving 30% of water for other use. The following are recommendations for further studies:

- i. To conduct an open field across multiple growing seasons to analyse the different forms of selenium not only sodium selenate form so as to evaluate the effects of foliar selenium application on water stress management of common beans.
- ii. The current study applied selenium at specific growth stages. Additional research is required to ascertain when and how often selenium should be taken during different phenological stages to maximize uptake and impact on yield.
- iii. Although the agronomic benefits of selenium were clear, the study did not assess the economic viability of selenium foliar application. Future studies should include cost-benefit analyses to evaluate the profitability of selenium use under various farming systems, especially for smallholder farmers.
- iv. An analysis of soil and irrigation water to determine available selenium content before and after cropping in order to determine the available selenium and ensures

that even if added as foliar or soil application how long will it take to be added so that it does not cause harmful to the soils.

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## APPENDICES

### APPENDICES A: PICTURES

#### Appendix A.1: Field Preparation



#### Appendix A.2: Drip Irrigation System Layout



**Appendix A.3: Sowing of Common Beans (Rose Coco Variety)**



**Appendix A.4: Two Weeks after Sowing**



**Appendix A.5: One Month after Sowing**



**Appendix A.6: Two Months after Sowing**



**Appendix A.7: Three Months after Sowing**



**Appendix A.8 Three Months after Sowing**



**Appendix A.9: Mixing of Acids**



**Appendix A.10: Digestion of Beans Sample**



**Appendix A.11: Filtering of Digested Sample by Using Whatman Paper**



**Appendix A.12: Analysis of Selenium by using AAS**



## APPENDICES B: TABLES

**Appendix B.1: Crop Coefficients for a Specific Crop (Allen *et al.*, 1998)**

CROP	Crop development stages					Total growing period
	Initial	Crop development	Mid-season	Late season	At harvest	
<b>Banana</b>						
Tropical	0.4-0.5	0.7-0.85	1.0-1.1	0.9-1.0	0.75-0.85	0.7-0.8
Subtropical	0.5-0.65	0.8-0.9	1.0-1.2	1.0-1.15	1.0-1.15	0.85-0.95
<b>Bean</b>						
Green	0.3-0.4	0.65-0.75	0.95-1.05	0.9-0.95	0.85-0.95	0.85-0.9
Dry	0.4	0.7-0.8	1.05-1.2	0.65-0.75	0.25-0.3	0.7-0.8
Cabbage	0.4-0.5	0.7-0.8	0.95-1.1	0.9-1.0	0.8-0.95	0.7-0.8
Cotton	0.4-0.4	0.7-0.8	1.05-1.25	0.8-0.9	0.65-0.7	0.8-0.9
Grape	0.35-0.55	0.6-0.8	0.7-0.9	0.6-0.8	0.55-0.7	0.55-0.75
Groundnut	0.4-0.5	0.7-0.8	0.95-1.1	0.75-0.85	0.55-0.6	0.75-0.8
<b>Maize</b>						
Sweet	0.3-0.5	0.7-0.9	1.05-1.2	1.0-1.15	0.95-1.1	0.8-0.95
Grain	0.3-0.5	0.7-0.85	1.05-1.2	0.8-0.95	0.55-0.6	0.75-0.9
<b>Onion</b>						
Dry	0.4-0.6	0.7-0.8	0.95-1.1	0.85-0.9	0.75-0.85	0.8-0.9
Green	0.4-0.6	0.6-0.75	0.95-1.05	0.95-1.05	0.95-1.05	0.65-0.8
Pea, fresh	0.4-0.5	0.7-0.85	1.05-1.2	1.0-1.15	0.95-1.1	0.8-0.95
Pepper, fresh	0.3-0.4	0.6-0.75	0.95-1.1	0.85-1.0	0.8-0.9	0.7-0.8
Potato	0.4-0.5	0.7-0.8	1.05-1.2	0.85-0.95	0.7-0.75	0.75-0.9
Rice	1.1-1.15	1.1-1.5	1.1-1.3	0.95-1.05	0.95-1.05	1.05-1.2

Rice	1.1-1.15	1.1-1.5	1.1-1.3	0.95-1.05	0.95-1.05	1.05-1.2
Safflower	0.3-0.4	0.7-0.8	0.7-0.8	0.65-0.7	0.2-0.25	0.65-0.7
Sorghum	0.3-0.4	0.7-0.8	1.0-1.15	0.75-0.8	0.5-0.55	0.75-0.85
Soybean	0.3-0.4	0.7-0.8	1.0-1.15	0.7-0.8	0.4-0.5	0.75-0.9
Sugar beet	0.4-0.5	0.75-0.85	1.05-1.2	0.9-1.0	0.6-0.7	0.8-0.9
Sugarcane	0.4-0.5	0.7-1.0	0.7-1.0	0.75-0.8	0.5-0.6	0.85-1.05
Sunflower	0.3-0.4	0.7-0.8	1.05-1.2	0.7-0.8	0.7-0.8	0.75-0.85
Tobacco	0.3-0.4	0.7-0.8	1.0-1.2	0.9-1.0	0.75-0.85	0.85-0.95
Tomato	0.4-0.5	0.7-0.8	1.05-1.25	0.8-0.95	0.6-0.65	0.75-0.9
Watermelon	0.4-0.5	0.7-0.8	0.95-1.05	0.8-0.9	0.65-0.75	0.75-0.85
Wheat	0.3-0.4	0.7-0.8	1.05-1.2	0.65-0.75	0.2-0.25	0.8-0.9
Alfalfa	0.3-0.4				1.05-1.2	0.85-1.05
Citrus						
Clean weeding						0.65-0.75
No weed control						0.85-0.9
Olive						0.4-0.6

**Appendix B.2: Analysis of Variance for Growth Parameters (Plant Height, Number of Leaves, Number of Branches and Leaf Area Index) at Different Selenium Rates and Irrigation Levels**

<i>Response</i>	<i>Sources of variation</i>	<i>SS</i>	<i>DF</i>	<i>MS</i>	<i>F</i>	<i>P</i>	<i>F<sub>crit</sub></i>
Plant Height (cm)	Irrigation	2108.31	2	1054.15	228.83	0.0003	3.40
	Se Conc.	367.91	3	122.64	26.63	0.0008	3.01
	Irrigation * Se Conc.	31.72	6	5.29	1.15	0.3662	2.51
	Error	110.56	24	4.61			
	Total	2618.50	35				
Number of Leaves	Irrigation levels	3461.63	2	1730.82	53.45	0.0007	3.40
	Se. Conc.	315.73	3	105.25	3.25	0.0394	3.01
	Irrigation * Se Conc.	89.45	6	14.91	0.46	0.8309	2.51
	Error	777.19	24	32.38			
	Total	4644	35				
Number of Branches	Irrigation levels	114.70	2	57.35	69.53	0.0002	3.40
	Se Conc.	1.08	3	0.36	0.43	0.7301	3.01
	Irrigation * Se. Conc.	9.27	6	1.55	1.87	0.1276	2.51
	Error	19.80	24	0.82			
	Total	144.84	35				
Leaf Area Index	Irrigation levels	114.70	2	0.111	17.632	0.0007	3.403
	Se Conc.	1.08	3	0.0019	0.2973	0.8269	3.009
	Irrigation * Se. Conc.	9.27	6	0.0054	0.8604	0.5375	2.508
	Error	19.80	24	0.0063			
	Total	144.84	35				

**Appendix B.3: Analysis of Variance for Selected Yield Parameters (Pod length, Number of pods, Number of Seeds per Plant and Pod Yield) at Different Selenium Rates and Irrigation Levels**

<i>Response</i>	<i>Sources of variation</i>	<i>SS</i>	<i>Df</i>	<i>MS</i>	<i>F</i>	<i>P</i>	<i>F<sub>crit</sub></i>
Pod length (cm)	Se. concentration(mg/L)	8.063	3	2.688	4.932	0.0087	3.009
	Irrigation Level (%)	76.937	2	38.469	70.584	0.0002	3.403
	Se. concentration(mg/L)	3.549	6	0.591	1.085	0.3991	2.508
	*Irrigation Level (%)						
	Error	13.08	24	0.545			
	Total	101.629	35				
Pod number	Se. concentration(mg/L)	391.667	3	130.556	12.668	0.0006	3.009
	Irrigation Level (%)	887.722	2	443.861	43.070	0.0004	3.403
	Se. concentration(mg/L)	17.167	6	2.861	0.277628	0.2421	2.508
	*Irrigation Level (%)						
	Error	247.333	24	10.306			
	Total	1543.889	35				
Number of seeds	Se. concentration(mg/L)	2166.306	3	722.102	7.003	0.0015	3.009
	Irrigation Level (%)	13900.837	2	6950.419	67.401	0.0001	3.403
	Se. concentration(mg/L)	818.403	6	136.400	1.323	0.2855	2.508
	*Irrigation Level (%)						3
	Error	2474.893	24	103.121			
	Total	19360.439	35				
Yield (Kg/Ha)	Se. concentration(mg/L)	79700562.4		26566854.14	87.84	0.0005	3.009
	Irrigation Level (%)	318819780.5	3	159409890.3	527.08	0.0003	3.403
	Se. concentration(mg/L)	4975775.03	6	829295.839	2.74	0.0352	2.508
	*Irrigation Level (%)						
	Error	7258600.8	24	302441.701			
	Total	410754718.8	35				

**Appendix B.4: Biomass and Yield of Common Beans**

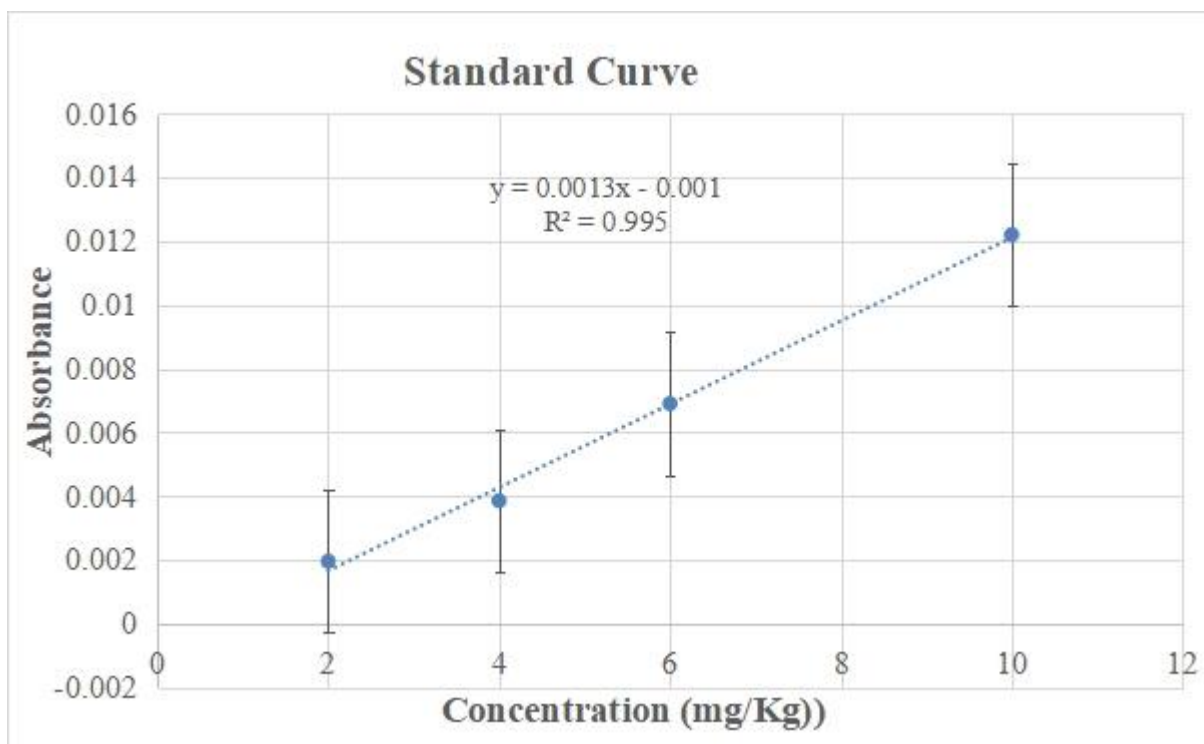
<b>Treatment</b>	<b>Biomass (Kgs)</b>	<b>Yield (Kgs)</b>
100% 0.5 mg/L	8.77	5.43
70% 0.5 mg/L	5.95	3.98
50% 0.5 mg/L	2.13	1.92
100% 1.0 mg/L	8.64	5.75
70% 1.0 mg/L	7.04	4.05
50% 1.0 mg/L	2.50	2.04
100% 1.5 mg/L	9.13	5.93
70% 1.5 mg/L	8.05	5.76
50% 1.5 mg/L	3.83	3.01
100% No Se	7.35	3.95
70% No Se	4.69	3.05
50% No Se	1.64	1.03

**Appendix B.5: Water Productivity of Common Beans**

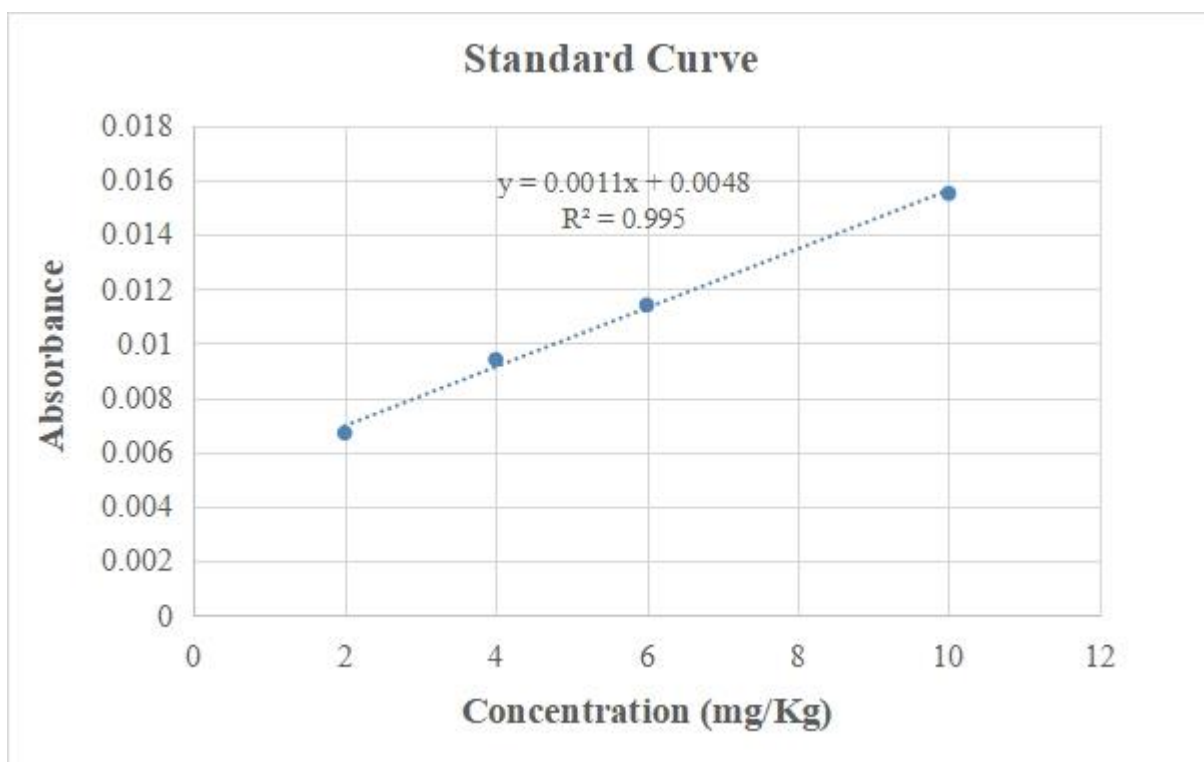
<b>Treatment</b>	<b>Yield (Kgs)</b>	<b>WUE (Kg/m<sup>3</sup>)</b>
100% 0.5 mg/L	5.43	0.329
70% 0.5 mg/L	3.98	0.270
50% 0.5 mg/L	1.92	0.197
100% 1.0 mg/L	5.75	0.349
70% 1.0 mg/L	4.05	0.289
50% 1.0 mg/L	2.04	0.209
100% 1.5 mg/L	5.93	0.341
70% 1.5 mg/L	5.76	0.357
50% 1.5 mg/L	3.01	0.308
100% No Se	3.95	0.240
70% No Se	3.05	0.218
50% No Se	1.03	0.106

## APPENDICES C: GRAPHS

### Appendix C.1: Standard Calibration Curve for Bean Plant



### Appendix C.2: Standard Calibration Curve for Bean Grains





## Appendix D.2: Snapshot of Publication Abstract

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### EFFECT OF DEFICIT IRRIGATION ON THE GROWTH PARAMETERS, YIELD AND WATER USE EFFICIENCY OF COMMON BEANS (*PHASEOLUS VULGARIS* L) UNDER FOLIAR SELENIUM APPLICATION

\* V.L. Gamba, R.O. Okwany, S. Nyakach and P.B. Sesani

Department of Agricultural Engineering, Egerton University,

P.O. Box 536, Egerton, Kenya

\*Corresponding Author: [victoriagamba015@gmail.com](mailto:victoriagamba015@gmail.com) / [gamba.1002023@student.egerton.ac.ke](mailto:gamba.1002023@student.egerton.ac.ke)/cell:+254791585017

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#### ABSTRACT

Water scarcity remains a major constraint to sustainable crop production, particularly in arid and semi-arid regions. This study investigated the effects of foliar selenium (Se) application as water stress management strategy on common bean (*Phaseolus vulgaris* L.). It assessed growth and water productivity under Deficit Irrigation (DI). A greenhouse experiment was conducted at the Tatton Agricultural Park at Egerton University for one season using a randomized complete block design with three replicates. The experiment consisted of three irrigation regimes; 100%, 70%, and 50% of crop evapotranspiration ( $ET_c$ ) and four selenium concentrations (0, 0.5, 1.0, and 1.5 mg/L). The results revealed that full irrigation 100%  $ET_c$  and moderate water deficit at 70%  $ET_c$ , combined with foliar application of 1.5 mg/L Se, significantly ( $p < 0.05$ ) improved growth and yield parameters. Further, water productivity was highest under the 70%  $ET_c$  and 1.5 mg/L by Se treatment, suggesting enhanced physiological efficiency and drought resilience. Selenium application mitigated the adverse effects of water stress by supporting plant metabolism, antioxidative defense, and stomatal regulation. Furthermore, the highest total pod yield (13177.8Kg/Ha) was obtained at 100%  $ET_c$  combined with 1.5mg/L of foliar selenium, but statistically on pair with 70%  $ET_c$  and 1.5mg/L of selenium concentration compared to the control treatment 100%  $ET_c$  and no foliar selenium application (8785.2Kg/Ha), while the lowest pod yield (2288.9Kg/Ha) was attained at 50%  $ET_c$  combined with no foliar selenium application. These findings demonstrate that supplying 70%  $ET_c$  with 1.5 mg/L of selenium concentration instead of full water requirement can be a good strategic approach to improving water use efficiency and sustaining common bean production under limited water availability. The study provides valuable insight for developing climate-smart irrigation practices thus contributing to sustainable water management.

**Keywords:** Water Productivity, Water Stress Mitigation, Water Management; Climate Smart and Drip Irrigation