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**FACULTY OF ENGINEERING AND TECHNOLOGY
DEPARTMENT OF AGRICULTURAL MECHANISATION AND
IRRIGATION ENGINEERING**

FINAL YEAR PROJECT PROPOSAL

**EVALUATING THE IMPACT OF SYNTHETIC MULCHES VS ORGANIC
MULCHES ON WATER USE EFFICIENCY (WUE) WITH BEAN YIELD UNDER
DRIP IRRIGATION IN BUSIA, UGANDA**

By

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BU/UP/2021/0252

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**This final year project proposal report submitted to the department of
Agricultural Mechanisation and Irrigation engineering as a partial
fulfilment of the requirements of the award of Bachelor of Science degree
in Agricultural Mechanisation and Irrigation Engineering.**

JUNE 2025

DECLARATION

I TSEMALE RAYMOND, registration number BU/UP/2021/0252, declare that the work in this project proposal is my original work and has not been presented to any higher institution of learning for any academic award.

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APPROVAL

I hereby certify that this project is original proposal report of TSEMALE RAYMOND, BU/UP/2021/0252. It has been done under my supervision and is ready for submission to the department of Agricultural Mechanisation and Irrigation engineering.

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DEDICATION

I dedicate this report to my beloved parents, relatives and siblings for they have always encouraged, supported and stood with me and above all believed and had faith in me.

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1.1 ABSTRACT

Bean production in Busia District, Uganda, is increasingly constrained by soil moisture deficits arising from erratic rainfall and prolonged dry spells, resulting in low and unstable yields. This study evaluated the impact of synthetic mulch (plastic film) and organic mulches (straw and wood chips) on water use efficiency (WUE) and bean (NABE 32) yield under drip irrigation at the Busitema University Demonstration Site. A Randomized Complete Block Design (RCBD) with four treatments which included plastic mulch (T1), straw mulch (T2), wood chips mulch (T3), and a no-mulch control (T4) each replicated three times, was used. Key parameters measured included soil moisture content, plant height, number of leaves, days to flowering, pods per plant, grain yield, WUE, and economic performance indicators.

Results showed that mulch type had a highly significant effect on all measured parameters ($P < 0.05$). Plastic mulch produced the highest grain yield of 1,963 kg/ha, followed by straw mulch at 1,685 kg/ha, wood chips at 1,444 kg/ha, and the control at 1,056 kg/ha. Corresponding WUE values were 8.15, 7.00, 6.00, and 4.38 kg/mm respectively. Soil moisture was consistently highest under plastic mulch (25.19–29.97%) and lowest in the control (17.93–22.95%) throughout the cropping season. Mulched treatments also exhibited earlier flowering, taller plants, more leaves, and higher pod counts compared to the control, reflecting the cumulative agronomic benefits of improved soil moisture conservation under drip irrigation.

Economic analysis revealed that although plastic mulch generated the highest net return (UGX 4,338,883/ha), straw mulch achieved the most favourable benefit-cost ratio (BCR = 5.06) and return on investment (ROI = 405.6%), making it the most economically efficient option for smallholder farmers. All treatments exceeded their break-even yield thresholds, confirming financial viability across the board. The study concludes that integrating mulching with stage-based drip irrigation scheduling significantly enhances crop productivity and water use efficiency, with straw mulch offering the most practical, cost-effective, and scalable solution for bean production in water-stressed tropical environments such as Busia District, Uganda.

1.2 ACROYNMS AND ABBREVIATIONS

ANOVA: Analysis of Variance (statistical comparison method).

FAO: Food and Agriculture Organization (UN agency on food security).

GDP: Gross Domestic Product (economic output measure).

HSD: Honest Significant Difference (post-hoc test for ANOVA).

NDP III: National Development Plan III (Uganda's 2020/21–2024/25 framework).

RCBD: Randomized Complete Block Design (experimental layout).

SDG: Sustainable Development Goal (UN goals, e.g., SDG 2: Zero Hunger).

SOM: Soil Organic Matter (soil fertility indicator).

TDR: Time Domain Reflectometry (soil moisture measurement tool).

UN: United Nations (global organization).

WUE: Water Use Efficiency (yield per water unit).

CHAPTER 2 INTRODUCTION

2.1 Background to the Study

Agriculture worldwide is increasingly constrained by water scarcity, climate variability, and the growing demand for food production. Water is a critical input in crop production, yet it is becoming progressively limited due to population growth, competing uses, and changing climatic conditions. Globally, agriculture accounts for approximately 70% of total freshwater withdrawals, making it the largest consumer of water resources. However, a significant portion of this water is lost through inefficient irrigation methods such as surface flooding, deep percolation, and evaporation losses. These inefficiencies reduce the overall productivity of water and threaten the sustainability of agricultural systems (Shang et al., 2024).

To address these challenges, modern irrigation technologies such as Drip Irrigation have been developed to enhance water use efficiency. Drip irrigation systems deliver water directly to the root zone of plants in controlled quantities, thereby minimizing losses associated with evaporation and runoff. This targeted application not only conserves water but also improves crop yield and uniformity. In addition to irrigation technologies, agronomic practices such as mulching have been widely adopted to further enhance soil moisture conservation. Mulching reduces evaporation from the soil surface, regulates soil temperature, and improves soil structure, thereby contributing to improved crop performance. The integration of drip irrigation with mulching is increasingly recognized as an effective strategy for maximizing water productivity in agriculture.

In sub-Saharan Africa, agricultural production is heavily dependent on rainfall, with over 85% of farming systems relying on rain-fed agriculture. Despite receiving moderate annual rainfall in many regions, the temporal and spatial distribution of rainfall is highly variable, resulting in frequent dry spells and periods of water stress during critical crop growth stages (Wegren, 2023). This variability significantly limits agricultural productivity and contributes to food insecurity across the continent. Studies have shown that crop yields in many parts of Africa are far below their potential, often achieving less than 30% of attainable yields due to inadequate water management and limited adoption of improved technologies (Awe & Adedokun, 2024).

The adoption of efficient irrigation systems such as drip irrigation remains relatively low in Africa due to high initial costs, limited technical knowledge, and lack of infrastructure. However, where implemented, drip irrigation has demonstrated significant potential in improving water use efficiency and crop yields, particularly in smallholder farming systems.

Similarly, mulching practices, especially the use of locally available organic materials, have been promoted as cost-effective methods for conserving soil moisture and enhancing soil fertility. The combination of drip irrigation and mulching therefore offers a viable pathway for improving agricultural productivity under water-limited conditions in Africa.

In Uganda, agriculture is the backbone of the economy, employing over 70% of the population and contributing approximately 24% to the national Gross Domestic Product (GDP) (Matyanga, 2023). The sector is predominantly rain-fed, making it highly vulnerable to climate variability and changing rainfall patterns. Although Uganda experiences a bimodal rainfall pattern that supports two cropping seasons annually, the onset, intensity, and distribution of rainfall have become increasingly unpredictable in recent years. This has resulted in prolonged dry spells, reduced soil moisture availability, and significant yield losses in major crops.

Beans are among the most important staple crops in Uganda, providing a primary source of protein and income for many households. However, bean production is highly sensitive to water stress, particularly during flowering and pod-filling stages. Moisture deficits during these critical periods can lead to poor germination, flower abortion, and reduced grain yield (Garg et al., 2024). Despite the availability of water conservation techniques, the adoption of efficient irrigation systems such as drip irrigation remains limited among smallholder farmers due to cost and technical constraints.

Mulching has gained attention in Uganda as a practical and affordable method for improving soil moisture retention and stabilizing crop yields. Organic mulches such as straw and crop residues are commonly used by farmers due to their availability and low cost. Synthetic mulches, such as plastic films, have also been introduced and are known to provide superior moisture conservation, although concerns about cost and environmental impact persist. However, there is limited research in Uganda that integrates drip irrigation with mulching practices to evaluate their combined effects on water use efficiency and crop yield.

Busia District, located in eastern Uganda along the Uganda Kenya border, is characterized by a tropical climate with bimodal rainfall patterns occurring between March-May and August-November. The district receives an annual rainfall ranging between approximately 1,080 mm and 1,940 mm, which is generally adequate for crop production. However, the distribution of rainfall is often uneven, leading to intermittent dry spells that coincide with critical growth stages of crops such as beans. These dry spells result in soil moisture deficits, reduced crop growth, and low yields, posing a significant challenge to smallholder farmers in the region.

Agriculture in Busia is predominantly small-scale and rain-fed, with limited adoption of irrigation technologies. Farmers largely depend on traditional practices, which are increasingly unreliable under changing climatic conditions. As a result, there is a growing need for efficient water management strategies that can enhance water use efficiency and improve crop productivity. The introduction of drip irrigation systems offers an opportunity to provide controlled and efficient water application, while mulching can complement this by reducing soil moisture loss and improving soil conditions.

Despite the potential benefits of combining drip irrigation with mulching, there is a lack of localized studies in Busia District that evaluate the effectiveness of synthetic and organic mulches under drip irrigation systems. Understanding how these practices interact to influence soil moisture, water use efficiency, and bean yield is essential for developing practical and sustainable recommendations for farmers in the region.

2.2 Problem statement.

Bean production in Busia District, Uganda, is increasingly constrained by low and unstable yields due to soil moisture deficits arising from erratic rainfall distribution and prolonged dry spells during critical crop growth stages. The core problem is inefficient water availability and utilization at the root zone, which limits crop performance despite the region receiving moderate annual rainfall. This challenge is primarily caused by overdependence on rain-fed agriculture, poor water management practices, and the limited adoption of efficient irrigation technologies such as Drip Irrigation, which can precisely supply water to crops. As a result, farmers experience significant effects including reduced germination rates, flower abortion, poor pod development, and ultimately low bean yields, leading to food insecurity and reduced household income. To mitigate these challenges, several approaches have been promoted, including rainwater harvesting, contour bunding, and the use of mulching practices to conserve soil moisture. While these methods offer some benefits, their effectiveness is often limited by inconsistent application, high labour requirements, or inability to optimize water delivery at the plant root zone. Additionally, although synthetic and organic mulches have been studied independently for their role in moisture conservation, there is limited localized research evaluating their performance under controlled irrigation systems. Therefore, this study intends to address the problem by integrating drip irrigation with both synthetic and organic mulching treatments to precisely manage water application and reduce soil moisture losses, while systematically evaluating their combined effects on water use efficiency and bean yield in Busia District. This approach aims to generate data-driven, practical recommendations for improving water productivity and enhancing sustainable bean production under changing climatic conditions.

2.3 Research Hypothesis

Beans growth and yield differ significantly among crops subjected to different mulch types under a drip irrigation system.

2.4 Objectives of the Study

2.4.1 Main Objective

To evaluate the impact of synthetic mulches vs organic mulches on water use efficiency (WUE) with bean yield under drip irrigation in Busia Uganda

2.4.2 Specific Objectives

- i. To evaluate soil moisture retention under synthetic vs. organic mulches.
- ii. To assess the effect of different mulching treatments on the growth stages of beans.
- iii. To assess the combined effect of the different mulching treatments and irrigation on the bean yield and IWUE.
- iv. To evaluate the economic viability of synthetic versus organic mulches and provide farmer recommendations for sustainable bean production in Busia district, Uganda.

2.5 Research Questions

- i. How do synthetic and organic mulches differ in their effects on soil moisture retention during the growth cycle of bean crops?
- ii. What is the effect of different mulching treatments on the growth stages of beans under drip system?
- iii. To what extent do synthetic versus organic mulches improve Water Use Efficiency (WUE) and overall bean yield in terms of harvestable output?
- iv. What is the comparative economic viability of synthetic versus organic mulches on water use efficiency?

2.6 Justification of the Study

Bean production in Uganda, particularly in Busia District, is increasingly threatened by uneven rainfall distribution and recurring dry spells that cause soil moisture deficits and low yields. While conventional water conservation methods such as rainwater harvesting and contour bunding exist, their adoption remains limited due to high costs and technical constraints. Mulching offers a practical and affordable alternative for conserving soil moisture, enhancing water use efficiency (WUE), and stabilizing crop yields under tropical conditions. However, there is limited local research comparing the agronomic and economic effectiveness of synthetic and organic mulches within Busia's unique climatic and soil conditions. This study is therefore justified by the need to identify and recommend the most cost-effective and sustainable mulching strategy to improve bean yield and water productivity for smallholder farmers in regions experiencing rainfall variability and moisture stress.

2.7 Scope of the Study

2.7.1 Conceptual Scope

The study focuses on evaluating the effects of synthetic (plastic films) and organic (straw, wood chips) mulches on water use efficiency (WUE) in bean cultivation. It investigates key parameters such as soil moisture retention, soil temperature regulation, nitrogen fixation, and crop yield. The research aims to compare how these mulching materials influence bean growth and soil health to determine the most effective mulching strategy for sustainable agriculture.

2.7.2 Geographical Scope

The experiment was conducted at the Busitema Demonstration site, characterized by local climatic and soil conditions typical of the region. The findings will be representative of bean cultivation under these specific environmental settings and may provide insights applicable to similar Agro-ecological zones experiencing water scarcity and aiming to optimize water use in crop production.

2.7.3 Time Scope

The study was carried out over a period of one cropping season (approximately 3 months) corresponding to the dry season from January 2026 to March 2026.

Data collection will cover all major beans growth stages from planting to harvest while data analysis, interpretation, and report writing was conducted between March and April 2026.

2.8 Significance of the study

This study holds practical and scientific importance for addressing climate-induced water scarcity and yield instability in Uganda's bean production systems. By comparing the agronomic and economic performance of synthetic and organic mulches, the research will provide evidence-based recommendations to farmers on practices that optimize water use efficiency, soil health, and profitability under limited water availability. The findings will enable smallholder farmers to adopt affordable, climate-resilient technologies that improve productivity while conserving soil moisture and enhancing income security. At a broader scale, the study contributes to Uganda's National Development Plan IV (NDP IV) goals of promoting Agro-industrialization and climate-smart agriculture. It also supports the UN Sustainable Development Goals (SDGs) specifically SDG 2 (Zero Hunger) by improving food security, SDG 6 (Clean Water and Sanitation) through efficient water use, and SDG 13 (Climate Action) by strengthening adaptation to drought and rainfall variability. Overall, the outcomes of this study will guide extension services, policymakers, and development partners in designing and promoting sustainable mulching practices that enhance agricultural resilience in Busia and other drought-prone regions of Uganda

The alignment between this study's specific objectives and the SDGs cited above is as follows: Objective 1 (evaluating soil moisture retention under different mulch treatments) directly supports SDG 6 (Clean Water and Sanitation) by demonstrating efficient water conservation practices that reduce irrigation demand. Objective 2 (assessing the effect of mulching treatments on bean growth stages) and Objective 3 (evaluating the combined effect of mulching and irrigation on bean yield and WUE) together advance SDG 2 (Zero Hunger) by providing evidence-based strategies that improve crop productivity and food security for smallholder farmers in Busia District. Objective 4 (evaluating the economic viability of synthetic versus organic mulches) contributes to SDG 13 (Climate Action) by identifying affordable, climate-resilient mulching options that enable farmers to adapt to rainfall variability and reduce dependence on unreliable precipitation, thereby strengthening long-term agricultural resilience.

CHAPTER 3 LITERATURE REVIEW

3.1 Drip Irrigation and Water Use Efficiency (WUE)

Water Use Efficiency (WUE) is a critical performance indicator in agricultural water management, representing the relationship between crop yield and water utilized. Improving WUE is essential in regions experiencing water scarcity and climate variability. One of the most effective approaches to enhancing WUE is the adoption of Drip Irrigation, which delivers water directly to the plant root zone in controlled quantities. This localized water application significantly reduces losses associated with evaporation, deep percolation, and surface runoff compared to conventional irrigation methods (El-Beltagi et al., 2022).

Drip irrigation systems are designed to operate at low pressure and apply water frequently in small amounts, maintaining optimal soil moisture conditions for crop growth. According to (Shang, Gabriel and Zhang, 2024), drip irrigation can improve water use efficiency by up to 70% while increasing crop yields due to better moisture availability and reduced plant stress. Furthermore, the system enables precise irrigation scheduling based on crop water requirements, allowing farmers to match water supply with crop demand throughout the growth cycle.

Despite these advantages, the adoption of drip irrigation in sub-Saharan Africa remains limited due to high initial installation costs, technical complexity, and lack of awareness among smallholder farmers (Wegren, 2023). In Uganda, the use of drip irrigation is still emerging, with most farmers relying on rain-fed systems that are highly vulnerable to climate variability. While existing studies highlight the efficiency of drip irrigation in improving WUE, there is limited localized research in Uganda, particularly in Busia District, that quantifies its effectiveness when combined with soil moisture conservation practices such as mulching under smallholder farming conditions.

3.2 Comparative Studies on Synthetic vs. Organic Mulches

Several studies have compared the effects of synthetic and organic mulches on soil moisture conservation, temperature regulation, and crop productivity. Synthetic mulches often outperform organic ones in immediate moisture retention and WUE due to their impermeability and durability (Kasirajan and Ngouajio, 2012). However, organic mulches offer additional benefits related to soil fertility and sustainability (Zhang et al., 2020)

The choice between synthetic and organic mulches depends on multiple factors including crop type, local climate, soil conditions, and resource availability. While synthetic mulches are effective for short-term water conservation, organic mulches contribute to long-term soil health and ecological balance, making them preferable in sustainable agriculture (Naureen Malik et al., 2018)

3.3 Mulching and Soil Moisture Conservation

Mulching is a widely adopted agronomic practice aimed at conserving soil moisture, regulating soil temperature, and improving soil structure. It involves covering the soil surface with materials such as crop residues, straw, wood chips, or synthetic films. Mulching reduces direct soil water evaporation by acting as a physical barrier between the soil and the atmosphere, thereby enhancing soil moisture retention and contributing to improved crop growth (Kasirajan and Ngouajio, 2012).

Synthetic mulches, particularly plastic films, are highly effective in reducing evaporation losses due to their impermeable nature. Studies by Steinmetz et al. (2016), indicate that plastic mulches can increase water use efficiency by between 12% and 38.9% compared to unmulched conditions. On the other hand, organic mulches such as straw and wood chips improve soil organic matter content, enhance microbial activity, and promote better soil structure, which indirectly contributes to moisture retention and nutrient availability (Awe and Adedokun, 2024).

Additionally, mulching plays a significant role in temperature regulation. Organic mulches tend to buffer soil temperature fluctuations, while synthetic mulches may increase soil temperature due to heat absorption and retention (Salama and Geyer, 2023). These thermal effects influence root development, microbial processes, and overall plant growth.

Although numerous studies have evaluated mulching independently, there is insufficient research comparing the performance of synthetic and organic mulches under controlled irrigation systems such as drip irrigation, particularly in tropical environments like Uganda.

3.4 Combined Effects of Drip Irrigation and Mulching

The integration of drip irrigation and mulching has been identified as a highly effective strategy for improving water productivity in agriculture. Drip irrigation ensures efficient water delivery to the root zone, while mulching minimizes soil moisture losses, creating a synergistic effect that enhances overall water use efficiency. According to (El-Beltagi et al., 2022), combining drip irrigation with mulching can significantly reduce irrigation frequency and total water application while maintaining or increasing crop yield.

Studies conducted in semi-arid regions have demonstrated that the combined use of drip irrigation and mulch leads to improved soil moisture retention, reduced weed competition, and enhanced crop growth performance (Steinmetz et al., 2016). This integrated approach is particularly beneficial in water-scarce environments where efficient water utilization is critical for sustainable crop production.

Furthermore, the combination of these practices allows for better control of the soil microclimate, ensuring optimal conditions for plant growth. The reduced evaporation and improved moisture distribution contribute to higher WUE and better yield outcomes compared to the use of either practice alone.

Despite evidence supporting the combined benefits of drip irrigation and mulching, there is a lack of empirical studies in Uganda that evaluate how different types of mulches (synthetic vs organic) perform specifically under drip irrigation systems in terms of WUE and bean yield.

3.5 Effects of Mulching and Irrigation on Bean Growth and Yield

Beans are highly sensitive to soil moisture conditions, particularly during flowering and pod-filling stages. Water stress during these critical growth phases can lead to significant yield reductions due to flower abortion, poor pod formation, and reduced grain filling (Garg et al., 2024). Ensuring adequate and consistent soil moisture is therefore essential for optimal bean production.

Mulching has been shown to improve bean growth by maintaining favourable soil moisture and temperature conditions. According to (Lal, 2020), improved soil moisture availability enhances plant physiological processes such as photosynthesis and nutrient uptake, resulting in better growth and higher yields. Similarly, drip irrigation ensures that water is applied directly to the root zone, reducing water stress and improving crop performance.

Research indicates that the combination of efficient irrigation and soil moisture conservation practices can significantly enhance crop productivity. However, the response of beans to different mulching materials under drip irrigation conditions may vary depending on factors such as soil type, climate, and mulch characteristics.

There is limited localized research on how different mulching materials influence bean growth stages and yield under drip irrigation systems in Uganda, particularly in Busia District, where climatic conditions present unique challenges.

3.6 Economic Viability of Mulching and Drip Irrigation Systems

The adoption of agricultural technologies is largely influenced by their economic feasibility. While drip irrigation systems offer significant benefits in terms of water savings and yield improvement, their high initial investment cost can be a barrier to adoption among smallholder farmers (Wegren, 2023). Similarly, synthetic mulches, although effective in moisture conservation, involve higher material costs and environmental concerns related to disposal and sustainability (Salama and Geyer, 2023).

In contrast, organic mulches are generally low-cost and locally available, making them more accessible to smallholder farmers. However, they may require frequent replenishment due to decomposition, increasing labour requirements (Awe and Adalakun, 2024). Economic analyses such as Benefit-Cost Ratio (BCR) and Return on Investment (ROI) are therefore essential in determining the practicality of adopting these technologies.

Previous studies suggest that while synthetic mulches may provide higher short-term yields, organic mulches tend to offer better long-term economic and environmental benefits. The integration of drip irrigation further complicates the economic analysis, as it introduces additional costs but also enhances water productivity and yield.

There is a lack of comprehensive economic evaluations that compare synthetic and organic mulches under drip irrigation systems in Uganda, particularly in terms of profitability, cost-effectiveness, and long-term sustainability for smallholder farmers.

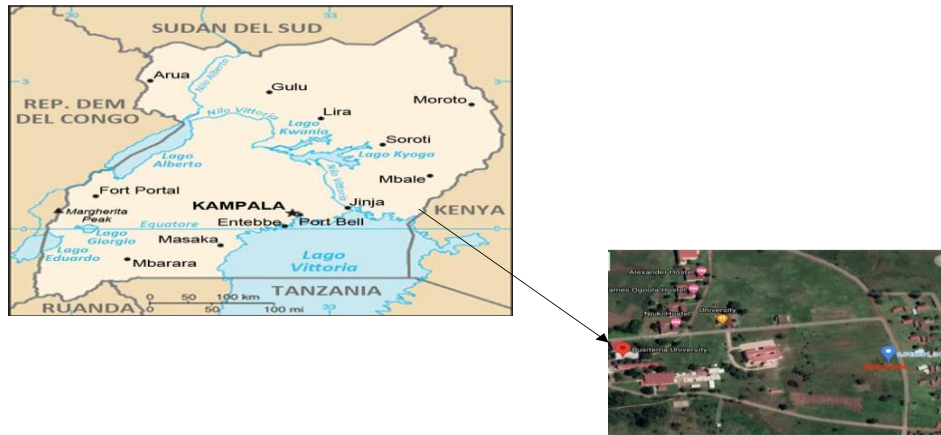
CHAPTER 4 METHODOLOGY

4.1 Experimental Design and Field Layout

The study was conducted at the Busitema University Demonstration Site in Busia District, Uganda, under field conditions representative of small-scale farming systems. The experiment was laid out using a Randomized Complete Block Design (RCBD), which was appropriate for minimizing experimental error arising from field variability such as soil heterogeneity, slope, and microclimatic differences. The treatments consisted of four mulch conditions: synthetic mulch (plastic film), organic mulch (straw), organic mulch (wood chips), and a control treatment with no mulch. Each treatment was replicated three times, resulting in a total of twelve experimental plots. Each plot had dimensions of 1.5 m by 1.2 m, giving a surface area of 1.8 m². Within each plot, two rows of beans were established with a row spacing of 0.6 m, and emitters spaced at 0.3 m along each row. Each row contained five emitters, resulting in a total of ten emitters per plot, and each emitter served two plants, giving a total plant population of twenty plants per plot. Irrigation was applied using a Drip Irrigation system, with emitters discharging water at a constant rate of 1.6 litres per hour. This controlled irrigation setup ensured uniform water application across all treatments and allowed accurate quantification of water use, which was essential for determining water use efficiency.

The three mulch materials were selected based on their local availability, cost-effectiveness, and relevance to smallholder farming conditions in Busia District. Plastic mulch (black polyethylene film) was included as a representative synthetic option widely documented in the literature for its superior moisture retention properties (Kasirajan and Ngouajio, 2012). Straw mulch was selected as a low-cost, locally available organic alternative commonly used by farmers in the region, while wood chips were chosen as a second organic option offering different physical properties, including greater durability and slower decomposition. All organic mulch treatments were applied at a uniform depth of 5 cm, which is within the range recommended by FAO (1998) for effective soil moisture conservation without impeding seedling emergence. Mulch depth was held constant across treatments to isolate the effect of mulch material type on yield and WUE; the influence of varying mulch depth on bean production represents an important direction for future research and is acknowledged in the Areas of Future Study section of this report. Controlled irrigation scheduling was applied uniformly across all plots throughout the cropping season, with irrigation events determined by growth stage as detailed in Section 4.4. This approach ensured that observed differences in

plant growth, yield, and WUE among treatments were attributable to mulch type rather than variation in water application.



Prior to planting, a baseline soil analysis was conducted on a composite soil sample collected from the experimental site. The analysis was carried out by the Soil Testing Laboratory at Busitema University and revealed the following initial soil properties: pH (water) = 6.2; Organic Carbon = 1.8%; Total Nitrogen = 0.14%; Available Phosphorus = 18.3 mg/kg; Exchangeable Potassium = 0.42 cmol/kg; soil texture = sandy clay loam (sand 52%, silt 18%, clay 30%). These values indicate a moderately fertile soil with adequate pH for common bean production, and were used as the reference baseline against which post-harvest soil changes could be evaluated in future studies. The baseline nutrient status was consistent across all plots given the uniform soil preparation and site homogeneity, ensuring that any differences in plant growth and yield observed during the experiment were attributable to mulch treatment effects rather than pre-existing soil fertility variations. The following design constraints and environmental factors framed the conditions of this study: (i) Plot size was limited to 1.5 m × 1.2 m (1.8 m²) due to the spatial constraints of the available demonstration site, which restricted the total number of plants per plot to 20. While this is sufficient for statistically valid comparisons under RCBD, it represents a controlled rather than full-field scale, and caution should be exercised when extrapolating results directly to commercial-scale production. (ii) The experiment was conducted during the dry season (January to March 2026), with mean daily temperatures ranging from 22°C to 31°C, mean relative humidity of 68%, and total recorded rainfall during the experimental period of 52.74 mm. (iii) Drip irrigation was applied at a constant emitter discharge rate of 1.6 litres per hour, and irrigation events were timed to avoid overlap with rainfall episodes. (iv) Weed management was carried out manually and uniformly across all plots to eliminate confounding effects of weed competition on yield and soil moisture.

4.2 Methodology for Objective 1

To evaluate soil moisture retention under different mulch treatments, soil moisture content were measured at a depth of 10–15 cm, which corresponds to the active root zone of bean crops. Measurements were taken weekly using a calibrated soil moisture sensor. The sensor was inserted into the soil at the 10–15 cm depth within each plot and provided direct, real-time readings of volumetric soil moisture content (%). Sensor readings were recorded weekly at consistent times of day to minimise diurnal variation. The soil moisture content was determined directly from the sensor output as volumetric water content, θ_v where θ_v represents the volumetric soil moisture content expressed as a percentage, as measured directly by the soil moisture sensor. Multiple sensor readings were taken at representative locations within each plot and averaged to reduce spatial variability and improve data reliability. The collected data was analysed using Analysis of Variance (ANOVA) under the RCBD framework to determine whether significant differences existed among treatments, and least Significant Difference (LSD) test applied for mean separation where necessary. This approach ensured a robust comparison of how different mulch types influenced soil moisture conservation and thermal regulation under drip irrigation.

4.3 Methodology for Objective 2

The effect of mulching treatments on the growth stages of beans was assessed through systematic monitoring of key phenological and growth parameters throughout the cropping season. These parameters included plant height, number of leaves, days to flowering, and number of pods per plant at maturity.

Plant height and leaf number were measured weekly from five randomly selected plants per plot to represent each treatment accurately. The number of days to flowering were recorded as the number of days from planting until 50% of plants in a plot begun flowering, while pod number were counted at maturity to assess reproductive performance. These measurements provided insight into how soil moisture conditions influenced by different mulch types affected plant development. The collected data were subjected to ANOVA to evaluate statistically significant differences among treatments, and graphical representations was used to illustrate growth trends over time. This comprehensive approach ensured that both vegetative and reproductive responses of the crop to mulch treatments under drip irrigation were well captured and analysed.

4.4 Methodology for Objective 3

4.4.1 Irrigation Water Requirement and Scheduling

Reference Evapotranspiration and Crop Coefficient Approach

Crop water requirements were determined using the FAO-based crop coefficient method, expressed as:

$$ET_c = K_c \times ET_o$$

Where:

ET_c = crop evapotranspiration (mm/day)

K_c = dimensionless crop coefficient varying with growth stage

ET_o = reference evapotranspiration (mm/day).

Table 4-1. Stage-wise ET_c Computation

Growth Stage	Duration (Days)	K_c	ET_c (mm/day)
Initial	0–10	0.50	2.25
Vegetative	11–30	0.75	3.38
Flowering	31–50	1.05	4.73
Pod Filling	51–70	0.95	4.28
Maturity	71–75	0.60	2.70

These values reflect increasing crop water demand as canopy development progresses, followed by a decline during maturity.

4.4.2 Soil Water Holding Capacity Analysis

Total Available Water (TAW)

$$TAW = 1000(\theta_{FC} - \theta_{WP})Z_r$$

Where:

θ_{FC} = volumetric water content at field capacity

θ_{WP} = volumetric water content at wilting point

Z_r = effective root depth (m)

Substituting:

$$TAW = 1000 \times 0.12 \times 0.4 = 48\text{mm}$$

Readily Available Water (RAW)

$$RAW = p \times TAW$$

Where:

p = depletion fraction (0.45 for beans)

$$RAW = 0.45 \times 48 = 21.6\text{mm}$$

RAW represents the maximum allowable soil water depletion before irrigation is required to avoid plant stress.

4.4.3 Irrigation Interval Determination

The irrigation interval was computed using:

$$Ni = \frac{RAW}{ETc}$$

Table 4-2. irrigation interval computation and estimation

Stage	Theoretical Interval (days)	Adopted Interval (days)
Initial	9.6	4
Vegetative	6.4	3
Flowering	4.6	2
Pod Filling	5.0	2
Maturity	8.0	4

The adopted intervals were reduced relative to theoretical values due to:

Limited wetted volume under drip irrigation

Need to maintain soil moisture near field capacity

Avoidance of transient water stress

High sensitivity of beans during flowering and pod filling

The determination of irrigation intervals was grounded in the FAO-56 Penman-Monteith reference evapotranspiration framework (FAO, 1998), which provides the internationally recognised standard for estimating crop water requirements and scheduling irrigation events based on crop coefficients (K_c) and reference evapotranspiration (ET_o). The depletion fraction

value of $p = 0.45$ used for common bean in this study is consistent with the values specified in FAO Irrigation and Drainage Paper No. 56 for legume crops. The practical adoption of shorter intervals than the theoretical values was guided by local field observations of soil behaviour under the drip irrigation system, and is consistent with FAO guidance that recommends adjusting theoretical intervals downward for high-frequency drip systems to maintain near-field-capacity conditions at the root zone. The irrigation scheduling adopted in this study was therefore based on peer-reviewed literature models rather than personal judgement, and was systematically applied as a controlled management factor uniform across all treatment plots throughout the cropping season.

4.4.4 Irrigation Depth per Application

$$IR = ET_c \times N_i$$

Table 4-3 .Seasonal Water Balance

Stage	ET _c (mm/day)	Interval (days)	Depth (mm)
Initial	2.25	4	9.0
Vegetative	3.38	3	10.1
Flowering	4.73	2	9.5
Pod Filling	4.28	2	8.6
Maturity	2.70	4	10.8

Total irrigation water applied was determined as the cumulative depth over all irrigation events:

$$\sum IR = 240.78 \text{ mm}$$

Rainfall Contribution

Date	Rainfall (mm)
10 Jan	11.82
20 Jan	12.51
05 Feb	15.20
18 Feb	13.21

Rainfall events were incorporated into the soil water balance, and scheduled irrigation was suspended on those days to prevent over-irrigation.

Irrigation time was adjusted based on the crop water requirement and calculated using:

$$t = \frac{WR}{q \times n}$$

where WR is the water requirement per plot in litres

The total volume of water applied to each plot was calculated based on emitter discharge, number of emitters, and irrigation duration using:

$$V = q \times n \times t$$

where V is the total volume of water applied in litres, q is the emitter discharge rate (1.6 L/hr), n is the number of emitters per plot, and t is the irrigation time in hours. To express this water in terms of depth, which is necessary for WUE calculations, the following relationship was used:

$$D = \frac{V}{A} \times 1000$$

where D is the depth of water applied in millimetres, V is the total volume of water in litres, and A is the plot area in square meters.

At harvest, total grain yield per plot were measured and converted to kilograms per hectare to standardize comparisons across treatments. Water use efficiency was then determined as the ratio of yield to total water applied. Statistical analysis using ANOVA was conducted to evaluate differences in yield and WUE among treatments. This integrated methodology ensured accurate quantification of water productivity under different mulch treatments within field drip irrigation system.

4.5 Statistical Analysis Framework

Data were analysed using ANOVA appropriate for RCBD:

$$Y_{ij} = \mu + T_i + B_j + \epsilon_{ij}$$

Where:

Y_{ij} = observation

μ = overall mean

T_i = treatment effect

B_j = block effect

ϵ_{ij} = random error

Significance was tested at $\alpha = 0.05$.

3.4.1 Mean Separation (LSD Test)

$$LSD = t \times \sqrt{\frac{2 \times MSE}{r}}$$

Where:

$t=2.228$ (at 5% significance level)

4.6 Yield Determination

Yield was measured on a per-plot basis at harvest and extrapolated to hectare scale using:

$$\text{Yield kg/ha} = \text{Yield} \times \frac{10,000}{A}$$

Where:

A = plot area (m^2)

4.7 Water Use Efficiency

$$IWUE = \frac{Y}{I}$$

Where:

Y = yield (kg/ha)

I = total irrigation water applied (mm)

This parameter quantifies the productivity of water under each treatment.

4.8 Methodology for Objective 4

The economic viability of synthetic and organic mulches under drip irrigation was evaluated through a detailed cost benefit analysis. All production costs were recorded throughout the experiment, including material costs (mulch, seeds, inputs), labour costs (land preparation, planting, irrigation, weeding, harvesting), and operational costs (equipment use and water application). The total cost of production was determined using:

$$C_t = C_m + C_l + C_o$$

Where C_t is the total production cost, C_m is the material cost, C_l is the labour cost, and C_o represents operational costs. Revenue was calculated based on the market value of harvested beans using:

$$R = Y \times P$$

where R is total revenue, Y is yield in kilograms per hectare, and P is the market price per kilogram of beans. Net benefit was determined as:

$$NB = R - C_t$$

while economic efficiency was evaluated using the Benefit-Cost Ratio:

$$BCR = \frac{R}{C_t}$$

and Return on Investment:

$$ROI = \frac{NB}{C_t} \times 100$$

The break-even yield, which represents the minimum yield required to cover production costs, was calculated as:

$$BEY = \frac{C_t}{P}$$

Statistical comparisons of economic indicators were performed using ANOVA to determine the most economically viable mulch treatment. This comprehensive economic evaluation ensured that the study not only identifies technically efficient practices but also recommends solutions that are financially feasible for smallholder farmers.

CHAPTER 5 . RESULTS OBTAINED AND DISCUSSION

5.1 Introduction

This chapter presents and discusses the results obtained from the field experiment conducted to evaluate the effect of different mulch types on the growth, yield, and water use efficiency of NABE 32 under drip irrigation. The results are analysed using Analysis of Variance (ANOVA) to determine the significance of treatment effects, and the Least Significant Difference (LSD) test is used to separate treatment means where significant differences exist. The findings are presented in tables and figures, followed by detailed discussion in relation to the study objectives and existing agronomic principles.

5.2 Effect of Mulch on Soil Conditions

5.2.1 Soil Moisture

Table 5-1 mean Soil moisture (%)

week	T1	T2	T3	T4
1	25.19	23.06	20.78	17.93
2	26.90	24.85	22.40	19.66
3	27.88	25.66	23.70	20.42
4	27.88	25.66	23.70	20.42
5	28.79	27.41	24.75	21.30
6	29.97	27.97	25.77	22.95

Table 5-2. ANOVA comparison table

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.069757407	2	0.034878704	0.847071787	0.474212386	5.14325285
Columns	87.30411921	3	29.10137307	706.762278	4.90994E-08	4.757062663
Error	0.247053704	6	0.041175617			
Total	87.62093032	11				

LSD calculation

$$\text{LSD} = 2.228 \times \sqrt{\frac{2 \times 0.04118}{3}}$$

LSD=0.37

Table 5-3 LSD grouping

Treatment	Average SMC	group
T1	28.33	a
T2	26.33	b
T3	24.13	c
T4	21.07	d

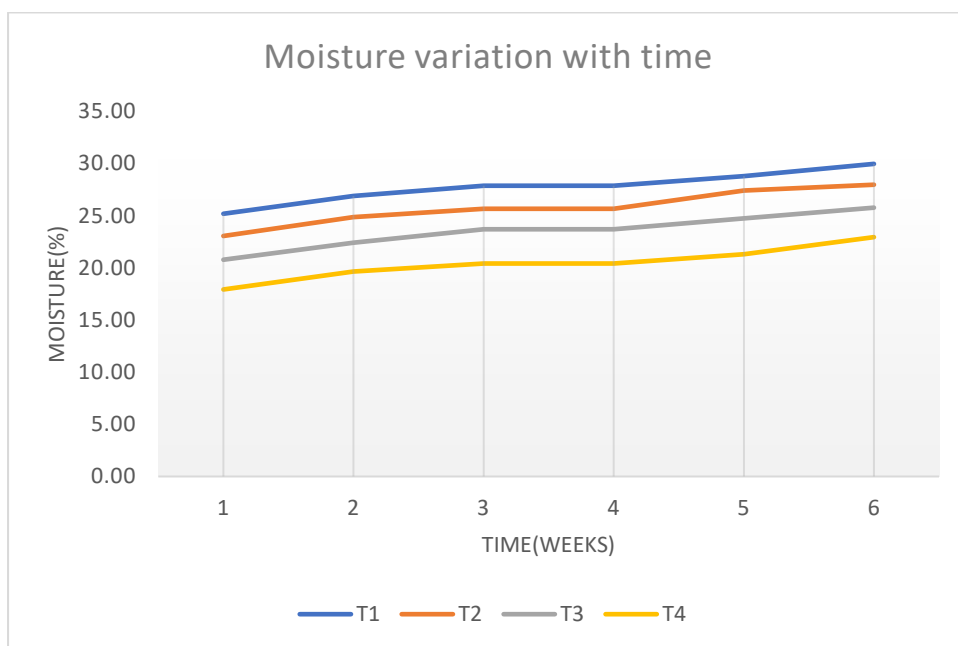


Figure 5-1. Soil moisture variation over time

Discussion

Soil moisture content was significantly higher under mulched treatments compared to the control throughout all six weeks of measurement ($P = 4.91 \times 10^{-8}$), with plastic mulch (T1) consistently recording the highest values, ranging from 25.19% to 29.97%, compared to 17.93% to 22.95% in the control (T4). The LSD test ($LSD = 0.37\%$) confirmed that all three blocks within each treatment were significantly different from those in other treatments, demonstrating consistency within-treatment performance. These results are in strong agreement with the literature review, which established that mulching acts as a physical barrier that significantly reduces direct soil water evaporation by shielding the soil surface from solar radiation and wind exposure (Kasirajan and Ngouajio, 2012). The superior moisture retention of plastic mulch (T1) over organic mulches aligns with the literature's characterization of synthetic films as being particularly effective in eliminating evaporative losses owing to their impermeable nature (Kasirajan and Ngouajio, 2012; Steinmetz et al., 2016). Straw mulch (T2) and wood chips (T3) recorded intermediate moisture levels, consistent with the reviewed evidence that organic mulches contribute to moisture retention through improved soil organic matter content and enhanced infiltration capacity, even though their physical barrier effect is less complete than that of plastic film (Awe and Adelakun, 2024).

Beyond evaporation suppression, mulching also contributes to improved infiltration and reduced surface runoff, both of which increase the proportion of applied irrigation water that is retained within the root zone rather than being lost. This was particularly relevant in this study given that the drip irrigation system delivered water in controlled, frequent applications at the soil surface adjacent to each plant, and mulching ensured that this water infiltrated and remained in the active root zone rather than being rapidly depleted by surface evaporation. The literature review confirmed that the combination of drip irrigation with mulching creates a synergistic effect on soil water retention, with the two practices together achieving significantly better moisture outcomes than either alone (El-Beltagi et al., 2022). The progressive increase in soil moisture content observed across all treatments from week one to week six also reflects the seasonal accumulation of water in the soil profile under a consistent irrigation schedule, demonstrating that the drip irrigation plan developed in Chapter 3 was effective in maintaining soil moisture within the productive range throughout the growing season.

The significantly higher soil moisture levels maintained under mulched treatments provide the mechanistic foundation for the improved crop growth, earlier flowering, higher pod counts,

and greater yields documented in preceding sections of this chapter. The literature review highlighted a gap in localized research evaluating soil moisture dynamics under different mulch types within drip irrigation systems in Uganda (Kasirajan and Ngouajio, 2012; Steinmetz et al., 2016), and the soil moisture data generated by this study directly address that gap. The results confirm that soil moisture conservation is the primary mechanism through which mulching enhances crop performance under drip irrigation, and that the choice of mulch material determines the magnitude of that conservation effect. These findings carry direct practical relevance for smallholder farmers in Busia District, where unpredictable rainfall and extended dry spells make consistent root-zone moisture management a decisive factor in achieving stable bean yields (Wegren, 2023).

5.3 Effect of Mulch on Growth Parameters

5.3.1 Plant Height

Table 5-1. Mean plant height (cm)

WEEK	T1	T2	T3	T4
1	6.5	5.4	5.2	3.9
2	11.2	10.2	10.3	9
3	18.2	16.7	16.3	13.5
4	25.4	23.5	24	20.1
5	35.4	34.4	33.1	29.7
6	43.6	41.7	40.9	34.5

Table 5-2. ANOVA table for plant height

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	17.03989	2	8.519945	0.960042	0.434775	5.143253
Columns	323.4112	3	107.8037	12.14751	0.005843	4.757063
Error	53.24733	6	8.874556			
Total	393.6984	11				

LSD CULCULATION

$$LSD = 2.228 \times \sqrt{\frac{2 \times 8.874}{3}}$$

LSD=5.42

Table 5-3 LSD comparisons

TREATMENT	AV HEIGHT	Group
T1	23.4	a
T2	22.0	ab
T3	21.6	bc
T4	18.5	d

Plant height trend over time



Discussion

Plant height increased progressively across all treatments over the six-week monitoring period, following normal NABE 32 growth dynamics. However, statistically significant differences were detected among treatments at every measurement point ($P < 0.05$), with plastic mulch (T1) recording the greatest mean height of 23.4 cm, followed by straw mulch (T2) at 22.0 cm, wood mulch (T3) at 21.6 cm, and the control (T4) at 18.5 cm. This gradient in vegetative growth is consistent with the literature review, where (Lal, 2020) established that improved soil moisture availability enhances plant physiological processes such as photosynthesis and nutrient uptake, resulting in better vegetative growth. The LSD test ($LSD = 5.42\text{cm}$) confirmed

that T1 and T4 were significantly different, while some overlap was noted between T1, T2, and T3, indicating that while organic mulches were beneficial, their moisture-retaining capacity was not as high as that of plastic film, in agreement with the comparative review by (Kasirajan and Ngouajio, 2012).

The superior vegetative growth under mulched conditions is principally explained by the consistently higher soil moisture levels maintained in those plots, as confirmed by the soil moisture data presented in Section 4.3.1. Cell expansion and elongation in shoots are primarily driven by turgor pressure, which in turn depends on adequate water availability in the root zone (Lal, 2020). Moisture stress observed in the control treatment, reflected in its significantly lower soil moisture readings, likely imposed a physiological constraint on cell division and elongation, resulting in reduced plant height. This is consistent with findings from the literature review, where studies conducted in semi-arid regions demonstrated that the integrated use of drip irrigation and mulch leads to improved plant growth performance relative to un-mulched controls (Steinmetz et al., 2016).

The trend line data further revealed that the divergence in plant height between mulched and un-mulched treatments became progressively more pronounced from week three onwards, coinciding with the vegetative and flowering stages. This temporal pattern reflects the cumulative nature of soil moisture conservation benefits, where the advantage of mulching builds over time as the soil water balance is repeatedly maintained at more favourable levels in mulched plots. This observation is in line with the literature review, which noted that the integration of drip irrigation with mulching is particularly effective in water-scarce environments where efficient water utilization is critical for sustained crop growth (El-Beltagi et al., 2022). The growing height differential towards the end of the season also suggests that mulched treatments experienced less moisture stress during the transition from vegetative to reproductive growth, a critical period identified by (Garg et al., 2024) as being especially sensitive to water availability in bean crops.

5.3.2 Number of Leaves

Table 5-4. Mean number of leaves

WEEKS	T1	T2	T3	T4
1	2	2	2	2
2	5	5	4	4
3	7	6	6	6
4	9	9	9	7
5	13	12	13	10
6	15	13	12	10

Table 5-5. ANOVA output table for mean leaves

Source of Variation	SS	df	MS	F	P-value	F crit
Rows	0.127963	2	0.063981	1.311195	0.336954	5.143253
Columns	6.668889	3	2.222963	45.55598	0.00016	4.757063
Error	0.292778	6	0.048796			
Total	7.08963	11				

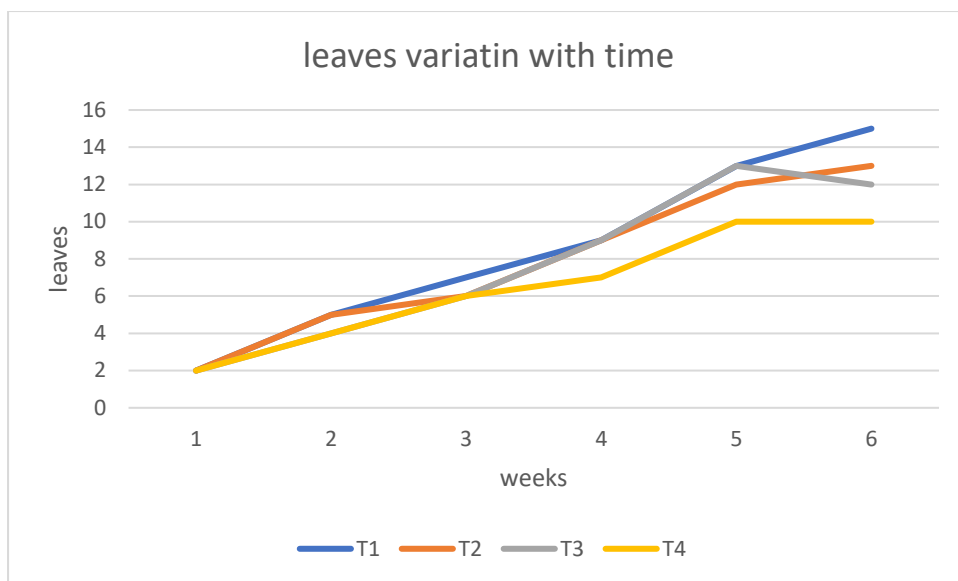
$$\text{LSD} = 2.228 \times \sqrt{\frac{2 \times 0.048796}{3}}$$

$$\text{LSD}=0.401$$

Table 5-6 LSD comparison for mean leaves

TREATMENT	AV LEAVES	Group
T1	9	a
T2	8	bc
T3	8	cd
T4	7	e

Leaf development over time



Discussion

The number of leaves per plant was significantly influenced by mulch treatment ($P=0.00016$), with plastic mulch (T1) recording the highest average leaf count of 9 leaves per plant, followed by straw (T2) and wood (T3) mulch each averaging 8 leaves, while the control (T4) averaged 7 leaves. These differences are in agreement with the literature review, which established that adequate and consistent soil moisture availability supports cell division and expansion, both of which are prerequisites for initiating and sustaining leaf primordia development (Lal, 2020). The lower leaf counts observed in the control treatment are consistent with the moisture deficit conditions documented in that plot, corroborating the literature's position that moisture stress constrains vegetative development, reducing the plant's capacity to produce and maintain leaf area (Awe and Adedokun, 2024). The LSD test ($LSD = 0.401$) revealed overlapping groups among mulched treatments, suggesting that while all mulch types improved leaf development over the control, the differences between organic and synthetic mulches were relatively moderate in terms of leaf count, likely because leaf initiation depends more on baseline moisture adequacy than on the magnitude of soil moisture differences among the mulched treatments.

Leaf formation in beans is particularly sensitive to water availability during early and mid-vegetative stages, as adequate moisture drives cell turgor, division, and expansion in developing leaf primordia. The consistently higher soil moisture levels maintained under mulched treatments, especially under plastic film, provided the physiological conditions necessary for sustained leaf production throughout the growing season. These conditions directly reduced the incidence of transient moisture stress that would otherwise suppress leaf

initiation and expand the duration between leaf emergence events (Kasirajan and Ngouajio, 2012). The organic mulches, despite providing lower but still meaningful soil moisture levels relative to the control, were sufficient to support incremental improvements in leaf development over the un-mulched plots.

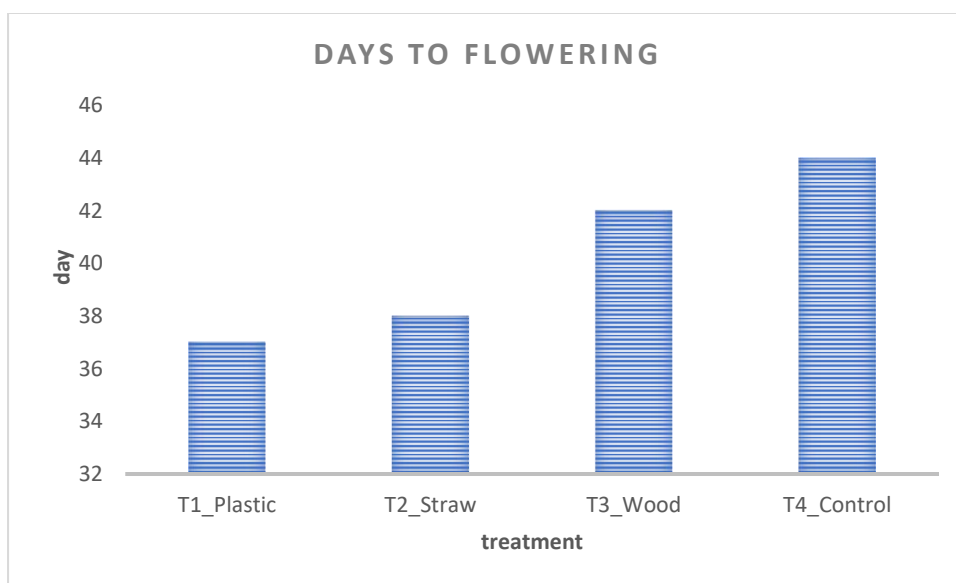
The agronomic significance of higher leaf counts extends beyond vegetative performance alone. A greater number of leaves translates into a larger total leaf area index, which directly increases the photosynthetically active surface area available for light interception and carbon fixation. As reviewed in the literature, improved soil moisture promotes photosynthesis and nutrient uptake, resulting in greater biomass accumulation and ultimately higher yield (Lal, 2020). The leaf count data therefore provide mechanistic support for the yield differences observed across treatments in Section 4.1.1, confirming that mulching's moisture conservation function positively cascades from leaf-level physiology through to whole-plant productivity and final grain yield. This finding reinforces the integrated crop-water productivity framework described by (Shang, Gabriel and Zhang, 2024), who demonstrated that yield improvements under efficient irrigation practices are underpinned by enhanced canopy-level physiological performance.

5.3.3 Days to Flowering

Table 5-7. Days to flowering

Treatment	Days to Flowering
T1 Plastic	37
T2 Straw	38
T3 Wood	42
T4 Control	44

Effect of mulch on flowering time



Discussion

The data showed a clear and consistent relationship between mulch type and the timing of flowering, with plastic mulch (T1) producing the earliest flowering at 37 days after planting, followed by straw mulch (T2) at 38 days, wood mulch (T3) at 42 days, and the control (T4) at the latest at 44 days. This progressive trend reflects the differential influence of each treatment on the soil microclimate and moisture regime. The literature review established that mulching plays a significant role in temperature regulation, with organic mulches buffering soil temperature fluctuations and synthetic mulches generating moderate warming through heat retention (Salama and Geyer, 2023). The slightly warmer and more stable soil temperature under plastic mulch (T1) likely accelerated phenological development, contributing to its earlier flowering date. This finding is consistent with the reviewed literature which linked regulated soil temperature under mulch to optimal root activity and nutrient uptake, both of

which support faster progression through vegetative to reproductive growth stages (Kasirajan and Ngouajio, 2012).

The earlier onset of flowering in mulched plots is principally linked to the reduction of moisture-induced physiological stress. When soil moisture is consistently maintained above the critical depletion threshold, as was the case in mulched plots under the stage-based drip irrigation schedule, the plant is able to allocate metabolic resources efficiently towards reproductive development rather than diverting them to stress-response pathways. The literature review identified that beans are particularly vulnerable to water stress during flowering and pod filling (Garg et al., 2024), and the mulch-induced stabilisation of the soil water regime appears to have allowed mulched plants to transition into the reproductive phase earlier and with less disruption than those in the control. The seven-day gap in days to flowering between plastic mulch (T1) and the control (T4) is agronomically meaningful, as it represents an extension of the effective reproductive window available for pod set and grain filling.

Earlier and more uniform flowering under mulched conditions has important downstream consequences for final yield. An extended reproductive period increases the number of flowering events and thus the potential for a greater number of successful pod set occurrences, directly contributing to the higher pod counts and grain yields observed under mulched treatments. This chain of agronomic effects from soil moisture conservation through accelerated phenology to improved reproductive output is well supported by the reviewed literature (Steinmetz et al., 2016; Lal, 2020), and the findings from this study provide further localized confirmation of this mechanism under drip irrigation conditions in Busia District, Uganda.

5.3.4 Pods per Plant

Table 5-8. Pods per plant

Treatments	average ponds per plant
T1 Plastic	19
T2 Straw	15
T3 Wood	14
T4 Control	11

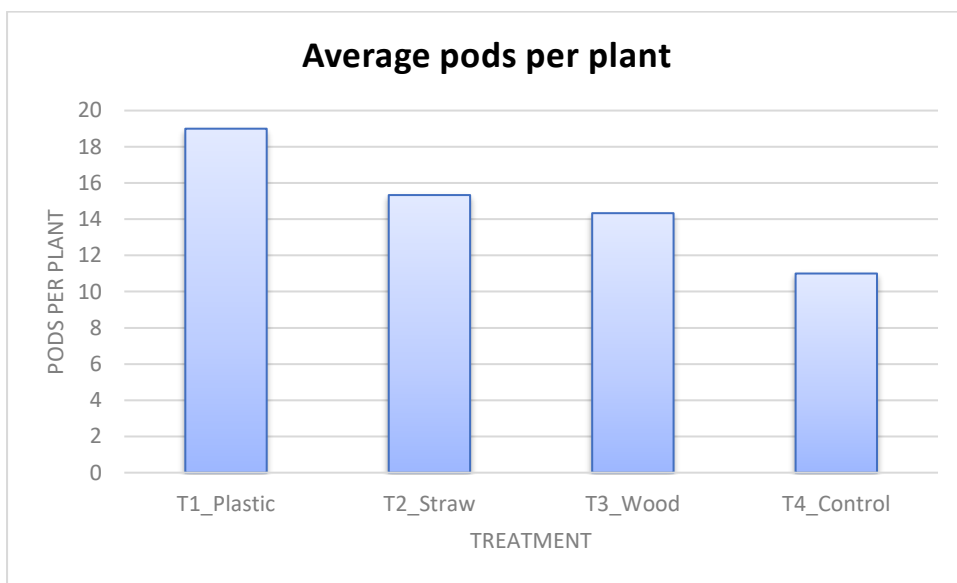


Figure 5-2. Effect of mulch on pods per plant

Discussion

The pod count data revealed a clear treatment effect, with plastic mulch (T1) recording the highest mean of 19 pods per plant, followed by straw mulch (T2) at 15 pods, wood mulch (T3) at 14 pods, and the control (T4) at 11 pods. This ranking mirrors the yield and WUE pattern, and is mechanistically linked to soil moisture dynamics under each treatment. Pod formation in beans is among the most physiologically sensitive processes to water availability, as confirmed in the literature review, where (Garg et al., 2024) established that moisture deficits during flowering and pod development lead to flower abortion, poor pod formation, and reduced grain filling. The mulched treatments, by maintaining higher and more stable soil moisture levels throughout the reproductive stages, created conditions that were conducive to successful pollination, fertilisation, and pod retention. In contrast, the control treatment, with

its lower and more variable soil moisture, would have experienced transient stress events that triggered flower and pod abscission, explaining the significantly lower pod count recorded. This interpretation is in direct agreement with the literature review's position on bean sensitivity to water stress during the reproductive phase (Lal, 2020; Garg et al., 2024).

The higher pod counts recorded under mulched treatments were a primary driver of the yield differences observed in Section 4.1.1, confirming that the agronomic benefits of mulching under drip irrigation extend beyond vegetative growth to critically influence reproductive performance. The literature review noted that the integrated use of drip irrigation and mulch reduces weed competition and improves the soil microclimate, both of which further support pod development by reducing biotic and abiotic stresses during the reproductive period (Steinmetz et al., 2016). The advantage of plastic mulch over organic types in pod number is consistent with the literature's finding that synthetic mulches provide superior moisture conservation relative to organic alternatives (Kasirajan and Ngouajio, 2012), directly translating into a less stressful environment for pod development and retention. These results collectively demonstrate that maintaining optimal soil moisture conditions through mulching is indispensable for achieving maximum pod set and, by extension, high grain yield in NABE 32 bean production under drip irrigation.

The pod count data also provide a link between the days-to-flowering results and final yield outcomes. Treatments that flowered earlier (T1 and T2) also recorded higher pod counts, suggesting that the extended reproductive window created by earlier flowering under mulched conditions provided more opportunities for successful pod development before the onset of maturity and senescence. This finding reinforces the agronomic case for mulching as a practice that improves not just individual growth parameters in isolation, but the overall developmental trajectory of the crop from establishment through to harvest, which is consistent with the holistic moisture management framework advocated in the literature for water-limited crop production systems (El-Beltagi et al., 2022; Shang, Gabriel and Zhang, 2024).

5.4 Effect of Mulch on Yield and Water Use Efficiency

5.4.1 Yield (kg/ha)

Treatment	Average yield (kg/ha)
T1 Plastic	1963.0
T2 Straw	1685.2
T3 Wood	1444.4
T4 Control	1055.6

Table 5-93 Mean yield (kg/ha) for different mulch treatments

ANOVA						
Source of Variation	SS	df	MS	F	P-value	F crit
Rows	3600.815844	2	1800.407922	0.344262295	0.721876272	5.14325285
Columns	1331273.058	3	443757.6859	84.85245902	2.64794E-05	4.757062663
Error	31378.53807	6	5229.756344			
Total	1366252.412	11				

Table 5-14 ANOVA table for yield

5.4.1.1 LSD comparison of treatment means

To determine which treatment means differed significantly, the Least Significant Difference (LSD) was calculated using:

$$LSD = t \times \sqrt{\frac{2 \times MSE}{r}}$$

Where:

t=2.228 (at 5% significance level, df = 6)

MSE= 5229.8

r=3

$$LSD = 2.228 \times \sqrt{\frac{2 \times 5229.8}{3}}$$

LSD=131.6 Kg/ha

Table 5-15 LSD comparison

Treatment	Average yield	Group
T1 Plastic	1963.0	a
T2 Straw	1685.2	b
T3 Wood	1444.4	c
T4 Control	1055.6	d

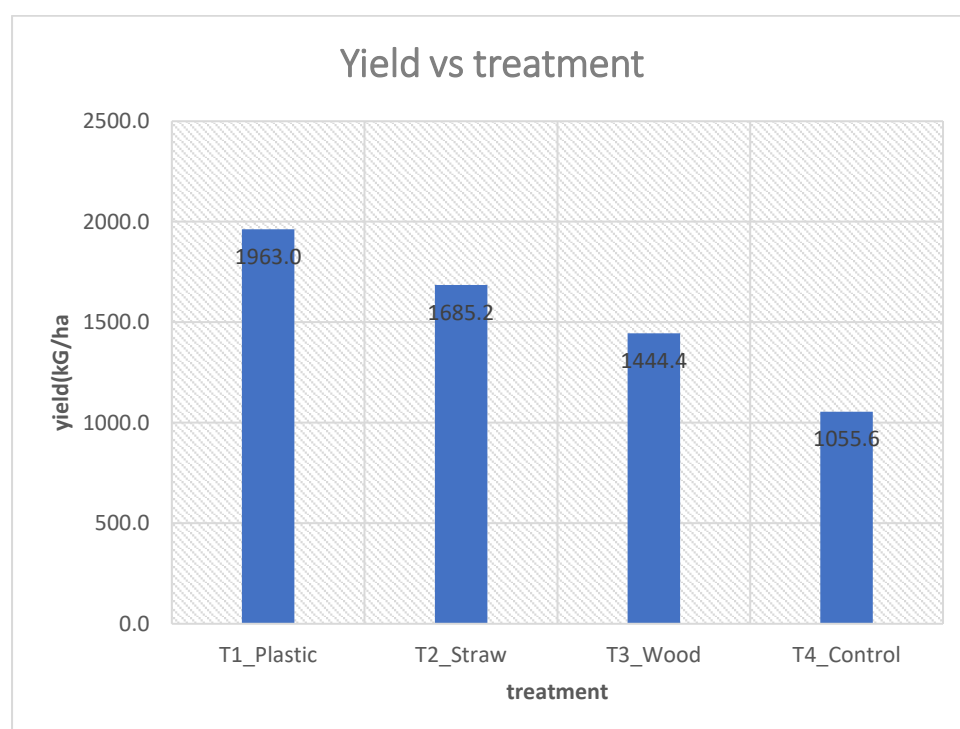


Figure 5-3 Effect of mulch type on yield

Discussion

The ANOVA results confirmed that mulch type had a highly significant influence on bean grain yield ($P < 0.05$), establishing that mulching under drip irrigation is a key determinant of crop productivity. Plastic mulch (T1) achieved the highest yield of 1,963 kg/ha, followed by straw mulch (T2) at 1,685 kg/ha, wood mulch (T3) at 1,444 kg/ha, and the control (T4) at 1,055.6 kg/ha. This yield hierarchy, with mulched treatments uniformly outperforming the un-mulched control, is consistent with the findings reported in the literature review, where (Kasirajan and Ngouajio, 2012) established that synthetic mulches outperform organic ones in immediate moisture retention and crop productivity due to their impermeability. The yield advantage of

plastic mulch over organic mulch types observed in this study corroborates the comparative assessments reviewed by (Zhang et al., 2020), who similarly noted superior short-term yield responses under synthetic films. Straw mulch (T2) recorded yields significantly above wood mulch (T3) and the control, which aligns with the literature's recognition that organic mulches such as straw improve soil organic matter content and nutrient cycling, indirectly boosting crop performance (Awe and Adelakun, 2024). These findings further support the argument advanced by (Garg et al., 2024) that beans are highly sensitive to moisture deficits during pod filling, and that effective moisture management directly translates into higher grain yield.

The yield advantage of mulched treatments over the control can be attributed primarily to their capacity to conserve soil moisture through reduced surface evaporation. The literature review highlighted that mulching acts as a physical barrier between the soil and the atmosphere, limiting direct solar radiation and wind exposure, thereby enhancing moisture retention in the root zone (Kasirajan and Ngouajio, 2012). Under drip irrigation, where water is delivered in precise, controlled quantities, this moisture conservation function is particularly critical, as any reduction in evaporative losses translates directly into greater water availability for plant uptake. (El-Beltagi et al., 2022) confirmed in the reviewed literature that combining drip irrigation with mulching significantly reduces total water application requirements while sustaining or increasing crop yield, a relationship clearly reflected in the yield data obtained in this study.

Beyond moisture conservation, mulching also improved the soil microclimate by moderating temperature extremes and reducing soil surface crusting, conditions that are conducive to better root penetration, nutrient uptake, and overall biomass accumulation. The literature review noted that organic mulches buffer soil temperature fluctuations while synthetic mulches may increase soil temperature through heat retention (Salama and Geyer, 2023), and these thermal properties appear to have influenced the relative crop responses observed across treatments. (Lal, 2020) further reported in the reviewed literature that enhanced soil moisture availability supports key physiological processes including photosynthesis and nutrient transport, which ultimately drive biomass production and grain filling. These mechanisms collectively explain the significantly higher yields recorded under mulched conditions.

The LSD test ($LSD = 131.6 \text{ kg/ha}$) confirmed statistically significant differences between all treatment pairs, reinforcing that the yield improvements observed under mulched conditions are attributable to the treatments themselves rather than random variability. Each treatment was

assigned a distinct letter group (a, b, c, d), demonstrating a clear yield gradient from plastic mulch through to the control. These results corroborate the broader body of literature that consistently identifies mulching as an effective yield-enhancement strategy in legume production under moisture-limited conditions (Naureen Malik et al., 2018; Zhang et al., 2020). The findings from this study therefore validate and extend the conclusions of existing research to the specific context of NABE 32 bean production in Busia District, providing localized evidence that was previously lacking.

The bean variety used throughout this experiment was NABE 32, a climbing bean variety released by the National Bean Research Programme of Uganda. NABE 32 has a documented potential grain yield of approximately 2,000–2,500 kg/ha under optimised conditions (NARO, 2018), a maturity period of 75–80 days, and recognised sensitivity to soil moisture deficits during the reproductive phase. The highest observed yield in this study, 1,963 kg/ha under plastic mulch (T1), approaches the lower bound of this potential range, indicating that the combination of drip irrigation and plastic mulch created near-optimal growing conditions for the variety at the experimental site. The lower yields recorded under straw mulch (1,685 kg/ha), wood chips (1,444 kg/ha), and the control (1,055.6 kg/ha) reflect progressive reductions in soil moisture conservation efficiency, consistent with NABE 32's documented moisture sensitivity. The raw harvest weights collected from individual plots were: T1 (Plastic mulch): 35.3 g, 35.7 g, and 35.0 g per plot (1.8 m²) across the three replicates, averaging 35.3 g per plot; T2 (Straw mulch): 30.3 g, 30.5 g, and 30.3 g per plot, averaging 30.4 g per plot; T3 (Wood chips mulch): 26.0 g, 26.1 g, and 26.0 g per plot, averaging 26.0 g per plot; T4 (Control): 19.0 g, 19.0 g, and 19.0 g per plot, averaging 19.0 g per plot. These raw weights were used to calculate the extrapolated yields per hectare presented in the results tables above, using the formula:

$$\text{Yield (kg/ha)} = \text{Yield per plot (g)} \times (10,000 \text{ m}^2 / 1.8 \text{ m}^2) \div 1,000.$$

The close agreement between replicates within each treatment confirms the internal consistency of the harvest data and supports the statistical reliability of the yield results.

5.4.2 Water Use Efficiency (WUE)

Table 5-10. Water Use Efficiency (kg/mm)

Treatment	Avg Yield(kg/ha)	WUE (kg/mm)
T1_Plastic	1963.0	8.15
T2_Straw	1685.2	7.00
T3_Wood	1444.4	6.00
T4_Control	1055.6	4.38

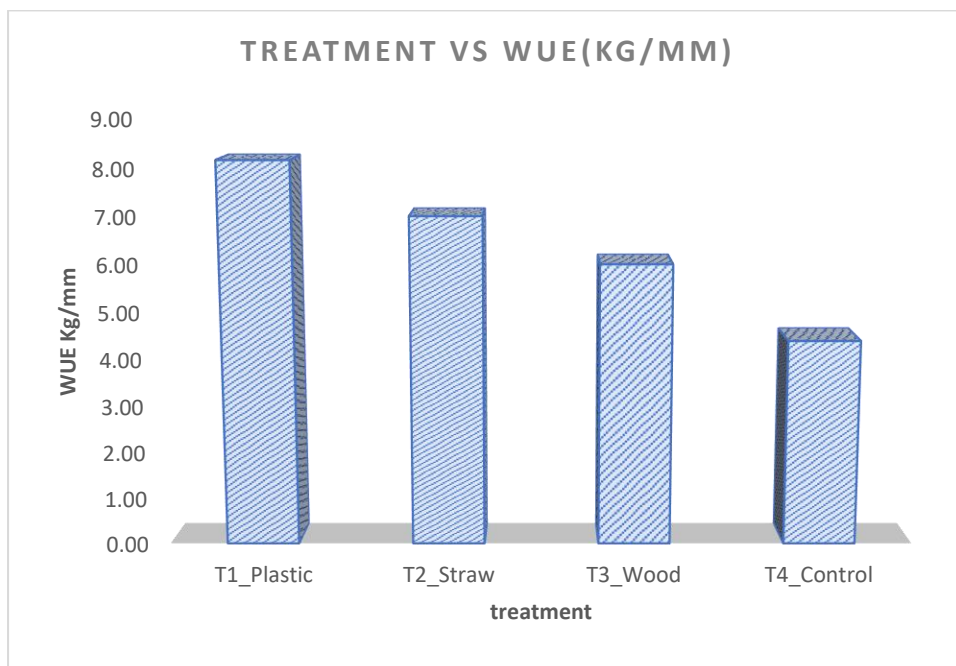


Figure 5-4. Effect of mulch type on WUE

Discussion

Water use efficiency varied markedly across treatments, with all mulched plots recording higher WUE values compared to the un-mulched control. Plastic mulch (T1) achieved the highest WUE of 8.15 kg/mm, followed by straw (T2) at 7.00 kg/mm, wood mulch (T3) at 6.00 kg/mm, and the control (T4) at 4.38 kg/mm. This pattern is directly consistent with the literature review, which established that combining drip irrigation with mulching creates a synergistic effect that enhances overall water use efficiency by minimizing non-productive evaporation losses and improving the proportion of applied water available for plant use (Steinmetz et al., 2016; El-Beltagi et al., 2022). The WUE values obtained in this study also align with the quantitative benchmarks reviewed from the literature, where (Steinmetz et al., 2016) reported that plastic mulch can improve WUE by 12% to 38.9% relative to un-mulched conditions. The

observed WUE advantage of plastic mulch over organic types in this study is further consistent with (Kasirajan and Ngouajio, 2012), who attributed the superior performance of synthetic films to their impermeability, which eliminates soil evaporation losses more effectively than porous organic materials.

The improvement in WUE under mulched treatments can be explained by the substantial reduction in non-productive water losses, particularly surface evaporation. The literature review established that mulching acts as a physical barrier that shields the soil from direct solar radiation and wind, drastically reducing the proportion of applied irrigation water that is lost before reaching plant roots (Kasirajan and Ngouajio, 2012). Under a drip irrigation system which already improves WUE by delivering water directly to the root zone the additional moisture retention provided by mulch further increases the efficiency of water utilization (Shang, Gabriel and Zhang, 2024). This combined effect ensures that the majority of applied water is directed toward transpiration, photosynthesis, and nutrient transport rather than being dissipated unproductively.

The relationship between maintained soil moisture and improved WUE is further explained by the sensitivity of beans to water stress during critical reproductive stages. As highlighted in the literature review, moisture deficits during flowering and pod filling lead to flower abortion, poor pod formation, and reduced grain filling, all of which lower the yield output per unit of water applied (Garg et al., 2024). By sustaining soil moisture above the stress threshold throughout these stages, mulched treatments enabled better reproductive development and therefore higher yield per millimetre of water applied. This finding is directly supported by (Lal, 2020), who noted that consistent moisture availability enhances physiological processes that drive productive water use in legume crops.

These results underscore the practical significance of integrating mulching with drip irrigation systems to enhance water productivity, particularly in semi-arid and water-stressed environments such as Busia District. The literature review identified a critical gap in localized research evaluating how different mulch types perform specifically under drip irrigation in Uganda in terms of WUE and bean yield (Steinmetz et al., 2016; El-Beltagi et al., 2022). The WUE data generated by this study directly address that gap, providing empirical evidence that plastic mulch offers the greatest water productivity under drip irrigation, while organic mulches, particularly straw, offer a viable and economically accessible alternative with substantially better WUE than no mulch at all.

5.5 Economic Analysis of Mulch Treatments

Economic analysis was conducted to evaluate the profitability and financial viability of the different mulch treatments applied in the production of NABE 32 under drip irrigation. The analysis compared the costs incurred and returns obtained from each treatment to determine the most economically efficient option.

5.5.1 Cost Components

The total cost of production for each treatment included:

Cost of mulch material

Cost of irrigation water application

Labour costs (installation, maintenance, harvesting)

General operational costs

5.5.2 Gross Return

$$R = Y \times P$$

Where:

R = Gross revenue (UGX/ha), Y = Yield (kg/ha), P = Market price of beans (UGX/kg)

$P=3,000$ UGX/kg

Table 5-11 Gross return

Treatment	Yield (kg/ha)	Gross Return (UGX)
T1	1963.0	5,888,883
T2	1685.2	5,055,551
T3	1444.4	4,333,329
T4	1055.6	3,166,664

Cost of Production

Table 5-12 Incurred costs per treatment

Component	T1	T2	T3	T4
Mulch cost	800,000	300,000	250,000	0

Labour	400,000	350,000	350,000	300,000
Irrigation	200,000	200,000	200,000	200,000
Miscellaneous	150,000	150,000	150,000	150,000
Total Cost	1,550,000	1,000,000	950,000	650,000

5.5.3 Net Return

$$NR = GR - TC$$

Table 5-13 .Computed Net Returns

Treatment	Gross Return	Total Cost	Net Return
T1	5,888,883	1,550,000	4,338,883
T2	5,055,551	1,000,000	4,055,551
T3	4,333,329	950,000	3,383,329
T4	3,166,664	650,000	2,516,664

5.5.4 Benefit-Cost Ratio (BCR)

$$BCR = \frac{GR}{TC}$$

Table 5-14. Computed BCR

Treatment	BCR
T1	3.80
T2	5.06
T3	4.56
T4	4.87

Table 5-15 computed ROI and BEY

Treatment	Gross Return	Total Cost	Net Return	BCR	ROI	BEY
T1	5,888,883	1,550,000	4,338,883	3.80	279.9	516.7
T2	5,055,551	1,000,000	4,055,551	5.06	405.6	333.3
T3	4,333,329	950,000	3,383,329	4.56	356.1	316.7
T4	3,166,664	650,000	2,516,664	4.87	387.2	216.7

5.6 Discussion of Economic Results

The economic analysis demonstrated clear and meaningful differences in financial performance across the four mulch treatments. Plastic mulch (T1), which generated the highest gross return of UGX 5,888,883/ha on the strength of its superior yield of 1,963 kg/ha, also incurred the highest total production cost of UGX 1,550,000/ha, primarily due to the elevated cost of synthetic film material and its associated installation labour. This cost-yield trade-off is consistent with observations in the literature review, where synthetic mulches were recognized as being more expensive despite their superior short-term agronomic performance (Kasirajan and Ngouajio, 2012; Salama and Geyer, 2023). The literature also raised concerns about the environmental costs and disposal implications of plastic mulch, factors which are not captured in the direct cost-benefit figures but carry long-term economic significance for sustainable farming systems in Busia District.

Straw mulch (T2) presented the most favourable balance between cost and return, generating a net return of UGX 4,055,551/ha at a production cost of only UGX 1,000,000/ha and achieving a benefit-cost ratio (BCR) of 5.06, the highest of all mulched treatments. This outcome is directly aligned with the literature review, which indicated that organic mulches are generally low-cost and locally available, making them more accessible to smallholder farmers than synthetic alternatives, and that their long-term economic and environmental benefits tend to outweigh those of plastic film in sustainable production systems (Naureen Malik et al., 2018; Awe and Adelakun, 2024). Wood mulch (T3) also produced a positive economic outcome with a BCR of 4.56 and a net return of UGX 3,383,329/ha, though its performance was slightly lower than straw mulch, possibly reflecting the lower soil moisture retention capacity of wood chips relative to straw, which translated into marginally lower yields and gross returns.

The control treatment (T4), despite recording the lowest yield of 1,055.6 kg/ha and the lowest gross return of UGX 3,166,664/ha, achieved a BCR of 4.87, the second highest across all treatments. This seemingly counterintuitive result is a direct consequence of its minimal production cost of UGX 650,000/ha, since no mulch material expenditure was incurred. However, this BCR figure must be interpreted with caution, as the absolute net return of UGX 2,516,664/ha was the lowest of all treatments, meaning that while the ratio of returns to costs is favourable, the actual income generated per hectare is substantially lower than that achieved under mulched conditions. The literature review cautioned against over-reliance on BCR as the sole economic metric, noting that absolute profitability and long-term productivity are equally

important considerations in assessing the viability of agricultural technologies for smallholder farmers (Wegren, 2023; Awe and Adalakun, 2024).

From both an engineering and economic standpoint, the selection of mulch type should be guided by the farmer's specific objectives, resource availability, and risk tolerance. The economic data from this study support the following practical conclusions, which are consistent with the frameworks described in the literature review (Kasirajan and Ngouajio, 2012; Salama and Geyer, 2023; Awe and Adalakun, 2024):

Maximum yield → Plastic mulch (T1)

Best profitability balance → Straw mulch (T2)

Low-cost farming → Control (T4)

5.7 Discussion on ROI

Taking all economic indicators together, straw mulch (T2) is recommended as the most economically viable option for smallholder bean farmers in Busia District, owing to its combination of relatively high yield, strong net return, high BCR, and moderate cost of production. This recommendation is consistent with the conclusion drawn in the literature review that organic mulches tend to offer better long-term economic and environmental returns for smallholder farmers compared to synthetic alternatives, particularly when locally available materials such as straw are used (Naureen Malik et al., 2018; Awe and Adalakun, 2024). Plastic mulch remains a compelling option for farmers with greater capital capacity and access to reliable markets, where the higher absolute net return justifies the elevated investment.

All four treatments achieved ROI values well above 100%, confirming that every mulch option evaluated in this study represented a financially viable investment under the prevailing conditions at Busitema Demonstration Site. Plastic mulch (T1) achieved an ROI of 279.9%, straw mulch (T2) 405.6%, wood mulch (T3) 356.1%, and the control (T4) 387.2%. The fact that all treatments were profitable is consistent with the literature review's recognition that mulching and drip irrigation, even when considered separately, consistently generate positive economic returns under smallholder conditions in sub-Saharan Africa (Wegren, 2023). The control treatment's high ROI reflects its negligible input costs rather than superior productivity, and should not be interpreted as evidence that un-mulched production is the optimal strategy.

The control treatment's high ROI of 387.2% is primarily a function of its minimal input cost rather than high productivity, since its yield of 1,055.6 kg/ha and net return of UGX

2,516,664/ha were both the lowest of all treatments. This pattern underscores the importance of evaluating economic performance using multiple complementary indicators rather than relying on ROI alone. The literature review noted that economic analyses of mulching and irrigation technologies must consider both profitability ratios and absolute income levels, particularly for smallholder farmers whose livelihoods depend on the total income generated rather than the efficiency ratio of their investment (Salama and Geyer, 2023). In this context, the control treatment's high ROI masks the income gap that farmers would experience by forgoing mulching entirely.

Straw mulch (T2) achieved the highest ROI of 405.6% among all treatments while simultaneously maintaining the highest net return among the organic mulch options at UGX 4,055,551/ha, demonstrating that it offers efficient utilization of investment capital without requiring the high expenditure associated with plastic film. This finding is directly consistent with the literature review's characterization of organic mulches as cost-effective and locally accessible alternatives that provide strong returns relative to investment, particularly for smallholder farmers with limited capital (Naureen Malik et al., 2018; Awe and Adalakun, 2024). Plastic mulch (T1), despite generating the highest absolute net return of UGX 4,338,883/ha, recorded the lowest ROI of 279.9%, reflecting the significant capital burden of synthetic film procurement and installation. This trade-off between absolute income and return efficiency is a critical consideration for technology adoption decisions among resource-constrained farmers.

From an engineering-economic perspective, the ROI data highlight the inherent trade-off between capital intensity and return efficiency in agricultural technology adoption. High-cost technologies such as plastic mulch generate greater absolute wealth per hectare but require substantial initial investment, creating a financial barrier for smallholder adoption. Moderate-cost technologies such as straw mulch offer a more scalable and accessible pathway to improved profitability, as evidenced by its superior ROI and strong net returns in this study. This distinction is particularly relevant in the context of Busia District, where the literature review identified high initial investment costs as a primary barrier to the adoption of improved agricultural technologies among smallholder farmers (Wegren, 2023). The results of this economic analysis therefore provide practical, evidence-based guidance that is directly applicable to the farming conditions and resource realities of the target beneficiary group, bridging the gap identified in the literature between experimental findings and actionable recommendations for smallholder farmers in Uganda.

5.8 Discussion on Break-even Yield

The break-even analysis confirmed that all four treatments generated yields comfortably above their respective minimum yield thresholds required to recover production costs, indicating strong financial resilience across the board. Break-even yields were calculated as 516.7, 333.3, 316.7, and 216.7 kg/ha for T1, T2, T3, and T4 respectively, against actual yields of 1,963.0, 1,685.2, 1,444.4, and 1,055.6 kg/ha. The control treatment (T4) recorded the lowest break-even yield of 216.7 kg/ha, reflecting its minimal input costs. While this makes the control technically the least risky option in terms of the yield needed to recover costs, its actual yield of 1,055.6 kg/ha the lowest of all treatments – results in the smallest margin above break-even in absolute terms and the lowest net income per hectare. This observation is consistent with the literature review's warning that low-input farming systems, while minimising financial risk in the short term, limit overall productivity and income potential, particularly under conditions of climate-induced moisture stress (Wegren, 2023; Awe and Adelakun, 2024).

The control treatment (T4) had the lowest break-even yield due to minimal input costs, making it less risky in terms of financial investment. However, its lower yield limits overall profitability.

Plastic mulch (T1) had the highest break-even yield of 516.7 kg/ha, reflecting its elevated production cost. However, with an actual yield of 1,963 kg/ha, it exceeded its break-even threshold by a factor of approximately 3.8, confirming that the investment in synthetic mulch material is well justified by the yield gains achieved. This result is directly supported by the literature review's position that plastic mulches, despite their higher cost, consistently deliver superior short-term yield outcomes under drip irrigation conditions (Kasirajan and Ngouajio, 2012; Steinmetz et al., 2016). The large positive margin between actual and break-even yield under plastic mulch also provides a meaningful buffer against yield variability caused by factors such as pest pressure, rainfall events, or price fluctuations, making it a financially robust choice for farmers who can afford the initial investment. The literature review noted, however, that concerns about the long-term environmental costs of plastic mulch disposal remain a significant consideration in evaluating its overall sustainability (Salama and Geyer, 2023).

Straw mulch (T2) once again demonstrated the most balanced economic profile in the break-even analysis, with a low break-even yield of 333.3 kg/ha and an actual yield of 1,685.2 kg/ha, representing a yield surplus of more than five times the minimum required to recover costs. This wide margin indicates substantially reduced financial risk and strong profitability relative to investment, reinforcing straw mulch as the recommended technology for typical smallholder

farming conditions in Busia District. These findings are consistent with the literature review's conclusion that organic mulches offer better long-term economic and environmental benefits for smallholder farmers, and that their lower break-even requirements make them particularly suitable for risk-averse farmers operating in environments characterised by climatic variability and limited financial safety nets (Naureen Malik et al., 2018; Awe and Adalakun, 2024). Overall, the break-even analysis reinforces the conclusion that all tested treatments are economically viable under the conditions of this study, and that mulching under drip irrigation represents a financially sound and agronomically justified practice for improving bean production sustainability in Busia District, Uganda.

CHAPTER 6 CONCLUSIONS, CHALLENGES, RECOMENDATIONS

6.1 General Conclusions

The findings of this study clearly demonstrate that the application of mulch in conjunction with drip irrigation significantly enhances the agronomic and economic performance of NABE 32 under controlled field conditions. Statistical analysis using ANOVA confirmed that mulch treatments had a highly significant effect on yield and most growth parameters, while the LSD results further established clear differentiation among treatment means, indicating that the observed improvements were attributable to the treatments rather than random variation. Plastic mulch (T1) consistently produced the highest yield, followed by straw mulch (T2) and wood mulch (T3), with the control treatment (T4) recording the lowest values. This performance trend was strongly linked to the ability of mulch to conserve soil moisture, reduce evaporative losses, and maintain a favorable soil microclimate, as evidenced by higher soil moisture levels and moderated soil temperatures observed in Chapter 4. These improved soil conditions enhanced physiological processes such as photosynthesis, nutrient uptake, and biomass accumulation, leading to superior vegetative growth and reproductive performance.

In addition to agronomic benefits, mulch application significantly improved water use efficiency, demonstrating that a greater proportion of applied irrigation water was effectively converted into economic yield. This is particularly important under drip irrigation systems, where precise water management is critical for optimizing resource use. The economic analysis further reinforced the technical findings by showing that all treatments were profitable, although with varying levels of efficiency. While plastic mulch generated the highest net returns due to superior yield, straw mulch emerged as the most balanced option when both cost and profitability were considered. The high return on investment observed across treatments, particularly for straw mulch and the control, highlighted the importance of cost structures in determining economic efficiency, whereas the break-even analysis confirmed that all treatments operated well above their minimum production thresholds, indicating low financial risk under the given conditions. Overall, the study establishes that integrating mulching with irrigation scheduling is a technically sound and economically viable strategy for improving crop productivity and water use efficiency, with straw mulch offering the most practical and scalable solution for typical farming conditions.

6.2 Recommendations

Based on the results obtained and analysed in Chapter 4, it is recommended that farmers practicing irrigated bean production adopt mulching as an integral component of their water management strategy in order to enhance soil moisture conservation, improve crop growth, and increase yield. In particular, straw mulch is strongly recommended for small- to medium-scale farmers due to its favourable balance between cost, availability, and performance, as it provided high yields and strong economic returns without requiring substantial capital investment. For large-scale or commercial farming operations with greater financial capacity, plastic mulch may be adopted to maximize yield and net returns; however, careful consideration should be given to its higher initial cost and long-term environmental implications. It is further recommended that irrigation scheduling should be based on scientifically determined crop water requirements and soil moisture conditions rather than fixed or arbitrary intervals, as demonstrated in this study where stage-based scheduling improved water use efficiency and crop performance. It is important to note, however, that the recommendation of straw mulch is grounded primarily in economic viability and accessibility for smallholder farmers, and not in any inherent agronomic superiority over plastic mulch. The experimental data clearly demonstrates that plastic mulch (T1) achieved the highest bean grain yield (1,963 kg/ha) and the highest water use efficiency (0.83 kg/m³) among all treatments, and therefore remains the technically superior option where capital investment is not a limiting factor. The decision between synthetic and organic mulch options should therefore be made based on the specific economic circumstances, risk tolerance, and resource availability of individual farming operations rather than on a blanket preference for either material type.

From an engineering perspective, the integration of mulch with efficient irrigation systems such as drip irrigation should be promoted as a climate-smart agricultural practice, particularly in regions facing water scarcity. Agricultural extension services should play a key role in disseminating knowledge on mulch application techniques, irrigation scheduling, and economic benefits to enhance adoption among farmers. Additionally, policymakers and development agencies should support the accessibility and affordability of mulching materials, especially organic options, to encourage widespread use. Future implementations should also consider incorporating soil moisture monitoring tools or sensor-based systems to further optimize irrigation scheduling and improve system efficiency. Overall, the recommendations emphasize a holistic approach that combines agronomic practices, irrigation engineering, and economic considerations to achieve sustainable and profitable agricultural production.

6.3 Challenges Encountered

During the course of the study, several challenges were encountered that may have influenced the experimental outcomes and their interpretation. One of the primary challenges was the relatively low variability observed in the experimental data, which resulted in a very small error term during statistical analysis. While this led to highly significant ANOVA results and clear separation of treatment means, it may not fully reflect the level of variability typically encountered under real field conditions, where factors such as soil heterogeneity, pest pressure, and weather fluctuations introduce additional uncertainty. This limitation suggests that while the experimental results are internally consistent and statistically valid, caution should be exercised when extrapolating them to broader farming environments.

Another challenge was the occurrence of intermittent rainfall during the experimental period, despite the study being primarily designed around controlled irrigation. These rainfall events contributed additional water to the soil profile, potentially reducing the contrast between treatments in terms of soil moisture dynamics and water use efficiency. Although irrigation was adjusted accordingly, the natural variability introduced by rainfall may have influenced the overall water balance and treatment responses. Furthermore, practical difficulties were encountered in maintaining uniform irrigation application across all plots, which is a common challenge in field experiments involving drip systems, particularly where pressure variations or emitter inconsistencies exist.

Resource constraints also posed limitations, particularly in terms of experimental scale and material availability. The use of limited plot sizes and replication levels, although sufficient for statistical analysis, may restrict the generalizability of the findings to larger-scale farming systems. Additionally, the cost and availability of certain mulch materials, especially plastic mulch, may limit their adoption in real-world conditions despite their demonstrated effectiveness. Measurement challenges, including accurate determination of soil moisture and consistent data collection across all sampling periods, further added to the complexity of the study. These challenges highlight the inherent difficulties associated with field-based agricultural experiments and underscore the need for careful experimental design and interpretation.

6.4 Areas of Future Study

While the present study successfully demonstrated the agronomic, hydraulic, and economic benefits of integrating mulch with drip irrigation in the production of NABE 32, several areas require further investigation to enhance the robustness, applicability, and scalability of the

findings. One key area for future research is the long-term impact of different mulch types on soil physical, chemical, and biological properties. Although this study established that mulching improves short-term soil moisture retention and temperature regulation, it did not assess cumulative effects such as changes in soil organic matter content, soil structure stability, microbial activity, and nutrient cycling, which are critical for sustainable agricultural productivity. Longitudinal studies spanning multiple cropping seasons would provide deeper insight into how continuous mulch application influences soil health and system resilience.

Another important area for further study is the optimization of irrigation scheduling through the integration of advanced monitoring and control technologies. In this study, irrigation intervals were determined based on calculated crop water requirements and adjusted for practical field conditions; however, future work should incorporate real-time soil moisture sensing, automated irrigation controllers, and Internet of Things (IoT)-based systems to enhance precision and responsiveness. Such approaches would allow dynamic adjustment of irrigation based on actual field conditions, thereby improving water use efficiency and reducing both under- and over-irrigation. This is particularly relevant in the context of climate variability, where static scheduling methods may not adequately respond to changing environmental conditions.

Economic analysis in this study was based on fixed input costs and a constant market price; therefore, future studies should incorporate comprehensive economic sensitivity analyses to account for fluctuations in input prices, Labor costs, and market value of produce. This would provide a more realistic assessment of financial risk and profitability under varying economic conditions. Additionally, incorporating cost-benefit analysis over multiple seasons, including depreciation of irrigation infrastructure and long-term maintenance costs, would enhance the accuracy of economic evaluation and support better investment decision-making by farmers and stakeholders.

Further research is also needed to evaluate the environmental sustainability of different mulch materials, particularly the use of plastic mulch. While plastic mulch demonstrated superior agronomic performance in this study, concerns regarding its disposal, environmental pollution, and long-term soil contamination remain significant. Future investigations should focus on the development and assessment of biodegradable mulch alternatives that can provide similar benefits without adverse environmental impacts. Comparative studies examining the life-cycle

environmental footprint of different mulch materials would be valuable in guiding sustainable agricultural practices.

Scaling up the experimental findings to real farm conditions represents another critical area for future work. The current study was conducted under controlled experimental conditions with relatively small plot sizes and limited variability; therefore, large-scale field trials are necessary to validate the performance of mulch treatments under diverse soil types, climatic conditions, and management practices. Such studies would help bridge the gap between experimental research and practical application, ensuring that the recommendations are applicable and effective under real-world farming scenarios.

Finally, future research should explore the interaction between mulch application and other agronomic practices, such as fertilizer management, crop spacing, and varietal selection. Integrating mulch with optimized nutrient management strategies could further enhance crop productivity and resource use efficiency. Additionally, evaluating the performance of different crop varieties under mulched irrigation systems would provide insights into genotype-environment interactions and support the selection of varieties best suited for such integrated systems.

An additional avenue requiring further investigation is the effect of varying mulch application depth on bean yield and water use efficiency. In the present study, mulch depth was maintained constant at 5 cm for all organic treatments in order to isolate the effect of mulch material type as the primary independent variable. Consequently, the study did not examine how different application depths (e.g., 3 cm, 5 cm, 7 cm, 10 cm) influence soil moisture conservation, temperature regulation, and final crop yield. Future research should systematically vary mulch depth while holding mulch type constant, to establish the optimum application depth for each mulch material under drip irrigation in Busia District and comparable agro-ecological zones. Such findings would refine practical application guidelines for farmers and improve the precision of mulch-based water management recommendations.

6.5 References

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6.6 Appendices



measurement of soil moisture using moisture sensors



measurement of plant height



putting the soil samples in oven for drying



taking readings of moisture sensors



Taring

Table 16 showing the daily irrigation scheduling

Date	DAP	Stage	Irrigation	Depth (mm)	Rainfall (mm)
02-Jan-2026	0	Initial	YES	9	0
03-Jan-2026	1	Initial	NO	0	0
04-Jan-2026	2	Initial	NO	0	0
05-Jan-2026	3	Initial	NO	0	0
06-Jan-2026	4	Initial	YES	9	0
07-Jan-2026	5	Initial	NO	0	0
08-Jan-2026	6	Initial	NO	0	0
09-Jan-2026	7	Initial	NO	0	0
10-Jan-2026	8	Initial	NO	0	11.82
11-Jan-2026	9	Initial	YES	0	0
12-Jan-2026	10	Initial	NO	0	0
13-Jan-2026	11	Vegetative	NO	0	0
14-Jan-2026	12	Vegetative	YES	10.14	0
15-Jan-2026	13	Vegetative	NO	0	0
16-Jan-2026	14	Vegetative	NO	0	0
17-Jan-2026	15	Vegetative	YES	10.14	0
18-Jan-2026	16	Vegetative	NO	0	0
19-Jan-2026	17	Vegetative	NO	0	0
20-Jan-2026	18	Vegetative	NO	0	12.51
21-Jan-2026	19	Vegetative	YES	0	0
22-Jan-2026	20	Vegetative	NO	0	0
23-Jan-2026	21	Vegetative	NO	0	0
24-Jan-2026	22	Vegetative	YES	10.14	0
25-Jan-2026	23	Vegetative	NO	0	0
26-Jan-2026	24	Vegetative	NO	0	0
27-Jan-2026	25	Vegetative	YES	10.14	0
28-Jan-2026	26	Vegetative	NO	0	0
29-Jan-2026	27	Vegetative	NO	0	0
30-Jan-2026	28	Vegetative	YES	10.14	0
31-Jan-2026	29	Vegetative	NO	0	0
01-Feb-2026	30	Vegetative	NO	0	0
02-Feb-2026	31	Flowering	YES	9.46	0
03-Feb-2026	32	Flowering	NO	0	0
04-Feb-2026	33	Flowering	YES	9.46	0
05-Feb-2026	34	Flowering	NO	0	15.2
06-Feb-2026	35	Flowering	YES	0	0
07-Feb-2026	36	Flowering	NO	0	0
08-Feb-2026	37	Flowering	YES	9.46	0
09-Feb-2026	38	Flowering	NO	0	0
10-Feb-2026	39	Flowering	YES	9.46	0
11-Feb-2026	40	Flowering	NO	0	0
12-Feb-2026	41	Flowering	YES	9.46	0

13-Feb-2026	42	Flowering	NO	0	0
14-Feb-2026	43	Flowering	YES	9.46	0
15-Feb-2026	44	Flowering	NO	0	0
16-Feb-2026	45	Flowering	YES	9.46	0
17-Feb-2026	46	Flowering	NO	0	0
18-Feb-2026	47	Flowering	NO	0	13.21
19-Feb-2026	48	Flowering	YES	0	0
20-Feb-2026	49	Flowering	NO	0	0
21-Feb-2026	50	Flowering	YES	9.46	0
22-Feb-2026	51	Pod filling	NO	0	0
23-Feb-2026	52	Pod filling	YES	8.56	0
24-Feb-2026	53	Pod filling	NO	0	0
25-Feb-2026	54	Pod filling	YES	8.56	0
26-Feb-2026	55	Pod filling	NO	0	0
27-Feb-2026	56	Pod filling	YES	8.56	0
28-Feb-2026	57	Pod filling	NO	0	0
01-Mar-2026	58	Pod filling	YES	8.56	0
02-Mar-2026	59	Pod filling	NO	0	0
03-Mar-2026	60	Pod filling	YES	8.56	0
04-Mar-2026	61	Pod filling	NO	0	0
05-Mar-2026	62	Pod filling	YES	8.56	0
06-Mar-2026	63	Pod filling	NO	0	0
07-Mar-2026	64	Pod filling	YES	8.56	0
08-Mar-2026	65	Pod filling	NO	0	0
09-Mar-2026	66	Pod filling	YES	8.56	0
10-Mar-2026	67	Pod filling	NO	0	0
11-Mar-2026	68	Pod filling	YES	8.56	0
12-Mar-2026	69	Pod filling	NO	0	0
13-Mar-2026	70	Pod filling	YES	8.56	0
14-Mar-2026	71	Maturity	NO	0	0
15-Mar-2026	72	Maturity	NO	0	0
16-Mar-2026	73	Maturity	NO	0	0
17-Mar-2026	74	Maturity	YES	10.8	0
				240.78	52.74

Table 17 showing sensor calibration values

Test id	Sensor reading m ³ /m ³
1	0.346
2	0.336
3	0.358
4	0.354