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FDRE TECHNICAL & VOCATIONAL TRAINING INSTITUTE

FACULTY OF AGRICULTURE AND AGRO-PROCESSING TECHNOLOGY

DEPARTMENT OF FRUIT AND VEGETABLE PROCESSING TECHNOLOGY

RESPONSE OF CABBAGE VARIETIES TO NPS, UREA AND KCL FERTILIZER RATES IN HARBU DISTRICT, AMHARA, ETHIOPIA

MSc THESIS

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JUNE, 2026

ADDIS ABABA, ETHIOPIA

RESPONSE OF CABBAGE (*Brassica oleracea* L.) VARIETIES TO NPS, UREA AND KCL FERTILIZER RATES IN HARBU DISTRICT, AMHARA, ETHIOPIA

A THESIS SUBMITTED TO FEDERAL TECHNICAL AND VOCATIONAL TRAINING INSTITUTE, FACULTY OF AGRICULTURE AND AGRO-PROCESSING TECHNOLOGY

DEPARTMENT OF FRUIT AND VEGETABLE PROCESSING TECHNOLOGY

IN PARTIAL FULFILMENT OF THE REQUIRMENTS FOR THE DEGREE OF MASTER OF SCIENCE IN FRUIT AND VEGETABLE PRODUCTION TECHNOLOGY

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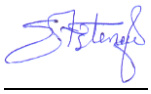
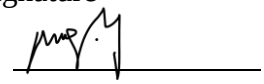
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ACKNOWLEDGMENT

First of all, I deeply thank Almighty GOD for giving me strength in my life. I would like to express my deepest gratitude and thank to my advisers, Getachew Shumye (Assist. prof.), Habtamu Ashagere (Assoc. Prof.) and Matyas Yigletu (Senior Horticultural Advisor), for their generous help in all aspects of my study at FTVT. Their continuous, absolute, and constructive guidance and support are highly acknowledged. They also helped me in finding the experimental site for my research. Moreover, they approach is highly appreciated and I am happy to have worked under their guidance.

My thanks are also extended to Department of Fruit and Vegetable Crop Production Technology and SNV Horti-life project III in general, for providing me with financial and technical support for this thesis work.

I would like to extend my thanks to Kombolcha Polytechnic Collage, Harbu Agriculture campus for giving me the land that was used in this study. I am indebted to my families, friends, and other individuals who supported me morally and contributed their fair share to the completion of this study.

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LIST OF ACRONYMS AND ABBREVIATIONS

ANOVA	Analysis of Variance
CEC	Cation Exchange Capacity
CIMMYT	Center of International for Maize and Wheat Improvement
CSA	Central Statistical Agency
CV	Coefficient of Variation
DAT	Days after transplant
DBARC:	DebreBrihan Agricultural Research Center
EIAR:	Ethiopian institute of Agricultural Research
HANRDO	Harbu Agricultural Natural Resource development Office
HSD	Honestly Significant Difference
NPS	Nitrogen Phosphors and Sulfur
RCBD:	Randomized Complete Block Design
SOM	Soil Organic Matter

Response of cabbage (Brassica oleracea L.) varieties to NPS, urea and Kcl fertilizer rates in Harbu District, Amhara, Ethiopia

ABSTRACT

Ethiopia faces a significant cabbage yield gap driven by low-yielding varieties and unbalanced fertilization. A field experiment was conducted in Harbu District, Amhara Region, using a Randomized Complete Block Design with a 3×5 factorial arrangement replicated three times. The objective was to evaluate the growth, yield, and economic feasibility of cabbage cultivars under various blending fertilizer rates. Three cultivars (Copenhagen Market, Chaka, and Tacoma) were evaluated across five fertilizer levels: a control (0), a standard recommended rate (242 kg NPS ha⁻¹ + 150 kg urea ha⁻¹), and three escalating tiers of NPS, Urea, and KCl combinations ranging (200kg + 160 kg + 50 kg ha^{-1} ,400kg + 320 kg + 100 kg ha^{-1}and 600 kg + 480 kg + 150 kg ha⁻¹).The variety and fertilizer interaction significantly ($p < 0.001$) influenced phenology, growth, and yield. Hybrid varieties (Tacoma and Chaka) consistently outperformed the open-pollinated Copenhagen Market in vegetative vigor and biomass. Days to 50% head initiation, days to 90% maturity, leaf number, and dry weight were significantly ($p < 0.001$) affected by the main effects. The highest head diameter (31.30 cm), total fresh weight (2.98 kg), fresh head weight (2.49 kg), marketable yield (73.82 t ha⁻¹), total yield (75.41 t ha⁻¹), and harvest index (82.53%) were recorded under the maximum rate with the Tacoma variety. Tacoma achieved the highest absolute net benefit, though partial budget analysis revealed clear economic trade-offs based on farmer capital. Further multi-season and multi-location investigations are suggested to develop precise recommendations.

***Keywords**: Blended fertilizer, Cabbage yield gap, Hybrid cultivars, Marginal rate of return, Partial budget analysis*

1. INTRODUCTION

1.1 Background of the Study

Cabbage (*Brassica oleracea L.*) is a biennial vegetable from the *cruciferae* family, widely cultivated for its compact head of over lapping its leaf. Cabbage is known worldwide as an excellent source of vitamin C and K, Fiber, and essential antioxidants; it contributes to human health and nutrition and is used as slaws, salads, and even cooked dishes. It is a rich source of sulfur-containing amino acids, minerals, beta carotenes, ascorbic acid, and antioxidants (Terefe *et al*., 2016). In addition, it has some medicinal value as it has a cooling effect, increases appetite, helps prevents constipation, speeds up digestion and is very useful for diabetic patient (Uuh-narvaez, 2021). Among other vegetable crops, cabbage is one of the easiest to cultivate and the majority of people grow it in backyard gardens. It is also essential economical and rational crop (Belay, 2021).

For optimum growth, cabbage requires best in with ideal temperature range is 10-25 ^{0}c (MoA, 2024)and mean relative humidity between 60 and 90 percent. Both insufficient and excessive water supply can result in inadequate head development or root rot develop, respectively (Daniel *et al.*, 2023). Although it can grow in a wide range of soils from light sand to heavier clays. Soils with high organic matter content give the best yields. Well-drained sandy loam soil with good organic content and soil pH of between 6.0 and 7.5 is high preferred for maximum yields (MoA, 2024).

Globally, Cabbage and other brassica crops are produced in more than 145 countries. The top five top major cabbage growers in the world are china, India, Germany japan south Korea and South Africa. According to Eyasu (2024), the total global area under cabbage cultivation in 2022 was about 2,326,179 ha, with an average productivity of about 31.21 t ha^{-1}. China and India produced about 60% of the world cabbage production with share of 46.4% and 12.8% respectively (Brief, 2022)

In Ethiopia, cabbage is usually grown in the mid and high altitude areas serving both as stable for household consumption and as a crucial source of income. Moreover, the portion of cabbage is exported to neighboring countries of Djibouti and Somalia (Sherka and Shiferie, 2025). Currently, in Ethiopia head cabbage is cultivated on about 38000 ha, with productivity of 10.4 t ha^{-1}, (Ayalew

and Girma, 2025). This productivity is very low as compared to the world average of 31.21 t ha^{-1}(Eyasu, 2024). According to Wale *et al*. (2025), the area under head cabbage production in Amhara regional state was 3511 ha with productivity of 8.48 t ha^{-1} which accounted 53.64% of the area under cabbage production in the country in 2022.

One of the primary driving factors behind this low productivity in the country and region is improper soil fertility management and suboptimal nutrient application. More over macro-nutrients play an important role in the growth and development process of the plant. Among this nitrogen, is essential primary nutrient as it is the major component of amino acids, and also encourages vegetative growth. Similarly, phosphorus encourages root development and also provides energy by forming ATP. Likewise sulfur plays an important role for protein metabolism, nutritional vitamins, and chlorophyll enzyme activation and in the formation of the fundamental component of proteins (Atnafu, 2020) and K enhances water retention and compactness (Srivastava *et al.*, 2018).

Despite these requirements, depletion of soil nutrients and limited cabbage variats have limited cabbage yields. Thus, applying the appropriate rate of NPS, Urea and Kcl fertilizers is essential for the enhanced cabbage productivity and securing sustainable yield. In Ethiopia, Potassium Chloride Kcl or Muriate of Potash) is vital for improving cabbage yield, head weight, and disease resistance when used in combination with organic fertilizer to bridge nutrient gaps. Applying Kcl (often around 50 kg/ha) increases cabbage head size and marketability by enhancing potassium uptake, which is essential in Ethiopian soils that are often potassium-deficient (Ali *et al*., 2025).

1. 2. Statement of the Problem

In Amhara region, including Harbu district, Cabbage is vital source of income and livelihood for farmers. However, the current productivity and productivity are meager, yet yields remain low as compared to its potential yield. This is due to low fertility status of the soil, in appropriate use of fertilizer rate, poor farming methods, lack of improved cabbage varieties, and insect pests and disease damage (Getachew *et al*., 2022). Consequently, the cabbage produced in the study area is often of poor quality; some are with small and very large cabbage heads, cracked, burst rotten and loose heads which severely reduces its market acceptability and farmers financial returns.

A major contributing factor to this low productivity is the suboptimal and unbalanced use of plant nutrients. Farmers in Harbu district apply deficient amounts of essential nutrients (N, P, S, K, and cll) and rely on limited hybrid varieties. Currently, the blanket fertilizer recommendation for cabbage in Ethiopia, including the study area, is an average of 50 kg ha^{-1} Kcl, 242 kg ha^{-1} NPS, and 150 kg ha^{-1} Urea applied in splits (Taye *et al*., 2025). Although the Ministry of Agriculture and the Agricultural Transformation Agency (ATA/MoA) introduced blended NPS fertilizer to substitute DAP, most farmers in the study area still do not utilize optimum levels. Evidence shows that this generic blanket recommendation may not sufficient to meet the specific nutrient needs of cabbage plants across different agro-ecologies (Fentaye & Bewuket, 2023). Unbalanced inorganic fertilizer application triggers soil health degradation, nutrient deficiencies, and a loss of microbial activity, ultimately threatening food security and household income (Muhamed, 2024).

Many experiments show that optimum inorganic fertilizer application significantly increases the total yield of cabbage, which if known to be a heavy feeder crop (Fentaye & Bewuket, 2023; Tehulie & Belete, 2021b). For instance, research done by Yebirzaf (2017) showed that nitrogen application increases the total yield of cabbage when managed properly in terms of rate and time of application. Belay (2021) also emphasized that selecting the specific type and rate of fertilizer is essential for improving soil fertility and increasing productivity while ensuring environmental sustainability.

Despite the necessity of good nutrient management and variety selection for sustainable cabbage production (Belay 2021),their precise interactions under the soil fertility limits of the Harbu district remain unknown. This absence of data immediately hurts local smallholders who experience low cabbage yields on limited land plots. Furthermore, because cabbage production in this area relies on an irrigated framework, understanding these aspects is particularly vital for dry-season urban agriculture—a system essential for providing year-round metropolitan food supplies Therefore, exploring optimal fertilizer rates and adaptable varieties under regulated watering regimes is crucial to build a resource-efficient production blueprint for urban farmers when rainfall is scarce.

1.3. Objective

General Objective:

- ✓ To evaluate the response of cabbage (*Brassica oleracea* L.) varieties to NPS, Urea, and Kcl fertilizer rates in Harbu District, Ethiopia.

Specific Objectives:

- ✓ To evaluate the effects of NPS, Urea and Kcl fertilizer rates on phenology, growth, yield and yield components of cabbage varieties in Harbu District.
- ✓ To identify the best-performing cabbage variety in the study area under varying fertilizer applications in Harbu District
- ✓ To determine the most economically feasible rates of NPS, Urea and Kcl fertilizer rates for cabbage production in the study area.

1.4 Research Hypotheses

Based on the specific objectives of the study, the following hypotheses were formulated:

- Hypothesis 1 (H_1): Application of varied amounts of blended NPS, Urea, and Kcl fertilizers con siderably increases the phenology, vegetative growth, and yield components of cabbage varieties i n the Harbu District.
- Hypothesis 2 (H_2): Hybrid cabbage varieties (such as Tacoma and Chaka) display considerabl y higer growth vigor and yield potential compared to openpollinated varieties (such as Copenha gen Market) under the agro-ecological conditions of the research area.
- Hypothesis 3 (H_3): Combined applications of certain amounts of NPS, Urea, and Kcl fertilizer rates result in an economically feasible net return and greater marginal rate of return for cabbage production in Harbu District.
- Hypothesis 4 (H_4): There is a significant interaction effect between cabbage varieties and blended fertilizer rates

2. LITERATURE REVIEW

2.1 Origin, Distribution and Botany of Cabbage

Cabbage (*Brassica Oleracea var. capitate* L.) is a member of the *Brassicaceae* family believed to have evolved from a wild, non-heading progenitor known as colewort found along the northern Mediterranean and Western European coasts (Gelaye, 2024b). The genus Brassica comprises approximately 100 species, most of which are native to the Mediterranean region (Tehulie & Belete, 2021). Domestication of the crop spans over three millennia, with records from ancient Greece dating back to 600 BC and the development of hard-headed varieties occurring in Europe between the 9th and 14th centuries (Ali, 2025). Following its establishment in Europe, the crop was introduced to African nations and specifically Ethiopia during the 16th century and subsequent colonial periods by European colonialists and missionaries (Eyasu, 2024).

Cabbage is a widely grown vegetable across five continents, with an estimated annual production of 73.8 million metric tons, covering approximately 3.2 million hectares globally (Tehulie & Belete, 2021). Asia is the largest producer, contributing 77.4% of the world's cabbage output, while Africa, the Americas, and Oceania account for the rest (Ali, 2025). In Africa, the top cabbage-producing countries include Kenya, Egypt, Ethiopia, Niger, and South Africa (Atnafu, 2020). In Ethiopia, cabbage is mainly grown by smallholder farmers in the highland and mid-altitude regions of the Oromia and Amhara provinces. The country contributes 12% of Africa's total cabbage production (Eyasu, 2024; Gosa and Fufa, 2023).

Cabbage is an herbaceous biennial plant, although it is commonly treated as an annual crop because of its dense vegetative head, which is classified as a large terminal structure (Gelaye, 2024b).It has a diploid chromosome number of 2n=2x=18 and features a short, thick stem that is encircled by overlapping leaves (Asomah *et al*., 2021).The shape of the head can differ greatly among different varieties, ranging from round and oval to conical, while the root system is mainly adventitious (Eyasu, 2024; Jaleta, 2019).In Ethiopia, common varieties like Copenhagen and Early Drumhead are preferred by farmers due to their specific maturity times and ability to adapt to different environmental conditions (Terefa, 2017).

For the best growth, cabbage thrives in cool weather with an average daily temperature of 17°C and a relative humidity level between 60% and 90% (Yebirzaf, 2017).

Nutritionally, cabbage is rich in Vitamin A and C, offering about 24 kcal of energy and 92% water in every 100g of edible part (Gosa and Fufa, 2023).In addition to its energy content, the vegetable provides important minerals like calcium (40 mg) and iron (0.6 mg), as well as notable amounts of antioxidants, riboflavin, and niacin (Terefa, 2017).

2.2 Cabbage Productivity in Ethiopia

Cabbage, scientifically known as Brassica oleracea L., plays a vital role in Ethiopian horticulture and is the second most important crop in terms of production and land use after red pepper (Teshome *et al*., 2018).Ethiopia holds a prominent position among the top five cabbage-producing countries in Africa, reflecting the crop's regional importance. Most cabbage is grown by small-scale farmers in mid-altitude and highland areas, contributing significantly to rural incomes and national food security (Eyasu, 2024). Cultivation is mainly done during the rainy season, although irrigation is increasingly being used to support dry-season farming for commercial purposes. Although direct sowing is an option, transplanting is the most commonly practiced method in Ethiopia. According to Kena and Latera (2024), a seed rate of 500–700 grams per hectare is enough to produce the necessary seedlings in a nursery for one hectare of land.

Despite its importance, Ethiopia's ability to compete globally in cabbage production is constrained by inadequate farming techniques, a lack of suitable varieties, and improper fertilizer use (Eyasu, 2024).These challenges result in a considerable difference between actual and potential yields. Mossie *et al*. (2022) found that traditional farming methods often yield as little as 8 tons per hectare, while research stations have achieved up to 96.9 tons per hectare using the Landin variety with optimized nitrogen application and precise spacing of 40 × 30 cm. Therefore, shifting from commonly used varieties such as Copenhagen to high-yielding hybrids, combined with recommended farming practices, is crucial for improving productivity and reducing the current yield gap.

2.3. Effect of Inorganic Fertilizer on Cabbage

2.3.1. Effect of NPS Fertilizer on Cabbage

Days to 50% head initiation

Accumulating evidence from regional agro-ecological studies shows a common trend where the use of blended NPS fertilizers consistently improves the growth timing of cabbage by enhancing nutrient availability in the soil around the roots. This quick growth is caused by the strong combined effect of NPS, which supports faster cell division, increases early photosynthesis efficiency, and speeds up the growth of plant tissues, leading to a quicker shift from the growth stage to the flowering stage. At moderate levels, both Muhamed (2024) and Yebirzaf (2017)found that applying 150 kg per hectare of NPS significantly speeds up the time it takes for the plant to start forming heads. Muhamed (2024)noted that this moderate rate reduced the time needed for head initiation by eight days compared to plots without fertilizer, while Yebirzaf (2017) showed that it cut the growth period to just 55 days. However, when the amount of nutrients is increased further, the effect on growth timing becomes even more noticeable; Fentaye and Bewuket (2023) found that doubling the application rate to 300 kg per hectare results in the earliest head formation ever recorded, which is much faster than any lower levels of input.

Despite this, there is still a key area that needs more research, as the combined effect of the three fertilizers NPS, Urea, and KCl has not been studied in the specific agro-ecological conditions of the Harbu District. Most existing research focuses on using NPS or nitrogen alone, and there is very little data on how combining different nutrients affects modern hybrid cabbage varieties like Tacoma and Chaka compared to traditional open-pollinated types in this area. This study fills this gap by providing a local reference that helps small-scale farmers in the region make informed decisions about how to use nutrients more effectively.

Days to 90% maturity

NPS availability plays a major role in determining the physiological maturity of cabbage. In areas where nutrients are scarce, Teshome and Amide (2020) observed that low levels of Nitrogen and Phosphorus cause the plant to transition to maturity too early, but in a stunted manner, which stops

it from achieving its full phenological development. On the other hand, applying too much of these nutrients can lead to excessive vegetative growth, which actually delays maturity and lengthens the overall crop cycle, according to Tehulie and Belete (2021).When comparing different application rates, a moderate dose of 150 kg per hectare was found to speed up healthy maturity, reaching it in 88.5 days, as noted by Yebirzaf (2017)..In contrast, increasing this amount to 300 kg per hectare, which is considered an intensive application, leads to 90% maturity in 92.33 days, as reported by Fentaye and Bewuket (2023).This shows that higher levels of chemical inputs can extend the time it takes for the plant to move from the vegetative to the reproductive stage. To manage this, combining NPS with organic materials helps maintain consistent maturity rates while protecting the soil's health, as suggested by Ali (2025).Much of the current research focuses on using NPS or Nitrogen alone, leaving a gap in understanding how optimizing multiple nutrients affects the maturity of modern hybrid varieties compared to open-pollinated ones in this particular region.

Plant height

The existing literature shows a consistent pattern indicating that the use of integrated mineral fertilizers, especially blended NPS, plays a key role in increasing the height of cabbage plants by encouraging quick cell growth and vegetative development. Although individual nutrients like phosphorus can also lead to greater vertical growth, as noted by Tehulie and Belete (2021), combining nitrogen and sulfur is important for achieving the best possible plant height.

When looking at real-world data, the growth response depends on the exact levels and proportions of nutrients used. For example, a standard NP fertilizer was found to produce a maximum height of 21.92 cm, according to Asomah *et al*. (2021). Similarly, Fentaye and Bewuket (2023)observed a slightly lower peak height of 22.36 cm using a 102.5:115:21.18 $kgha^{-1}$ NPS blend. However, when they increased the application rate to a higher level of 195:114:21 $kgha^{-1}$ NPS, the plant height significantly increased to 39.5 cm over two growing seasons.

Despite these findings, there is still a major gap in research. The combined effect of three fertilizers NPS, Urea, and KCl has not yet been studied under the specific environmental conditions of the Harbu District. Most current studies focus on using just two nutrients or one at a time, which means

there is little information on how optimizing multiple nutrients affects the growth of modern hybrid cabbage varieties compared to open-pollinated ones in this particular area.

Plant spread

Blended NPS fertilization is a primary determinant of cabbage canopy structure, optimizing plant spread to maximize light interception and photosynthetic efficiency. Empirical data show a strong positive correlation between NPS rates and canopy diameter. When comparing and contrasting lateral growth thresholds, empirical data shows a strong positive correlation between NPS rates and canopy diameter. Both Yebirzaf (2017) and Muhamed (2024)recorded a peak plant spread of 60.2 cm at an application rate of 150 kg ha^{-1}. Corroborating this positive trend at the exact same 150 kg ha^{-1}. threshold, Gosa and Fufa (2023) achieved their maximum recorded spread of 43.70 cm, significantly outperforming lower-dosage treatments. Regarding the upper physiological limits, Fentaye and Bewuket (2023) identified that the optimal range for maximizing spread lies between 150 and 195 kg ha^{-1}, beyond which lateral growth reaches a plateau with no incremental gains.

Leaf width

Cabbage's vegetative structure, especially the width of its leaves, changes a lot depending on how much nitrogen and phosphorus (NPS) and nitrogen-rich fertilizers are used. Even though more nutrients usually lead to better plant growth, studies show that the best amount of nutrients depends on the specific area because soil fertility levels can be different. In the Chiha district, Fentaye and Bewuket (2023) found that using 300 kg of NPS per hectare gave the highest total yield and widest leaves. This matches the results from Debre Markos, where Yebirzaf (2017) noted maximum leaf growth at a similar nitrogen level of 300 kg per hectare. However, Gosa and Fufa (2023) showed that applying a lower amount of 150 kg of NPS per hectare was enough to reach peak leaf width, which was 28.07 cm. These differences show that in some areas, adding more nutrients beyond a certain point doesn't give much more benefit. This highlights the importance of tailoring nutrient use to each location to best support the plant's growth and achieve high crop yields.

Number of leaves

The addition of sulfur in NPS mixtures is essential for the production of chlorophyll in cabbage and for enhancing the plant's ability to perform photosynthesis. Zhou *et al.* (2023) explain that higher chlorophyll levels, which make the leaves appear darker green, supply the energy needed to support

greater leaf production during the growth phase. Haile *et al.* (2025) also show that the combined use of sulfur, nitrogen, and phosphorus greatly improves the plant's growth and the total number of leaves compared to situations where the nutrient balance is not correct. In field experiments, Gosa and Fufa (2023) found that at an NPS application rate of 150 kg per hectare, plants had a maximum of 11.45 leaves each, which is a major improvement over treatments with lower nutrient levels. Together, these results highlight how sulfur plays a key role in improving the plant's physical performance and its ability to produce a large canopy, which is essential for growing cabbage with high yields.

Head diameter

The physical structure of the cabbage, particularly the head diameter, is influenced by the combined effect of nitrogen, phosphorus, and sulfur. These nutrients work together to support cell growth and overall biomass. Fentaye and Bewuket (2023) found that increasing levels of NPS or NPK consistently leads to larger head diameters compared to plants that lack these nutrients.

When comparing the best application rates, a standard threshold of 150 kg NPS per hectare is considered optimal, resulting in head diameters of 11.83 cm (Gosa and Fufa (2023), 11.04 cm (Mohammed, 2024), and 18.7 cm (Yebirzaf (2017).However, when higher input levels are applied, such as 235 kg N and 82 kg P per hectare, the head diameter increases significantly to 25.44 cm (Teshome and Amide, 2020).Similarly, Asomah *et al.* (2021) showed that a balanced NPK application increases the diameter from 8.86 cm to 11.33 cm, highlighting that increasing the supply of balanced nutrients leads to greater physical development. These studies collectively emphasize that a balanced and sufficient supply of nitrogen, phosphorus, and sulfur is essential for maximizing both the physical structure and commercial value of the crop.

Fresh weight

Cabbage fresh head weight is a primary indicator of nutrient-use efficiency and total biomass accumulation is largely driven by the synergistic effect of nitrogen, phosphorus, and sulfur, which collectively stimulate the vegetative vigor required for denser, heavier heads Fentaye and Bewuket (2023).comparing optimal inorganic management, empirical data confirms that blended fertilizers consistently double yields compared to unfertilized plots. Specifically, applying150kg NPS

benchmark yields fresh weights of 0.810 kg per plant Gosa and Fufa (2023) and 0.771 kg per plant compared to a 0.442 kg control Muhamed (2024). Under optimal inorganic management, Tehulie and Belete (2021) consistently reported head weights) demonstrated that NPK applications between 100–200 kg ha^{-1} maintain consistently high head weights of 800 to 900 grams, significantly enhancing overall marketable quality and nutrient-use efficiency.

Dry weight

Cabbage dry matter accumulation, which shows how well the plant is producing biomass, is mainly influenced by the combined availability of nitrogen, phosphorus, and sulfur. These nutrients help improve the plant's structure, such as making leaves thicker and the canopy larger, which speeds up the growth of the plant and leads to bigger, heavier heads compared to plants without fertilizer, as found by Gelaye (2024).In the Ethiopian highlands, where there is often a lack of phosphorus and sulfur, Tehulie and Belete (2021) suggest that using blended NPS fertilizers is important to address these soil issues and keep crop production high. This is supported by Gosa and Fufa (2023), who found that applying 150 kg per hectare is the best amount for maximum growth, resulting in a peak dry weight of 0.0117 kg per plant. Together, these studies show that using blended NPS fertilizers is key to improving the growth and commercial value of cabbage, especially in soils that are low in nutrients.

Marketable and unmarketable yields

The reviewed literature shows that nitrogen and phosphorus supply (NPS) fertilization is a key factor affecting the commercial value of cabbage. There is a strong positive link between nitrogen application rates and the amount of marketable yield, while there is an inverse relationship with unmarketable yield, which includes small, split, or rotten heads. When comparing actual data, optimizing NPS consistently leads to higher commercial benefits compared to plots without fertilizer. Marketable yields reached a peak of 64.5 tons per hectare with 92 kg of nitrogen from blended NPS, according to Terefa (2017). Similarly, Eyasu (2024) reported a marketable yield of 46.74 tons per hectare with 109.5 kg of nitrogen per hectare. In contrast, unmarketable yields decreased significantly from a baseline of 30.91 tons per hectare in the control treatment to just 7 tons per hectare under optimized management, as found by Terefa (2017). This trend was also observed by Eyasu (2024), who reduced unmarketable heads from 19.41 tons per hectare in the

control to 6.69 tons per hectare. However, Abie and Tizazu (2024) noted a significant trade-off, where the highest level of unmarketable yield, at 2.19 tons per hectare, occurred at their maximum nitrogen application of 109.5 kg per hectare, due to excessive head splitting and rotting caused by over-stimulation.

Harvest index

NPS fertilization helps cabbage grow better by improving how well the plant uses sunlight and absorbs nutrients (Tehulie and Belete, 2021). According to Muhamed (2024) found that providing the right balance of nutrients increases the Harvest Index (HI) by moving the energy from the leaves to the parts of the plant that produce seeds, leading to bigger and heavier cabbage heads. This is supported by Gelaye (2024), who showed that using 150 kg per hectare of NPS along with 92 kg per hectare of Nitrogen results in the best use of nutrients, achieving the highest weight for cabbage heads, which is 2.93 kg. Together, these results show that managing NPS carefully is important for getting the best growth and quality in cabbage that can be sold in the market.

However, there is still a major gap in research because no studies have looked at how the three fertilizers NPS, Urea, and KCl work together in the specific farming conditions of the Harbu District. Most research has focused on NPS alone, leaving a lack of real data on how optimizing multiple nutrients in local conditions affects both growth and yield in modern hybrid cabbage varieties compared to traditional open-pollinated ones.

2.3.2. Effect of Nitrogen Fertilizer on Cabbage

Days to 50% head initiation

When comparing empirical data, moderate to high optimized nitrogen application rates significantly shorten the time it takes for crops to reach the 50% heading stage compared to unfertilized controls. For example, applying nitrogen allows crops to achieve the 50% heading milestone much earlier than a control group, which took 68.8 days, as shown by Ali (2025).An intensive nitrogen application regime further reduced the heading time to 63.33 days from an 81.66-day control, according to Teshome *et al.* (2018).On the other hand, applying nitrogen beyond optimal levels reverses this effect. Fentaye and Bewuket (2023) found that excessive urea application (195 kg N per hectare) paradoxically lengthened the vegetative period to 89.33 days, which is a 13-day delay

compared to the control. Overall, these findings show that while nitrogen is essential for timely crop development, precise application is necessary to prevent delays caused by nutrient over application..

Days to 90% maturity

Some research has shown that nitrogen derived from urea plays a major role in determining how long it takes for cabbage to reach 90% physiological maturity. Teshome *et al*. (2018) found that applying a high amount of nitrogen 294 kg per hectare reduced the time needed for maturity to 112 days, compared to 140.66 days in plants that were not fertilized. Abie and Tizazu (2024) reported that the Lendini variety reached maturity in 75 days with 109.5 kg of nitrogen per hectare, whereas the Tana variety took 116 days without any fertilizer. Ali (2025) also found that applying 92 kg of nitrogen per hectare cut the maturity period to 88.5 days, from a baseline of 103.27 days without fertilization. However, Fentaye and Bewuket (2023) noted that there is a non-linear relationship between nitrogen application and maturity time. They observed that too much nitrogen can actually delay maturity; in their study, plants without nitrogen matured earliest, in 92 days, while those with 195 kg of nitrogen per hectare took more than 105 days to mature. These results suggest that while nitrogen generally promotes faster growth, using too much can lead to excessive vegetative growth and slow down the process of reaching maturity. This indicates the importance of carefully managing nutrient levels to achieve the best results in crop development.

Plant height

Nitrogen fertilization serves as a primary determinant of cabbage plant height and overall vegetative growth. Eyasu (2024) observed that an application of 150 kg Nha^{-1} produced the greatest plant height of 33.60 cm. This positive response to nitrogen is further supported by Terefa (2017), who recorded a maximum height of 24.65 cm using 92 kg Nha^{-1}, emphasizing the synergy between nutrient availability and moisture. Additionally, Teshome and Amide (2020) reported that a combination of 235 kg Nha^{-1} and 138 kg Pha^{-1} achieved a maximum height of 26.4 cm, compared to only 16.9 cm in unfertilized control groups. Collectively, these studies demonstrate that increasing nitrogen levels, whether applied alone or in combination with phosphorus and optimal management practices, is essential for maximizing the vertical development of cabbage.

Plant spread

Urea-derived nitrogen plays a key role in the growth and spread of cabbage plants, but its effectiveness depends on the specific conditions of the area. Studies conducted in various parts of Ethiopia show that nitrogen usually helps plants grow wider, but using too much can cause problems, such as a flattened plant shape or smaller size. For example, Gosa and Fufa (2023) found that applying 150 kilograms of nitrogen per hectare resulted in a maximum plant spread of 43.70 centimeters, which is higher than the 39.43 centimeters seen in untreated plants. Similarly, Demoz (2016) observed that 102.5 kilograms of nitrogen per hectare led to a maximum spread of 32.51 centimeters, which is much better than the 18.66 centimeters measured in fields with no fertilizer. At a more balanced level, Terefa (2017) noted that 92 kilograms of nitrogen per hectare achieved a maximum spread of 38.77 centimeters, compared to a baseline of 24.46 centimeters. Most interestingly, Eyasu (2024) recorded a maximum spread of 73.66 centimeters at a rate of 150 kilograms of nitrogen per hectare, which is a significant increase from the 52.68 centimeters in control plots. Overall, these results indicate that nitrogen is important for plant growth, but the amount of growth it causes can change depending on the environment. Therefore, it is important to apply nitrogen carefully to achieve the best possible plant structure.

Leaf width

Soil nitrogen availability is a key factor that determines how cabbage leaves grow, directly affecting the plant's structure and its ability to perform photosynthesis (Manea 2017).Nitrogen is important for increasing leaf width, but the best amount of nitrogen needed to achieve the most growth varies depending on the specific type of cabbage and environmental conditions.

When looking at real-world data, applying nitrogen fertilizer consistently leads to greater lateral leaf growth compared to not using fertilizer. For example, Yebirzaf (2017)found that cabbage leaves reached a maximum width of 21.81 cm when nitrogen was applied, compared to just 16.93 cm in plots without nitrogen. However, Fentaye and Bewuket (2023) found a different pattern; while leaf width increased from 15.61 cm to 25.63 cm with a high nitrogen rate of 195 kg N per hectare, the widest leaves were actually observed at a lower rate of 102.5 kg N per hectare, which reached 32.51 cm. This shows that too much nitrogen can sometimes limit how wide the leaves can grow.

There is still an important research gap because the combined effect of three fertilizers NPS, Urea, and KCl has not been studied in the specific climate and farming conditions of the Harbu District. Most existing studies focus on using nitrogen or urea alone, meaning there is a lack of data on how combining different nutrients can influence leaf width in modern hybrid cabbage varieties compared to traditional open-pollinated types.

Number of leaves

The available studies show a common pattern where the use of nitrogen is a key factor in promoting the growth and health of cabbage plants, including their vegetative development, biomass increase every two weeks, and leaf production (Terefa 2017). Additionally, the availability of nitrogen influences the physical differences between internal wrapper (folded) and external non-wrapper (unfolded) leaves. Typically, as nutrient levels improve, the internal head of the cabbage develops more than the outer leaves.

When looking at the number of leaves and how the plant structures itself, higher amounts of nitrogen significantly improve leaf differentiation, regardless of the environment or type of cabbage. In high-altitude settings, applying 294 kg of nitrogen per hectare led to a maximum of 16.66 leaves per plant (Teshome *et al.* 2018). For the internal structure, the number of wrapper leaves was best when 150 kg of nitrogen per hectare was applied, resulting in 10.39 wrapper leaves per plant (Yebirzaf 2017).The Lendini cultivar achieved 36.00 folded leaves when 109.5 kg of nitrogen per hectare was used (Abie and Tizazu 2024). On the other hand, the response of the unfolded outer leaves is inconsistent; Abie and Tizazu (2024) found that 109.5 kg of nitrogen per hectare maximized the number of unfolded leaves (26.67) in the Copenhagen Market variety. However, Terefa (2017) observed the opposite effect, where control plots without nitrogen application had the highest number of outer leaves (18.86), while nitrogen application led to a steady decrease in their number.

Head diameter

Nitrogen application plays a key role in determining the size of cabbage heads, and the best amounts of nitrogen needed can vary a lot depending on the type of farming area. Studies show that there is a strong connection between the availability of nitrogen and how big the cabbage heads become.

For instance, Teshome and Amide (2020) found that applying 235 kg of nitrogen per hectare resulted in cabbage heads that were 25.44 cm in diameter, which is much larger than the 10.31 cm observed in plants that were not fertilized. Other regional studies also support this trend: Abie and Tizazu (2024)observed a head diameter of 20.68 cm with 109.5 kg of nitrogen per hectare in North West Amhara, while Terefa (2017)noted 17.43 cm with 92 kg of nitrogen per hectare and Jaleta (2019) recorded 17.03 cm with 150 kg of nitrogen per hectare. However, Teshome *et al.* (2018) found that in Southern Oromia, the head size reached its peak at 17.03 cm with 235 kg of nitrogen per hectare, but it started to decrease when more nitrogen was applied. This suggests that there is a point where adding more nitrogen does not lead to bigger heads and may even harm plant growth by encouraging too much leaf growth instead. Therefore, it is important to tailor nitrogen application to specific growing areas to avoid using too much, which can slow down the growth of the cabbage heads.

Fresh weight

Urea-derived nitrogen plays a key role in determining the fresh head weight of cabbage, leading to significant increases in biomass and yield compared to areas without fertilization, regardless of the environmental conditions. Implementing variable-rate precision nutrient management allows for a reduction of up to 25% in nitrogen application without affecting the fresh head weight, highlighting the importance of efficient fertilizer use and economic sustainability (Mashabela *et al.* 2018).

When comparing regional data, the response in terms of yield varies depending on environmental factors and soil characteristics. In areas with high input usage, applying 150 kg of nitrogen per hectare nearly doubled the head weight, reaching 0.771 kg per plant in Debre Markos (Yebirzaf, 2017), and in another trial, it reached up to 2.5 kg per plant compared to plots with no fertilizer (Jaleta, 2019).Surprisingly, high yields were also achieved with more moderate nitrogen levels. In Jimma, applying 92 kg of nitrogen per hectare maximized fresh head weight to 5.7 kg per plant (Terefa,2017) and 3.28 kg per plant (Mohammed, 2024), which were much higher than the yields observed in the control treatments.

Dry weight

Nitrogen fertilization plays a key role in the buildup of dry matter in cabbage plants. It directly shows how well the plant is able to produce and store energy, along with its nutritional value and how tightly packed its structure. More nitrogen available in small amounts helps the plant use the energy it gets from photosynthesis more effectively, leading to more compact and productive dry biomass.

Looking at the differences in structural density and dry weight from field tests, it shows that using the right amount of nitrogen can almost double the biological productivity compared to plants that don't get enough nutrients. Research by Terefa (2017) found that the highest amount of dry matter was 7.36% when 92 kg of nitrogen was applied per hectare, compared to 3.43% in plants that didn't get enough nutrients. When looking at actual weight, applying 150 kg of nitrogen per hectare resulted in each cabbage plant having a dry weight of 0.114 kg, which is much higher than the 0.043 kg seen in control plants (Yebirzaf, 2017). Fentaye and Bewuket (2023) showed that when nitrogen is used properly, it's possible for total dry biomass to reach up to 1.94 kg per plant. All these results show that having the right amount of nitrogen is important for helping cabbage plants grow more and produce higher yields.

Marketable and unmarketable yield

Nitrogen fertilization plays a key role in the accumulation of dry matter in cabbage, directly showing how much the plant can produce in terms of biomass. Studies show that nitrogen levels strongly influence the commercial value of cabbage, with higher nitrogen input linked to better marketable yields and less waste, such as undersized, split, or rotten heads. However, it is important to carefully manage nitrogen levels because too much can damage the cabbage, making it less saleable.

Looking at real data, using nitrogen improves commercial results significantly when compared to growing without it. The highest marketable yield was 64.5 tons per hectare with 92 kg of nitrogen per hectare (Terefa, 2017), 46.74 tons per hectare with 109.5 kg of nitrogen per hectare (Abie and Tizazu, 2024), and up to 94.96 tons per hectare with 150 kg of nitrogen per hectare (Eyasu (2024).At the same time, unmarketable waste decreased from 30.91 tons per hectare in untreated crops to 7

tons per hectare (Terefa, 2017), a trend supported by Eyasu (2024), who saw unmarketable heads drop from 19.41 tons per hectare to 6.69 tons per hectare. However, Abie and Tizazu (2024) found that using too much nitrogen, such as 109.5 kg per hectare, led to the highest unmarketable yield (2.19 tons per hectare) because it caused excessive splitting and rotting. Overall, these results highlight that while nitrogen is important for increasing cabbage weight, it is necessary to use the right amount to keep the cabbage strong and suitable for sale.

Harvest index

The harvest index (HI) is an important measure of how efficiently a plant uses its resources and biomass to produce a valuable yield. In the case of cabbage, the availability of nitrogen plays a key role in how the plant allocates its growth from leaves to the head. Eyasu (2024) found that applying 150 kg of nitrogen per hectare increased the harvest index to 94.08%, which is much higher than the 72.05% seen in plots without fertilizer. Terefa (2017) also showed that using 92 kg of nitrogen per hectare led to a maximum harvest index of 60%, compared to 36.19% in untreated plots. These results highlight the importance of managing nitrogen levels properly to improve the plant's ability to produce high-quality cabbage that is suitable for sale.

However, there is still a gap in research because no studies have looked at how combining three fertilizers NPS, Urea, and KCl affects cabbage grown in the specific environmental conditions of the Harbu District. Most existing studies focus on using nitrogen alone, leaving little information on how combining different nutrients can influence both growth and yield in modern hybrid and open-pollinated cabbage varieties.

2.3.3. Effect of Kcl on Phenology, Growth and Yield of Cabbage

Potassium (K) is crucial nutrient for cabbage production as it regulates water balance, improves head firmness, and maximize yields. Potassium Chloride (Kcl) also known as Murate of Potash, plays a key role in many physiological processes like managing water balance, helping with stomatal movement, transporting carbohydrates, activating enzymes, and accumulating dry matter (Ahmad *et al.,* 2019). Cabbage, being a heavy potassium user, tends to show noticeable growth changes when K levels are low or just barely available in the soil (Mullualem *et al*., 2024).

Phenology parameters

By increasing enzyme activity and carbohydrate synthesis, potassium (K) nutrition essentially controls cabbage phenological velocity, according to the reviewed literature (Lu *et al*., 2022). In contrast to potassium deficiency, which delays maturity due to chlorosis and limited carbohydrate translocations (Attia *et al*., 2022), optimal potassium availability accelerates developmental timing and reduces the time to head initiation and physiological maturity by enabling plants to reach marketable size more quickly (Srivastava *et al*., 2018).

The form of distribution and dosage have a significant impact on cabbage's developing response when compared to particular chemical thresholds and application techniques. Although using Kcl for seed halo-priming greatly increases germination rates, vigor, and early seedling growth (Oliveira *et al*., 2019), direct soil application has severe constraints because of salinity hazards. Over application of Kcl to the soil increases electrical conductivity (EC), resulting in salt toxicity that actively prevents early growth (Mahato, 2019). When application rates of 117–127 kg K2O ha-1 are synchronized 15–21 days after transplanting, the most reliable accelerating response in head development is obtained globally (Wang *et al*., 2025).

(Oliveira *et al*., 2019), direct soil application possesses strict limitations due to salinity risks. Excessive soil-applied Kcl elevates electrical conductivity (EC), causing salt toxicity that actively inhibits early growth ((Mahato, 2019).Globally, the most consistent accelerating response in head development is achieved at application rates of 117–127 kg K_2O ha^{-1}, provided it is synchronized 15–21 days after transplanting (Wang *et al*., 2025).

However, the synergistic effect of these three fertilizers (KCl, urea, and KCl) used in combination has not yet been investigated under the unique agro-ecological circumstances of the Harbu District, leaving a crucial research gap. There is a dearth of localized empirical data on how combining Kcl with blended NPS and urea determines the phenological timeline of contemporary hybrid cabbage varieties versus open-pollinated standard, as the majority of current international literature focuses on isolated potassium dynamics or generalized global baselines.

Growth parameters

By increasing cell turgidity, canopy expansion, and photosynthetic capacity, potassium nutrition is a major factor in cabbage growth and structural development (Lu *et al*., 2022). Although higher foliar and shoot K concentrations are physiologically driven by higher potassium inputs, the growth relationship is non-linear because high application rates run the risk of creating serious nutritional imbalances with secondary and micronutrients like calcium, magnesium, and zinc (Silva *et al.*, 2021).

Based on nutrient balances, structural dimensions differ considerably when comparing particular thresholds and chemical sources. Mahato (2019), for example, reached a maximum head diameter of 19.05 cm at a rate of 150 kg K2o, whereas vertical head height can rise to 128 kg K2O (Silva *et al.*, 2021). In terms of the chemical carriers, Kcl actively facilitates the uptake of phosphorus and potassium, whereas other forms, such as K2SO4, may facilitate a more efficient absorption of secondary cations, such as calcium, magnesium, iron, and manganese *(Zhao et al*., 2025).

However, the synergistic effect of these three fertilizers (NPS, urea, and KCl) applied in combination has not yet been investigated under the unique agro-ecological circumstances of the Harbu District, leaving a crucial research vacuum. There is a dearth of empirical evidence on how localized multi-nutrient optimization controls vegetative growth characteristics across contemporary hybrid cabbage varieties in comparison to open-pollinated standards because the majority of current studies focus on solo or isolated potassium treatments.

Yield parameter

Potassium fertilization significantly increases the accumulation of dry matter and fresh biomass as it enhances the translocation of carbohydrates from the outer leaves to the storage tissues of the head*(Attia et al*., 2022). The weight of the head is one of the most sensitive traits and K improves water retention and compactness (Srivastava *et al.*, 2018). Meta-analyses(Silva *et al.*, 2021) have found that optimum K rates can increase single head mass by ~25.46%. At application rates of 150 kg K2O ha-1, yields of up to 1.87 kg per head are possible(Kumbhare and Daniel, 2023).

Application of potassium has been demonstrated to increase the total cabbage production by a mean of 32.82% as compared to unfertilized trials(Wang *et al*., 2025). In addition to weight, potassium improved quality parameters such as vitamin C concentration (Choudhary *et al*., 2024). In some soil situations, the difference in productivity between Kcl and K2SO4 is negligible if the Potassium status in the soil is adequate. However, researchers have found a plateau effect where the yield gains drop after a modest K threshold is reached(Oliveira *et al.*, 2019).

2.4. Response of Cabbage Varieties for Inorganic Fertilizer Application Rate

Genotypic selection is an important factor for productivity and seasonal adaptability of cabbage. Samuel (2023) found Landini to outperform the Victoria variety in terms of maximum head weights of 2.86–2.9 kg and marketable yields of 51–52.08 tha-1 in Belg and Kiremit seasons. This physiological dominance was also reported by Habib *et al.* (2018),who found that Atlas-70 significantly out yielded Super tropic in plant height, spread, leaf size, lateral root development, stem diameter and final head weights at 75 days after transplanting .

Cabbage productivity is basically related to intensified nitrogen (N) and phosphorus (P) fertilization, but maximum results are obtained by an integrated approach. Moreover, Teshome *et al.* (2018), reported that the best benchmarks for maximizing the head diameter and marketable yield were 235 kg urea ha^{-1} and 82 kg P2O5 ha^{-1} when the chemical fertilizers were combined with organic manure. In the Ethiopian context, , Muhamed (2024) reported that 240 kg urea ha^{-1} was a very effective rate and the yield increased linearly from 18.2 to 31.4 t ha^{-1} as urea rates increased from 100 to 240 kg ha^{-1} but they noted that nitrogen recovery efficiency started to decline as yields approached the 300 kg urea ha^{-1} threshold.

Maximizing commercial output requires a phased management strategy, utilizing early nitrogen for vegetative expansion followed by phosphorus and potassium for head structural integrity. While higher urea levels improve head uniformity and leaf area, Muhamed (2024) cautioned that excessive application increases relative core length and reduces head dry matter content. Furthermore, Teshome *et al.* (2018) emphasized that over-fertilization beyond established thresholds can lead to soil acidification. Collectively, these studies underscore that sustainable, high-yield production depends on pairing high-performing genotypes with precisely calibrated nutrient inputs to balance total tonnage against structural quality and soil health.

2.5. Theoretical /conceptual framework of the study

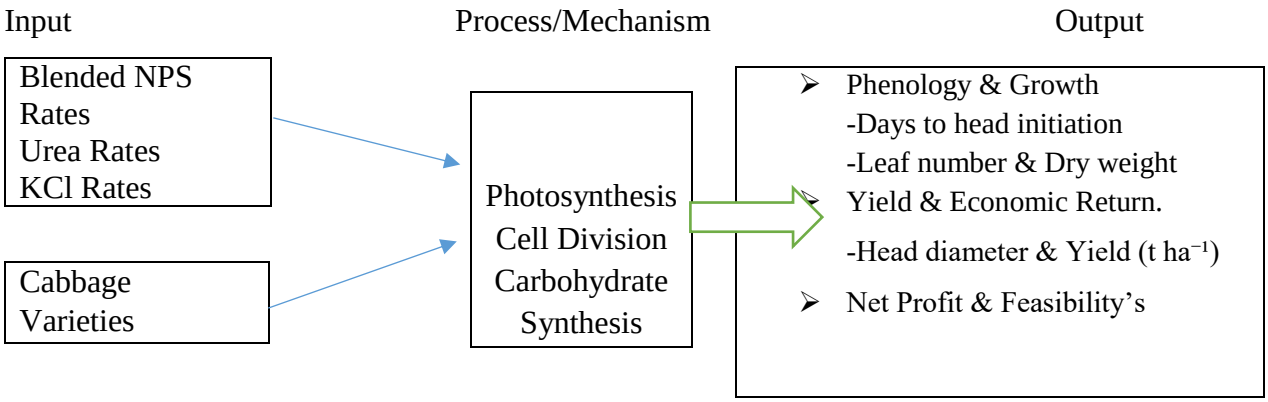


Figure 1: Illustrates the conceptual framework of the study.

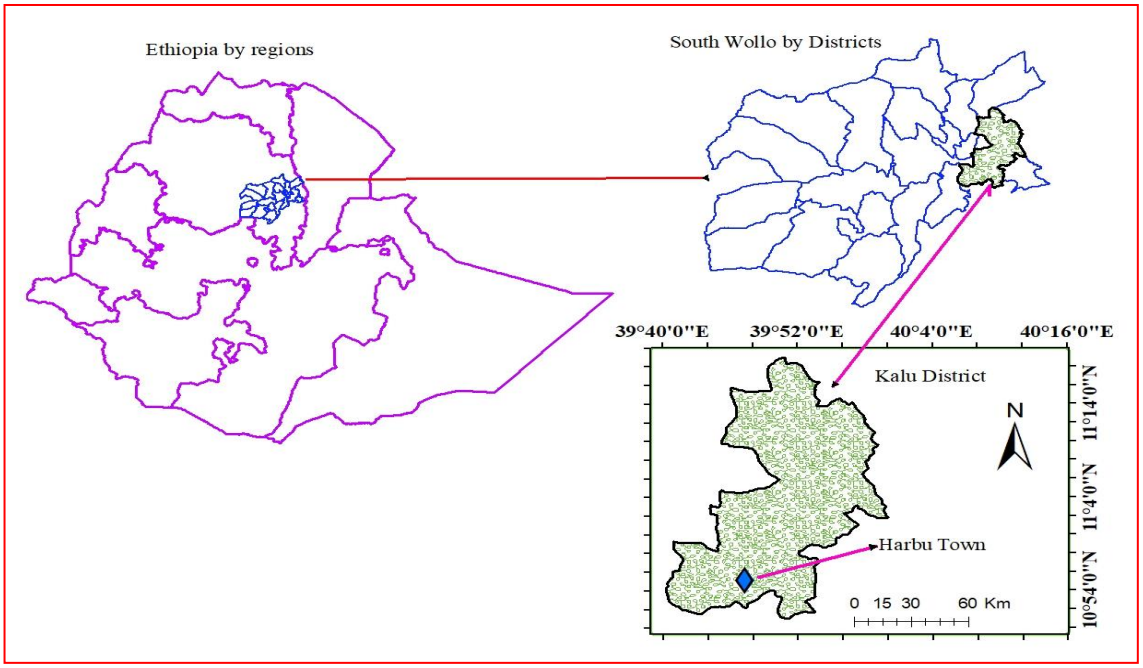
Diagram of the relationship between the independent and dependent variable. The independent variables are composed of agronomic treatments, i.e. three cabbage varieties and five levels of blended NPS, Urea and Kcl fertilizer rates. The framework suggests that the systematic variation and interaction of these nutrients directly influence the physiological and biochemical processes of the cabbage plants (like photosynthesis and cell division). The consequences are reflected in the dependent variables, such as phenological traits, vegetative growth measurements, final fresh head yields and the overall economic viability of the production system.

3. MATERIAL AND METHODS

3.1 Description of the Experimental Study Area

The experiment was conducted during the 2025/2026 irrigated cropping season at the practical site of Kombolcha Polytechnic College, Harbu District, South Wollo Zone of Amhara Region, Ethiopia. It is situated approximately 354 km from Addis Ababa and 54 km southeast of Dessie, and geographically positioned at 10°55'12"N latitude and 39°47'13"E longitude, with an elevation of 1000 mater above sea level (masl.) (Chekole and Ahmed, 2023). The study area follows a bimodal rainfall pattern that is the main season (Kiremit) spans July to September, and instead of short season (Belg) extends from March to June. According to Kombolcha Meteorological station (KMS, 2023), the area receives an annual average rainfall between 800 mm and 1,200 mm. Thermal records indicate a mean minimum temperature of 13.22°C and a mean maximum of 27.43°C. Additional environmental parameters provided by KMS (2023) include an average relative humidity of 48.7%, a wind run of 0.73 km/h, and a mean sunshine duration of 7.5 hours.

The soil of the experimental site is dominantly composed of clay, clay loam, and sandy loam textures, with a pH range of 6.6 to 8.0, indicating conditions ranging from slightly acidic to slightly alkaline. The Harbu Agricultural and Natural Resources Development Office (HANRDO, 2023) identifies the district's primary agricultural output as a mix of cereals, legumes, and fruits, alongside key vegetable crops including cabbage, onion, tomato, and carrot.



Source: Harbu district agricultural office.

Figure 2: Map of study area

3.2. Description of Experimental Materials

3.2.1. Planting Material

The cabbage variety commonly grown in the area (Copenhagen Market) and two hybrid varieties (Chaka, Tacoma) were used for the experiment and the seeds were collected from a commercial seed trader named Green life Trading Plc and Ethio Veg-fruit farm Private limited company. The choices of these varieties were made based on their early maturity (75-110 days) after transplanting, and heads are more uniform with a weight of 2.5 kg, making them the best choice for growers and consumers in the area.

Table 1: Description of the cabbage Varieties used for experiment

Crop	Cultivars	Yield potential(Q/ha)	Head shape	Altitude adaptation (masl)	Maturity time
Cabbage	Copenhagen (OPV)	> 300	Round	500-3000	75-95 days
	Chaka (hybrid)	1083 and 1270 on farm and on station	Round	500-3000	90-110 days
	Tacoma (hybrid)		flat-round	500-3000	70-86 days

Source: (MoA, (2019)

3.2.2 Fertilizer description

The inorganic fertilizers used in the study included NPS (19% N, 38% P_2O_5, and 7% S), Urea (46% N), and Kcl (60% K_2O). These fertilizers were sourced from the Borkena Multi-Purpose Farmers' Cooperative Union and the SNV-Kalu Project organization.

3.3. Soil Sample Analysis

Prior to transplanting, soil samples were collected at a depth of 0-20 cm from twenty sampling points across the experimental field using a zigzag pattern and composited into a single representative sample according to the procedures the procedures described by Abera *et al*. (2020). The composite soil was air-dried, ground, and passed through a 2 mm sieve, after which a 1 kg representative sub-sample was submitted to Debre Berhan Agricultural Research Center for physico-chemical analysis.

Laboratory determinations was conducted to characterize the baseline soil fertility status of the experimental site using standard analytical procedures(Terefa, 2017). Soil texture was determined using Bouyoucos hydrometer method. Soil pH was measured potentiometrically using a digital pH

meter in a 1:2.5 soil-to-water suspension. Total nitrogen (N) was analyzed using the micro-Kjeldahl digestion and distillation method. Available phosphorus (P) was extracted using the Olsen method, while available sulfur (S) was determined using the turbidimetric method after sulfate extraction. Exchangeable potassium (K) and cation exchange capacity were determined using the 1M ammonium acetate (PH 7.0) method. Furthermore, soil organic carbon (SOC) was determined using the Walkley and Black wet oxidation method.

3.4 Experimental design and Treatment

The experiment was laid out in a Randomized Complete Block Design (RCBD) with a 3 × 5 factorial arrangement replicated three times, resulting in a total of 45 experimental plots. The treatments comprised two factors: cabbage cultivars and inorganic fertilizer rates. The cultivar factor included three varieties: one open-pollinated variety (Copenhagen Market) and two hybrids (Chaka and Tacoma). The fertilizer factor consisted of five rates based on SNV and Bureau of Agriculture (BoA) recommendations:

T_1 (Control): 0 kg NPS + 0 kg Urea + 0 kg KCl ha^{-1}

T_2:242 kg NPS + 150 kg Urea + 0 kg KCl ha^{-1}

T_3: 200 kg NPS + 160 kg Urea + 50 kg KCl ha^{-1}

T_4: 400 kg NPS + 320 kg Urea + 100 kg KCl ha^{-1}

T_5: 600 kg NPS + 480 kg Urea + 150 kg KCl ha^{-1}.

3.5. Experimental Procedures and Field Management

3.5.1. Nursery Operation

Cabbage seedlings were raised on well-prepared nursery beds at the Harbu Agriculture Campus. Before sowing, 50 g NPS and 60 g Kcl per $5m^2$ were applied. Sowing was conducted on September 12, 2025. Following sowing, the beds were mulched with sacks and irrigated daily until germination was achieved, at which point the mulching material was removed when the seeds germinate and usually 5-7 days to facilitate vigorous growth under full solar radiation. Twenty days' after sowing,

50 g urea per 5m² was applied by broadcasting. The seedlings were maintained in the nursery until they developed two pairs of true leaves, meeting the appropriate stage for transplanting to the experimental field in accordance with the guidelines established by MoA (2019).

3.5.2. Land Preparation, and Production Procedure

The experimental field was prepared through two rounds of oxen ploughing to achieve a fine tilth and was leveled before transplanting. The experiment was arranged in a randomized complete block design (RCBD), with treatments randomly assigned within each block to minimize experimental error. Each plot measured 3 m × 3 m (9 m²) and consisted of five rows of cabbage. Plants were spaced at 60 cm between rows and 40 cm within rows, resulting in 40 plants per plot (Mossie *et al*., 2022)Blocks were separated by 1 m and plots by 0.5 m. The outermost rows and end plants served as border plants, while data were collected from the three central rows, giving a net plot area of 3.96 m².

Following MoA and SNV recommendations, 100% of NPS and Kcl fertilizers were applied two days before transplanting (Taye *et al.*, 2025). Urea was applied in two equal splits: 50% two weeks after transplanting and the remaining 50% five weeks after transplanting (Eyasu, 2024).Thirty-four-day-old seedlings were transplanted on October 16, 2025, at a spacing of 60 cm × 40 cm. Missing plants were replaced within 10 days after transplanting to maintain a uniform plant population (Terefa, 2017).

Irrigation was performed uniformly across all plots using the furrow method. To ensure optimal root zone moisture and avoid water stress, plots were irrigated at a 3-day interval during the initial growth stage, transitioning to a 6-day frequency during head development. The volume of water applied per event was adjusted according to the cabbage crop water requirements (ETc.), delivering approximately 25 mm of water per irrigation to keep the soil moisture near field capacity(Eyasu, 2024). Water application was scheduled exclusively in the late evening to minimize evaporation losses and maintain strict uniformity across all 45 experimental plots.

All agronomic practices, including weeding, and cultivation, were applied uniformly across all treatments following standard recommendations (Gelaye & Tadele, 2022). Fastac 10 EC (1 ml L^{-1} water) was used to control aphids and leaf caterpillars, while Mancozeb 80 WP was applied to

prevent fungal diseases. Both chemicals were sprayed twice at 15-day intervals when infestation symptoms first appeared (Gelaye & Tadele, 2022). No significant disease incidence was observed during the experimental period.

Harvesting was carried out selectively as heads reached physiological maturity, indicated by optimum firmness and compactness. Since maturity was not uniform, harvesting was conducted in stages to ensure accurate assessment of marketable yield.

3.6. Crop Data Collection and Measurements

Growth and yield parameters were recorded from ten randomly selected plants within the 3.96 m^2 net plot area, following the established sampling protocols established by Abera *et al*. (2020). Total yield data obtained from the central three rows were converted to a per-hectare basis (t ha^{-1}) for standardized comparison.

3.6.1. Phenology and growth parameters

Days to 50% head initiation. Was recorded by counting the duration from the date of transplanting until 50% of the plants in each net plot area exhibited visible head formation (Teshome *et al*., 2018).

Days to 90% maturity. Was recorded for each net plot area by calculating the time elapsed from transplanting until 90% of the cabbage heads reached full compactness and firmness with fingers and by visual observation and the number of days was used for analysis (Teshome *et al.*, 2018).

Number of Leaves (No.) Leaf counts was recorded by counting outer non-wrapped leaves at 45 day after transplanting before curling of leaf from ten randomly selected plants in the central rows (Abie and Tizazu, 2024).

Plant spread (cm) . To avoid border effects, this parameter was measured at harvest time from 10 randomly selected sample plants within the central rows of each experimental plot. Measurement was taken using a ruler from East-to-West and North-to-South directions, and the mean values were used for analysis(Eyasu, 2024).

Leaf width (cm). The maximum width of the longest leaf was measured at its widest point using a ruler from ten randomly selected and pre-tagged plants per plot at the **50% head initiation stage**(Abera *et al*., 2020).

3.6.2. Yield and yield components

Head diameter (cm) was measured using a ruler during harvesting from ten randomly selected and pre-tagged plants by sectioned horizontally at the middle portion with a sharp knife during harvesting and the mean value is used for analysis (Fentaye & Bewuket, 2023).

Whole plant fresh weight (WPFW) (kg plant^{-1}). randomly selected sample plants were taken from the central rows of each plot area and the entire biomass of the whole plant parts was measured using sensitive digital balance (Eyasu, 2024).

Head Fresh weight (kg plant^{-1}). was determined by harvesting ten randomly selected plants from the central rows of each net plot and measuring the entire biomass, including closely wrapped leaves, using sensitive balance to calculate the average weight in kilograms per plant (Eyasu, 2024).

Dry weight (kg plant^{-1}) was determined by preparing 100 g homogenate sub-samples from ten randomly selected, washed, and chopped cabbage heads per plot area, oven-drying them in paper bags at 70°C for 48 hours until a constant weight was attained, and finally weighing the samples on a sensitive digital balance to calculate the ratio of dry weight to initial fresh weight multiplied by 100 (Eyasu, 2024).

Dry Weight (kg plant^{-1}) $=\frac{\mathrm{DSW}}{\mathrm{FSW}}$*Head Fresh Weight (kg plant^{-1})

Where: DSW = Dry sample weight (g), and FSW = Initial fresh sample weight (100 g)

Marketable yield (t ha $^{-1}$)*:* was determined by harvesting cabbage heads exclusively from the central rows of each net plot area to eliminate border effects and isolate true treatment responses. Harvested head were sorted based on quality parameters; only well-formed, compact heads free from pests, diseases, or mechanical damage, and meeting a strict commercial threshold of 0.5 kg, were classified as marketable to align with Ethiopian consumer preferences (Mohammed, 2024). The sorted heads were weighed with sensitive balance to determine the economically viable yield,

and the net plot data was converted to tons per hectare (t ha^{-1}) for standardized agronomic comparison.

Unmarketable yield (t ha^{-1}) was determined by harvesting cabbage heads from the net plot area, excluding border rows to eliminate edge-effect anomalies and isolating those unfit for commercial sale. Gelaye (2024a) noted that, heads that were diseased, rotted, pest damaged, split, undersized (<0.5kg), or loose were classified as unmarketable to eliminate human bias and match local Ethiopian market rejection standards. Documenting these specific defects serves as a direct physiological indicator of nutrient imbalances (such as splitting from excessive Urea or loose heads from KCl deficiency) and genetic vulnerabilities. The rejected heads were weighted using sensitive balance to prevent the overestimation of economic returns, and the net plot data was converted to tons per hectare (t ha^{-1}) to calculate accurate total biological yield and enable standardized agronomic accounting.

Total yield (t ha^{-1}) was recorded by summing the marketable and unmarketable cabbage yield weights. The total was expressed on a ton per hectare basis (Eyasu, 2024).

Harvest index (HI %) was determined by calculating the ratio of the fresh cabbage head weight (economic yield) to the total weight of the whole plant excluding the root (biological yield), based on measurements taken from ten randomly selected plants per net plot (Terefa, 2017).

$$HI=\frac{EHW}{TBY}*100$$

Where, HI=Harvest index, EHW=Economic head yield, TBY=Total biological yield

3.7. Statistical Data analyses:

Agronomic data were subjected to an the analysis of variance (ANOVA) following the procedures described by Gomez *et al*. (1984). Statistical analysis were performed using R software and the mean separation was conducted using the Tukeys Honestly Significant Difference (HSD) test at 5% probability level ($p \leq 0.05$).

3.8. Partial Budget Analysis:

A partial budget analysis was performed to evaluate the relative economic feasibility of the treatments using the methodology described by CIMMYT (1988). To account for the management variability between experimental conditions and smallholder farmer practices, the harvested cabbage yields were adjusted downward by 10% (Abera *et al*., 2020). Economic data were calculated based on prevailing market prices in Harbu, South Wollo Zone.

The following economic indicators were utilizes

Gross Benefit (GB) Calculated as the product of the adjusted yield (t ha^{-1}) and the field price of cabbage (25 Birr kg^{-1}).

$GB=(AY * FP)$

Where, GB=Gross benefit, AY=Adjusted yield, FP=Field price

Net Benefit (NB): Derived by subtracting the Total Variable Cost (TVC) from the Gross Benefit. TVC included fertilizer costs (NPS, Urea, and KCl), labor.

$NB=GB - TVC$

Where, NB=Net benefit, GB=Gross benefit, TVC=Total variable cost

Dominance Analysis: Treatments were ranked in order of increasing total variable costs. A treatment was considered dominated and excluded from further marginal analysis if it resulted in a lower net benefit than a preceding treatment with a lower variable cost.

Marginal Rate of Return (MRR): Calculated for undominated treatments to measure the percentage increase in net benefit relative to the increase in variable cost when moving from a lower-cost to a higher-cost treatment. The MRR was determined using the formula:

$$MRR\ (\%) = \frac{NB}{TVC} * 100$$

Where, MRR=Marginal rate of return, NB=Net benefit, TVC=Total variable cost

4. RESULT AND DISCUSSION

4.1 Soil Physical and Chemical Characterization

The soil samples collected from the study site in Habru district were analyzed at Debre Birhan Agricultural Research Center (DBARC) Soil and Water Laboratory. The results, represents the baseline and postharvest edaphic conditions of the experimental site, are presented in table 2.

Soil Texture

The soil of the experimental site has sand (28%), clay (34%), and silt (38%) which is texturally classified as a Clay Loam which is suitable for cabbage production. This texture suggests the soil has a high water-holding capacity and moderate drainage.

Soil pH and Electrical Conductivity

The soil pH of 7.5 indicates a slightly alkaline reaction. While this range is generally suitable for most highland crops, it is approaching the threshold where the availability of certain micronutrients (such as manganese and Iron) and phosphors may become limited due to precipitation. The Electrical Conductivity (EC) of 0.165 ds/m is well below the 2.0 ds/m threshold, indicating that the soil is non-saline and poses no osmotic stress to crops (Yunan *et al*., 2018).

Soil Organic Matter and Nitrogen Status

The soil of the study area had low Organic Matter (1.79%) and low Total Nitrogen (0.10%) contents according to the (MoA, 2020) ratings. This suggests a depletion of soil organic reserves, likely due to intensive cultivation or low organic input return. Nitrogen is likely the primary limiting macronutrient in this soil, and its deficiency may hinder crop vegetative growth and yield potential.

Available Phosphorus, Potassium and Sulfur In contrast to many tropical soils, the experimental plot available Phosphorus (18.14 ppm) is low rate. This could be due to either high native phosphorus content or a history of High Crop residual Removal without sufficient fertilizer

replenishment during preceding in the last cropping season. Similarly, Exchangeable Potassium (0.60 cmol/kg) is moderate, suggesting that K is a limiting factor for production in this specific site (Bodena *et al*., 2016). The baseline available of Sulfur (S) content was (10.6ppm) which is classified low to marginal.

Cation Exchange Capacity (CEC) and Exchangeable Bases

The CEC was found to be 45.85 cmol(+)/kg, which is rated as very high (Yunan *et al.*, 2018). This indicates a superior capacity of the soil to retain and exchange cations, reflecting a high nutrient-buffering capacity. The exchangeable complex is dominated by Calcium (30.65 meq/100g) and Magnesium (9.25 meq/100g). Notably, the Exchangeable Sodium Percentage (ESP) is approximately 8.8%. While this is below the 15% threshold for sodic soils, it is high enough to potentially affect soil structure and aggregate stability in clay-heavy soils *(Hur et al*., 2009).

Micronutrient Status

Micronutrient concentrations of Cl for the study site is rated low while Fe, Mn, Zn, and Cu are all within the sufficient to high range (Table 2). Despite the slightly alkaline pH, there is currently no evidence of micronutrient deficiency, though Manganese levels are notably robust. In general, the results suggested that the fertility status of the experimental site soil was low and required the application of fertilizer for crop growth.

Table 2: The major chemical and physical property of soil analysis before transplanting

Parameter	Unit	Value	Rating	Reference
Physical Properties				
Sand / Clay / Silt	%	28 / 34 / 38	—	
Textural Class	—	Clay Loam		Bouyoucos (1962)
Chemical Properties				
pH (1:2.5)	—	7.5	slightly alkaline	(Hazelton and Murphy, 2016)
Elect. Conductivity (EC)	dS/m	0.165	Non-saline	Tekalign *et al*. (1991) and Berhanu (1980)

Organic Carbon (OC)	%	1.04	Low	(Yunan *et al*., 2018).
Organic Matter (OM)	%	1.79	Low	(Yunan *et al.*, 2018).
Cation Exchange Cap. (CEC)	cmol(+)/kg	45.85	Very high	(Yunan *et al*., 2018).
Macronutrients				(Yunan *et al*., 2018).
Total Nitrogen (TN)	%	0.1	Low	(MoA, 2020)
Available Phosphorus (P)	Ppm	18.14	Low	(Yunan et al., 2018).
Exchangeable Sodium (Na)	Cmol/kg	4.04	High	Tekalign *et al*. (1991) and Berhanu (1980)
Exchangeable Potassium (K)	cmol(+)/kg	0.60	Moderate	(Bodena *et al*., 2016).
Exchangeable Calcium (Ca)	meq/100g	30.65	Very high	(Hur et al., 2009).
Exchangeable Magnesium (Mg)	meq/100g	9.25	High	(Hur *et al*., 2009).
Available Sulfur (S)	Ppm	10.6	Low	Tekalign *et al*. (1991) and Berhanu (1980)
Micronutrients				
Chloride(cl^-)	(meq/L)	3.2	Low	(Abera & Kassa, 2017)
Iron (Fe)	Ppm	27.64	Suffitent	(Abera & Kassa, 2017)
Manganese (Mn)	Ppm	33.32	High	(Abera & Kassa, 2017)
Zinc (Zn)	Ppm	3.39	High	(Abera & Kassa, 2017)
Copper (Cu)	Ppm	1.98	High	(Abera & Kassa, 2017)

Note: Rating was done based on standard FAO/Landon (1991) soil interpretation guidelines.

4.2 Post-harvest soil Analysis

Total Nitrogen

The pre-planting analysis characterized the soil as having a critical deficiency in total nitrogen at 0.10%, which is considered low. Following harvest, total soil N ranged from 0.079% to 0.249% (Appendix Table 4). Control plots for the 'Copenhagen', 'Chaka', and 'Tacoma' varieties exhibited a slight decline to 0.079%, 0.085%, and 0.081%, respectively, indicating nutrient mining by the crop. In contrast, application of the highest fertilizer rate (600kg NPS + 480kg Urea + 150kg Kcl

ha^{-1}) significantly elevated post-harvest total N to 0.240% ('Copenhagen'), 0.249% ('Chaka'), and 0.249% ('Tacoma') (Appendix table 4). The stable-to-slight increase in fertilized plots was

attributed to the application of Urea (46% N) and NPS (19% N). As described by Gelaye (2024), nitrogen is a primary constraint for cabbage vegetative vigor, and its split application as practiced in this study helps maintain residual levels despite high crop uptake. However, the relatively small increase suggests that cabbage, being a heavy feeder, utilized a significant portion of the applied nitrogen for biomass and head development, or due to leaching.

Available Phosphorus

This parameter showed the most significant transformation. The pre-planting status was recorded at 18.14 ppm, which is classified as a "low" rate. This low initial level could be due to continuous crop removal (nutrient mining) under intensive cultivation without adequate replenishment of phosphate fertilizers. Post-harvest levels ranged from 14.32 to 48.96 ppm, where the lowest content was obtained from the control plot with the Copenhagen variety, and the maximum was from the Takoma variety treated with 600 kg NPS + 480 kg Urea + 150 kg Kcl ha^{-1} (Appendix Table 4).

While the control plot showed a slight decline due to further crop uptake, treatments with the 400 kg NPS + 320 kg Urea + 100 kg Kcl ha^{-1} and 200 kg NPS + 160 kg Urea + 50 kg Kcl ha^{-1}resulted in a sharp rise. This significant increase is directly linked to the application of NPS fertilizer, which contains 38% P_2O_5. Phosphorus is relatively immobile in the soil compared to nitrogen; therefore, consistent application leads to accumulation in the rhizosphere. According to Fentaye and Bewuket (2023), NPS fertilization optimizes nutrient availability and accelerates Phenological development. The high residual P suggests that the maximum application rates (up to 600 kg ha^{-1} NPS) exceeded the immediate removal capacity of the crop, thereby building up the soil's phosphorus bank across all varieties.

Exchangeable Potassium

The baseline soil was characterized as having a medium potassium capacity of 0.60 cmol (+) $kg^{-1.}$ Post-harvest values ranged from 0.565 to 0.895 cmol (+) kg^{-1}, where the lowest and highest values were recorded from the control plot and the 600 kg NPS + 480 kg Urea + 150 kg Kcl ha^{-1}treated

Chaka variety, respectively (Appendix Table 4). While the control plot showed a slight decline from the baseline due to crop uptake, the treated plots remained robust within the moderate-to-high range. Although the soil initially had a medium potassium status, the addition of Kcl (60% K_2O) helped maintain and build up these levels. Potassium is essential for osmotic regulation and the quality of cabbage heads. Choudhary et al. (2024) emphasize that integrated potassium management is vital for optimizing crop quality. The slight fluctuations across treatments might be due to the varying growth rates and subsequent K-uptake between the Chaka and Tacoma varieties.

Available of Sulfur

Post-harvest analysis highlighted a remarkable and highly treatment-dependent shift in available soil sulfur, transitioning from a low baseline of 10.6 ppm to a post-harvest range of 9.9 ppm to 38.2 ppm. While the lowest values were tracked within the unfertilized control plots—dropping to 9.90 ppm in the Tacoma plots due to severe nutrient exhaustion by the growing crop—the sulfur levels in fertilized plots surged significantly. Specifically, available sulfur reached its peak of 38.20 ppm for both the Chaka and Tacoma hybrid plots under the maximum application rate of 600 kg NPS + 480 kg Urea + 150 kg Kcl ha^{-1}, representing a 285.8% increase over the control. This major accumulation is directly associated with the sulfur (7% S) component embedded within the blended NPS matrix. This accumulation is beneficial because sulfur plays a vital biochemical role in protein synthesis, enzyme activation, and nitrogen-use efficiency in cabbage crops.

Chlorine (Cl) and Varietal Differences

Post-harvest analysis measured soil chlorine (Cl^-) levels, which ranged from a minimum of 1.6 meq L^{-1} (recorded in the Copenhagen control plots) to a maximum of 6.0 meq L^{-1} (recorded in the high-rate Tacoma plots), a trend likely introduced via Kcl application. Under unfertilized control conditions, chlorine levels were 1.6 meq L^{-1} for Copenhagen and 1.8 meq L^{-1} for Chaka. Interestingly, at the maximum fertilizer application rate (600 kg NPS + 480 kg Urea + 150 kg Kcl ha^{-1}), the Tacoma variety plots maintained the highest available chlorine levels (6.0 meq L^{-1}), followed by Chaka (5.6 meq L^{-1}), while the open-pollinated Copenhagen variety showed the lowest response among the three, reaching only 5.2 meq L^{-1}.

This variance suggests that the hybrid varieties (Tacoma and Chaka) possess superior nutrient utilization efficiencies or distinct rhizosphere interactions at elevated fertilizer rates compared to

the open-pollinated Copenhagen. This distinction strongly aligns with Eyasu (2024), who emphasized the necessity of transitioning to high-performing hybrids paired with optimized fertilizer packages to maximize nutrient response.

Table 3: The soil analysis after harvest

Soil Parameter	Pre-Planting (Baseline Value)	**Status**	Post-Harvest (Range) & Associated Treatment Rates	**Rating**	Reason / Reference
Total Nitrogen	0.10% (Low)	Low/ deficit	0.079% at Control / No fertilizer)	Medium (0.15–0.25%)	Tekalign (1991)
			0.249% (at Highest NPS/Urea rate)		
Available Phosphorus	18.14ppm low	Low	14.37ppm (at Control / No NPS)	Medium (30–50 ppm)	Tekalign (1991)
			48.96 ppm (at Highest NPS rate)		
Exchangeable Potassium	0.60cmol/kg Low	Low/ deficit	0.565 cmol+/kg at 0 kg/ha Kcl)	High (0.80–1.20 cmol(+)/kg	(FAO, 2006)
			0.895 cmol+/kg (at 150 kg/ha Kcl)		
Available Sulfur	10.6ppm (Low)	Low/ deficit	9.90 ppm (at Control / No NPS)	Medium (20–40 ppm)	(EthioSIS, 2014)
			38.20ppm (at Highest NPS rate)		

4.3. Phenological Parameters

4.3.1. Days to head formation

The analysis of variance (ANOVA) indicated that the number of days to 50% head initiation in cabbage was highly significant ($P < 0.01$) influenced by the main effects of variety and fertilizer levels while the interaction effect was not statistically significant (Appendix Table 1). The data

revealed that the earliest head initiation (53.31 days) observed from the application of 600 kg NPS ha^{-1} + 480 kg Urea + 150 kg Kcl ha^{-1} whereas the longest duration (60.2 days) was recorded in the control treatment (Table 4).the control treatment was statically at pare with 400 kg NPS ha^{-1} + 320 kg Urea + 100 kg Kcl ha^{-1} fertilizer rate (57.98 days), and the BoA recommendation rate (242 kg NPS + 150 kg ha^{-1}urea) (57.40 days) (Table 4)

The application of increased fertilizer from (200 kg NPS ha^{-1} + 160 kg Urea + 50 kg Kcl $ha^{-1)}$ rate to the (400 kg NPS ha^{-1} + 320 kg Urea + 100 kg Kcl $ha^{-1)}$, significantly reduced the number of days to head initiation, and a further increased to 200 kg NPS ha^{-1} + 160 kg Urea + 50 kg Kcl ha^{-1} fertilizer rate resulted in a shortest head initiation time. This implies that reduced fertilizer rates by half resulted in delayed head initiation. This might be due to inadequate availability of nutrient, specifically nitrogen and phosphorus, which are essential for early vegetative growth. The acceleration of days from highest fertilizer rates comes mainly from the combination of Nitrogen (N), Phosphorus (P), and Sulfur(S). This mix encourages strong biomass growth and speeds up the shift from the vegetative phase to the reproductive phase. This trend matches the findings of Fentaye and Bewuket (2023), who revealed that, high NPS application rates result in the earliest head formation by improving nutrient availability in the rhizosphere. Similarly, Fentaye and Bewuket (2023) demonstrated that high NPS application rates optimize nutrient availability in the rhizosphere, significantly reducing the time to head formation. While all varieties responded to highest fertilizer rate by heading earlier but the magnitude of this response was varied. Additionally, the role Potassium (K) in accelerating head initiation could be attributed to its involvement in enzyme activity and carbohydrate synthesis.

Regarding the varietal effect, the variety Copenhagen reached 50% head initiation early (50.26 days), while the longest duration (63.70 days) was recorded in the Chaka variety (Table 4). This variation confirms that genotypic selection is a primary determinant of cabbage productivity and Phenological timing. Habib *et al.* (2018), approves this idea, revealing that different cabbage varieties set its head at different time. .

4.3.2 Days to maturity

The ANOVA indicated that the number of days to 90% maturity in cabbage was highly significantly ($p < 0.001$) influenced by the main effects of variety and fertilizer level, however, the interaction

effect between fertilizer and variety was not statistically significant (Appendix Table 1). The longest duration (91.47 days) to reach physiological maturity was recorded from control treatment while the earliest maturity (80.13 days) was achieved by the Copenhagen variety treated with 50% plus the SNV rate, but non-significant difference with the (400 kg NPS ha^{-1} + 320 kg Urea + 100 kg Kcl ha^{-1} (Table 3).generally, Maturity date of cabbage decreases as the fertilizer rate increases. This trend matches the findings of Fentaye and Bewuket (2023), who noted that high rates of NPS and Kcl result in earlier maturity by boosting biomass growth and speeding up the shift from the vegetative stage -to-reproductive phase transition.

Choosing the right variety had an even more pronounced effect on maturity than fertilization. The Chaka variety exhibited a significantly longer growth cycle, maturing at 98.17 days, whereas Copenhagen and Tacoma matured significantly earlier at 78.58 and 79.21 days, respectively which showed non-significant difference among them (Table 4). This disparity underscores that genotypic selection is a primary determinant of cabbage productivity and seasonal timing. The variation among these varieties reflects the environmental adaptability and specific maturity periods for which Ethiopian farmers select their crops (Habib *et al*., 2018).

Table 4: Effect of NPS, Urea and Kcl fertilizer rates and Cabbage Varieties on days to 50% head initiation and 90% maturity day.

Treatment	Days to 50% head initiation	Days to 90% maturity
Fertilizer (NPS + Urea + Kcl kg ha^{-1})		
Control (0+0+0)	60.22[a]	91.47[a]
242 + 150+0	57.40[ab]	85.19[bc]
200 + 160 + 50	57.98[a]	86.91[b]
400 + 320 + 100	54.39[bc]	82.90[cd]
600 + 480 + 150	53.31[c]	80.13[d]
MSD (0.05)	3.41	3.63
Variety		
Chaka	63.70[a]	98.17[a]
Tacoma	56.02[b]	79.21[b]
Copenhagen	50.26[c]	78.58[b]
HSD (%)	2.25	2.39

CV (%)	4.39	3.1

Note: Means within columns followed by the same letter are not significantly different at ($p < 0.05$) according to Significant Difference (HSD) test.

4.4 Growth Parameters of Cabbage

4.4.1 Plant height

Plant height of cabbage was highly significant ($P < 0.001$) influenced by the main effects of fertilizer, variety, and ($P < 0.05$) by their interaction (Appendix Table 2). The highest plant height (37.97 cm) was recorded in Chaka variety treated with the (600kg NPS + 80kg Urea + 150 kg Kcl) ha^{-1}, while the lowest plant height (16.60 cm) was observed in the Copenhagen variety under the control treatment (Table 5). All varieties increased in height as fertilizers were added, however the magnitude of increase was variety-dependent. For instance, the increase from 400kg NPS + 320kg Urea + 100kg Kcl ha^{-1} to 600kg NPS + 480kg Urea + 150kg Kcl ha^{-1} resulted in a significant height increment for Chaka (5.5 cm) but a smaller increase for Tacoma (1.0 cm)(Table5).

The application of reduced fertilizer by (200 kg NPS, 160 kg urea, and 50 kg Kcl ha^{-1}) significantly reduced the plant height , and a further increased to (600 kg NPS, 480 kg urea, and 150 kg Kcl ha^{-1}) resulted in a highest plant height across all varieties. This is due to improved nutrient availability, where nitrogen promotes cell division and leaf expansion, phosphorus helps in root development and energy transfer, and potassium enhances photosynthesis and water regulation (Habib *et al.* (2018).

This superior response highlights a strong synergy between the high genetic potential of hybrid-type varieties and a balanced supply of Nitrogen (N), Phosphorus (P), Sulfur (S), and Potassium (K). According to Samuel (2023) and Habib *et al.* (2018), modern varieties like Chaka possess a physiological dominance that allows them to utilize intensive nutrient regimes more efficiently for structural expansion than traditional cultivars. The presence of Potassium in the 150 kg Kcl ha^{-1} blend likely facilitated this height and leaf expansion by optimizing water balance and stomatal movement, which are essential for maintaining cell turgidity during rapid growth phases (Ahmad *et al.*, 2019). Moreover as noted by Fentaye and Bewuket (2023), lateral expansion and height are governed by the synergistic interaction of N, P and S, which drives cellular expansion.

Table 5: Interaction effect of inorganic Fertilizers (NPS, Urea, and Kcl) rates and cabbage varieties on plant height (cm).

Treatment	Variety			Mean
Fertilizer (NPS + Urea + Kcl kg ha^{-1})	Chaka	Tacoma	Copenhagen	
Control (0+0+0)	24.53^{i}	21.00^{j}	16.60^{k}	20.71^{e}
242 + 150 + 0	29.34^{e}	26.50^{g}	25.34^{h}	27.06^{c}
200 + 160 + 50	28.67^{e}	25.57^{h}	24.03^{i}	26.09^{d}
400 + 320 + 100	32.45^{b}	30.50^{d}	27.27^{f}	30.07^{b}
600 + 480 + 150	37.97^{a}	31.50^{c}	32.47^{b}	33.98^{a}
Mean	30.59^{a}	27.01^{b}	25.14^{c}	
HSD (%)	5.18%			
CV (%)	4.32			

Note: Means within the columns and rows followed by the same letter(s) are not significantly different at according to Tukey's Honest Significant Difference (HSD)

4.4.2. Plant spread

The analysis of variance indicated that the plant spread of cabbage was significantly ($p < 0.001$) influenced by the main effects of fertilizer levels, variety, and their interaction (Appendix Table 2).

The significant interaction suggests that the lateral expansion of the cabbage canopy is not solely determined by nutrient availability but also depends heavily on how specific genotypes exploit those nutrients. The highest plant spread (54.02 cm) was recorded in the interaction between the variety Chaka with 600kg NPS + 480 kg Urea+150kg Kcl ha^{-1} fertilizer combination (Table 6),

while the lowest plant spread values (26.23 and 28.81 cm) were recorded from Tacoma and Copenhagen varieties in control treatment, respectively .

Chaka showed a dramatic increase in spread when moving from (400kg NPS+320kg Urea+100kg Kcl $ha^{-1}$to (600kg NPS+480kg Urea+150kg Kcl ha^{-1})(26.8% from 42.60cm to 54.02cm), whereas Tacoma and Copenhagen showed much smaller, percent increases with the same levels (4.6% and 4.5%, respectively)(Table6).

This aligns with the findings of Fentaye and Bewuket (2023), who identified that certain varieties reach a peak spread where further nutrient application yields no significant incremental gains. Chaka appears to have a much higher genetic ceiling for lateral expansion than Tacoma or Copenhagen.

The case of the lowest plant spread values observed in the unfertilized treatments with Tacoma and Copenhagen varieties could be due to lack of sufficient NPS, Urea and Kcl fertilizer rate required for growth. These results are in line with the findings of Teshome and Amide (2020), who argued that insufficient Nitrogen and Phosphorus levels result in stunted vegetative development.

Table 6: Plant spread (cm) of Cabbage influenced by the interaction of varieties and inorganic fertilizers (NPS, Urea, and Kcl).

	Variety			
Fertilizer (NPS + Urea + Kcl kg ha^{-1})	Chaka	Tacoma	Copenhagen	Mean
Control (0+0+0)	32.46^{d}	26.23^{e}	28.81^{e}	29.17^{e}
242 + 150 + 0	38.18^{c}	33.33^{d}	33.47^{d}	35^{c}
200 + 160 + 50	37.34^{c}	28.63^{e}	32.10^{d}	32.69^{d}
400 + 320 + 100	42.60^{b}	37.83^{c}	37.63^{c}	39.02^{b}
600 + 480 + 150	54.02^{a}	39.59^{bc}	39.33^{bc}	44.31^{a}
Mean	40.92^{a}	33.12^{c}	34.07^{b}	
HSD (0.05)	5.25			
CV (%)	4.81%			

Note: Means within columns and rows followed by the same letter are not significantly different at ($p < 0.05$) according to Tukey's Honest Significant Difference (HSD) test

4.4.3 Leaf number

The analysis of variance (ANOVA) revealed that the number of leaves per plant was highly significantly ($p < 0.001$) influenced by the application of inorganic fertilizers rates and significantly ($p < 0.01$) influenced by the variety (Appendix Table 2). However, the interaction effect between fertilizer and variety was not statistically significant (Appendix Table 2).

Regarding the main effect of fertilizer, the application of reduced fertilizer by (200 kg NPS, 160 kg urea, and 50 kg Kcl ha^{-1}) significantly reduced the number of leaves, and a further increased to (600 kg NPS, 480 kg urea, and 150 kg Kcl ha^{-1}) resulted in a highest leaf number (17.26), but this was statistically at par with the (400 kg NPS, 320 kg urea, and 100 kg Kcl ha^{-1}) fertilizer rate (15.67cm), and the BoA recommended fertilizer rate(242kg NPS, 150 kg urea, ha^{-1}) is (14.61cm) (Table 7).

This might be due to improved nutrient availability, where nitrogen promotes cell division and leaf expansion, phosphorus helps in root development and energy transfer. However, the magnitude of this increment was relatively smaller and non-significant as compared with the leaf number in the (400 kg NPS, 320 kg urea, and 100 kg Kcl ha^{-1}) rate , which indicating a diminishing response at higher nutrient rate. According to Haile *et al.* (2025), the combination of these nutrients greatly improves plant growth and overall leaf count compared to unbalanced diets. Nitrogen, in particular, is a key factor in leaf production. Terefa (2017) noted that urea treatment supports steady increases in leaf count throughout the vegetative stage.

Regarding varietal performance, Chaka (15.05) and Tacoma (14.98) produced significantly more leaves than the Copenhagen variety (12.17). This variation indicates that genotypic selection is a major factor in the development of the cabbage structure. This is consistent with the findings of Samuel (2023), who reported that high-performing genotypes such as have greater physiological dominance than older varieties. The lower number of leaves in Copenhagen could be explained by the specific genetic threshold for biomass accumulation compared to the more robust varieties of Chaka and Tacoma. As noted by Abie and Tizazu (2024), the ability of cultivars to physiologically distinguish between wrapper and non-wrapper leaves varies depending on their genetic makeup.

4.4.4. Leaf Width

The analysis of variance (ANOVA) revealed that leaf width was highly significantly ($p<.001$) influenced by both inorganic fertilizer application rates and cabbage varieties. However, the interaction effect between fertilizer and variety was not statistically significant (Appendix Table 2).

The main effect of inorganic fertilizer application demonstrated a progressive increase in leaf width with higher nutrient inputs. The maximum leaf width (31.56 cm) was recorded from the 50% plus SNV recommendation rate (600kg NPS + 480kg Urea + 150kg Kcl ha^{-1}), significantly outperforming all other treatments, while the lowest were recorded from the control treatment (Table7) which implies the nutrient deficiency greatly limits, leaf development and expansion (Table 7). The increasing fertilizer rates resulted to increased leaf width, while reducing the rates by half, resulted in a significant reduction in leaf width. The increased fertilizer rates by 50% from the recommended rate enhanced the leaf width, which implies a positive growth response to higher nutrient input. This confirms that intensive fertilization promotes vegetative structural vigor. Fentaye and Bewuket (2023) stated that the higher nutrient application rate maximizes the leaf expansion by supplying the essential nutrients for cellular growth. This is also supported by Yebirzaf (2017) who reported peak leaf expansion at high nitrogen rates.

With respect to main effect of variety, the Chaka variety developed a significantly wider leaf (28.12 cm) than both Tacoma (25.76 cm) and Copenhagen (24.45 cm (Table7). This variation indicates that the productivity and structural development of cabbage is mainly determined by genotypic selection. As Samuel (2023) observed that high performing genotypes had higher physiological dominance in structural. The increased leaf area in Chaka could lead to higher light interception and photosynthetic capacity, which are essential for high-yielding crops (Zhou *et al*., 2023).

Table 7: The leaf number and leaf width (cm) of cabbage as influenced by the fertilizer rates (NPS + Urea + Kcl kg ha^{-1}) and varieties.

Treatment	Leaf number	Leaf width (cm)
Fertilizer (NPS + Urea + Kcl kg ha^{-1})		
Control (0+0+0)	8.92^{c}	20.29^{d}

242 + 150+0	14.61[ab]	25.99[bc]
200 + 160 + 50	13.85[b]	24.37[c]
400 + 320 + 100	15.67[ab]	28.36[b]
600 + 480 + 150	17.26[a]	31.56[a]
HSD (0.05)	3.23	2.38
Variety		
Chaka	15.05[a]	28.12[a]
Tacoma	14.98[a]	25.76[b]
Copenhagen	12.17[b]	24.45[b]
HSD (0.05)	2.12	1.56
CV (%)	16.72	6.63

Note: Means within the columns followed by the same letter are not significantly different at ($p < 0.05$) according to Tukey's Honest Significant Difference (HSD) test. CV:

4.4.5. Head diameter

The analysis of variance indicated that the head diameter of cabbage was significantly influenced by the variety, NPS, Urea and Kcl fertilizer rates, and their interaction ($p < 0.01$) (Appendix Table 2).

The head diameter of cabbage demonstrated consistently increased with the increasing of fertilizer rates. The maximum head diameter (31.30 cm) was recorded from Tacoma variety treated with (600kg NPS + 480kg urea+ 150kg Kcl ha^{-1}) which is statistically the same with Chaka under the same treatment combination (28.90 cm)(Table 8), while the lowest head diameter (12.12 cm) was recorded in the Copenhagen under the control treatment (Table 8). This shows the head development highly responded positively for the treated nutrients, and the soil nutrient reservoir alone are not sufficient for the optimal cabbage head formation.

The magnitude of the response to fertilizer reductions varied noticeably among the genotypes. For instance. when the fertilizer rate reduced by (down to 200 kg NPS+160 kg urea+50 kg Kcl ha^{-1}) the head diameter significantly dropped to 27.33cmin Tacoma and 24.13cm in Chaka (Table 8).interestingly, for both Tacoma and Chaka, these reduced rate values were statistically non-significant ($p>0.05$) when compared to their respective head diameters under the (400 kg NPS, 320 kg urea, and 100 kg Kcl ha^{-1}) rate (26.14cm) and the BoA rate (26.73cm) and (23.80cm).

The significant increase in diameter of cabbage attributes head expansion to the synergistic interaction of nitrogen, phosphorus, sulfur and potassium. Teshome and Amide (2020) observed that high-input regimes drive cellular expansion and biomass accumulation, resulting in larger diameters. The inclusion of Potassium (Kcl) in the treatment likely enhanced this expansion, as Mahato (2019) noted that head measurements are sensitive to K levels, with higher rates promoting better cell turgidity and leaf area development.

Furthermore, the varieties exhibited distinct responses to the nutrient packages. Tacoma consistently produced the largest head diameters (26.30cm) compared to Chaka (23.95cm) and Copenhagen (19.02) (Table8). While Copenhagen showed a positive response to fertilization, reaching its peak of 25.72 cm under (600kg NPS+ 480kg Urea+ 150kg Kcl ha^{-1}), it remained significantly smaller than Tacoma and Chaka at lower nutrient levels. This confirms the literature's assertion that older varieties like Copenhagen are less efficient than high-performing hybrids in closing the yield gap (Getachew *et al.*, 2022). The data suggests that Tacoma and Chaka have a higher genetic character for physical head building than Copenhagen.

Table 8: The head diameter (cm) of cabbage as influenced by the interaction of inorganic fertilizers (NPS, Urea, and Kcl) and varieties

	Variety			
Fertilizer (NPS + Urea + Kcl kg ha^{-1})	Tacoma	Chaka	Copenhagen	Mean
Control (0+0+0)	20.00^{ef}	17.98^{fg}	12.12^{h}	16.70^{d}
242 + 150 + 0	26.73^{bc}	23.80^{cd}	18.50^{fg}	23.01^{bc}
200 + 160 + 50	27.33^{bc}	24.13^{cd}	16.43^{g}	22.63^{c}

400 + 320 + 100	26.14^{bc}	24.94^{cd}	22.33^{de}	24.47^{b}
600 + 480 + 150	31.30^{a}	28.90^{ab}	25.72^{bcd}	28.64^{a}
Variety Mean	26.30^{a}	23.95^{b}	19.02^{c}	
HSD (0.05)	3.56			
CV (%)	5.1			

Note: Means within the columns and rows followed by the same letter(s) are not significantly different at ($p < 0.05$) according to Tukey's Honest Significant Difference (HSD) test

4.5 Yield Parameters of Cabbage

4.5.1. Fresh Head weight

Fresh head weight of cabbage is significantly influenced by the synergistic effect of NPS, urea and Kcl fertilizer rates and variety, as well as the main effect of these fertilizer rates and varieties ($P < 0.001$) (Appendix Table 3).

The physiological mechanism behind the dramatic biomass accumulation under the highest fertilizer intensive regime (600kg NPS + 480kg Urea+ 150kg Kcl ha^{-1}) is directly linked to enhanced source-sink dynamics. Coordinated and high rates of Nitrogen (N) and Phosphorus (P) stimulate cell division, accelerate leaf area expansion, and increase chlorophyll content, thereby maximizing photosynthetic capacity (Srivastava *et al.*, 2018). Simultaneously, the inclusion of Potassium (K) acts as a biochemical catalyst. Potassium regulates stomatal movement, maintains cellular turgor pressure, and directly activates starch synthase enzymes. This accelerates the active translocation of newly synthesized photo-assimilates from the outer wrapper leaves into the compact central core (sink), dramatically boosting single head mass. This is consistent with (Srivastava *et al.*, 2018), who noted that optimal K thresholds enhance head compactness and water retention capacity, which translates to a heavier fresh mass.

However, an intriguing genetic and environmental gap is observed when comparing these findings to regional baselines. In Ethiopia, under ideal commercial open-field or high-altitude conditions,

the Copenhagen variety typically averages 1.3 - 2.5kg, while the Tacoma and Chaka hybrid showcases an aggressive genetic potential of 4 kg per head. In this study, even under maximum input supply, Chaka reached a peak of only 2.49kg and 2.20 kg respectively. Underperforming its regional potential by nearly 32%. This discrepancy implies that while nutrient availability was non-limiting, external environmental or agro-ecological stress factors acted as an upper ceiling, preventing the hybrid from expressing its full genetic potential. Cabbage head formulation is highly sensitive to ambient temperature thresholds and moisture availability during the critical wrapping stage. High temperatures or localized micro-climate variations at the experimental site may have shortened the vegetative period or increased respiration rates, thereby reducing the net daily carbohydrate accumulation needed to build a 4 kg head. This discrepancy strongly suggests that nutrient availability was not the primary limiting factor at higher treatment tiers. Instead, an agro-ecological or management 'upper ceiling' likely suppressed the full expression of their hybrid vigor (heterosis).Therefore, future research must re-evaluate these varieties by controlling for and investigating other external stressors.

Furthermore, the fact that varietal differences completely collapsed and became non-significant under the control and lower fertilizer regimes (242kg NPS + 150 kg urea ha^{-1} and 200 kg NPS+160 kg urea+50 kg Kcl ha^{-1}) confirms that severe nutrient deficiency acts as a strict physiological bottleneck. Under severe N and P starvation, the advanced metabolic machinery of high-yielding hybrids like Tacoma and Chaka cannot function, reducing their performance to the level of the low-yielding local standard (Copenhagen). This critical boundary supports the principles laid out by (Teshome *et al.*, 2018) and Samuel (2023) that the phenotypic expression of superior cabbage genotypes requires a precise synchronization with luxury nutrient thresholds to translate genetic efficiency into commercial tonnage.

Table 9: The fresh head weight (kg) of cabbage as influenced by the interaction of inorganic Fertilizers (NPS, Urea, and Kcl kg -1) and varieties.

	Variety			
Fertilizer (NPS + Urea + Kcl kg ha^{-1})	Tacoma	Chaka	Copenhagen	Mean
Control (0+0+0)	1.03^{f}	1.03^{f}	0.73^{g}	0.93^{e}

242 + 150 + 0	1.57^{de}	1.56^{de}	1.43^{e}	1.52^{c}
200 + 160 + 50	1.43^{e}	1.35^{e}	1.40^{e}	1.39^{d}
400 + 320 + 100	2.23^{b}	2.17^{b}	1.70^{cd}	2.03^{b}
600 + 480 + 150	2.49^{a}	2.20^{b}	1.88^{c}	2.19^{a}
Mean	1.75^{a}	1.66^{b}	1.43^{c}	
HSD (0.05)	0.24			
CV (%)	4.84			

Note: Means within the columns and rows followed by the same letter(s) are not significantly different at ($p < 0.05$) according to Tukey's Honest Significant Difference (HSD) test.

4.5.2. Total fresh weight

The analysis of variance indicated that the total fresh weight of cabbage was significantly ($p < 0.001$) influenced by the interaction between variety and fertilizer levels. Moreover, the variety and fertilizer rates influenced the total fresh weight too (Appendix Table 3). This indicates the response of varieties depended on the rates of the fertilizer applied.

The highest total fresh weights (2.98 kg) were recorded on Tacoma variety under the (600kg NPS + 480kg Urea + 150kg Kcl ha^{-1}) which is statistically at par with Chaka under the same fertilizer treatment, and Tacoma under (400kg NPS + 320kg Urea + 100kg Kcl ha^{-1}) by producing 2.7 and 2.73 kg fresh weight respectively. On the other hand, the lowest total fresh weights (1.28 kg) were observed in Copenhagen with control treatment, which is statistically the same with Tacoma and Chaka under control treatment (Table 9). When the fertilizer rate were reduced by half from the (200 kg NPS, 160 kg urea, and 50 kg Kcl ha^{-1}), and under the BoA fertilizer recommendation rate (242kg NPS + 150 kg urea ha^{-1}), the total fresh weight was remarkably reduced and the difference among varieties were non-significance difference.

The varieties exhibited different responses to the fertilizer levels. Tacoma achieved its highest weight at the (600kgNPS+ 480kg Urea+ 150kg Kcl ha^{-1} level, suggesting it reached its physiological plateau at a more moderate nutrient level. In contrast, Chaka required the highest

input level which is (600kgNPS+ 480kg Urea+ 150kg Kcl ha^{-1}) to reach its peak total fresh weight of 2.7 kg. Copenhagen consistently produced the lowest fresh weights among the varieties at each fertilizer level, peaking at only 2.36 kg at high rate of fertilizer level which represents a 14.4% increase. This discrepancy supports the findings of Samuel (2023) and Getachew *et al*. (2022), who emphasize that transitioning from extensively used varieties like Copenhagen to high-performing hybrids is essential for maximizing total fresh weight.

Table 10: Total fresh weight (kg) of Cabbage Varieties as Influenced by the Interaction of Inorganic Fertilizers (NPS, Urea, and Kcl).

	Variety			
Fertilizer (NPS + Urea + Kcl kg ha^{-1})	Tacoma	Chaka	Copenhagen	Mean
Control (0+0+0)	1.49^{g}	1.56^{fg}	1.28^{g}	1.44^{d}
242 + 150 + 0	2.04^{de}	2.02^{de}	1.90^{ef}	1.99^{c}
200 + 160 + 50	1.84^{ef}	1.84^{ef}	1.87^{ef}	1.85^{c}
400 + 320 + 100	2.73^{ab}	2.59^{bc}	2.16^{de}	2.49^{b}
600 + 480 + 150	2.98^{a}	2.70^{abc}	2.36^{cd}	2.68^{a}
Mean	2.22^{a}	2.14^{a}	1.92^{b}	
HSD (0.05)	0.34			
CV (%)	5.41			

Note: Means within the columns and rows followed by the same letter(s) are not significantly different at ($p < 0.05$) according to Tukey's Honest Significant Difference (HSD) test.

4.5.3 Dry weight

The dry weight of cabbage was highly significantly ($p < 0.001$) influenced by the NPS, urea and KCl application rate, and influenced by the variety (Appendix Table 3). However, the interaction

effect between these fertilizer rates and variety was not statistically significant, indicating that the varieties responded with a similar trend to the varying nutrient levels.

The maximum mean dry weight (0.172 kg) was recorded under the (600kg NPS + 480kg Urea + 150kg Kcl ha^{-1}), followed by the (0.1499kg)(Table11). On the other hand, under the (200 kg NPS+ 160 kg urea + 50 kg Kcl ha^{-1}) and BoA fertilizer recommendation (242 kg NPS and 150 kg urea ha^{-1}), the dry weight contents were still lower and showed non-significance($p>0.05$) among them. Under the unfertilized or control conditions, the cabbage produced the lowest dry weight content (0.07336kg) (figure 3).

Overall, the dry weight of cabbage increased with a substantial increase of fertilizer compared to the unfertilized or control treatments. The result confirms that the combination of Nitrogen, Phosphorus, and Sulfur with Potassium provides the necessary metabolic energy and transport mechanisms for maximum productivity. These findings is strongly supported by Attia *et al.* (2022), who state that potassium fertilization greatly increases dry matter accumulation by promoting the transfer of carbohydrates from source leaves into the head's storage tissues. Furthermore, Gelaye (2024) notes that NPS-induced structural improvements, such as increased leaf thickness, significantly accelerate biomass accumulation.

The dry matter accumulation of cabbage mainly depends on the joint availability of nitrogen, phosphorus and sulfur that increases structural density. This is supported by Tehulie and Belete (2021) who mentioned that blended NPS fertilizers are an important corrective measure to sustain high intensity biomass production in the Ethiopian highlands.

Regarding varietal performance, Tacoma (0.1323 kg) and Chaka (0.1311 kg) produced significantly higher dry weights than the Copenhagen variety (0.1138 kg). This variation confirms that genotypic selection is a major determinant for cabbage productivity and structural development (Samuel, 2023). The higher dry matter content in Tacoma and Chaka indicates a better physiological ability of these varieties for biomass partitioning as compared to the traditional Copenhagen variety, which is in agreement with reports by Habib *et al.* (2018) on the physiological dominance of modern genotypes.

Figure 3: The fertilizer response curves of varieties to different fertilizer rates on Head Dry weight (kg) of Cabbage Varieties :

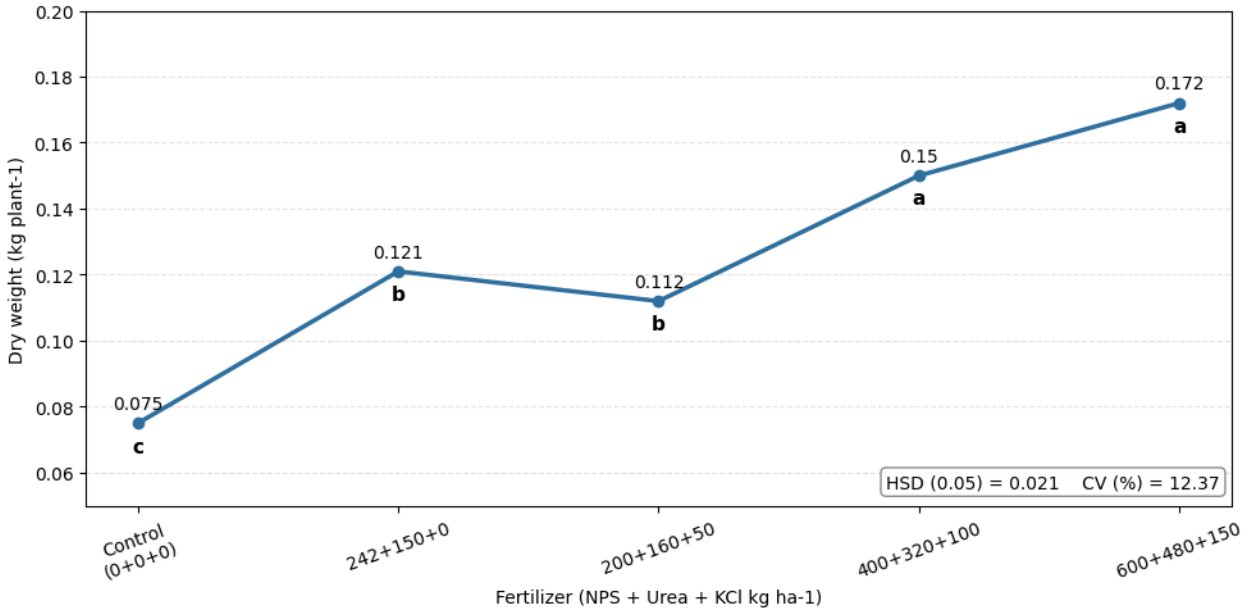


Figure 3: The fertilizer response curves of varieties to different fertilizer rates on Head Dry weight (kg) of Cabbage Varieties

Note: Means within the figure followed by the same letter(s) are not significantly different at ($p < 0.05$) according to Tukey's Honest Significant Difference (HSD) test.

4.5.4. Marketable yield

The statistical analysis revealed that the marketable yield of cabbage was highly significantly ($p < 0.001$) influenced by the interaction between fertilizer rates and cabbage varieties, as well as the main effect fertilizer and variety (Appendix Table 3).

The highest marketable yield (73.82 t ha^{-1}) was recorded from the Tacoma variety under the (600kg NPS + 480kg Urea + 150kg Kcl ha^{-1}). According to Turkey's HSD test, this peak yield was statically at par ($p>0.05$) with Chaka under the same maximum treatment (70.37 t ha^{-1}), and the Tacoma under (400 kg NPS, 320 kg urea, and 100 kg Kcl ha^{-1}) (70.04 t ha^{-1}) (figure 4).conversely, the lowest marketable yield (21.33 t ha^{-1}) was observed in the unfertilized Copenhagen variety under the control treatment.

Across two high performing hybrid varieties, there were no significance difference between the (400kg NPS + 320kg Urea+ 100kg Kcl ha^{-1}) and The (600kg NPS + 480kg Urea + 150kg Kcl ha^{-1}), which indicates a diminishing response at highest nutrient rate

The study revealed that even though inorganic fertilization is a primary driver for yield, the magnitude of the response is governed by the genetic potential and nutrient recovery efficiency of the specific variety. The balanced application of Nitrogen, Phosphorus, Sulfur and Potassium in the (600kgNPS+ 480kg Urea+ 150kg Kcl ha^{-1}) optimized the physiological development needed for high yield in Tacoma and Chaka varieties. This study is in line with the findings of Muhamed (2024), who noted that intensified nitrogen from NPS fertilizers is highly effective for increasing output.

Furthermore, the data reveal that Tacoma and Chaka varieties consistently outperformed Copenhagen across nearly all fertilizer levels. This illustrating those high performing hybrids requires precisely calibrated nutrient inputs to reach their peak commercial output (Teshome *et al.*, 2018). The marked reduction in yield in the control plots across all varieties underscores the severe limitations of nutrient deficient in the soil.

4.5.5 Unmarketable Yield

The unmarketable yield in cabbage was significantly influenced by the interaction of fertilizer rates and variety, and the main effect of fertilizer and variety ($p < 0.001$) (Appendix Table 3).

The highest unmarketable yield (4.34 t ha^{-1}), was recorded in the unfertilized Copenhagen variety whereas the lowest (1.59 t ha^{-1}) was achieved by the Tacoma variety under the (600kg NPS + 480kg Urea+ 150kg Kcl ha^{-1}). According to Turkey's HSD test this minimum value was statistically par ($P>0.05$) with Tacoma variety under the (400 kg NPS, 320 kg urea, and 100 kg Kcl ha^{-1}) (1.93 t ha^{-1} and Chaka variety under both (400 kg NPS, 320 kg urea, and 100 kg Kcl ha^{-1}) (1.98 t $ha^{-1}$and under the (600kg NPS + 480kg Urea+ 150kg Kcl ha^{-1}) (1.61 t ha^{-1}) (Figure 4).

The high unmarketable yield in the control plots across all varieties suggests that nutrient-deficient soils impede the crop's ability to reach its compact, marketable form. A significant reduction in unmarketable yield was observed as fertilizer rates increased across all varieties. This inverse relationship between nutrient supply and unmarketable yield is supported by Gosa and Fufa (2023), who noted that cabbage is highly sensitive to environmental and nutritional thresholds and inadequate nutrition often leads to physiological disorders or undersized heads that fail to meet market standards.

Copenhagen variety consistently produced higher unmarketable yields (2.24(t ha^{-1}) compared to Tacoma and Chaka at similar fertilizer levels. This aligns with Asomah *et al.* (2021), who emphasized that modern hybrids possess superior genetic stability for uniformity and marketable head formation compared to older varieties. Furthermore, the efficacy of the (600kg NPS + 480kg Urea + 150 kg Kcl ha^{-1}) treatment in minimizing unmarketable yield supports the findings of Muhamed (2024), who established that intensified nitrogen and phosphorus fertilization improves head uniformity.

Figure 4: the interaction effect of fertilizer rates and variety on marketable and unmarketable cabbage yield, and a comparison of marketable and unmarketable cabbage yield. :

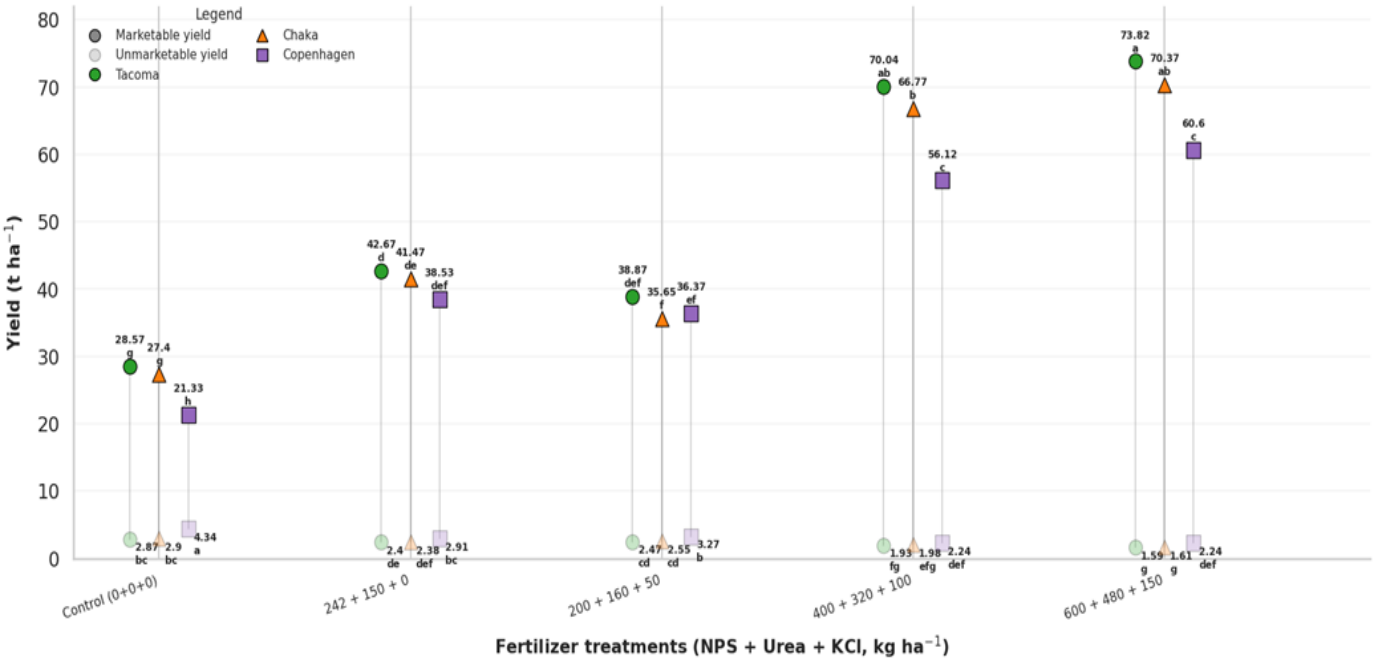


Figure 4. The interaction effect of fertilizer rates and variety on marketable and unmarketable cabbage yield, and a comparison of marketable and unmarketable cabbage yield.

Note: Means within the unmarketable yield, and within the marketable yields followed by the same letter(s) are not significantly different at (P< 0.05) according to Tukey's Honest Significant Difference (HSD) test. (for marketable= HSD (5%): 5.32CV (%):3.72 and for unmarketable= HSD (5%): 0.46CV (%):5.99%).

4.5.6. Total yield

Analysis of variance reveals that the total yield of cabbage was highly significantly ($p < 0.001$) influenced by the interaction effect of NPS, urea and Kcl fertilizer rates and varieties (Appendix Table 3).

The highest total yield (75.41 t ha^{-1}) was achieved by the Tacoma variety under the (600kg NPS + 480kg Urea + 150kg Kcl ha^{-1}) .According toTokyes test, this peak performance was statistically at par ($P > 0.05$) with Tacoma under the (400 kg NPS, 320 kg urea, and 100 kg Kcl ha^{-1}) (71.97 t ha^{-1}), and Chaka under(600kg NPS + 480kg Urea + 150kg Kcl ha^{-1}) (71.98 t ha^{-1}) (Figure 5). On the other hand, the lowest (25.67 t ha^{-1}) was recorded from the unfertilized Copenhagen variety (Figure 5). According to data from the Ministry of Agriculture (MoA) website, the potential yields for both 'Tacoma' and 'Chaka' hybrid varieties are 108.3t ha^{-1} on-farm and 127.0t ha^{-1} on-station. Although the yields achieved in this experiment are promising and approach these standard references, they still fall short of full potential. Therefore, further research is highly recommended across a broader range of crop varieties and diverse agro-climatic conditions to optimize and validate these yield outcomes.

The peak performance of Tacoma and Chaka under high-input of NPS, Urea, and Kcl indicates the synergy between Nitrogen (N), Phosphorus (P), and Potassium (K) in these treatments likely facilitated superior biomass accumulation compared to single-nutrient or low-rate applications. This finding is in agreement with Teshome *et al.* (2018), who identified that achieving optimal benchmarks for yield requires pairing chemical fertilizers with specific nutrient-demanding genotypes.

The data further show that the Copenhagen variety consistently produced lower total yields compared to Tacoma and Chaka at similar fertilizer levels. Asomah *et al*. (2021) also reported that modern cabbage varieties and hybrids exhibit vastly different genetic potentials for head formation and compact growth. The dramatic yield gap between the fertilized treatments and the control highlights the severe productivity constraints of nutrient-deficient soils, where insufficient N and P limit physiological development. Furthermore, the high performance of the treatments suggests that the inclusion of Potassium (Kcl) alongside NPS and Urea provided the necessary balance for

structural energy and water regulation, which, as noted by Gosa and Fufa (2023), is critical for maintaining the high relative humidity and nutrient density required for optimal cabbage production in the Ethiopian context.

Figure 5: The interaction effect of fertilizer rates and varieties on total yield of cabbage

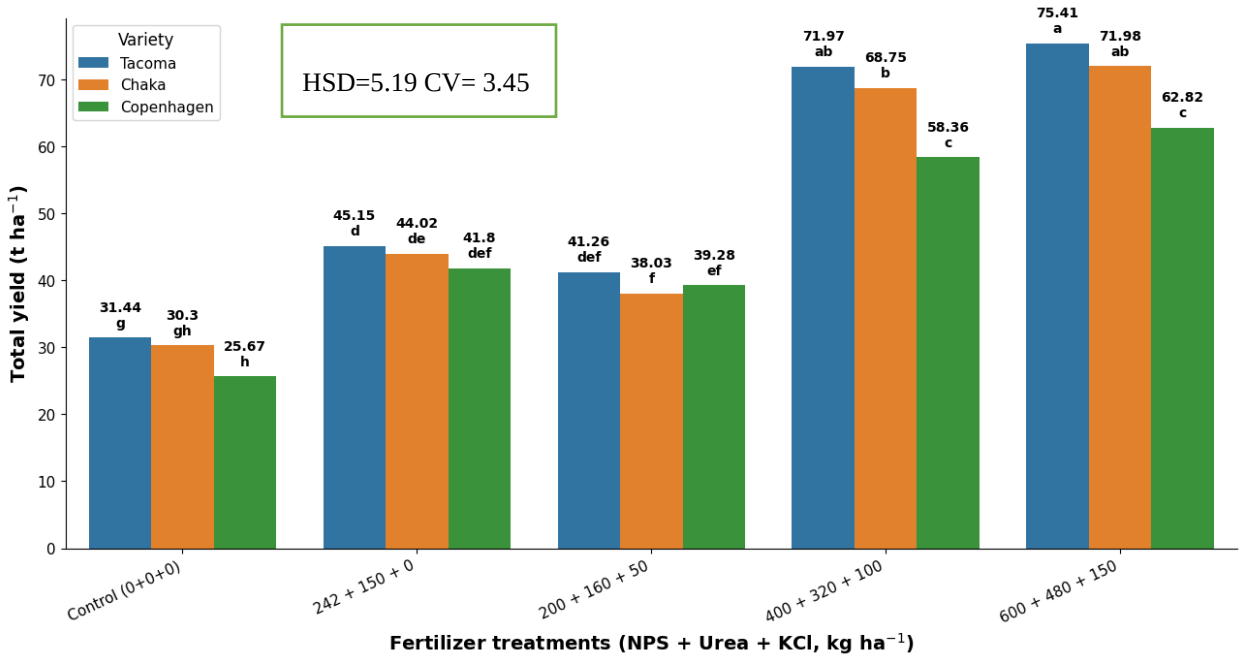


Figure 5.The interaction effect of fertilizer rates and varieties on total yield of cabbage

Note: Means within the followed by the same letter(s) are not significantly different at ($P < 0.05$) according to Tukey's Honest Significant Difference (HSD) test.

4.5.7 Harvest index

Harvest index was significantly ($p < 0.001$) influenced by the interaction of NPS, Urea and Kcl fertilizer rate and variety (Appendix Table 3), where the highest harvest index (82.53%) was gained from Tacoma variety (600kg NPS + 480kg Urea + 150kg Kcl ha^{-1}).According to Tukeys test, this peak value was statistically at par ($P > 0.05$) with all studied varieties treated under both (400kg NPS + 320kg Urea + 100kg Kcl ha-^{1}) and (600kg NPS + 480kg Urea + 150kg KCl ha^{-1}) as sharing of the letter 'a' indicates. However, the lowest (57.30%) was gained in the unfertilized Copenhagen variety (Table 11).

The significant increase in HI across all varieties under the (600kg NPS + 480kg Urea+ 150kg Kcl ha^{-1}) and (400kg NPS+ 320kg Urea + 100kg Kcl $ha^{-1)}$ suggests that balanced nutrient application optimizes the physiological requirement of the cabbage crop. This aligns with the findings of Muhamed (2024), who noted that while intensified nitrogen (N) and phosphorus (P) from NPS

fertilizers significantly increase head weight rather than excessive outer leaf growth, which contributed for increased harvest index.

Furthermore, the Tacoma variety consistently maintained a superior harvest index compared to Copenhagen across all fertilizer rates, while reaming statistically identical to Chaka in its overall main effect mean((76.90%) and (75.65% respectively). This variation supports the observation by Teshome *et al*. (2018) that maximizing commercial output depends on pairing high-performing genotypes with nutrient thresholds that balance total tonnage against structural economy quality.

Table 11: Harvest Index (%) of Cabbage Influenced by the Interaction of Varieties and Inorganic Fertilizers (NPS, Urea, and Kcl)

	Variety			
Fertilizer (NPS + Urea + Kcl kg ha^{-1})	Chaka	Copenhagen	Tacoma	Mean
Control (0+0+0)	64.67^{f}	57.30^{g}	66.67^{f}	62.88^{c}
242 + 150+0	76.77^{cde}	75.50^{de}	77.20^{bcde}	76.49^{b}
200 + 160 + 50	74.47^{e}	74.53^{e}	76.67^{cde}	75.22^{b}
400 + 320 + 100	81.03^{abc}	78.77^{abcde}	81.43^{ab}	80.41^{a}
600 + 480 + 150	81.33^{ab}	79.53^{abcd}	82.53^{a}	81.13^{a}
Mean	75.65^{a}	73.13^{b}	76.90^{a}	
HSD (0.05)	4.51			
CV (%)	2%			

Note: Means within the columns and rows followed by the same letter(s) are not significantly different at ($P < 0.05$) according to Tukey's Honest Significant Difference (HSD) test.

4.6. Correlation Analysis

The Pearson correlation analysis among the measured phenological, growth, physiological, and yield traits provides critical insights into the internal dynamics of the cabbage crop system under

semi-arid conditions. These correlation coefficients (r) expose structural associations that reveal how growth parameters co-regulate crop productivity and how dry matter is distributed into marketable harvest.

The parameters representing vegetative development, Leaf Number (LN), Plant Height (PH), Plant Spread (PS), and Leaf Width (LW), exhibit exceptionally strong, positive, and highly significant linear relationships ($P < 0.001$). For instance, Plant Height is tightly correlated with Leaf Width ($r = 0.893^{***}$) and Plant Spread ($r = 0.867^{***}$). Leaf Number also displays a solid relationship with leaf width ($r = 0.750^{***}$). From a physiological perspective, this robust co-development confirms that vertical growth and horizontal canopy expansion occur simultaneously. A larger canopy with a higher leaf number establishes an enhanced photosynthetic area, which amplifies intercepted photosynthetically active radiation (PAR), driving vigorous structural synthesis. This is confirmed by the highly significant positive correlation between vegetative growth markers and overall structural accumulation, such as Dry Weight (DW), which shares a strong connection with both Plant Height ($r = 0.842^{***}$) and Leaf Width ($r = 0.862^{***}$).

One of the primary outcomes of this trial is the absolute positive association between fresh head weight (FW), Marketable Yield (MY), and Total Yield (TY). Marketable Yield and Total Yield are essentially perfectly correlated ($r = 1.000^{***}$), meaning that increases in total productivity are directly reflected in usable, commercial volumes. Furthermore, Head Weight per plant (FW) and dry weight accumulation (DW) act as major drivers for economic output; FW is almost perfectly associated with Marketable Yield ($r = 0.979^{***}$) and Total Yield ($r = 0.977^{***}$). DW is similarly highly correlated with Marketable Yield ($r = 0.979^{***}$) and Total Yield ($r = 0.977^{***}$). Biologically, this reflects excellent source-sink alignment. The vegetative machinery ("source" organs like leaves) produced enough carbohydrates to continually fill the storage capacity of the developing heads ("sink" organs). When individual head weight and total accumulated plant dry matter increase, it serves as a direct indicator that photo-assimilates were successfully translocated from the vegetative canopy into harvestable units. This is further verified by Head Diameter (HD), which displays a highly significant positive correlation with Fresh Head Weight ($r = 0.790^{***}$) and Marketable Yield ($r = 0.753^{***}$). Larger head structures physically accommodate greater weight, leading directly to higher metric tonnage per hectare.

In contrast, Unmarketable Yield (UMY) acts inversely to all key growth and productivity traits, exhibiting highly significant negative correlations across the matrix: UMY vs. Plant Height (PH) (r = 0.843***), UMY vs. head Weight (FW) (r = 0.865^***), UMY vs. Head Diameter (HD) (r = 0.869***) and UMY vs. Marketable Yield (MY) (r = 0.840***). This consistently strong negative correlation reveals a critical physiological trade-off. Robust growth conditions that stimulated tall, expansive plants with high dry matter accumulation effectively minimized unmarketable losses, ensuring that major energy investments went directly into commercial-grade yield. Conversely, in plots where growth was restricted or stunted, the cabbage heads failed to expand normally, resulting in smaller head diameters (HD) and lighter individual fresh head weights (FW). Because these traits are inversely related to UMY, such stunted development statistically corresponds to a higher proportion of unmarketable, undersized, or visually substandard heads.

Interestingly, Days to Maturity (MD) and Total Fresh Weight (TFW) showed distinct independence from the rest of the agronomic data. Maturity Date (MD) has weak or non-significant (ns) correlations with most variables, except for a high positive correlation with the Harvest Index (HI, r = 0.899***) and a mild negative correlation with Total Yield (TY, r = -0.300*). This negative correlation suggests that plants that matured excessively late suffered a slight decline in ultimate yield, possibly due to shifting moisture constraints or heat stress late in the semi-arid growing season. Total Fresh Weight (TFW) showed no significant correlations with any variable in the study (r values near zero, labeled ns). This complete independence implies that overall field fresh biomass fluctuated due to external environmental variables (such as localized cell moisture levels or soil water status at sampling) rather than tracking the structural or genetic performance of the specific treatments.

In conclusion, this correlation analysis confirms that cabbage yield in the study area is directly determined by canopy performance and dry matter accumulation. To optimize marketable yield, agricultural practices must focus on maximizing early vegetative growth (Leaf Number, Plant Height, and Spread). Building a robust vegetative structure ensures strong carbohydrate source support, which directly increases head diameter and individual weight, while concurrently suppressing unmarketable yield losses

Table 12: Effect of correlation

	LN	PH	PS	LW	HI1	MD	FW	TFW	HD	DW	MY	UMY	TY	H
LN	1													
PH	0.724***	1												
PS	0.635***	0.867***	1											
LW	0.750***	0.893***	0.810***	1										
HI1	0.024ns	0.048ns	0.058ns	0.031ns	1									
MD	0.088ns	0.065ns	0.172ns	0.037ns	0.899***	1								
FW	0.780***	0.837***	0.728***	0.834***	0.207ns	0.261ns	1							
TFW	0.069ns	0.123ns	0.082ns	0.103ns	0.129ns	0.141ns	0.134ns	1						
HD	0.777***	0.757***	0.558***	0.717***	0.039ns	0.138ns	0.790***	0.011ns	1					
DW	0.772***	0.842***	0.742***	0.862***	0.178ns	0.229ns	0.937***	0.132ns	0.748***	1				
MY	0.736***	0.833***	0.753***	0.836***	0.275ns	0.292ns	0.979***	0.087ns	0.753***	0.913***	1			
UMY	0.774***	0.843***	0.674***	0.796***	0.081ns	0.049ns	0.865***	0.011ns	0.869***	0.843***	0.840***	1		

TY	0.729***	0.827***	0.751***	0.831***	0.288ns	0.300*	0.977***	0.091ns	0.743***	0.910***	1.000***	0.827***	1	
HI2	0.772***	0.823***	0.624***	0.796***	0.200ns	0.285ns	0.890***	0.163ns	0.791***	0.859***	0.845***	0.858***	0.839***	1

Note:-LN=Leaf number, PH=plant height, PS= plant spread, LW= leaf width, HI= 50%head initiation, MD= maturity date, FW= fresh weight, TFW= total fresh weight, HD= head diameter, DW=dry weight, MY= marketable yield, UMY= unmarketable yield, T total yield, HI= harvest index

4.7. Partial Budget Analysis

The economic analysis was done using partial budget procedure as described by CIMMYT (1988). Seed and fertilizer costs for cabbage production was used for analysis. This analysis was performed in order to evaluate the economic feasibility of the treatments at the minimum rate of return 50 to 100% (CIMMYT, 1988). Yield of cabbage from experimental plots were adjusted down ward by 10% for management and plot size differences to regulate the difference between the experimental yield and the yield that farmers could expect from the same treatment. Farm gate marketable prices of Cabbage were ETB 25 $kg^{-1}$and unmarketable yield was ETB5 kg^{-1} of the average of one month from the time of crop harvesting, Cabbage seed price ETB 1250/packet for Tacoma and Chaka, and ETB 510/packet for Copenhagen variety. Fertilizer cost is ETB 100 kg^{-1} for NPS and KCl, ETB 82 kg^{-1} for Urea and ETB 4 kg^{-1} of fertilizer application cost.

The partial budget analysis demonstrates that both fertilizer rates and variety choice significantly influenced the profitability of cabbage production, revealing a distinct divergence between biological potential and economic feasibility. The highest net benefit of ETB 1,527,703.13 ha^{-1} with a marginal rate of return (MRR) of 1922.2%was obtained from Tacoma combined under 600kg NPS + 480kg Urea+150kg Kcl fertilizer rate. This specific fertilizer-variety combination is identified as the most biologically productive and economically viable strategy for maximizing farmer profits in the study area. Treatments with MRR of less than 100% are consider unacceptable, because investing one ETB credited less than one ETB.

Treatment Combination	MY (kg ha⁻¹)	UMY (kg ha⁻¹)	Adj. MY 10%	Adj. UMY 10%	Gross Return (ETB ha⁻¹)	TVC (ETB ha⁻¹)	Net Benefit (ETB ha⁻¹)	MRR (%)
Control X Copen	21.33	4.34	19.190	3.906	499,280	10,625.00	488,655.00	—
Control X Tacoma	28.56	2.87	25.704	2.583	655,415	26,041.88	629,373.13	912.75
Control X Chaka	27.40	2.90	24.660	2.610	629,550	26,041.88	603,508.13	D
242NPS + Urea150 X Copen	38.53	3.26	34.677	2.934	881,595	47,125.00	834,470.00	972.82
200NPS + 160Urea + 50KCl X Copen	36.36	2.91	32.724	2.619	831,195	48,745.00	782,450.00	D
242NPS + Urea150 X Tacoma	42.66	2.46	38.394	2.214	970,920	62,541.88	908,378.13	479.38
242NPS + Urea150 X Chaka	41.46	2.55	37.305	2.295	943,975	62,541.88	881,433.13	D
200NPS + 160Urea + 50KCl X Tacoma	38.86	2.39	34.974	2.151	861,655	64,161.88	797,493.13	D
200NPS + 160Urea + 50KCl X Chaka	35.65	2.38	32.085	2.142	812,825	64,161.88	748,663.13	D

400NPS + 320Urea + 100KCl X Copen	56.12	2.24	50.508	2.016	1,272,780	86,865.00	1,185,915.00	1,141.25
400NPS + 320Urea + 100KCl X Tacoma	70.04	1.92	63.036	1.728	1,584,540	102,281.88	1,482,258.13	1,922.21
400NPS + 320Urea + 100KCl X Chaka	66.76	1.98	60.084	1.782	1,511,010	102,281.88	1,408,728.22	D
600NPS + 480Urea + 150KCl X Copen	60.60	2.23	54.540	2.007	1,372,735	124,985.00	1,247,750.00	D
600NPS + 480Urea + 150KCl X Tacoma	73.82	1.59	66.438	1.431	1,668,105	140,401.88	1,527,703.13	120.00
600NPS + 480Urea + 150KCl X Chaka	70.36	1.61	63.324	1.449	1,590,345	140,401.88	1,449,943.13	D

Table 13: Partial budget analysis of inorganic fertilizer and cabbage varieties at Habru district in 2026

Note: **D** stands for Dominated treatment (where net benefits are lower than or equal to a treatment with lower variable costs, making it economically unviable).Where: MMR=Marginal rate of return MY = Marketable Yield, UMY = Unmarketable Yield, TVC = Total Variable Cost, MRR = Marginal Rate of Return, Copen = Copenhagen)

5. CONCLUSION AND RECOMMENDATION

5.1 Conclusion

The present study addressed the significant yield gap in Ethiopian cabbage production in the Harbu district, driven by poor variety selection and soil fertility management. Baseline soil analysis confirmed critical deficiencies in total nitrogen (0.1%), available phosphorus (18.34 ppm), sulfur (10.6ppm), and organic matter (1.79%), proving that nutrient constraints severely limit vegetative vigor and marketable head development. Among the tested combinations, Tacoma consistently outperformed Copenhagen in most growth and yield parameters, indicating its superior response to balanced nutrient application under the agro ecological conditions of Harbu District.

The highest marketable yield (73.82 t ha^{-1}), total yield (75.41 t ha^{-1}), and net benefit (ETB 1,527,703 ha^{-1}) were obtained from Tacoma supplied with 600 kg NPS + 480 kg Urea + 150 kg Kcl ha^{-1}. Although this treatment generated the maximum economic return and an acceptable marginal rate of return (120%), it required substantially greater fertilizer investment. In contrast, Copenhagen at the same fertilizer rate produced a lower net benefit (ETB 1,247,750 ha^{-1}) and was economically dominated.

Considering both agronomic performance and economic feasibility, Tacoma supplied with 400 kg NPS + 320 kg Urea + 100 kg KCl ha^{-1} is considered the economic optimum. This treatment achieved near-maximum productivity with lower production costs and superior economic efficiency, making it more suitable for resource-constrained farmers.

Therefore, Tacoma combined with 400 kg NPS + 320 kg Urea + 100 kg KCl ha^{-1} is recommended for cabbage production in Harbu District and similar agro ecological areas to achieve high productivity, profitability, and efficient use of production inputs. Therefore, soil nutrient management should optimize economic efficiency rather than just biological maximization.

Limitations of study

Despite the valuable findings generated by this study, several limitations should be acknowledged. The experiment was conducted at a single location and during only one growing season, which may limit the broader applicability of the results across different environments and years. In addition, only three cabbage varieties were evaluated, restricting the scope for assessing varietal responses to fertilizer

application. The economic analysis was based on prevailing input and output market prices during the study period; therefore, changes in market conditions may influence the profitability of the recommended treatments. Consequently, the agronomic and economic performance observed in this study may vary under different agro ecological, climatic, and market conditions. Nevertheless, these limitations provide important opportunities for future research. Multi-location and multi-season experiments involving a wider range of cabbage varieties are recommended to validate and refine the findings and to develop more robust fertilizer recommendations for diverse production environments.

5.2 Recommendation

Based on the agronomic and economic results of this study, the combination of Tacoma cabbage variety with 400 kg NPS + 320 kg Urea + 100 kg KCl ha^{-1} is recommended for irrigated cabbage production in Harbu District and similar agro ecological areas. Although the application of 600 kg NPS + 480 kg Urea + 150 kg KCl ha^{-1} produced the highest yield and net benefit, the intermediate fertilizer rate provided comparable productivity with lower production costs and the highest marginal rate of return (1922.21%), making it the most economically efficient option for resource-constrained farmers.

Development partners, particularly the SNV Horti-Life Project and other organizations engaged in horticultural development, are encouraged to integrate the recommended fertilizer–variety package into their extension and scaling-up programs. Efforts should focus on supporting large-scale field demonstrations, improving farmers' access to quality Tacoma hybrid seed, and strengthening market linkages to ensure profitable marketing opportunities for the increased cabbage production.

Agricultural research institutions, including the Ethiopian Institute of Agricultural Research (AARI) and regional research centers, should further validate the findings through multi-location and multi-season experiments. Future studies should also evaluate additional cabbage varieties and fertilizer combinations across diverse agro ecological conditions of South Wollo and other cabbage-producing areas to enhance the robustness and wider applicability of the recommendations.

Farmers are advised to adopt the recommended Tacoma variety and fertilizer package to improve cabbage productivity and farm profitability. Extension services should promote the technology through demonstration plots, field days, and farmer training programs focusing on balanced fertilizer management and improved cabbage production practices. In addition, input suppliers, cooperatives, and relevant

stakeholders should ensure the timely availability and affordability of Tacoma seed and the required NPS, Urea, and Kcl fertilizers to facilitate wider adoption of the recommended technology package.

Based on the partial budget analysis, resource-constrained smallholders should adopt the economic optimum of 400 kg ha^{-1} NPS + 320 kg ha^{-1} Urea + 100 kg ha^{-1} Kcl, which minimizes financial risk and guarantees the highest return on investment (1,922.21% MRR). Therefore, farmers in the Harbu District should be encouraged to adopt high-performing hybrid genotypes alongside this economically viable rate, supported actively by local extension services. Meanwhile, although various agronomic parameters demonstrated statistically comparable outcomes under the 100, the maximum application rate (600 kg ha^{-1} NPS + 480 kg Urea + 150 kg Kcl) yielded the highest absolute net profit. This maximum rate is highly recommended for well-capitalized commercial growers who prioritize maximizing total volume and biomass over marginal returns, and who can absorb the steep upfront capital required. However, for resource-limited smallholders, transitioning to this intensive input tier may not be economically justified, given its lower marginal return (119.16%). Multi-location and multi-season trials are further recommended to validate these recommendations across varying environmental conditions.

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7. APPENDIX

Appendix 1：ANOVA table of Phenological parameters of cabbage varieties

Source of Variation	Df	DH	MD
Replication	2	2.06	11.08
Fertilizer	4	70.59***	164.76***
Variety	2	681.45***	1858.92***
Fertilizer × Variety	8	5.47	5.53
Error (MSE)	28	6.18	7
CV (%)		4.38	3.09

NOT:- *= significant, ** = highly significant, DF: degree of freedom, DH: day of head initiation, MD: maturity date

Appendix 2： ANOVA Table of Growth parameters of cabbage

Source of Variation	df	LN (MS)	PH (MS)	PS (MS)	LW (MS)	HD (MS)
Replication	2	0.358	5.09	5.02	3.343	1.89
Fertilizer	4	89.234***	217.843***	307.98***	161.312***	165.991***
Variety	2	40.507**	115.047***	271.605***	52.017***	207.024***
Fertilizer × Variety	8	0.442	4.711*	20.054***	3.802	6.117**
Error	28	5.529	2.045	3.009	3	1.385

CV (%)	16.72	5.18	4.81	6.63	5.09

NOTE: LN (MS) =Mean Square of Leaf Number, PH (MS): Plant Height, PS (MS) =Plant Spread, LW (MS) =Leaf width, HD (MS), Head Diameter

Appendix 3：ANOVA Table of Yield parameters of cabbage

Source of Variation	Df	FW	TFW	DW	MY	UMY	TY	HI
Replication	2	0.00013	0.00205	0.0002338	1.94	0.0224	2.12	0.83
Fertilizer	4	2.32325***	2.24847***	0.0127319***	3015.80***	3.3880***	2824.48***	485.67***
Variety	2	0.41402***	0.36939***	0.0016015**	265.67***	2.6765***	217.07***	55.44***
Fertilizer × Variety	8	0.05663***	0.06604***	0.0002117	25.41***	0.1946***	26.57***	9.41***
Error	28	0.00611	0.01279	0.0002418	3.09	0.0227	2.95	2.22
CV (%)		4.84	5.4	12.37	3.71	5.99	3.45	2

NOTE:FW=fresh Wight, TFW=total fresh weight, DW=dray weight, MY=marketable yield, UMY=unmarketable yield, TY=total yield, HI=harvest index

Appendix 4: The soil chemical properties (pH, total nitrogen (%), available phosphorus (ppm), and exchangeable potassium (Cmol(+)/100Kg of each treatment plot after crop harvest.

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Amhara Regional Agricultural Research Institute (ARARI)

DebreBirhan Agricultural Research Center

Treatments	TN (%)	P (ppm)	K cmol kg-1	S ppm	CL (meq/L
F1C1	0.081	14.32	0.575	10.1	1.6
F2C1	0.156	34.62	0.652	22	4
F3C1	0.152	36.78	0.568	21.5	2.8
F4C1	0.232	37.02	0.739	30.2	4.8
F5C1	0.241	37.34	0.767	32.1	5.2
F1C2	0.079	17.74	0.565	10.1	1.8
F2C2	0.151	33.72	0.691	21	4
F3C2	0.151	34.74	0.567	22.4	2
F4C2	0.246	41.58	0.844	35.3	5
F5C2	0.249	46.32	0.895	38.2	5.6
F1C3	0.085	17.32	0.588	9.9	1.8
F2C3	0.156	38.46	0.627	22	3.6
F3C3	0.154	39	0.579	23.4	2.8
F4C3	0.247	45	0.767	36.5	4.2
F5C3	0.249	48.96	0.87	38.2	6

Note: TN = Total Nitrogen; P = Available Phosphorus; K = Exchangeable Potassium; S = Available Sulfur; Cl = Chloride concentration. BoA = Bureau of Agriculture recommended rate).

Appendix 5: table 1: Layout of the experimental design

(Plot)	(Block 1)	(Block 2)	(Block 3)
Plot 1	Copenhagen + 400	Copenhagen + 242	Chaka + 400
Plot 2	Chaka + 400	Tacoma + No Ferti	Tacoma + 600
Plot 3	Copenhagen + 600	Copenhagen + 400	Tacoma + 200
Plot 4	Tacoma + 400	Chaka + 600	Copenhagen + No Ferti
Plot 5	Chaka + 600	Copenhagen + 600	Chaka + 600
Plot 6	Copenhagen + 200	Tacoma + 242	Tacoma + 400
Plot 7	Tacoma + 200	Chaka + No Ferti	Chaka + 242
Plot 8	Copenhagen + No Ferti	Tacoma + 600	Tacoma + 242
Plot 9	Tacoma + 242	Copenhagen + 200	Copenhagen + 600
Plot 10	Tacoma + No Ferti	Chaka + 200	Chaka + No Ferti
Plot 11	Chaka + 242	Tacoma + 400	Copenhagen + 242
Plot 12	Copenhagen + 242	Chaka + 400	Tacoma + No Ferti
Plot 13	Tacoma + 600	Copenhagen + No Ferti	Copenhagen + 400
Plot 14	Chaka + 200	Tacoma + 200	Chaka + 200
Plot 15	Chaka + No Ferti	*Chaka + 242*	Copenhagen + 200

Note, distance between Block=1m and between plot=0.5m, plot length and width =3m

Appendix 6: Appendix figure 2. Cabbage seed sowing field, good transplanted plant





Appendix 7: figure photo showing a regional supervisor and a university advisor conducting field monitoring and support



Appendix 8: figure Filed day preparation and crop harvest



Appendix 9: figure 5. This image shows better performance of Tacoma variety.

