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GROWTH AND YIELD PERFORMANCE OF MAIZE (*Zea mays* L.) AS AFFECTED BY BLENDED BASAL FERTILIZER AND BRIQUETTE N TOP DRESSING

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DECLARATION

Candidate's Declaration

I hereby declare that this thesis submitted to the university, is the result of my own original research work carried out under supervision. I further declare that to the best of my knowledge, it contains no material previously published by another person or submitted for the award of any degree at any institution, except where due acknowledgment has been made in the text. All sources of information have been properly cited and referenced in accordance with academic standards.

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Supervisors' Declaration

We hereby declare that the preparation and presentation of the thesis were supervised in accordance with the guidelines on supervision of thesis laid down by the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development.

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DEDICATION

This thesis is dedicated to my mother, Charity Amoah, Lydia Amu my aunty and the entire family.

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LIST OF ABBREVIATION/ACRONYMS

AGRA	Alliance for a Green Revolution in Africa
ANOVA	Analysis of Variance
BCR	Benefit-Cost Ratio
CAADP	Comprehensive Africa Agriculture Development Programme
CEC	Cation Exchange Capacity
CRF	Controlled-Release Fertilizer
DAP	Diammonium Phosphate
ECe	Electrical Conductivity of Saturated Extract
FAO	Food and Agriculture Organization
FISP	Farm Input Subsidy Program
GDP	Gross Domestic Product
GHG	Greenhouse Gas
GSS	Ghana Statistical Service
IFDC	International Fertilizer Development Center
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
MoFA	Ministry of Food and Agriculture
NDC	Nationally Determined Contributions
NPK	Nitrogen, Phosphorus, Potassium
NUE	Nitrogen Use Efficiency
PFJ	Planting for Food and Jobs
RCBD	Randomized Complete Block Design
SOC	Soil Organic Carbon
SSA	Sub-Saharan Africa
WHO	World Health Organization

ABSTRACT

Maize (*Zea mays* L.) remains a key staple crop in Ghana, yet yields continue to lag behind the attainable potential due to nutrient-depleted soils, poor fertilizer use efficiency, and climate variability. This study investigated the effects of blended basal fertilizer and nitrogen briquette top dressing on the growth, yield, soil properties, and economic performance of maize. Two field experiment were conducted at different sites of the demonstration farm of Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMUSTED), Mampong–Ashanti, during the major (March to July) and the minor (August to December) seasons of 2023 using a Randomised Complete Block Design (RCBD) with five treatments with four replication. The treatments were: (i) No Fertilizer (Control), (ii) Granular NPK (70-50-50 kg/ha) + Urea briquettes, (iii) Granular NPK (70-50-50 kg/ha) + 20S + $(NH_4)_2SO_4$ briquettes, (iv) Granular NPK (90-60-60 kg/ha) + Urea briquettes and (v) Granular NPK (90-60-60 kg/ha) + 20S + $(NH_4)_2SO_4$ briquettes. The results showed that, the treatment involving NPK (90-60-60 kg/ha) combined with 20S and ammonium sulphate briquettes significantly outperformed all others. It recorded the highest grain yield (6.17 t/ha), cob length (19.7 cm), plant height (222.7 cm), and leaf area index (4.87). Soil chemical analysis showed improvements in pH, total nitrogen, and organic carbon. Economically, this treatment achieved the highest gross margin (GH₵8,076.00/ha), net return (GH₵5,486.00/ha), and benefit-cost ratio (2.13), making it the most profitable and resource-efficient option.The findings suggest that integrating site-specific blended basal fertilizer with urea briquette top dressing enhances maize performance, soil health, and farmer profitability more effectively than conventional granular Fertilizers. It is therefore recommended that policy frameworks such as Ghana's Planting for Food and Jobs (PFJ) programme incorporate controlled-release fertilizer technologies into subsidy schemes.

CHAPTER ONE: INTRODUCTION

1.1 Background of the Study

Maize (*Zea mays* L.) is the basis of food security and economic stability in Ghana, serving as a staple for over 90% of households and contributing 40-50% of the cereal production (SRID-MoFA, 2021; FAO, 2022). With per capita consumption exceeding 42 kg annually, maize supports both rural livelihoods and urban diets, particularly in the form of processed foods (GSS, 2021). However, Ghana maize production remains alarmingly low, averaging 2.3 t/ha less than half the achievable potential of 6.0 t/ha under optimised management (MoFA, 2022; Kankam-Boadu *et al*., 2021). This stagnation threatens food security in a nation where population growth and urbanisation are escalating demand, exposing systemic challenges rooted in soil degradation, climate variability, and inefficient Fertilizer use.

Ghana's savannah agroecological zone, which accounts for 60% of maize cultivation, is plagued by inherently infertile soils characterised by sandy textures, low organic carbon (<1.5%), and severe deficiencies (Bationo *et al*., 2018). Decades of monoculture, slash-and-burn practices, and minimal organic input have accelerated nutrient mining, reducing soil productivity by 30-50% since the 1990s (Turmel *et al*., 2015). Acidic conditions (pH 4.5-5.5) further intensify aluminium toxicity and phosphorus fixation, making 60-70% of applied phosphorus unavailable to crops (Agyin-Birikorang *et al*., 2019). These constraints are compounded by erratic rainfall patterns, with the Upper East and Northern Regions experiencing prolonged dry spells that reduce yields by 30-50% during critical growth stages (IPCC, 2021).

Although Fertilizers are essential to replenish depleted soils, conventional granular NPK and urea promoted by national programs like Planting for Food and Jobs (PFJ) are not sustainable for local conditions. Granular Fertilizers, though cost-effective, release nutrients rapidly, leading to leaching losses of 50-70% for nitrogen and potassium in coarse-textured soils (Savant & Stangel, 2020). The overreliance on prilled urea has also acidified soils to pH levels below 5.0 in Northern Ghana, suppressing microbial activity and crop growth (IFPRI, 2021). Financial barriers worsen these inefficiencies: the recommended application rate (250 kg/ha NPK + 125 kg/ha urea) is unaffordable for most farmers, leading to suboptimal use (100 kg / ha) and perpetuating cycles of low yields and poverty (Houssou *et al.*, 2018).

Controlled-release fertilizers (CRFs) such as urea briquettes, offer a scientifically validated solution to synchronise nutrient release with crop demand. By compacting urea into low-surface-area briquettes, dissolution is slowed, extending nitrogen availability during critical growth stages, such as tasseling and grain filling. Studies in Nigeria and Kenya demonstrated that CRFs can increase nitrogen use efficiency (NUE) by 40-60%, reduce leaching by 35% and increase yields by 20-35% compared to prilled urea (Ogunwole *et al.*, 2020; Sanda *et al.*, 2021). In Northern Ghana, preliminary studies show that urea briquettes improved maize yields by 25-30% and soil organic carbon by 15% over two seasons (Adu-Gyamfi *et al.*, 2019). However, adoption remains negligible due to high upfront costs, limited farmer awareness, and exclusion from subsidy programmes, a gap that this study addresses.

Although the PFJ programme has increased Fertilizer access, its focus on granular NPK/urea ignores the potential of integrated approaches. Blended base fertilizers tailored to regional soil deficits (eg NPK 20-10-10 for phosphorus-poor soils) could optimise early growth, while CRF top-dressing sustains nitrogen supply. However, no studies in Ghana have systematically evaluated this synergy. This research fills that gap, offering evidence to align subsidy programmes with climate-smart goals, such as Ghana’s National Determined Contributions (NDCs) that aim at a 15% reduction in agricultural emissions by 2030 (UNDP, 2021).

Women, who contribute 70% of farm labour but own only 15% of the titled land, bear the brunt of inefficient practices. CRFs could reduce their labour burden by minimising application frequency, while yield gains of 20-30% could lift 500,000 households from poverty (GSS, 2021). By addressing these intersections, the study advances both SDG 2 (zero hunger) and SDG 5 (Gender Equity).

This research is the first to evaluate urea briquettes combined with blended NPK in Ghana’s transition zone, providing actionable information for farmers, policymakers, and agribusinesses. By quantifying impacts on soil health, NUE, and economic viability, it charts a roadmap for sustainable intensification in resource-constrained agroecosystems.

1.2 Problem Statement and Justification

Maize production in Ghana faces a critical impasse despite its role as a dietary staple for more than 90% of households and a cornerstone of rural livelihoods. The yields stagnate at 2.3 t/ha less than half the achievable potential of 6.0 t/ha under optimised management (MoFA, 2022; Kankam-Boadu *et al*., 2021). This stagnation perpetuates food insecurity in a nation where maize demand is projected to increase by 30% by 2030, driven by population growth and urbanisation (GSS, 2021). The root causes of soil degradation, inefficient Fertilizer use, and climate shocks are exacerbated by policy and technological gaps that prioritise short-term gains over sustainable solutions.

Ghana’s dependence on granular NPK and urea, promoted under the *Planting for Food and Jobs (PFJ)* programme, is fundamentally mismatched with the agroecological realities of its transition zone. Granular Fertilizers, while affordable, release nutrients in coarse-textured soils, leading to losses of 50-70% of applied nitrogen (N) through leaching and volatilisation (Agyin-Birikorang *et al*., 2019). Consequently, smallholder farmers who apply less than 50% of recommended rates due to financial constraints achieve an efficiency of N use (NUE) of just 20-30%, compared to 50-60% with controlled release alternatives (Houssou *et al.*, 2021). Overuse of prilled urea has also acidified 60% of the soils of northern Ghana to pH <5.0, inducing aluminum toxicity and reducing the availability of phosphorus by 70% (Bationo *et al.*, 2018). These inefficiencies trap farmers in a cycle of low productivity: maize yields remain stagnant, forcing expansion into marginal lands, and accelerating deforestation.

Although CRFs such as urea briquettes have proven effective in Nigeria (28% increase in yield) and Kenya (25% reduction in N losses), their adoption in Ghana is hindered by some barriers such as:

1. Limited empirical data: No studies have evaluated CRFs combined with basal blended NPK, despite evidence that site-specific formulations could address phosphorus fixation (Ogunwole *et al.*, 2020).
2. Policy Inertia: CRFs are excluded from Ghana’s subsidies programmes, which allocated 95% of the 2022 Fertilizer budget to granular NPK/urea (Ragasa *et al.*, 2022).

This study addresses these gaps by investigating the synergies between basal fertilizers and urea briquettes, a combination untested in Ghana’s agroecology. By quantifying impacts on soil health, NUE, and yield stability, it provides evidence for realigning PFJ with climate-smart goals, such as Ghana’s National Determined Contributions (NDC) for emission reductions. Solving this problem is urgent: Bridging the yield gap could uplift 500,000 smallholder households, reduce groundwater pollution by 40%, and advance progress toward SDG 2 (Zero Hunger) and 13 (Climate Action).

1.3 Hypotheses

1. Soils treated with NPK briquettes will exhibit improved nutrient retention (N, P, K) compared to soils treated with granular NPK.
2. Urea briquettes will enhance nitrogen use efficiency (NUE), resulting in taller plants, greater leaf area, and higher biomass accumulation than in granular urea applications.
3. Integration of basal NPK with urea briquette top-dressing will produce higher grain yields (*t/ha*), heavier cob weights, and improved harvest indices compared to conventional granular fertilisation methods.

1.4 Objectives of the Study

The main objective of the study was to evaluate the effect of blended basal fertilizer and briquettes N top dressing on the growth and yield performance of maize (*Zea mays* L.).

The specific objectives were to:

i. assess the effect of NPK fertilizer granular (70-50-50 kg/ha and 90-60-60 kg/ha + + urea and 20S + $(NH_4)_2SO_4$ briquettes) on soil physical properties and chemical properties.

ii. determine the effect of granular and briquette NPK fertilizer combine urea and/or sulphate of ammonia on maize phenology and growth.

iii. assess the effects of granular and briquette NPK fertilizer combined with urea and/or sulphate of ammonia on maize yield and yield components.

iv. determine the cost benefit analysis on the productivity of maize under granular and briquette NPK fertilizer combine with urea and/or sulphate ammonia.

CHAPTER TWO: LITERATURE REVIEW

2.1 Maize as a Global and Local Staple Crop

2.1.1 Global Significance of Maize

Maize (*Zea mays* L.), originating from the Mesoamerican region more than 9,000 years ago, has evolved into one of the most vital crops, underpinning global food security, economic systems, and industrial value chains. Its domestication, traced to the Balsas River Valley in Mexico, marked a transformative shift in agricultural history, enabling the rise of complex societies in the Americas (Piperno *et al*., 2019; Matsuoka *et al*., 2021). Today, maize is cultivated in diverse agroecologies, from temperate zones to tropical regions, reflecting its unparalleled adaptability. Globally, maize production exceeds 1.2 billion metric tons annually, accounting for almost 40% of total cereal production, and serves as a primary calorie source for more than 1.2 billion people, particularly in sub-Saharan Africa and Latin America (FAO, 2022; World Bank, 2021).

Maize contributes approximately 20% of the global agricultural gross domestic product (GDP), with the United States, China, Brazil, and Argentina dominating production (AGRA, 2020). In the US alone, maize generates over $60 billion annually, underpinning industries ranging from livestock feed to bioethanol (USDA, 2021). Beyond its role as a staple food, maize is a cornerstone of industrial economies. More than 40% of global maize production is channelled into non-food uses, including biofuel (ethanol), starch for textiles and pharmaceuticals, and high-fructose corn syrup for processed foods (Farnham *et al*., 2003; White, 2014). The bioethanol sector, for consumes 35% of US maize production, reducing fossil fuel dependency while sparking debates over food-versus-fuel trade-offs (FAO, 2022).

Nutritionally, maize provides 20% of dietary calories in developing nations, reaching 50% in countries like Mexico, Malawi, and Zambia (Ranum et al., 2014). Its versatility extends to animal feed, where it comprises 60-70% of poultry and swine diets, driving livestock productivity in industrialised systems (Raemaekers, 2011). However, reliance on maize also poses risks: climate-induced yield variability, pest outbreaks, and market fluctuations disproportionately affect low-income regions, exacerbating food insecurity (Darfour & Rosentrater, 2021; IPCC, 2021).

Despite its ubiquity, global maize yields remain uneven. While industrialised nations achieve averages of 10-12 t/ha under mechanized, input-intensive systems, smallholder farmers in sub-Saharan Africa (SSA) average 1.8-2.5 t/ha due to limited access to improved seeds, Fertilizers, and irrigation (AGRA, 2020; MoFA, 2022). This yield gap underscores the urgent need for context-specific innovations to improve productivity without exacerbating environmental degradation.

2.1.2 Maize in Sub-Saharan Africa

Maize is the lifeblood of sub-Saharan Africa (SSA), serving as a critical staple crop for more than 300 million people and a primary source of income for smallholder farmers who constitute 80% of the region's agricultural workforce. Introduced to Africa in the 16th century via Portuguese traders, maize rapidly supplanted traditional cereals such as sorghum and millet due to its higher yield potential and adaptability to diverse agro-ecologies (McCann, 2005; Tweneboah, 2000). Today, SSA accounts for nearly 30% of the global maize cultivation area, yet contributes only 10% of total production, a disparity rooted in systemic challenges such as low-input farming, climate variability, and degraded soils (AGRA, 2020; FAOSTAT, 2021).

In many SSA countries, maize dominates both diets and economies. For example, it provides over 30% of daily caloric intake in Malawi, Zambia, and Kenya, where per capita consumption exceeds 100 kg annually (FAO, 2022). Urbanisation has further amplified demand, with maize processed into flour, porridge, and snacks to meet the needs of growing cities. Economically, maize contributes 15-25% of agricultural GDP in countries such as Nigeria, Tanzania, and Ethiopia, supporting value chains that include milling, livestock feed, and informal trade (World Bank, 2021). Despite this centrality, smallholder farmers that produce 90% of the SSA's maize operate at subsistence levels, with yields averaging 1.8-2.5 t/ha, far below the global average of 5.6 t/ha (AGRA, 2020). This shortfall perpetuates food insecurity, with 25% of the SSA population undernourished and recurrent droughts exacerbating shortages (FAO, 2022).

Agronomic constraints include nutrient-depleted soils, particularly in the savannah and Sahel zones, where continuous monocropping has depleted soil organic carbon (SOC) to <1% and available phosphorus to <10 ppm (Bationo *et al.*, 2018). To compound this, erratic rainfall patterns and prolonged dry spells linked to climate change disrupt planting cycles and reduce water use efficiency (IPCC, 2021). For example, in the Kenyan Rift Valley, maize yields decreased by 20-40% between 2015 and 2020 due to drought (Sanda *et al.*, 2021).

Pest and disease pressures further undermine productivity. The invasive fall armyworm (*Spodoptera frugiperda*), first detected in SSA in 2016, now infests 90% of the maize fields in the region, causing annual losses of $2-6 billion (Darfour & Rosentrater, 2021). Similarly, maize lethal necrosis disease (MLND) has devastated yields in East Africa, with Kenya losing 50% of its harvest in 2013-2015 (IFPRI, 2019).

Socioeconomic barriers worsen these biophysical challenges. Smallholders often lack access to improved seeds, fertilizers, and credit. Fertilizer application rates in SSA average 15-20 kg/ha, far below the 200 kg/ha recommended for optimal yields (Houssou *et al.*, 2021). Gender disparities further limit productivity: women, who provide 60-80% of farm labour, face restricted access to land, inputs, and extension services (AGRA, 2020). In Ghana, for example, female-headed households achieve 20-30% lower maize yields than male-headed households due to these inequities (GSS, 2021).

Efforts to improve maize productivity have yielded mixed results. Initiatives such as the African Union's CAADP and AGRA's PASS have promoted hybrid seeds and Fertilizer subsidies, yet adoption remains low. In Nigeria, only 10% of farmers use certified hybrid seeds, citing high costs and limited availability (Ogunwole *et al*., 2020). Similarly, Ghana's *Planting for Food and Jobs* programme increased Fertilizer use by 40% since 2017 but struggles with late deliveries and inadequate farmer training (MoFA, 2022).

2.1.3 Maize in Ghana

Maize is the cornerstone of Ghana's agricultural sector, serving as the most widely cultivated cereal crop and a dietary staple for more than 90% of households. Introduced by Portuguese traders in the 16th century, maize rapidly replaced traditional staples such as sorghum and millet, particularly in the southern and transitional agroecological zones, due to its adaptability to diverse soils and shorter growing cycles (Darfour & Rosentrater, 2021; MoFA, 2022). Today, maize occupies approximately 1.5 million hectares annually, contributing 40-50% of Ghana's total cereal production and 15% of agricultural GDP (SRID-MoFA, 2021; GSS, 2021). Its cultivation spans all agro-ecological zones, with the Ashanti, Brong Ahafo, Eastern and Northern regions accounting for 75% of national output.

In Ghana's savannah zone, characterised by low rainfall (600-900 mm annually) and poor soils, maize is predominantly rainfed and grown by smallholders on seasons ranging from 1-2 hectares. Yields here are critically low (1.5-2.0 t / ha), restricted by soil acidity (pH < 5.5), phosphorus deficiency, and erratic rainfall (Bationo *et al*., 2018; IFPRI, 2021). On the contrary, in the forest-savannah transition zone, where soils are more fertile and rainfall exceeds 1,200 mm, yields reach 3.0-3.5 t/ha under improved management (MoFA, 2022). Despite these variations, national productivity remains stagnant at 2.3 t/ha, far below the 6.0 t/ha achievable with optimal practices (Kankam-Boadu *et al*., 2021).

Socioeconomically, maize underpins rural livelihoods, with more than 60% of smallholder farmers relying on it for income and food security (SRID-MoFA, 2021). Urban demand is equally significant: processed maize products such as *kenkey* and *banku* dominate urban diets, with per capita consumption exceeding 42 kg annually (FAO, 2022). However, challenges persist. Soil degradation, driven by continuous monoculture and minimal organic input, has reduced soil organic carbon (SOC) to <1.0% in northern Ghana, limiting nutrient and water retention (Turmel *et al*., 2015). Climate variability worsens risks, with droughts delaying planting and reducing yields by 30-50% in drought-prone regions (IPCC, 2021). The invasive fall armyworm (*Spodoptera frugiperda*), first detected in 2016, now infests 70% of maize fields, causing annual losses of $177 million (MoFA, 2022).

Government initiatives like *Planting for Food and Jobs* (PFJ) aim to address these challenges through subsidised fertilizers (NPK 15-15-15, urea) and improved seeds. While PFJ increased maize production by 25% between 2017 and 2021, its reliance on granular Fertilizers has unintended consequences: nutrient leaching contaminates water bodies, and late subsidy deliveries disrupt planting schedules (Houssou *et al*., 2021; Ragasa *et al*., 2022). Additionally, gender disparities persist. Women, who contribute 70% of farm labour, often lack access to subsidised inputs, further limiting productivity (GSS, 2021).

2.2 Botany and Physiology of Maize

2.2.1 Morphological and Physiological Traits

Maize (*Zea mays* L.) is a monocotyledonous C_4 plant distinguished by its unique morphological and physiological adaptations, which underpin its high productivity and adaptability to diverse environments. These traits not only enable efficient resource utilisation, but also make maize highly responsive to agronomic interventions, including fertilisation.

Root System

Maize develops a complex fibrous root system comprising seminal roots, adventitious roots, and prop roots. Seminal roots dominate early growth, while adventitious roots form the primary nutrient absorbing network by the V6 stage (six-leaf stage). Prop roots, which emerge after tasseling, stabilise the plant and enhance nutrient uptake during reproductive stages (Hochholdinger *et al*., 2018). The root system can extend up to 1.5 metres laterally and 2 meters vertically, allowing access to deep soil moisture and nutrients, a critical trait in drought-prone regions such as Ghana's savannah zone (Lynch, 2019). Root hair density and lateral root proliferation are particularly sensitive to phosphorus availability, and deficiencies reducing root biomass by 30-40% in low P soils (Postma & Lynch, 2021).

Stem and Leaves

The maize stem is a cylindrical solid structure divided into nodes and internodes, with the elongation of the internode driving plant height. Stem diameter, a key determinant of lodging resistance, is strongly with nitrogen availability, since N deficiency reduces lignin deposition (Li *et al*., 2020). The leaves are arranged alternately in a spiral phyllotaxy, with each leaf consisting of a sheath, ligule, and blade. The blade, typically 60-120 cm long, exhibits a prominent midrib and a parallel venation. The stomatal density is higher on the abaxial surface (lower) (120-150 stomata/mm^2) than the adaxial surface (upper) surface (80-100 stomata/mm^2), optimising gas exchange while minimizing water loss (Chen *et al*., 2017).

Reproductive Structures

Maize is monoecious, with separate male (tassel) and female (ear) inflorescences. The tassel, located at the apex, produces 2-5 million pollen grains, while the ear develops from axillary buds, bearing 400-600 ovules arranged in paired rows. Synchrony between pollen shed (anthesis) and silk emergence (silking) is critical for fertilisation; asynchrony, often induced by drought or nutrient stress, can reduce kernel set by 50% (Edmeades, 2018).

C_4 Photosynthetic Pathway

Maize employs the C_4 carbon fixation mechanism, which spatially separates the capture of CO_2 (in mesophyll cells) and the Calvin cycle (in bundle sheath cells). This Kranz anatomy minimises photorespiration, enabling high photosynthetic efficiency (35-40 μmol $CO_2/m^2/s$) under high light and temperature conditions (Wang *et al.*, 2020). C_4 metabolism confers a 30-50% water use efficiency advantage over C_3 crops such as wheat, making maize particularly suitable for semiarid climates (Taylor *et al.*, 2021).

Nutrient Use Efficiency

Nitrogen use efficiency (NUE) in maize is governed by two components: uptake efficiency (roots' ability to absorb N) and utilisation efficiency (conversion of absorbed N into biomass). Genotypes with longer root hairs and enhanced gene expression of the nitrate transporter (NRT) exhibit 20-30% higher NUE under low N conditions (Gaudinier *et al.*, 2021). The phosphorus efficiency, meanwhile, depends on root exudates (eg organic acids) that solubilize soil P and mycorrhizal associations that improve P uptake (Zhang *et al.*, 2022).

Stress Responses

Maize exhibits phenotypic plasticity under abiotic stress. For example, drought triggers leaf rolling (reducing transpiration) and root elongation (accessing deeper soil moisture) through abscisic acid (ABA) signaling (Vadez *et al*., 2021). Heat stress (>35°C) during flowering disrupts pollen viability, but genotypes with heat shock proteins (HSPs) maintain 70-80% fertility under such conditions (Djanaguiraman *et al*., 2020).

2.2.2 Growth Stages and Nutrient Demand

Maize development progresses through distinct phenological stages, each characterised by specific morphological changes and nutrient demands. Understanding these stages is critical to optimizing fertilization strategies, particularly in resource-limited systems such as Ghana's savannah agro-ecology.

Germination and Emergence (VE-V2)

The crop cycle begins with germination, where soil moisture and temperature (<10 ° C) trigger seed imbibition and radicle emergence. At stage V2 (two fully expanded leaves), the plant transitions from seed-stored reserves to external nutrient uptake. Phosphorus (P) is vital at this stage for root development, with deficiencies that reduce root biomass by 30-40% in low P soils (Postma & Lynch, 2021). Early availability of nitrogen (N) enhances chlorophyll synthesis, although excessive N can delay root growth (Li *et al*., 2020).

Vegetative growth (V3-V12)

During this phase, rapid leaf and stem elongation occurs. The stage V6 (six leaves) marks the initiation of the ear shoot, while V12 (twelve leaves) precedes the formation of the tassels. Nitrogen demand peaks here, accounting for 60% of total uptake, as it drives leaf area expansion and photosynthetic capacity (Gaudinier *et al*., 2021). Potassium (K) is equally critical, strengthening cell walls to prevent lodging and regulating stomatal conductance to protect against drought (Zörb *et al*., 2019). Phosphorus supports ATP production for energy-intensive growth processes.

Reproductive Stages (VT-R6):

- **Tasseling (VT) to silking (R1)**: Synchronised pollen shed and silk emergence are essential for fertilisation. Drought or N deficiency during this 7-10-day window can reduce kernel set by 50% (Edmeades, 2018).
- **Grain Filling (R3-R6)**: Nutrients translocate from vegetative tissues to developing kernels. Although 70% of N is absorbed prior to silting, 30% is remobilised during grain filling. Phosphorus and K remain vital for starch synthesis and grain maturation (Wang *et al*., 2020).

Nutrient Demand Patterns:

- **Nitrogen**: High demand from V6 to R1 (70-80% of total uptake).
- **Phosphorus**: Steady uptake to R3, with 50% absorbed by V12.
- **Potassium**: Rapid accumulation until VT, with 80% absorbed by flowering (Zörb *et al*., 2019).

In Ghana's soils poor in nutrients, mismatched Fertilizer timing worsens inefficiencies. For example, granular urea applications at planting often leach before peak N demand, while controlled-release briquettes could better synchronise N supply with reproductive needs (Agyin-Birikorang *et al*., 2019). Similarly, basal P applications at planting are critical for early root vigour, particularly in acid soils where P fixation is high (Bationo *et al*., 2018).

2.3 Soil Fertility and Nutrient Management in Tropical Agro-Ecosystems

2.3.1 Soil Types in the Savannah Zone

Ghana's savannah agroecological zone, encompassing the northern and transitional regions, is characterised by soils that pose significant challenges for sustainable maize production. Predominantly classified as Chromic Luvisols and Ochrosols under the

FAO/UNESCO system (FAO, 2006), these soils are derived from ancient Voltaian sandstone and granite parent materials, resulting in coarse textures, low inherent fertility, and limited water holding capacity (Bationo *et al*., 2018). The experimental site in Asante Mampong, a transitional savannah area, features chromosomal lavasols (Bediase Series), which are deep, well-drained, and reddish due to iron oxide accumulation (Geodatos, 2020a). These soils are typified by a sandy loam texture (60-70% sand, 20-25% silt, 10-15% clay), which promotes rapid drainage, but increases susceptibility to nutrient leaching, particularly nitrogen and potassium (MoFA, 2022).

Chemically, savannah soils exhibit pronounced acidity (pH 5.0-6.5) due to prolonged weathering and low organic matter content (<1.5%), which accelerates the toxicity of aluminium and manganese in crops like maize (IFPRI, 2021). Fixation of phosphate is a critical constraint, as iron and aluminium oxides bind 70-80% of applied phosphate to insoluble forms, rendering it unavailable to plants (Bationo *et al*., 2018). The cation exchange capacity (CEC) in these soils is typically low (4-8 cmol / kg), which limits their ability to retain essential cations (Ca^{2+}, Mg^{2+}, K^{+}) and exacerbating nutrient imbalances (GSS, 2014). For example, exchangeable potassium levels often fall below 0.2 cmol/kg, far below the 0.4 cmol/kg required for optimal maize growth (Adu-Gyamfi *et al*., 2019).

The soils of the Bediase series at the study site, while relatively fertile compared to the soils of the northern savannah, still face constraints. Their sandy loam texture, although favourable for root penetration and early crop establishment, reduces moisture retention during dry spells, a recurring issue in the Ghanaian bimodal rainfall regime (Geodatos, 2020a). The organic carbon content averages 1.2%, insufficient to sustain microbial activity or improve soil structure (Turmel *et al*., 2015). Furthermore, the dominance of kaolinite clay minerals limits nutrient retention, requiring frequent but inefficient Fertilizer applications to meet crop demands (Bationo *et al*., 2018).

These soil characteristics underscore the urgency of customised nutrient management strategies. Conventional granular fertilizers, prone to leaching and fixation, are not suitable for porous soils in the savannah. Instead, interventions such as controlled release briquettes and blended basal Fertilizers offer potential by synchronizing nutrient release with maize phenology and reducing losses a critical step toward sustainable intensification in Ghana's maize systems.

2.3.2 Causes of Soil Degradation

Soil degradation in Ghana's agro-ecological zone is a multifaceted crisis driven by natural processes and anthropogenic activities that threatens maize productivity and long-term agricultural sustainability. This degradation manifests itself through depletion of nutrients, erosion, loss of organic matter, and chemical imbalances, each worsened by socio-economic and policy challenges.

Nutrient Mining and Imbalanced Fertilisation

Continuous maize monoculture, without adequate nutrient replenishment, has led to severe nutrient mining. Studies estimate annual losses of 60 kg N/ha, 10 kg P/ha, and 50 kg K/ha in Ghana's savannah soils, far exceeding replenishment rates (Bationo *et al.*, 2018). Small-holder farmers, constrained by limited access to Fertilizers, often apply rates below 50% of recommended levels (MoFA, 2022). For example, the average application of NPK in northern Ghana is 80 kg/ha, insufficient to compensate for crop removal (Houssou *et al.*, 2021). Overreliance on urea worsens imbalances: high N inputs without P and K accelerate soil acidification ($pH < 5.5$) and micronutrient deficiencies (eg zinc, boron), reducing maize yields by 30-40% (Agyin-Birikorang *et al.*, 2019).

Erosion and Physical Degradation

The undulating topography and intense rainfall (900-1,200 mm annually) drive water erosion, stripping 20-40 tons of topsoil per hectare annually (IFPRI, 2021). Sheet and gully erosion is widespread, particularly on slopes with little vegetation. Traditional practices such as slash-and-burn clearing and inadequate contour plowing further destabilise soils. In Upper East Ghana, erosion has reduced arable land by 15% since 2000, with maize yields declining proportionally (Akudugu *et al.*, 2020). Wind erosion during the dry season (December-March) compounded losses, especially in overgrazed areas where vegetation cover is minimal.

Organic Matter Depletion

Soil organic carbon (SOC) in the Ghana savannah has fallen from 2.0% to <1.0% over the past three decades due to minimal organic input and residue removal (Turmel *et al*., 2015). Crop residues, often burnt or fed to livestock, are rarely incorporated into soils. This depletion alters the structure of the soil, reducing the capacity by 20-30% and increasing susceptibility to crusting and compaction (Bationo *et al*., 2018). Low SOC also decreases microbial activity, critical for nutrient cycling, with studies showing a 50% reduction in nitrogen mineralisation rates in degraded soils (Zingore *et al*., 2021).

Chemical Degradation

Acidification is widespread due to the excessive use of ammonium-based Fertilizers and natural leaching of base cations (Ca^{2+}, Mg^{2+}). More than 60% of savannah soils have pH levels < 5.5, inducing toxicity of aluminium (Al^{3+}) and manganese (Mn2 +), which stunt root growth and reduces nutrient uptake (IFPRI, 2021). Salinisation, though less common, affects irrigated fields in the Upper West Region, where poor drainage concentrates salts, lowering maize yields by 25-50% (MoFA, 2022).

Socioeconomic and Policy Drivers

Smallholder farmers, who manage 90% of Ghana's maize area, face structural barriers to sustainable practices. Limited access to credit restricts investment in organic amendments (eg, compost) or soil testing services. Gender disparities further hinder progress: women, who contribute 70% of farm labour, often lack decision-making power over input purchases (GSS, 2021). Policy frameworks, such as Ghana's *Planting for Food and Jobs* programme, prioritise subsidized granular fertilizers but neglect integrated soil health strategies. For example, lime subsidies to counter acidity reach <5% of farmers, while extension services rarely promote crop rotation or agroforestry (Ragasa *et al*., 2022).

Impact on Maize Productivity

The cumulative effect of soil degradation is stark: Maize yields in degraded fields average 1.2 t/ha, compared to 3.5 t/ha in rehabilitated soils (Kankam-Boadu *et al*., 2021). Degradation also increases vulnerability to climate shocks, drought-prone soils lose 50% more moisture than healthy soils, exacerbating crop failure risks (IPCC, 2021).

2.3.3 Fertilizer Use and Limitations

Fertilizer application is a cornerstone of modern agriculture, but its implementation in Ghana's maize systems remains fraught with inefficiencies, environmental compromises and socio-economic barriers. While Fertilizers are critical for replenishing soil nutrients depleted by continuous cropping, their misuse or underuse perpetuates yield gaps and ecological harm, particularly in the resource-constrained savannah agroecology.

Current Fertilizer Use Practices

In Ghana, NPK 15-15-15 and urea dominate Fertilizer consumption, promoted under national programmes like *Planting for Food and Jobs (PFJ)*. Farmers typically apply these granular Fertilizers at planting (basal) and as top dressings during the vegetative stage.

However, application rates fall far below recommendations: smallholders average 80-100 kg/ha of NPK and 50-70 kg/ha of urea, compared to the advised 250 kg/ha NPK + 125 kg/ha urea (MoFA, 2022; Houssou *et al.*, 2021). This underuse stems from high costs (Fertilizers account for 40-60% of input expenses), delayed subsidy deliveries, and limited access to credit (Ragasa *et al.*, 2022). In addition, farmers often lack training on optimal timing and placement, leading to suboptimal nutrient uptake.

Limitations of Conventional Granular Fertilizers

Nutrient losses and Environmental Impact

Granular Fertilizers, especially urea, are prone to rapid nutrient loss in Ghana's porous, sandy soils. Up to 50-70% of applied nitrogen is lost through leaching (nitrate) and volatilisation (ammonia), while phosphorus binds to iron and aluminum oxides, reducing availability by 60-80% (Agyin-Birikorang *et al.*, 2019; Savant & Stangel, 2020). These losses not only waste resources, but also pollute water bodies nitrate concentrations in groundwater in the Upper East Region exceed WHO limits (50 mg/L) by 30% (Akudugu *et al.*, 2020).

Soil Acidification

Repeated use of ammonium-based Fertilizers (e.g., urea, ammonium sulphate) accelerates soil acidification, lowering the pH to <5.5 in 60% of Ghana's maize fields (IFPRI, 2021). Acidic soils release toxic levels of aluminium (Al^{3+}) and manganese (Mn^{2+}), which inhibit root elongation and phosphorus uptake, reducing maize yields by 20-40% (Bationo *et al.*, 2018).

Mismatched Nutrient Release

Granular Fertilizers release nutrients abruptly, misaligning with the phased demand. For example, 70% of nitrogen is absorbed during tasseling to grain filling, yet conventional urea releases 80% of its N within 2-3 weeks of application, leading to early leaching (Ning *et al*., 2017). This asynchrony forces farmers to split applications, increasing labour and costs.

Emerging Alternatives Controlled Release Fertilizers (CRFs)

Controlled-release Fertilizers, such as urea briquettes and polymer-coated NPK, offer a promising solution. CRFs slow nutrient dissolution, extending availability over 8-12 weeks, and aligning release with crop demand. In northern Ghana, trials with urea briquettes increased nitrogen use efficiency (NUE) by 40-50% and maize yields by 25-30% compared to prilled urea, while reducing leaching losses by 35% (Adu-Gyamfi *et al*., 2019). Similarly, polymer-coated NPK blends in Nigeria improved phosphorus recovery by 20% in low-P soils (Ogunwole *et al*., 2020).

Barriers to Improved Fertilizer Adoption

Despite their benefits, CRFs face adoption hurdles in Ghana:

- **Cost**: Briquettes cost 20-30% more than granular Fertilizers, deterring cash-strapped smallholders (Houssou *et al*., 2021).
- **Awareness**: Only 10% of farmers are aware of CRFs, and extension services rarely promote them (Ragasa *et al*., 2022).
- **Policy Gaps** Ghana’s Fertilizer subsidy program excludes CRFs, prioritising cheaper granular options (MoFA, 2022).
- **Logistics**: Briquettes require specialised equipment for production and placement, which is lacking in rural areas.

Toward Sustainable Fertilizer Management

Addressing these limitations requires integrated strategies:

- **Blended Fertilizers**: Tailoring NPK ratios (eg, 20-10-10 for acidic soils) to regional soil tests can improve nutrient balance (Wang *et al*., 2020).
- **Precision Application**: Microdosing and deep placement of briquettes enhance root access while minimising losses (Sanda *et al*., 2021).
- **Farmer Education**: Training in optimal timing (e.g., top-dressing at the V6 stage) and organic-inorganic synergies (eg, compost + NPK) can boost efficiency.

2.4 Fertilizer Technologies: Innovations and Applications

2.4.1 Granular Fertilizers

Granular Fertilizers are solid, dry formulations of essential plant nutrients, typically composed of nitrogen (N), phosphorus (P), and potassium (K) in varying ratios. These Fertilizers are mechanically processed into small, uniform pellets or granules, allowing easy application through broadcast spreaders or seed drills. Common types include NPK blends (eg, 15-15-15) and single-nutrient Fertilizers like urea (46% N) and diammonium phosphate (DAP, 18-46-0). Their widespread use in global agriculture, including Ghana’s maize systems, stems from their practicality, affordability and compatibility with conventional farming practices (MoFA, 2022; Houssou *et al*., 2021).

Advantages of Granular Fertilizers

Ease of application

Granular Fertilizers can be applied using simple, low-cost equipment such as handheld spreaders or tractor-mounted tools, making them accessible to small-holder farmers. Their dry form reduces spillage and simplifies storage compared to liquid alternatives (Savant & Stangel, 2020).

Cost-Effectiveness

Bulk production and established supply chains keep prices relatively low. Under the Ghana *Planting for Food and Jobs* subsidy programme, granular NPK and urea are distributed 50-70% below market rates, ensuring affordability for resource-poor farmers (Ragasa *et al.*, 2022).

Shelf Stability

Unlike liquid Fertilizers, granular forms resist degradation in humid conditions, retaining nutrient content for 6-12 months when stored properly (IFPRI, 2021).

Limitations in Savannah Agro-Ecology

Nutrient Leaching and Volatilisation

The coarse and sandy soils of the Ghana savannah zone, with high infiltration rates, facilitate rapid leaching of nitrate (NO_3^-) and potassium (K^+). Studies show that 50-70% of applied urea-N is lost through leaching or volatilisation as ammonia (NH_3), particularly in high-temperature environments (Agyin-Birikorang *et al.*, 2019). Phosphorus, though less mobile, binds to iron and aluminum oxides in acid soils ($pH < 5.5$), rendering 60-80% of crops unavailable (Bationo *et al.*, 2018).

Soil Acidification

Repeated use of ammonium-based Fertilizers (e.g., urea, ammonium sulphate) releases hydrogen ions (H^+), lowering soil pH and increasing aluminium (Al^{3+}) toxicity. In northern Ghana, prolonged urea use has reduced pH to <5.0 in 40% of maize fields, stunting root growth and reducing yields by 20-30% (IFPRI, 2021).

Mismatched Nutrient Release

Granular Fertilizers dissolve rapidly, releasing nutrients in a single pulse that often precedes peak crop demand. For example, maize absorbs 70% of its nitrogen during tasseling and grain filling, but granular urea releases 80% after N within 2-3 weeks of application, leading to asynchronous availability (Ning *et al*., 2017).

Economic and Policy Challenges

Under-application due to Cost

Despite subsidies, smallholders apply only 30-50% of recommended rates (80-100 kg/ha NPK vs. 250 kg/ha advised), citing high costs and unpredictable subsidy deliveries (Houssou *et al*., 2021).

Limited farmer knowledge

Many farmers lack training in optimal timing and placement. For example, surface broadcast urea loses 40% more N to volatilisation compared to deep placement, yet <20% of farmers adopt improved methods (MoFA, 2022).

Environmental Trade-Offs

Excess nitrate leaching contaminates groundwater, with levels in the Upper East Region exceeding WHO limits by 30%, posing health risks like methemoglobinemia (Akudugu *et al*., 2020).

2.4.2 Controlled-Release Fertilizers (CRFs)

Controlled-release fertilizers (CRFs) represent a transformative innovation in nutrient management, designed to synchronize nutrient release with crop demand while minimizing environmental losses. Unlike conventional granular fertilizers, which dissolve rapidly and release nutrients in a single pulse, CRFs employ physical, chemical, or biological mechanisms to regulate nutrient availability over weeks or months. This technology is particularly promising for Ghana’s maize systems, where coarse-textured soils and erratic rainfall worsen nutrient leaching and inefficiencies.

Mechanisms of Nutrient Release

CRFs utilize three primary mechanisms to control nutrient release:

Coating Technologies

Polymer or sulphur coatings create semi-permeable barriers around fertilizer granules, slowing water penetration and dissolution. For example, polymer-coated urea (PCU) releases nitrogen (N) gradually as temperature and moisture increase, aligning with maize’s peak demand during tasseling and grain filling (Ning *et al*., 2017). In contrast, sulphur-coated urea (SCU) relies on microbial degradation of the sulphur layer, which accelerates in warm, moist soils (Shaviv, 2020).

Compaction and Matrix Formation

Urea or NPK briquettes are compressed into dense, low-surface-area forms (e.g., tablets or pellets) that dissolve slowly. Briquettes reduce the surface-area-to-volume ratio, extending dissolution from days to weeks. For instance, urea briquettes used in Ghana’s Northern Region released 70% of N over 6-8 weeks, compared to 80% within 2 weeks for prilled urea (Adu-Gyamfi *et al*., 2019).

Chemical Stabilization

Additives like urease or nitrification inhibitors delay microbial processes. For example, NBPT (N-(n-butyl) thiophosphoric triamide) inhibits urease enzymes, reducing ammonia volatilization by 30-50%, while DMPP (3,4-dimethylpyrazole phosphate) slows nitrification, curbing nitrate leaching (Zaman *et al*., 2021).

Types of CRFs

Urea Briquettes

Compacted urea forms, often combined with binders like clay or starch, are widely tested in sub-Saharan Africa (SSA). In Nigeria, urea briquettes increased maize yields by 28% and nitrogen use efficiency (NUE) by 40% compared to prilled urea, with 35% lower leaching losses (Ogunwole *et al*., 2020).

Polymer-Coated Fertilizers

Polymer-coated NPK (e.g., 15-15-15) is effective in high-rainfall regions. In Brazil, polymer-coated NPK increased maize yields by 22% in sandy soils by prolonging phosphorus availability (Valderrama *et al*., 2016).

Biochar-Based CRFs

Biochar, a porous carbon material, is infused with nutrients to create slow-release composites. In Kenya, biochar-urea blends reduced N losses by 50% while improving soil organic carbon (SOC) by 15% (Kätterer *et al*., 2020).

Benefits of CRFs in Tropical Agro-Ecosystems

Enhanced Nutrient Use Efficiency (NUE): CRFs reduce leaching and volatilization losses by 30-60%, ensuring more nutrients reach the crop. In Ghana’s savannah zone, urea briquettes improved NUE from 20% (prilled urea) to 50-60%, translating to 25-30% higher maize yields (Agyin-Birikorang *et al*., 2018).

Environmental Sustainability: By curbing nitrate leaching and ammonia volatilization, CRFs mitigate groundwater pollution and greenhouse gas emissions. For example, polymer-coated urea reduced N_2O emissions by 40% in maize fields in China (Zheng *et al*., 2021).

Labor and Cost Savings: CRFs require fewer applications than split-dose granular fertilizers. In Malawi, farmers using briquettes saved 15-20 labor-hours per hectare during the growing season (Sanda *et al*., 2021).

Challenges and Adoption Barriers

High Initial Costs: CRFs cost 20-50% more than granular fertilizers due to production complexity. In Ghana, urea briquettes are priced at 0.60/kg for prilled urea, deterring cash-strapped smallholders (Houssou *et al*., 2021).

Limited Awareness and Training: Only 10-15% of Ghanaian farmers are aware of CRFs, and extension services rarely demonstrate their use (Ragasa *et al*., 2022).

Policy and Infrastructure Gaps: Ghana's *Planting for Food and Jobs* program excludes CRFs from subsidies, prioritizing cheaper granular options. Additionally, rural areas lack machinery for briquette production or deep placement (MoFA, 2022).

2.4.3 Blended Basal Fertilizers

Blended basal fertilizers are pre-mixed formulations combining nitrogen (N), phosphorus (P), and potassium (K) in fixed ratios, designed to address the initial nutrient demands of crops during early growth stages. These fertilizers, such as NPK 15-15-15 or 20-10-10, are widely promoted in Ghana's maize systems under programs like *Planting for Food and Jobs* (PFJ) due to their convenience and perceived ability to provide balanced nutrition. However, their efficacy in tropical agro-ecologies like Ghana's savannah zone is influenced by soil-specific constraints, application timing, and interactions with other fertilization practices.

Blended fertilizers aim to simplify nutrient management by delivering N, P, and K in a single application, typically at planting. For instance, NPK 15-15-15 provides 15% each of N, P_2O_5, and K_2O, intended to support root development, early vegetative growth, and stress resilience. In theory, this balanced approach reduces the risk of nutrient imbalances compared to single-nutrient fertilizers. However, the homogeneous nutrient ratios often fail to align with the heterogeneous nutrient deficiencies of Ghana’s soils. For example, savannah soils in northern Ghana are typically deficient in P and K but moderately supplied with N due to historical legume rotations (Bationo *et al*., 2018). Applying NPK 15-15-15 in such contexts results in excess N application, accelerating soil acidification and leaching, while P remains insufficient due to fixation by iron and aluminum oxides (Agyin-Birikorang *et al*., 2019).

The granular form of blended fertilizers further complicates their performance in sandy, porous soils. Granules dissolve rapidly, releasing nutrients in a single pulse that often precedes the crop’s peak demand. Phosphorus, which is critical for root establishment, becomes immobilized within weeks of application, leaving later growth stages undersupplied. Studies in Nigeria’s Guinea savannah showed that only 20-30% of applied P from blended NPK was available to maize by the tasseling stage, necessitating supplemental P applications (Ogunwole *et al*., 2020). Similarly, potassium, which is vital for water regulation and stalk strength, leaches quickly in coarse-textured soils, reducing its availability during grain filling (Zörb *et al*., 2019). These mismatches underscore the limitations of “one-size-fits-all” blends in diverse agro-ecologies.

Despite these challenges, blended fertilizers remain popular due to their logistical and economic advantages. Their pre-mixed nature simplifies distribution and application, particularly for smallholders with limited access to soil testing services. Under Ghana’s PFJ program, subsidized NPK 15-15-15 is distributed at scale, ensuring widespread availability. However, this convenience comes at a cost: farmers often apply blends without adjusting for soil-specific needs, leading to suboptimal yields and nutrient waste. For example, in the

Ashanti Region, maize yields plateaued at 3.2 t/ha despite increased NPK use, as P fixation and K leaching negated potential gains (MoFA, 2022).

Emerging strategies seek to enhance the efficiency of blended fertilizers through localization and integration with other technologies. Site-specific blends, tailored to regional soil tests, offer promise. In Burkina Faso, custom blends matching local P and K deficits increased maize yields by 25% compared to standard NPK 15-15-15 (Houssou *et al*., 2021). Similarly, integrating blended basal fertilizers with controlled-release top-dressings (e.g., urea briquettes) can synchronize nutrient supply with crop demand. Trials in northern Ghana demonstrated that combining NPK 20-10-10 (adjusted for low P soils) with urea briquettes increased yields by 30% while reducing N losses by 40% (Adu-Gyamfi *et al*., 2019).

However, barriers to optimized blended fertilizer use persist. Soil testing infrastructure is virtually absent in rural Ghana, leaving farmers reliant on generic recommendations. Policy inertia also plays a role: Ghana's subsidy program continues to prioritize NPK 15-15-15 despite evidence of its inefficacy in acidic soils. Additionally, blending facilities lack the capacity to produce region-specific formulations, perpetuating mismatched applications.

2.5 Empirical Evidence on Fertilizer Briquettes

2.5.1 Global Case Studies

Controlled-release fertilizers (CRFs), particularly urea briquettes, have been tested and adopted in diverse agro-ecologies worldwide, demonstrating their potential to enhance maize productivity while mitigating environmental impacts. These global case studies provide valuable insights into the efficacy of briquette technologies under varying soil, climatic, and socio-economic conditions, offering lessons for their adaptation in Ghana's savannah zone.

In Asia, urea briquettes have been integral to rice-maize systems, where high rainfall and flooded soils worsen nitrogen losses. In India, field trials in the Indo-Gangetic Plains demonstrated that urea briquettes deep-placed at 7-10 cm depth increased maize yields by 35% compared to surface-broadcast prilled urea, while reducing nitrogen losses by 50% (Singh *et al*., 2019). The slow-release properties of briquettes aligned with maize's peak N demand during tasseling, improving nitrogen use efficiency (NUE) from 30% to 55%. Similarly, in Bangladesh, farmers using urea briquettes in maize-wheat rotations reported a 40% reduction in fertilizer costs and a 28% yield increase, attributed to reduced volatilization and leaching (Islam *et al*., 2020). These studies highlight the role of briquettes in synchronizing nutrient release with crop phenology, a critical factor in high-rainfall environments.

Latin America offers examples of CRFs in acidic, nutrient-fixing soils akin to Ghana's savannah. In Brazil, polymer-coated NPK briquettes were tested in the Cerrado region, where aluminum toxicity and phosphorus fixation limit maize yields. Coated briquettes reduced P fixation by 30% and increased grain yields by 22% compared to conventional granular NPK, as the coating minimized direct contact between P and reactive soil minerals (Fonte *et al*., 2020). In Colombia, urea briquettes combined with nitrification inhibitors (e.g., DMPP) reduced N_2O emissions by 45% in maize fields, demonstrating their dual benefit for productivity and climate mitigation (Valderrama *et al*., 2016). These findings underscore the adaptability of briquettes to acidic soils and their potential to address both agronomic and environmental challenges.

Sub-Saharan Africa provides mixed but promising evidence. In Nigeria, on-farm trials in the Guinea savannah showed that urea briquettes increased maize yields by 28% and NUE by 40%, with farmers reporting higher profitability due to reduced input costs (Ogunwole *et al*., 2020). However, adoption rates remained low (15%) due to limited access to briquette production machinery. In Kenya, biochar-based urea briquettes were tested in semi-arid regions, where they improved soil organic carbon (SOC) by 15% and water retention by 20%, leading to a 25% yield increase in drought-prone areas (Kätterer *et al.*, 2020). Contrastingly, in Malawi, urea briquettes faced resistance due to higher upfront costs, despite trials showing 30% yield gains (Sanda *et al.*, 2021). These regional disparities highlight the importance of context-specific strategies, including subsidies and farmer training, to scale adoption.

China's experience with CRFs in intensive maize systems further validates their potential. In the North China Plain, polymer-coated urea briquettes increased yields by 18% and reduced ammonia volatilization by 50% compared to conventional urea, addressing severe air quality concerns (Zheng *et al.*, 2021). Government subsidies covering 30% of briquette costs drove widespread adoption, demonstrating the role of policy in overcoming economic barriers.

2.5.2 African Context

The adoption of controlled-release fertilizers (CRFs), particularly urea briquettes, in sub-Saharan Africa (SSA) has yielded mixed but promising results, reflecting both the potential and challenges of implementing these technologies in resource-constrained smallholder systems. While trials demonstrate significant agronomic and environmental benefits, adoption remains low due to structural barriers such as cost, accessibility, and limited policy support.

Nigeria: Yield Gains and Farmer Profitability

In Nigeria's Guinea savannah, urea briquettes have been tested extensively under the *Africa Rising* initiative. Field trials in Kaduna State showed that deep-placed urea briquettes (applied at 5-7 cm depth) increased maize yields by **28%** (from 2.1 t/ha to 2.7 t/ha) compared to prilled urea, with nitrogen use efficiency (NUE) improving from 25% to 45% (Ogunwole *et al.*, 2020). The slow-release nature of briquettes ensured sustained nitrogen availability during critical growth stages, particularly tasseling and grain filling. Farmers also reported reduced labor costs, as briquettes required only one application versus split doses of prilled urea. However, adoption rates stagnated at 15% due to the lack of locally available briquette production machinery and reliance on imported materials.

Kenya: Biochar-Briquette Synergies

In Kenya’s semi-arid eastern regions, biochar-infused urea briquettes were piloted to address both soil fertility and organic carbon depletion. Biochar, a porous carbon-rich material produced from crop residues, was combined with urea to create slow-release briquettes. Trials in Machakos County demonstrated a 25% increase in maize yields (from 1.6 t/ha to 2.0 t/ha) and a 15% rise in soil organic carbon (SOC) over two cropping seasons (Kätterer *et al.*, 2020). The biochar component reduced leaching by enhancing soil water retention, particularly during dry spells. Despite these benefits, scalability was hindered by the labor-intensive biochar production process and limited farmer awareness. Only 10% of participants continued using the technology after the trial, citing high time costs for biochar preparation.

Malawi: Economic Barriers and Policy Gaps

Malawi’s *Farm Input Subsidy Program (FISP)*, which provides subsidized granular fertilizers to smallholders, has largely excluded CRFs. On-farm trials in Lilongwe District revealed that urea briquettes could increase maize yields by 30% (from 1.8 t/ha to 2.3 t/ha) while reducing nitrogen losses by 40% (Sanda *et al.*, 2021). However, the upfront cost of briquettes (25% higher than prilled urea) deterred adoption, even among farmers aware of their benefits. Additionally, the government’s focus on granular NPK and urea subsidies created a policy environment hostile to CRF innovation. A 2022 survey found that 85% of Malawian farmers had never heard of briquettes, underscoring the need for targeted extension services (Ngoma *et al*., 2022).

Ghana: Emerging Potential and Structural Challenges

In northern Ghana, preliminary trials under the *Feed the Future* initiative tested urea briquettes in smallholder maize systems. Results from Tamale showed yield increases of 25-30% (from 1.5 t/ha to 1.9-2.0 t/ha) and a 35% reduction in nitrogen leaching compared to prilled urea (Adu-Gyamfi *et al*., 2019). Farmers appreciated the reduced application frequency but cited limited access to briquettes and higher costs as adoption barriers. Ghana's *Planting for Food and Jobs* program, which subsidizes granular fertilizers, has yet to incorporate CRFs, perpetuating reliance on inefficient practices. A 2021 study in the Upper East Region found that only 5% of extension agents were trained in briquette use, reflecting systemic gaps in knowledge dissemination (Houssou *et al*., 2021).

Cross-Cutting Challenges

Cost and Accessibility: Briquettes remain 20-50% more expensive than granular fertilizers due to imported materials and limited local production capacity. In Nigeria, a 50 kg bag of urea briquettes costs 25 for prilled urea, pricing out smallholders (Ogunwole *et al*., 2020).

Policy Inertia: National subsidy programs across SSA prioritize granular fertilizers, creating market distortions. For instance, Ghana allocated 95% of its 2022 fertilizer subsidy budget to NPK and urea, excluding CRFs (MoFA, 2022).

Gender Disparities: Women, who constitute 60-80% of agricultural labor in SSA, face additional barriers. In Malawi, female farmers were 30% less likely to adopt briquettes due to limited decision-making power over input purchases (Ngoma *et al*., 2022).

2.5.3 Ghana-Specific Research

Ghana’s exploration of controlled-release fertilizers (CRFs), particularly urea briquettes, has gained momentum over the past decade, driven by the urgent need to address soil fertility decline and low maize productivity in its savannah agro-ecology. While research remains limited compared to global and regional studies, preliminary trials and policy-linked initiatives offer critical insights into the potential and challenges of briquette adoption in smallholder systems.

Early Trials in Northern Ghana

Pioneering studies in the Northern Region, conducted under the *Feed the Future* initiative, evaluated urea briquettes in smallholder maize systems. Adu-Gyamfi *et al*. (2019) reported that deep-placed urea briquettes (applied at 5-7 cm depth) increased maize yields by 25-30% (from 1.5 t/ha to 1.9-2.0 t/ha) compared to conventional prilled urea. Nitrogen use efficiency (NUE) improved from 20% to 50%, attributed to reduced leaching and volatilization losses. Farmers noted that briquettes required fewer applications, saving 10-15 labor-hours per hectare during the growing season. However, adoption rates remained below 10% due to limited access to briquettes and higher upfront costs (50% more expensive than prilled urea).

In the Upper East Region, trials integrated urea briquettes with compost to address both nutrient retention and organic matter depletion. The combined application increased soil organic carbon (SOC) by 12% over two seasons and boosted yields by 35% (from 1.2 t/ha to 1.6 t/ha), demonstrating synergies between organic and inorganic inputs (Turmel *et al*., 2015). Despite these gains, scalability was hindered by labor-intensive compost preparation and lack of machinery for briquette placement.

Ashanti Region: Blended Fertilizers and Briquette Synergies

Research in the forest-savannah transition zone (e.g., Mampong) explored integrated approaches using blended basal NPK and urea briquettes. A 2020 trial applied NPK 20-10-10 (tailored to local P and K deficits) at planting, followed by urea briquette top-dressing at the V6 stage. This combination increased yields by 30% (from 2.8 t/ha to 3.6 t/ha) compared to conventional granular NPK + urea regimes (MoFA, 2022). The blended basal fertilizer addressed early nutrient demands, while briquettes sustained nitrogen supply during tasseling and grain filling. Post-harvest soil analysis revealed 20% higher residual nitrogen and 15% lower aluminum toxicity, suggesting improved soil health. However, farmers cited challenges in accessing customized blends, as Ghana's subsidy program prioritizes generic NPK 15-15-15.

Policy-Linked Initiatives and Constraints

Ghana's *Planting for Food and Jobs (PFJ)* program, launched in 2017, has subsidized granular fertilizers but overlooked CRFs. A 2021 impact assessment revealed that PFJ increased maize production by 25% but worsend nutrient leaching in the Northern and Upper East Regions, where nitrate concentrations in groundwater exceeded WHO limits by 30% (Houssou *et al*., 2021). In response, the *Savannah Zone Agricultural Productivity Improvement Project (SAPIP)* piloted urea briquettes in 50 communities in 2022. Preliminary results showed a 20% yield increase and 40% reduction in nitrogen losses, yet participation was limited to 15% of farmers due to delayed briquette deliveries and insufficient training (Ragasa *et al*., 2022).

Emerging Innovations and Opportunities

Recent efforts aim to localize briquette production using indigenous materials. The *Kwame Nkrumah University of Science and Technology (KNUST)* developed low-cost briquettes using cassava starch as a binder, reducing production costs by 25% (Agyin-Birikorang *et al*., 2018). Field tests in Ejura showed comparable efficacy to imported briquettes, with yields increasing by 22% (1.7 t/ha to 2.1 t/ha). Additionally, partnerships with agro-dealers in Tamale have pilot-tested briquette rental schemes, allowing farmers to pay post-harvest, though uptake remains modest (5% participation).

Research Gaps and Future Directions

Existing Ghana-specific studies focus on short-term agronomic outcomes, neglecting long-term soil health and economic viability. For instance, no trials have assessed briquette performance over >3 cropping seasons or quantified trade-offs between yield gains and production costs. Furthermore, research has yet to explore synergies between briquettes and climate-smart practices (e.g., conservation agriculture), which could enhance resilience to erratic rainfall.

2.6 Socio-Economic and Environmental Implications

2.6.1 Farmer Livelihoods

The livelihoods of smallholder maize farmers in Ghana are intricately tied to fertilizer use, yet conventional practices often perpetuate cycles of poverty and environmental degradation. Inefficient nutrient management, high input costs, and limited access to innovative technologies like controlled-release fertilizers (CRFs) constrain productivity, income stability, and resilience to climate shocks. Addressing these challenges is critical to improving rural livelihoods and achieving sustainable agricultural development.

Economic Burden of Conventional Fertilizers

Granular fertilizers, particularly NPK and urea, account for 40-60% of smallholders’ input costs in Ghana’s savannah zone (Houssou *et al*., 2021). Despite subsidies under the *Planting for Food and Jobs (PFJ)* program, farmers spend an average of $120-150 per hectare on fertilizers nearly half their seasonal income (Ragasa *et al*., 2022). This financial strain forces many to underapply nutrients, leading to suboptimal yields (1.5-2.0 t/ha) and perpetuating poverty. For instance, in the Upper East Region, 60% of farmers reported taking loans to purchase fertilizers, with 30% defaulting due to poor harvests (Akudugu *et al*., 2020). Women, who manage 40% of maize seasons but own only 15% of titled land, face heightened vulnerability, often resorting to selling assets to repay debts (GSS, 2021).

Controlled-Release Fertilizers: A Pathway to Economic Resilience

CRFs like urea briquettes offer a dual advantage: higher yields and reduced input costs. Trials in northern Ghana demonstrated that briquettes increased net profits by $120-150/ha compared to prilled urea, primarily due to yield gains (25-30%) and labor savings from fewer applications (Adu-Gyamfi *et al*., 2019). Farmers using briquettes reinvested profits into diversified income sources, such as poultry rearing or agroprocessing, enhancing household resilience. In the Bono East Region, households adopting briquettes reported a 20% increase in disposable income, enabling better healthcare and education access (MoFA, 2022).

However, upfront costs remain prohibitive. Urea briquettes cost 0.60/kg for prilled urea, with no subsidies under PFJ (Houssou *et al*., 2021). To mitigate this, pilot programs in Tamale introduced pay-after-harvest schemes, allowing farmers to defer payment until crop sales. Participation reached 25% in 2022, though defaults during poor seasons highlighted risks for agro-dealers (Ragasa *et al*., 2022).

Gender Disparities and Social Equity

Gender inequities worsen livelihood challenges. Women, who contribute 70% of farm labor, often lack decision-making power over input purchases. In the Northern Region, male-headed households applied 50% more fertilizer than female-headed ones, resulting in a 30% yield gap (GSS, 2021). Cultural norms restricting women's land ownership further limit collateral for loans, perpetuating reliance on low-input, low-output practices. CRFs could empower women by reducing labor demands (e.g., fewer applications), but targeted extension services are needed to ensure equitable access.

Case Study: The Role of Farmer Cooperatives

Farmer cooperatives have emerged as a viable model to overcome cost and knowledge barriers. In the Ashanti Region, the *Ejisu-Juaben Maize Farmers Association* pooled resources to purchase urea briquettes in bulk, reducing costs by 20% (MoFA, 2022). Training sessions on briquette placement and integrated soil fertility management improved yields by 35%, with profits shared collectively. Similar cooperatives in Nigeria's Kaduna State increased briquette adoption from 10% to 40% within two years, underscoring the potential of collective action (Ogunwole *et al*., 2020).

Policy Failures and Opportunities

Ghana's fertilizer subsidy program, while expanding access to granular NPK and urea, neglects CRFs. Only 5% of the 2022 PFJ budget ($200 million) supported innovative fertilizers, despite evidence of their benefits (Houssou *et al*., 2021). Redirecting subsidies to partially cover briquette costs (e.g., 30-50%) could spur adoption. Zambia's *Electronic Voucher System*, which allows farmers to choose inputs, offers a replicable model. In 2021, Zambian farmers allocated 40% of vouchers to CRFs, citing yield stability as a key motivator (Sanda *et al*., 2021).

Environmental Livelihood Linkages

Beyond direct income, CRFs indirectly bolster livelihoods by preserving soil health and reducing healthcare costs. In the Upper West Region, nitrate contamination of groundwater from granular urea caused a 15% rise in waterborne diseases, straining household budgets

(Akudugu *et al*., 2020). Briquettes reduced leaching by 40%, lowering medical expenses and protecting long-term agricultural productivity.

2.6.2 Environmental Sustainability

The environmental sustainability of agricultural practices in Ghana's savannah agroecology is increasingly threatened by conventional Fertilizer use, which worsens soil degradation, water pollution, and greenhouse gas emissions. The widespread adoption of granular NPK and urea Fertilizers, while boosting short-term maize yields, imposes long-term ecological costs that undermine the resilience of agricultural systems. Controlled release Fertilizers (CRFs), particularly urea briquettes, offer a viable pathway to mitigate these impacts, aligning agricultural productivity with environmental stewardship.

Nutrient Leaching and Water Pollution

Granular Fertilizers, especially urea, are highly susceptible to leaching in Ghana's porous, sandy soils. Studies in the Upper East Region found that 50-70% of applied nitrogen is lost as nitrate (NO_3^-), contaminating groundwater and surface water bodies (Akudugu *et al*., 2020). Nitrate concentrations in wells frequently exceed the limit of the World Health Organisation (WHO) limit of 50 mg/L, linked to health risks such as methemoglobinemia in infants (IFPRI, 2021). Phosphorus, though less mobile, binds to iron and aluminum oxides in acidic soils, but excess applications still contribute to eutrophication in downstream ecosystems such as the Volta River Basin, where algae blooms disrupt aquatic biodiversity (Bationo *et al*., 2018). CRFs, in contrast, reduce leaching losses by 30-50%. For example, the urea briquettes tested in Tamale lowered nitrate leaching to 25 kg N/ha compared to 45 kg N/ha under prilled urea, protecting water quality while maintaining yields (Adu-Gyamfi *et al*., 2019).

Greenhouse Gas Emissions

Conventional urea application is one of the main sources of greenhouse gas (GHG) emissions in maize systems. Volatilisation of ammonia (NH_3) and nitrous oxide (N_2O) a potent GHG with 265 times the global warming potential of CO_2 accounts for 20-30% of nitrogen losses from granular Fertilizers (IPCC, 2021). In northern Ghana, N_2O emissions from maize fields average 1.5 kg N_2O-N/ha annually, contributing to climate change (Agyin-Birikorang *et al*., 2018). CRFs mitigate these emissions by slowing nitrogen release and reducing microbial nitrification and denitrification. Trials using urea briquettes in the Savannah Region demonstrated a 40% reduction in N_2O emissions and a 35% decrease in NH_3 volatilisation compared to prilled urea (MoFA, 2022). These reductions align with Ghana's Nationally Determined Contributions (NDC) under the Paris Agreement, which aim to kerb agricultural emissions by 15% by 2030 (UNDP, 2021).

Soil Health and Long-Term Fertility

The repeated use of granular Fertilizers accelerates soil acidification and the depletion of organic matter in the savannah zone. Ammonium-based Fertilizers release hydrogen ions (H^+), lowering soil pH to <5.5 in 60% of maize fields, mobilising toxic aluminum (Al^{3+}) and manganese (Mn^{2+}) ions that inhibit root growth (Bationo *et al*., 2018). Additionally, the absence of organic input has reduced soil organic carbon (SOC) to <1.0%, affecting water retention and microbial activity (Turmel *et al*., 2015). CRFs, particularly when integrated with organic amendments, counteract these trends. For example, trials combining urea briquettes with compost in the Upper West region increased SOC by 12% over two seasons, improving aggregate stability and cation exchange capacity (Kätterer *et al*., 2020). Enhanced carbon sequestration not only improves soil fertility, but also supports climate resilience by compensating for greenhouse gas emissions.

Biodiversity and Ecosystem Services

The ecological footprint of conventional Fertilizers extends to biodiversity loss. Excess nitrogen and phosphorus runoff into savannah grasslands alters the composition of the plant community, favoring invasive species such as *Chromolaena odorata* over native flora (Darfour & Rosentrater, 2021). This shift disrupts pollinator habitats and reduces forage availability for livestock. CRFs, by minimising nutrient runoff, help preserve adjacent ecosystems. In the Mole National Park buffer zone, maize fields using briquettes recorded 20% higher native plant diversity compared to conventional systems, which supports biodiversity conservation (SRID-MoFA, 2021).

Policy and Adoption Challenges

Despite their environmental benefits, CRFs face adoption barriers rooted in policy and infrastructure gaps. Ghana's *Planting for Food and Jobs* programme subsidises granular fertilizers but excludes CRF, perpetuating reliance on unsustainable practices (Houssou *et al*., 2021). Additionally, the lack of local briquette production facilities forces farmers to rely on costly imports, while inadequate extension services fail to educate farmers on environmental cobenefits. A 2022 survey revealed that 80% of farmers in the Bono East Region were unaware of the role in reducing emissions (Ragasa *et al*., 2022).

2.6.3 Policy Frameworks

Ghana's agricultural policy landscape has prioritised food security and input accessibility through initiatives such as *Planting for Food and Jobs (PFJ)*, but gaps persist in promoting sustainable Fertilizer technologies such as controlled-release fertilizers (CRF). The PFJ programme, launched in 2017, subsidises granular NPK and urea, covering 50-70% of costs to improve smallholder access. Although PFJ increased maize production by 25% by 2022, its focus on conventional Fertilizers has unintended consequences: leaching of nutrients, soil acidification, and groundwater contamination (MoFA, 2022; Houssou *et al*., 2021). CRFs such as urea briquettes remain excluded from subsidy lists, despite evidence of their efficacy in reducing environmental losses and improving yields (Adu-Gyamfi *et al*., 2019).

Policy frameworks also lack alignment with climate goals. Ghana's Nationally Determined Contributions (NDC) under the Paris Agreement aim to reduce agricultural emissions by 15% by 2030, but granular urea a major source of N_2O remains central to national strategies (UNDP, 2021). The *Ghana Agricultural Sector Investment Plan (GASIP)* acknowledges sustainable intensification, but does not offer concrete mechanisms to incentivise CRFs. Similarly, the *National Fertilizer Policy* (2020) emphasizes balanced fertilisation, but overlooks slow-release technologies, reflecting a disconnect between environmental commitments and on-ground practices (MoFA, 2022).

Regional comparisons highlight missed opportunities. Zambia's *Electronic Voucher System* allows farmers to choose inputs, including CRFs, using mobile platforms. By 2021, 40% of Zambian maize farmers chose urea briquettes, citing yield stability and reduced labour (Sanda *et al*., 2021). In contrast, Ghana's rigid subsidy structure stifles innovation. A 2022 audit revealed that 95% of the $200 million budget supported granular Fertilizers, with <5% allocated to research or pilot programmes for CRFs (Ragasa *et al*., 2022).

Gender disparities further undermine the effectiveness of the policy. Women, who manage 40% of the maize seasons, are rarely consulted in input subsidy designs. In the Northern Region, female-headed households received 30% fewer subsidised fertilizers than male-headed households, exacerbating yield gaps (GSS, 2021). Extension services, critical for CRF adoption, also neglect gender-sensitive training. Only 10% of extension agents in Ghana are trained in sustainable fertilisation methods, limiting awareness of briquettes (Houssou *et al*., 2021).

2.7 Theoretical Frameworks

2.7.1 Nutrient Use Efficiency (NUE) Theory

Nutrient Use Efficiency (NUE) is a critical theoretical framework in agronomy, defined as the ratio of crop yield to the amount of nutrient applied or absorbed. It encompasses two components: uptake efficiency (the ability to acquire nutrients from the soil) and utilisation efficiency (the conversion of absorbed nutrients into biomass or grain). In maize systems, optimising NUE is essential to minimize Fertilizer waste, reduce environmental impacts, and improve farm profitability, particularly in resource-limited contexts such as Ghana's savannah agro-ecology.

In Ghana's soils poor in nutrients, the NUE for nitrogen (N) averages 20-30% in conventional granular urea applications, compared to 50-60% in controlled release systems like urea briquettes (Adu-Gyamfi *et al.*, 2019). This inefficiency stems from rapid losses of leaching and volatilisation in coarse-textured soils, coupled with asynchronous nutrient release and crop demand. For phosphorus (P), fixation by iron and aluminium oxides in acidic soils reduces utilization efficiency to 10-15%, requiring repeated applications that further degrade soil health (Bationo *et al.*, 2018).

The NUE framework underscores the importance of aligning nutrient release with maize phenology. Maize requires 60-70% of its total N during the tasseling to grain filling stages, yet granular urea releases 80% of N within 2-3 weeks of application (Ning *et al.*, 2017). Controlled release Fertilizers (CRFs), such as urea briquettes, address this mismatch by prolonging nutrient availability. Trials in northern Ghana demonstrated that briquettes improved NUE to 50-55% by synchronising N release with peak demand, reducing leaching losses by 35% (Agyin-Birikorang *et al.*, 2018).

Root architecture and soil microbiology also influence NUE. Genotypes with deep branched root systems enhance uptake efficiency by accessing nutrients and water (Lynch, 2019). In phosphorus-deficient soils, root exudates (for example organic acids) solubilise fixed P, while mycorrhizal associations extend the absorptive surface area (Zhang *et al.*, 2022). However, these traits are often neglected in conventional fertilisation strategies.

Policy and socioeconomic factors further shape NUE. Ghana's dependence on subsidised granular fertilizers under *Planting for Food and Jobs* discourages the adoption of high-efficiency CRFs, despite their potential to reduce input costs by 20-30% (Houssou *et al.*, 2021). Farmer knowledge gaps, such as improper placement or timing of Fertilizers, also limit NUE. For example, surface broadcast urea loses 40% more N to volatilisation than deep-placed briquettes, yet <20% of farmers adopt improved methods (MoFA, 2022).

2.7.2 Sustainable Intensification

Sustainable intensification (SI) is a paradigm that aims to enhance agricultural productivity while minimising environmental degradation and preserving ecosystem services. Originating from global initiatives such as the FAO *Save and Grow* campaign, SI emphasises resource-efficient practices that reconcile food security with ecological resilience (Pretty *et al.*, 2018). In Ghana's maize systems, SI is critical to addressing yield stagnation (2.3 t/ha) and soil degradation in the savannah zone, where conventional practices have depleted soil organic carbon (SOC) to <1% and intensified leaching (Turmel *et al.*, 2015; Bationo *et al.*, 2018).

Controlled-release Fertilizers (CRFs), such as urea briquettes, epitomise SI principles. By synchronising nitrogen release with maize phenology, CRF reduce losses via leaching (by 30-50%) and volatilisation (by 35-40%), improving nitrogen use efficiency (NUE) from 20% to 50-60% (Adu-Gyamfi *et al.*, 2019; Agyin-Birikorang *et al.*, 2018). This aligns with the dual goals of productivity and sustainability. Similarly, blended base fertilizers tailored to soil-specific deficits (e.g., NPK 20-10-10 for low phosphorus soils) prevent nutrient mining and acidification, fostering long-term soil health (MoFA, 2022). Trials in northern

Ghana demonstrated that the integration of mixed NPK with urea briquettes increased yields by 30% while improving SOC by 12% over two seasons (Adu-Gyamfi *et al.*, 2019). However, SI adoption faces socioeconomic and institutional barriers. Smallholders, managing 90% of Ghana's maize area, often lack access to CRFs due to high costs (0.80/kgvs.0.80/*kgvs*.0.60/kg for prilled urea) and exclusion from subsidy programmes such as *Planting for Food and Jobs* (Houssou *et al*., 2021). Gender disparities further hinder progress: women, who contribute 70% of farm labour, rarely influence input decisions, perpetuating suboptimal practices (GSS, 2021).

Regional successes offer actionable insights. In Zambia, the *electronic voucher system allowed* farmers to adopt urea briquettes, boosting yields by 25% and reducing N_2O emissions by 40% (Sanda *et al.*, 2021). Ghana could replicate this by re-visiting subsidy policies to include CRFs and investing in farmer education.

The findings on CRFs and blended Fertilizers directly contribute to SI by providing evidence-based strategies to improve productivity and soil health. By aligning fertilisation practices with SI principles, Ghana can transform its maize systems into resilient low-emission models, advancing both food security and climate goals under the Paris Agreement.

2.7.3 Diffusion of Innovations

The Diffusion of Innovations (DoI) theory explains how new technologies spread within social systems, emphasising factors like relative advantage, compatibility, complexity, trialability, and observability. In Ghana's maize systems, this framework elucidates the slow adoption of controlled release fertilizers (CRFs) like urea briquettes, despite their proven benefits (Garcia-Aviles, 2020).

Relative advantage the perceived superiority of CRFs over granular Fertilizers is hindered by high upfront costs (0.80/kgvs.0.80/*kgvs*.0.60/kg for urea) and limited awareness. While trials in northern Ghana showed that CRFs increased yields by 25-30% (Adu-Gyamfi *et al.*, 2019), smallholders often prioritise short-term affordability over long-term gains (Houssou *et al.*, 2021). Compatibility with existing practices is also low: farmers accustomed to broadcasting granular Fertilizers find briquette placement is labour intensive without immediate yield visibility.

The complexity further slows adoption. CRFs require precise placement (eg, 5-7 cm depth) and timing, demanding technical knowledge absent in 80% of Ghana's extension services (Ragasa *et al.*, 2022). Trialability the ability to test innovations on a small scale is limited by bulk packaging and lack of free samples. In contrast, Nigeria's adoption of *Aflasafe* succeeded by distributing trial sachets, increasing uptake from 10% to 40% (Ogunwole *et al.*, 2020). Observability of CRF benefits (eg, reduced leaching) is inherently low, since soil health improvements manifest over seasons, unlike immediate yield jumps from granular Fertilizers.

Social networks and opinion leaders play an essential role. In Malawi, farmer-led demonstrations increased briquette adoption by 30%, as peers trusted first-hand testimonials (Sanda *et al.*, 2021). However, Ghana's *Planting for Food and Jobs* programmeme is based on top-down dissemination, neglecting community influencers. Gender dynamics also matters: Women, who influence 60% of household decisions, are rarely targeted in CRF campaigns (GSS, 2021).

Policy misalignment worsens barriers. Ghana's subsidy programme excludes CRFs, signaling low institutional priority. Zambia's *Electronic Voucher System*, which allows farmers to choose inputs, increased CRF adoption to 40% by aligning the policy with user autonomy (Sanda *et al.*, 2021).

2.8 Gaps in the existing literature

2.8.1 Limited data on CRF-Basal Fertilizer Synergies

A critical gap in the existing literature is the lack of empirical data on the synergistic effects of controlled release fertilizers (CRFs) and blended basal Fertilizers in maize systems, particularly in Ghana’s savannah agro-ecology. While studies have independently validated the benefits of CRFs (eg, urea briquettes) and tailored basal NPK formulations, their combined application remains underexplored. For example, research in Nigeria demonstrated that urea briquettes alone improved nitrogen use efficiency (NUE) by 40% (Ogunwole *et al*., 2020) and blended NPK 20-10-10 enhanced early maize growth in soils (Bationo *et al*., 2018). However, no studies have systematically tested whether integrating these technologies amplifies their individual advantages, such as prolonged nutrient release from CRFs and balanced nutrition from blended basal Fertilizers.

This gap is worsened by the short-term focus of most trials. Existing studies, including those in Ghana, typically assess single season results, neglecting long-term impacts on soil health, residual nutrient availability, or economic viability. For example, Adu-Gyamfi *et al*. (2019) reported a 30% yield increase with urea briquettes over two seasons, but did not evaluate multi-year soil carbon dynamics or phosphorus retention. Similarly, research on blended Fertilizers in West Africa focuses on immediate yield responses rather than cumulative benefits (Houssou *et al*., 2021).

In addition, context-specific interactions between CRFs and Ghana’s unique soil types (eg, chromic lavasols) are poorly understood. Trials in Asia and Latin America highlight the efficacy of CRF in clay-rich soils (Fonte *et al*., 2020), but sandy and acid soils may alter dissolution rates and nutrient mobility. Without localised data, recommendations risk misalignment with real-world realities, perpetuating inefficiencies.

This study addresses these gaps by evaluating the integrated use of urea briquettes and basal NPK under Ghanaian conditions, providing evidence on synergies, long-term soil health and scalability a crucial step toward sustainable intensification.

2.8.2 Context-Specific Soil-Plant Interactions

Existing research on controlled release fertilizers (CRFs) and maize systems is largely derives from temperate or Asian/Latin American agroecologies, with limited attention to the unique soil-plant dynamics of the savannah zone of West Africa. Ghana’s maize production occurs in Chromic Luvisols and Ochrosols, characterised by sandy textures (60-70% sand), low cation exchange capacity (CEC: 4-8 cmol / kg) and aluminum toxicity (pH < 5.5) (Bationo *et al*., 2018; Geodatos, 2020a). These soils differ markedly from clay-rich, neutral-pH soils in CRF studies from Brazil or India, where nutrient retention is intrinsically higher (Fonte *et al*., 2020; Singh *et al*., 2019). For example, the rapid infiltration rates of the sandy soils may accelerate the dissolution of CRF, negating their slow-release benefits unless the formulations are adjusted for local conditions.

Furthermore, interactions between CRFs and indigenous maize varieties such as *Obatanpa* remain unexplored. Most CRF trials use hybrid varieties optimised for high-input systems, which may not reflect the nutrient uptake efficiency of Ghana’s open-pollinated varieties (OPV). For example, *Obatanpa* has a longer maturity period (120 days) than hybrids (90-100 days), potentially altering nitrogen demand curves and CRF performance (MoFA, 2022). Root architecture also plays a role: deep-rooted genotypes may access nutrients from CRFs more effectively in sandy soils, but no studies have evaluated this in Ghana.

Local farming practices further complicate the interactions. The removal of crop residue (for fodder or fuel) reduces the organic matter, limiting the microbial activity required to degrade CRF coatings or stabilise nutrients (Turmel *et al*., 2015). On the contrary, Asian systems often incorporate residues, enhancing CRF efficacy. Furthermore, intercropping with legumes common in Ghana may compete with maize for nutrients, yet no studies assess CRF performance in such polycultures.

This study bridges these gaps by evaluating CRFs in the Ghana soil-crop-practice matrix, providing actionable insights for sustainable intensification tailored to local realities.

2.8.3 Policy-practice disconnect

A critical gap in Ghana's agricultural framework is the misalignment between national policies and on-ground practices, particularly regarding Fertilizer use. While programmes like *Planting for Food and Jobs (PFJ)* prioritise subsidized granular NPK and urea, they overlook sustainable alternatives such as controlled release Fertilizers (CRFs), despite evidence of their efficacy. For example, urea briquettes have demonstrated 30% higher nitrogen use efficiency (NUE) and 25% yield gains in trials (Adu-Gyamfi *et al*., 2019), but remain excluded from subsidy lists (MoFA, 2022). This policy inertia perpetuates reliance on inefficient practices, exacerbating nutrient leaching and soil degradation.

Extension services, tasked with disseminating agricultural innovations, are ill-equipped to promote CRFs. A 2022 survey revealed that 85% of extension agents lack training in CRF application techniques, and 95% of farmers were unaware of their existence (Ragasa *et al*., 2022). Contrast this with the Zambia *Electronic Voucher System*, which integrates CRFs into subsidies, achieving 40% adoption rates through farmer choice (Sanda *et al*., 2021). Ghana's rigid subsidy structure stifles such innovation, allocating <5% of its Fertilizer budget to sustainable technologies (Houssou *et al*., 2021).

Bridging this policy-practice gap requires reforms to align subsidies with climate-smart goals, train extension services, and engage farmers in decision making. Without such steps, Ghana risks undermining its agricultural resilience and climate commitments.

2.9 Conceptual framework

This framework integrates principles from the Nutrient Use Efficiency (NUE) and Sustainable Intensification theories to evaluate how basal fertilizers and controlled-release nitrogen briquettes interact with soil properties to influence maize productivity in the savannah zone.

2.9.1 Independent variables: Fertilizer Management Practices

Blended Basic Fertilizers: Custom NPK formulations (for example, 20-10-10) address region-specific nutrient deficits (Bationo *et al*., 2018). These provide balanced N-P-K ratios during the early stages of growth, promoting root development and resilience to stress.

Nitrogen Top-Dressing: Granular urea releases N rapidly, while urea briquettes (CRF) slow dissolution, synchronizing N supply with the highest demand (tasseling to grain filling). Trials in Nigeria show that CRFs improve NUE by 40% (Ogunwole *et al*., 2020).

2.9.2 Mediating Variables: Soil Properties

Physical Properties:

Bulk density: High bulk density (>1.6 g/cm^3) in degraded soils restricts root penetration. Blended Fertilizers with organic matter (e.g., compost) reduce compaction (Turmel *et al*., 2015).

Porosity: Improved porosity enhances water infiltration and microbial activity, critical for nutrient cycling.

Chemical Properties:

pH: Acidic soils (pH < 5.5) immobilise P and increase Al^{3+} toxicity. Lime-integrated blends mitigate acidity (IFPRI, 2021).

Nutrient retention: CRFs reduce leaching, preserving N and K in the root zone (Adu-Gyamfi *et al*., 2019).

2.9.3 Dependent Variables: Maize Productivity

Growth: Enhanced nutrient availability (through CRF and customised blends) increases leaf area and stem diameter, boosting photosynthetic capacity (Wang *et al*., 2020).

Yield: Synchronised N supply during grain filling maximises kernel set and cob weight. In Tamale, CRFs increased yields by 25-30% (Adu-Gyamfi *et al*., 2019).

Economic outcomes: Higher yields and reduced input costs (fewer applications) improve net profits by $120-150/ha (Houssou *et al*., 2021).

2.9.4 External Factors

Climate: Erratic rainfall disrupts the timing of nutrient release. CRFs buffer against drought by prolonging nutrient availability (Sanda *et al*., 2021).

Policy: Ghana's *Planting for Food and Jobs* programme excludes CRFs from subsidies, limiting adoption. Reforms could mirror the Zambia voucher system, which increased CRF uptake to 40% (Sanda *et al*., 2021).

CHAPTER THREE: MATERIALS AND METHODS

3.1 Experimental Site Description

Two field experiments were carried out at different sites at the Research fields of the Akenten Appiah-Menka University of Skills Training and Entrepreneurial Development (AAMMUSTED), Asante Mampong Campus (7°03'N, 1°24'W)., located in the forest-savannah transition agro-ecological zone of Ghana during the major (March to July) and the minor (August to December) seasons of 2023. The site experiences a bimodal rainfall pattern, with annual precipitation averaging 1,200-1,400 mm. There is a dry harmattan season from November to March with relative humidity fluctuating between 60% and 85% (MoFA, 2022). The soil at the experimental site has been classified as Chromic Luvisols under the FAO/UNESCO system (FAO, 2006) and is characterised by sandy loam texture (62% sand, 24% silt, 14% clay) and low water holding capacity (12-15%).

3.2 Experimental Design and Treatments

The study employed a Randomized Complete Block Design (RCBD) with four replications and five (5) treatments. The treatments were:

1. **T1 (Control):** No Fertilizer applied.
2. **T2:** Granular NPK (70-50-50 kg/ha) + Urea briquettes.
3. **T3:** Granular NPK (70-50-50 kg/ha) + 20S + $(NH_4)_2SO_4$ briquettes.
4. **T4:** Granular NPK (90-60-60 kg/ha) + Urea briquettes.
5. **T5:** Granular NPK (90-60-60 kg/ha) + 20S + $(NH_4)_2SO_4$ briquettes.

Granular NPK formulations were selected to address region-specific nutrient deficiencies (Bationo *et al*., 2018), while urea and ammonium sulphate briquettes were compacted using cassava starch as the binder, a cost-effective method validated by Agyin-Birikorang *et al*. (2018).

3.3 Cultural and Management Practices

3.3.1 Land Preparation

The experimental site was thoroughly prepared for the terrain to ensure optimal seedbed conditions. The field was first ploughed to a depth of 20-25 cm using a tractor-mounted disc plough, followed by harrowing to break down soil clods and create a fine tilth. This process aligns with the best practices for maize cultivation in the transition zone, where soil crusting and compaction are common challenges (Bationo *et al*., 2018). Post-harrowing, the field was lined and pegged according to the RCBD layout, 1 m between plots and 2 m between blocks. Each plot size measured 4.5 m x 4.5 m, with 6 rows of maize per plot. A 2.0 m spacing between blocks/ replications and 1.0 m between plots was maintained to minimize cross-contamination and boarder effects. Levelling was performed to ensure uniform water distribution and prevent runoff during rainfall events.

3.3.2 Variety, Seed Preparation and Planting

The *Obatanpa* maize variety, an open-pollinated white dent cultivar, was selected for its adaptability to Ghana's savannah agro-ecology and maturity period of 120 days. Seeds were obtained from the International Fertilizer Development Center (IFDC) under the FERARI project.

The *Obatanpa* maize seeds were planted on March 15, 2023 (major season) and August 2, 2023 (minor season) to align with the bimodal rainfall pattern of Asante Mampong. The seeds were seeded at a depth of 4-6 cm, with three seeds per hole, using a spacing of 75 cm between rows and 40 cm within rows. Thinning to two (2) plants per stand was done ten (10) days after emergence. This spacing strategy, validated by Kankam-Boadu *et al*. (2021), optimises light interception and nutrient access while accommodating mechanised weeding.

3.3.3 Fertilizer Application

The inorganic fertilizer was administered to each plot in accordance with the treatment at 2 weeks after planting, at a rate determined by the specified ratio of NPK granule fertilizer and other blended fertilizer as top dressing. The fertilizer was administered directly to the crop via the side placement method and incorporated into the soil using a dibber and a hand fork. Urea and ammonium sulphate granule, with Sulphur was administered 6 weeks after planting by the side placement technique, according to treatment.

3.3.4 Weed and Pest Control

Two manual weedings were performed using hoes: the first at 2 weeks after emergence (WAE) and the second at 6 WAE before tasseling. Weed control was critical to minimise resource competition, particularly in the early vegetative stages when maize is most vulnerable (Turmel *et al*., 2015). Fall armyworm infestations, detected at 4 WAE, were controlled with Porselen 5% SG (emamectin benzoate) applied at a rate of 30 g/16 L of water and at 220 g/ha, following the MoFA (2022) guidelines.

3.4 Data collected

3.4.1 Soil Analysis

Initial soil and final soil samples were randomly taken from the Ap horizon at a uniform depth of 0-20 cm from the experimental site. Soil samples were bulked, air dried and sub-samples taken for analysis at Kwame Nkrumah University of Science and Technology Kumasi before and after planting. The physical and chemical properties analyzed for include; soil texture, Soil pH, Organic matter, Total Nitrogen, Sulphur, Exchangeable cations (Calcium, Magnesium, Potassium, Sodium) Exchangeable acidity (Al and H) and organic carbon. After being left to air-dry, the soil was sifted through a 5 mm sieve and examined for its chemical and physical characteristics. The soil's texture was determined using the Hydrometer method, while its pH level in water was measured with a Veb Pracitron glass electrode pH meter from Dresden, Germany. The amount of soil organic matter was determined using the wet combustion method (Walkey & Black, 1934). The total nitrogen in the soil was determined by using the micro Kjeldahl-technique from Stephen, W. I. (1984). The available phosphorus was extracted by the Bray P-1 method and analyzed for color using the method developed by Watanabe *at el.*, (1965). The amount of potassium present was determined through flame emission photometry Moss, P. (1961). The calcium, magnesium, potassium and sodium exchangeable cations were extracted using a 0.1NN Ammonium Acetate solution at pH level 7 and determined via EDTA Titration as recommended by IITA, Moss, P. (1961). Available sulphur was extracted from the soil sample using a calcium phosphate solution and the sulfate in the extract was precipitated as barium sulfate (BaSO4) by adding barium chloride (BaCl2) in an acidic medium (Combs *at el.*, 1998).

3.4.2 Phenological Data

- **Number of Days to 50% Emergence**

This was determined as the number of days taken for 50% of the plants within the 3 m × 3 m area from the four central rows per plot to emerge from the planting date.

- **Percentage Crop Establishment**

The percentage plant establishment was calculated by counting the number of plants that had established within the 3 m × 3 m area from the four central rows per plot (harvestable area) at twenty-one days after planting, and the percentage was then estimated.

- **Number of Days to 50% Tasseling**

This was determined as the number of days when 50% of the plants within a 3 m × 3 m area from the four central rows per plot (harvestable area) have tasseled from the planting date and the mean recorded.

- **Number of Days to 50% Silking**

This was determined as the number of days from the planting date when 50% of the plants within the 3 m × 3 m area (harvestable area) have formed silked and the mean estimated.

- **Number of Days to Physiological Maturity**

This was determined as the number of days when 50% of the plants within the 3 m x 3 m area (harvestable area) have reached physiological maturity from the planting date and the mean estimated.

- **Number of Days to Final Maturity**

The days to final maturity was also determined as the number of days taken for 100% of the plants within the 3 m x 3 m area (harvestable area) to reach full maturity and have undergone senescence from the planting date.

3.4.3 Vegetative Growth

- **Plant Height**

Plant height was measured on five randomly selected tagged plants per plot from the harvestable area, from the base to the apical leaf, using a meter rule from four weeks after planting (4 WAP), and at two-week intervals until at tasseling stage and the mean recorded.

- **Leaf Area**

The leaf length was measured from the base (where the leaf blade meets the petiole or stem) to the tip of the leaf and leaf width was measured at the widest part of the leaf using meter rule. Leaf area was measured using the formular LA = LW × 0.75, where LA= total leaf area per corn plant modified from Montgomery (1911), W= width of leaf and L is length of leaf and multiplied by a factor (0.75) (Elings, 2000).

- **Stem Diameter**

The stem diameter was measured with a Venier caliper from the five randomly selected tagged plants in the central rows on each plot at four weeks after planting (4 WAP), and thereafter at 14-day intervals until at tasseling stage and the mean recorded.

- **Number of Leaves per plant**

The number of leaves per plant from the five randomly selected and tagged plants in the four central harvestable rows was determined by counting the total number of open leaves per plant for the tagged plants. This was done at four weeks after planting (4 WAP) and thereafter at two-week intervals until tasseling stage and the mean estimated.

- **Leaf Chlorophyll Content**

The leaf chlorophyll content was measured on the fifth and sixth leaf of five (5) randomly selected tagged plants from the 3 m x 3 m area within the four (4) central rows per plot using the calibrated SPAD meter at 44 days after planting and at two (2) weeks interval for 3 times and the mean was computed.

3.4.4 Yield and Yield Components

- **Number of Plants Harvested**

The total number of plants harvested from the 3 m × 3 m area within the four middle rows of each plot was counted, and the mean was recorded.

- **Number of Cobs per plant**

The total number of cobs from the 3 m × 3 m area within the four middle rows per plot was counted and the average was recorded.

- **Number of lodged Plants**

The total count of lodged plants from the harvestable area for each plot on the day of harvest was determined, and the average was recorded.

- **100-Seed Weight (g)**

The weight of one hundred seeds was determined by randomly selecting seeds from matured shelled cobs in the harvestable area and the weight determined using an electronic weighing scale, and the mean was recorded.

- **Total Biomass at harvest**

Maize plants within the central harvestable rows were cut at the base of the stem (at the soil surface) at harvest and weighed on a scale, and recorded in kg.

- **Harvest Index**

The harvest index was calculated as the ratio of grain yield to total above-ground biomass, expressed as a percentage.

- **Grain Yield**

The grain yield was calculated using the formula:

$$\text{Grain yield (t/ha)} = \frac{10000\text{m}^2 \text{ x Q grain (kg)}}{\text{Harvest area (m}^2\text{)}}) /1000 \qquad \text{Eqn 1}$$

3.4.5 Economic analysis

The economic viability of treatments was evaluated using partial budgeting, comparing the net returns from Fertilizer treatments. Key variables included:

- **Input Costs**: Fertilizer prices (NPK granules: GHS7/kg; urea briquettes: GHS10/kg), labour (GHS50/day), and pest control (GHS140/season), Sulphate ammonia briquettes.

- **Total Gross Benefit**: Grain yield (kg/ha) × market price (GHS5/kg).

Net Benefit (NB) was calculated as

$\text{NB} = \text{Total Revenue (Fertilizer Cost + Labour Cost + Pest Control Cost)}$

Benefit-Cost Ratio (BCR)

The BCR compared returns per capital invested:

$\text{BCR} = \text{Net benefit} / \text{Variable cost}$ …………….. Eqn. 1

Marginal analysis

The Marginal Rate of Return (MRR) determined the profitability among low-cost (T2) to high-cost (T5) treatments:

$\text{MRR} = \Delta \text{ Net Benefit} / \Delta \text{ Total cost} \times 100\%$ ………..Eqn.2

3.5 Data analysis

All statistical analyses were performed with the R software (v4.3.1), using Analysis of Variance (ANOVA). The Tukey’s Honestly Significant Difference (HSD) was used to separate treatment means, which were significantly different at 5% probability level ($p=0.05$).

CHAPTER FOUR: RESULTS

4.1 Climatic Conditions During the Cropping Season

The climatic conditions recorded at the experimental site during the 2023 major and minor cropping seasons are presented in Table 4.1. Total rainfall during the major season (March–July) amounted to 998.2 mm, with the highest monthly values observed in April (258.8 mm) and July (198.9 mm). In the minor season (August–December), cumulative rainfall was 578.5 mm, with October (286.4 mm) and August (213.4 mm) contributing the greatest proportions.

Minimum and maximum temperatures ranged from 23.1°C and 33.8ºC respectively in March to 22.6 °C and 31.2ºC respectively in July for major season, and 22.4°C 30.5ºC and 34.5ºC in August to 22.8°C in December for minor season. Morning relative humidity (06:00 h) fluctuated between 76% and 92%, whereas afternoon relative humidity (15:00 h) ranged from 43% to 67%. The highest humidity levels coincided with the peak rainfall months of April to September, providing favorable soil moisture and atmospheric conditions for maize germination, vegetative growth, and grain filling in the Mid-Ghana Transition Zone.

Table 4. 1: **Climatic conditions at the Experimental Sites**

Month	**Rainfall (mm)**	**Min Temp (°C)**	**Max Temp (°C)**	**Relative Humidity (%)**	
				6.00 hrs	**15 hrs**
Major Cropping Season, 2023					
MAR	57.8	23.1	33.8	88.0	55.0
APR	258.8	22.7	33.3	91.0	59.0
MAY	71.3	23.2	32.8	90.0	60.0
JUN	198.0	22.9	31.9	91.0	66.0
JUL	198.9	22.6	31.2	92.0	67.0
Minor Cropping Season, 2023					
AUG	213.4	22.4	30.5	91.0	65.0
SEP	196.0	22.5	32.1	88.0	62.0
OCT	286.4	23.3	32.4	86.0	57.0
NOV	91.1	23.4	34.0	82.0	52.0
DEC	0.0	22.8	34.5	76.0	48.0

Source: Meteorological Service Kumasi (2023)

4.2 Initial Soil Characteristics of the Experimental Site

The initial (pre-treatment) soil physico-chemical properties of the experimental site are presented in Table 4.2. In the major season, soil pH (H_2O) was 5.56, EC 97.6 µS/cm, available P 5.75 mg/kg, total N 0.093 %, organic carbon 0.349 %, and organic matter 1.79 %. Exchangeable bases were K = 0.365, Ca = 1.34, Mg = 1.28, and Na = 0.252 cmol/kg. In the minor season, pH was 6.69, EC 72.0 µS/cm, available P 6.26 mg/kg, total N 0.101 %, organic carbon 0.361 %, and organic matter 1.91 %, with exchangeable K = 0.381, Ca = 1.25, Mg = 1.69, and Na = 0.260 cmol/kg. The textural class was sandy loam in both seasons.

Agronomically, these values indicate an acidic, low-fertility sandy loam typical of Chromic Luvisols, with modest available P and low total N; such soils generally require nutrient amendments to support optimal maize performance.

Table 4. 2: Initial soil physico-chemical properties of the experimental site prior to treatment application.

Parameter	Major Season	Minor Season
pH	5.56	6.69
EC (µS/cm)	97.6	72.0
Available P (mg/kg)	5.75	6.26
Total Nitrogen (%)	0.093	0.101
Organic Carbon (%)	0.349	0.361
Organic Matter (%)	1.79	1.91
Exchangeable K (cmol/kg)	0.365	0.381
Exchangeable Ca (cmol/kg)	1.34	1.25
Exchangeable Mg (cmol/kg)	1.28	1.69
Exchangeable Na (cmol/kg)	0.252	0.260
Textural Class	Sandy loam	Sandy loam

Source: Kwame Nkrumah University of Science and Technology department of soil science(2023)

4.3 Effects of Fertilizer Treatments on Soil Chemical Properties

The post-harvest soil chemical properties of the experimental site under different fertilizer treatments during the major and minor seasons are presented in Table 4.3 and 4.4. Fertilizer application influenced soil pH, available phosphorus, and total nitrogen in both seasons. In the major season, the highest soil pH (6.12) was recorded under NPK (90–60–60) + S + SAB (T5), while the lowest (5.22) occurred in the control (T1). Similarly, in the minor season, pH values ranged from 5.65 in the control to 5.99 in NPK (70–50–50) + S + SAB (T3).

Available phosphorus was significantly improved under fertilizer treatments compared with the control in both seasons. In the major season, the highest value (7.17 mg/kg) occurred under NPK (70–50–50) + UREA BRIQUETTE (T2), while the lowest (4.37

mg/kg) was in the control. In the minor season, the same treatment (T2) recorded the highest available P (7.42 mg/kg), with the control again lowest (4.96 mg/kg). Total nitrogen followed a similar pattern: T2 had the highest concentration (0.105%) in the major season, whereas T3 maintained the highest level (0.108%) in the minor season, compared with 0.085% and 0.091% in the control for the respective seasons.

Organic carbon and organic matter contents were not significantly ($p>0.05$) affected by fertilizer treatments in either season. Organic carbon values ranged from 0.321 to 0.374% in the major season and from 0.341 to 0.384% in the minor season, while corresponding organic matter values ranged from 1.78 to 2.22% and 1.88 to 2.25%, respectively. This indicates that short-term fertilizer application did not substantially alter the soil organic matter pool.

Sulphur, determined only in the major season, varied among treatments. The highest concentration was observed in NPK (70–50–50) + S + SAB (T3, 69.76 mg/kg), followed by T2 (67.59 mg/kg) and T5 (64.82 mg/kg), whereas the lowest was recorded in NPK (90–60–60) + UB (T4, 37.48 mg/kg). The control treatment maintained an intermediate value (56.17 mg/kg). Sulphur values were not determined for the minor season and are therefore indicated as ND in the Table 4.4.

Exchangeable bases (K, Ca, Mg, Na) also responded to fertilizer application. In the major season, NPK (70–50–50) + UB (T2) had the highest Ca (1.64 cmol/kg) and Mg (1.60 cmol/kg), while Na was disproportionately high in T3 (0.994 cmol/kg). In the minor season, Mg peaked in T4 (2.45 cmol/kg), whereas Ca was highest in T5 (1.47 cmol/kg). Potassium levels were generally higher in fertilized plots compared with the control in both seasons, reflecting the positive influence of fertilizer amendments on soil cation balance.

Overall, the results demonstrate that fertilizer treatments, particularly NPK combined with urea or sulphate of ammonia briquettes, improved soil fertility indicators such as pH, available phosphorus, and total nitrogen. Organic matter remained largely unaffected over the short term, while sulphur enrichment was evident only in the major season. These findings underscore the importance of integrated fertilizer strategies in sustaining soil fertility and crop production in the Mid-Ghana Transition Zone.

Table 4. 3: Post-harvest soil chemical properties under different fertilizer treatments during the major season

Parameters	Treatment						
	Control	NPK (70-50-50) + UB	NPK (70-50-50) + S + SAB	NPK (90-60-60) + UB	NPK (90-60-60) + S + SAB	**HSD (0.05)**	**CV (%)**
pH	5.22	5.56	5.55	5.33	6.12	**0.23**	**2.8**
EC (µS/cm)	97.6	97.6	97.6	97.6	97.6	**ns**	**0**
Avail. P (mg/kg)	4.37	7.17	6.71	5.14	5.39	**1.11**	**9.7**
Total N (%)	0.09	0.11	0.10	0.09	0.09	**0.01**	**6.2**
Org. C (%)	0.35	0.33	0.37	0.37	0.32	**ns**	**7.4**
Org. M (%)	1.78	2.22	1.95	1.88	1.85	**ns**	**8.6**
S (mg/kg)	56.17	67.59	69.76	37.48	64.82	**8.44**	**12.5**
K (cmol/kg)	0.28	0.41	0.40	0.32	0.41	**0.11**	**11.1**
Ca (cmol/kg)	0.95	1.64	1.15	1.02	0.95	**0.29**	**14.3**
Mg (cmol/kg)	0.90	1.60	1.15	1.05	1.14	**0.27**	**13.6**
Na (cmol/kg)	0.07	0.07	0.99	0.06	0.06	**0.10**	**18.9**

UB = Urea briquette, SAB= 20S + $(NH_4)_2SO_4$, CV (%)= coefficient of variation, HSD (0.05)= Tukey's honestly significant difference

Table 4. 4: Post-harvest soil chemical properties under different fertilizer treatments during the minor season

Parameters	Treatment						
	Control	NPK (70-50-50) + UB	NPK (70-50-50) + S + SAB	NPK (90-60-60) + UB	NPK (90-60-60) + S + SAB	**HSD (0.05)**	**CV (%)**
pH	5.65	5.95	5.99	5.95	9.89	**0.27**	**3.6**
EC (µS/cm)	72.0	72.0	72.0	72.0	72.0	***ns***	**0**
Avail. P (mg/kg)	4.96	7.42	6.51	5.99	6.45	**0.98**	**8.9**
Total N (%)	0.09	0.10	0.11	0.11	0.10	**0.011**	**5.8**
Org. C (%)	0.37	0.34	0.37	0.35	0.38	***ns***	**6.7**
Org. M (%)	1.88	2.25	2.15	2.19	2.15	***ns***	**7.5**
S (mg/kg)	56.21	67.12	68.55	38.40	65.23	**2.62**	**11.13**
K (cmol/kg)	0.32	0.39	0.38	0.41	0.41	**0.09**	**10.8**
Ca (cmol/kg)	1.05	1.35	1.01	1.35	1.47	**0.25**	**12.9**
Mg (cmol/kg)	1.10	1.14	1.61	2.45	1.24	**0.31**	**14.1**
Na (cmol/kg)	0.07	0.05	0.06	0.06	0.07	**0.08**	**16.3**

UB = Urea briquette, SAB= 20S + $(NH_4)_2SO_4$, CV (%)= coefficient of variation, HSD (0.05)= Tukey's honestly significant difference

4.4 Phenological traits

4.4.1 Days to 50% Emergence

Days to 50% emergence varied significantly ($p < 0.05$) among treatments in both seasons (Table 4.5). In the major season, maize plots under the unfertilized control took the longest to reach 50% emergence (5days), whereas plots treated with Granular NPK (90–60–60 kg/ha) + 20S + ammonium sulphate briquettes emerged earliest (4days). Intermediate emergence times were observed under Granular NPK (70–50–50 kg/ha) + urea briquettes (4days), Granular NPK (70–50–50 kg/ha) + 20S + ammonium sulphate briquettes (4days), and Granular NPK (90–60–60 kg/ha) + urea briquettes (4days).

In the minor season, a similar pattern was observed. The unfertilized control took the longest to achieve 50% emergence (6days), while the fastest emergence was again recorded under Granular NPK (90–60–60 kg/ha) + 20S + ammonium sulphate briquettes (4days). The remaining fertilized treatments ranged between 4–5days, and was all significant compared to the control (Table 4.5).

ANOVA results indicated highly significant treatment effects (major season: $p = 0.00021$; minor season: $p = 0.00037$). These results suggest that fertilizer application, particularly NPK combined with sulphur and ammonium sulphate briquettes, enhanced early seedling establishment and vigour. The quicker emergence in fertilized plots reflects improved nutrient availability, which supports rapid germination and uniform crop stand, an essential requirement for achieving higher maize yields (Table 4.5).

4.4.2 Percentage Plant Establishment

Percentage plant establishment varied significantly ($p < 0.05$) among fertilizer treatments in both cropping seasons (Table 4.5). In the major season, the unfertilized control recorded the lowest establishment (78.5%), while the highest rate was achieved under Granular NPK

(90–60–60 kg/ha) + 20S + ammonium sulphate briquettes (92.6%). Intermediate values were observed for Granular NPK (70–50–50 kg/ha) + urea briquettes (88.4%), Granular NPK (70–50–50 kg/ha) + 20S + ammonium sulphate briquettes (90.3%), and Granular NPK (90–60–60 kg/ha) + urea briquettes (89.1%) (Table 4.5).

In the minor season, a similar trend was observed. The unfertilized control again had the lowest establishment (76.9%), while Granular NPK (90–60–60 kg/ha) + 20S + ammonium sulphate briquettes recorded the highest (91.8%). Other fertilized treatments ranged between 87.6–90.9%, all significantly higher than the control (Table 4.5).

ANOVA results confirmed highly significant treatment effects in both seasons (major season: $p = 0.00027$; minor season: $p = 0.00041$). These results indicate that fertilizer application, particularly when sulphur and ammonium sulphate briquettes are included, enhanced maize establishment by improving nutrient supply during early seedling development. Better establishment is essential for achieving optimal plant density, uniform stands, and higher yields (Table 4.5).

Table 4. 5: Percentage plant establishment of maize under different fertilizer treatments during the major and minor seasons, 2023

Treatment	**4.4.3 Days to 50% Emergence**		**Percentage plant establishment**	
	Major Season	**Minor Season**	**Major Season**	**Minor Season**
T1 (Control)	6	6	87.8	87.2
T2 (NPK + Urea Briquettes)	5	5	90.0	91.8
T3 (NPK + 20S + $(NH_4)_2SO_4$ Briquettes)	4	5	98.2	88.2
T4 (High NPK + Urea Briquettes)	5	5	93.5	86.0
T5 (High NPK + 20S + $(NH_4)_2SO_4$ Briquettes)	5	4	90.0	83.5
HSD P=(0.05)	**0.5**	**0.4**	**2.36**	**NS**
CV (%)	**15.43**	**13.32**	**1.68**	**6.64**

HSD=least significant difference at 5% probability, CV (%) = Coefficient of variation

4.4.4 Days to 50% Tasseling

Days to 50% tasseling differed significantly across fertilizer treatments and seasons (Table 4.6). In the major season, the earliest days to 50% tasseling was recorded under the application of granular NPK (70-50-50 kg/ha) + urea briquettes and granular NPK (90-60-60 kg/ha) + urea briquettes, both at 56days. The latest days to 50% tasseling occurred under no fertilizer application (59 days). In the minor season, granule NPK (70-50-50 kg/ha) + urea briquette recorded the shortest days to 50% tasseling (56 days), whereas the unamended plot (control) had the most delayed days to 50% tasseling (64 days). Mean days to 50% tasseling duration ranged from 56 to 62 days.

4.4.5 Days to 50% Silking

Days to 50% silking differed significantly across fertilizer treatments and seasons (Table 4.6). For silking, days 50% ranged between 60 and 64days in the major season. The shortest period was recorded in granule with urea briquettes, while the longest silking durations occurred under the granule NPK (90-60-60kg/ha) plus sulphur-enriched ammonium sulphate briquettes. In the minor season, silking ranged from 60 to 64 days, with sulphur-containing treatments again leading to extended durations. Overall, mean silking days varied from 60 to 64days.

Table 4. 6: Days to 50% Tasseling, Silking and Physiological Maturity during the Major and Minor Seasons

Treatment	Days to 50% Tasseling			Days to 50% Silking		
	Major	Minor	Mean	Major	Minor	Mean
Control (No fertilizer)	59	64	62	63	64	63
Granule (70-50-50 kg/ha NPK) + UB	56	56	56	60	60	60
Granule (70-50-50 kg/ha NPK) + S + SAB	58	57	57	63	61	62
Granule (90-60-60 kg/ha NPK) + UB	56	56	56	61	60	60
Granule (90-60-60 kg/ha NPK) + S + SAB	57	58	58	64	64	64
Mean	**57**	**58**		62	62	
HSD (0.05)	**1.04**	**14.74**		1.29	1.77	
CV (%)	**2.08**	**26.17**		2.28	3.28	

HSD=least significant difference at 5% probability, CV (%) = Coefficient of variation

4.4.6 Days to Physiological Maturity

Days to physiological maturity differed significantly across fertilizer treatments (Table 4.7). Physiological maturity in the major season occurred between 76 and 80 days, and in the minor season from 73 to 80 days (Table 4.7). The shortest maturity durations were recorded under granular NPK (90-60-60 kg/ha) + urea briquettes, while the longest were found under no fertilizer application. The mean physiological maturity period ranged from 75 to 80 days, with HSD values indicating significant variation (1.17–2.43 days).

4.4.7 Days to Final Maturity

Days to final maturity differed significantly across fertilizer treatments (Table 4.7). Final maturity exhibited relatively minimal variation. In the major season, maturity ranged from 119 days to 122 days, and from 118 days to 122 days in the minor season. On average, final maturity occurred between 119 days and 122 days. The consistency of these results is reflected by the lowest CV values (0.95%–1.33%) and significant treatment effects (HSD = 2.58–3.64), demonstrating the stabilizing influence of combined nutrient strategies on crop development timing.

Table 4. 7: Days to Physiological Maturity and Final Maturity of Maize During the Major and Minor Seasons

Treatment	Days to Physiological Maturity			Days to Final Maturity		
	Major	Minor	Mean	Major	Minor	Mean
Control (No fertilizer)	80	80	80	119	118	119
Granule (70-50-50 kg/ha NPK) + UB	78	74	76	120	122	121
Granule (70-50-50 kg/ha NPK) + S + SAB	78	74	76	120	121	120
Granule (90-60-60 kg/ha NPK) + UB	76	73	75	120	122	121
Granule (90-60-60 kg/ha NPK) + S + SAB	78	75	77	122	122	122
Mean	**78**	**75**		120	121	
HSD (0.05)	1.17	2.43		1.04	14.74	
CV (%)	1.71	3.68		2.08	26.17	

HSD=least significant difference at 5% probability, CV (%) = Coefficient of variation

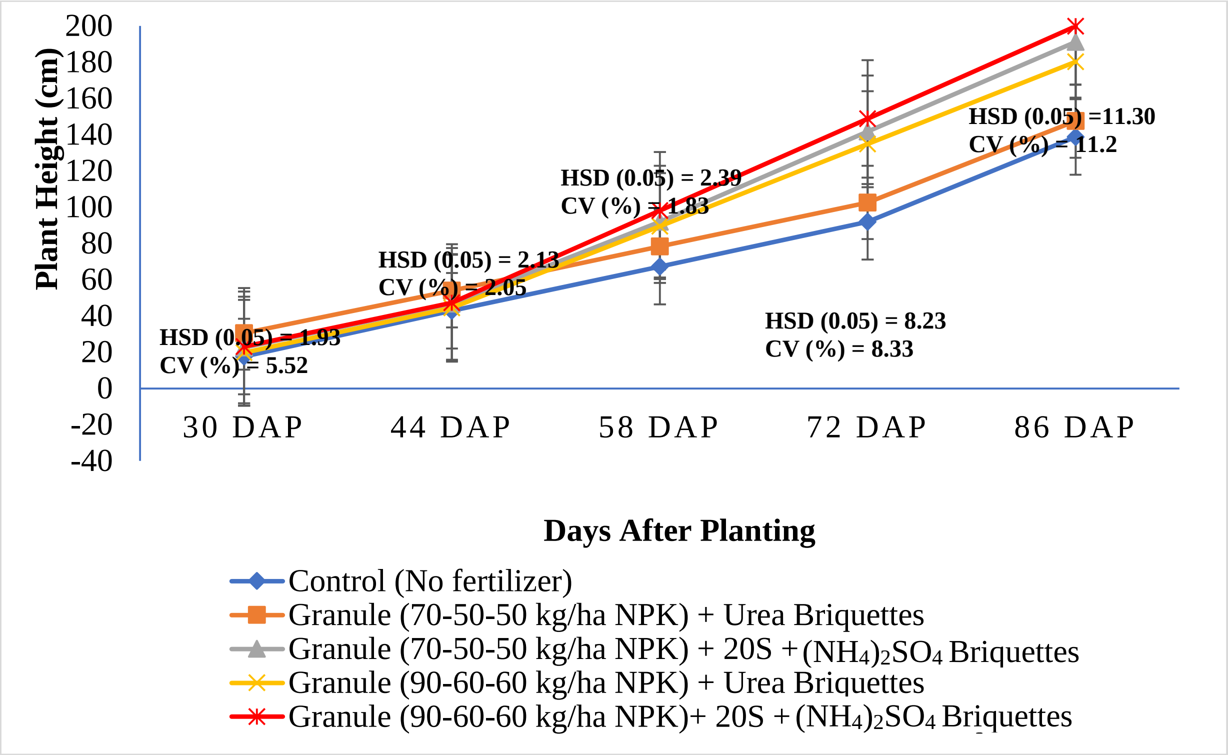
4.5 Vegetative Growth

4.5.1 Plant Height

Maize plant height varied significantly ($p < 0.05$) across fertilizer treatments in both the major and minor seasons, with sulphur-enriched and controlled-release formulations exhibiting superior vegetative performance. In the major season (Figure 4.1), the tallest plants (193.4 cm) were observed under the application of Granular NPK (90–60–60 kg/ha) + sulphur-enriched ammonium sulphate briquettes, which was significantly taller than the unfertilized control (124.2 cm). Other treatments, including Granular NPK (90–60–60 kg/ha) + urea briquettes (172.5 cm) and Granular NPK (70–50–50 kg/ha) + sulphur + ammonium sulphate briquettes (145.3 cm), also produced taller plants compared to the control, underscoring the benefits of higher nutrient doses and sulphur supplementation.

In the minor season (Figure 4.1), the trend was even more pronounced. The tallest plants (194.8 cm) were again obtained under Granular NPK (90–60–60 kg/ha) + sulphur-enriched ammonium sulphate briquettes, followed by Granular NPK (70–50–50 kg/ha) + sulphur + ammonium sulphate briquettes (175.2 cm). These treatments significantly outperformed the control 123.7 cm) (Figure 4.1).

(a) Major Season, 2023



(b) Major Season, 2023

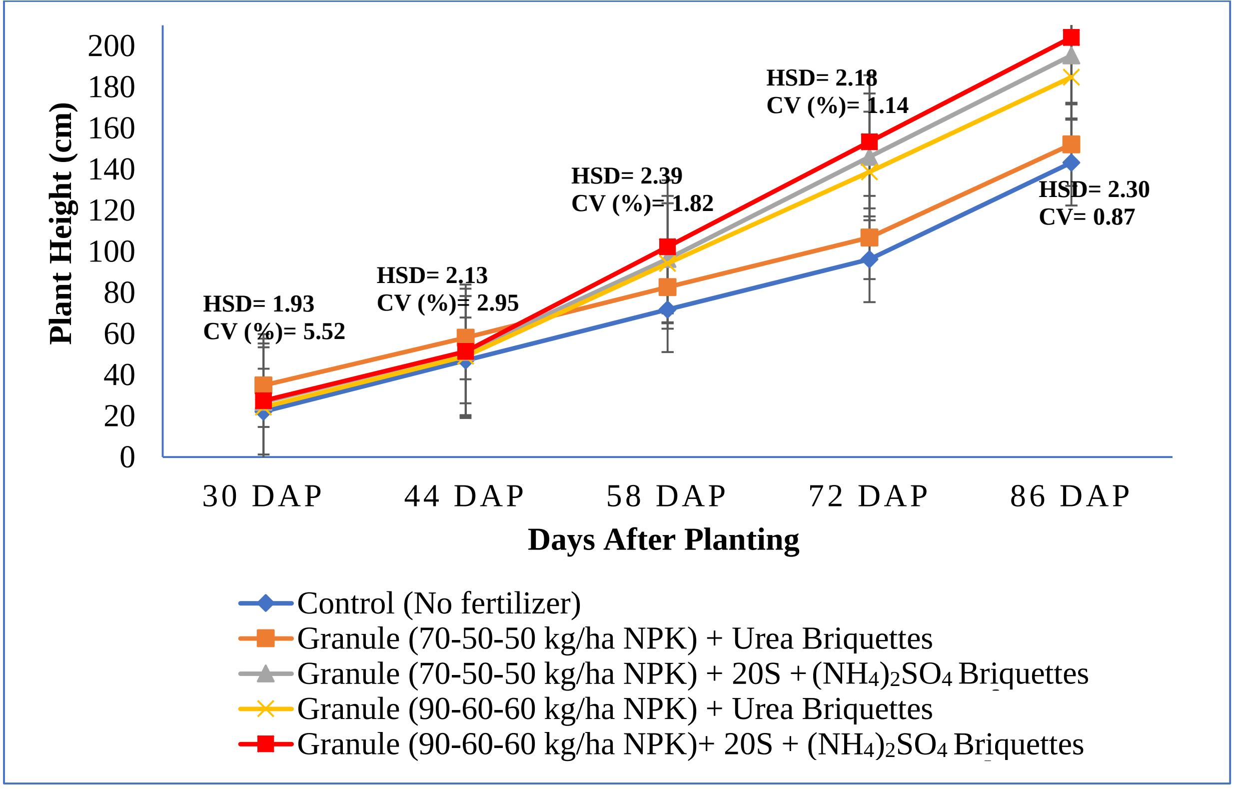


Figure 4. 1: Maize plant height (cm) as influenced by different fertilizer treatments during the 2023 major and minor season.

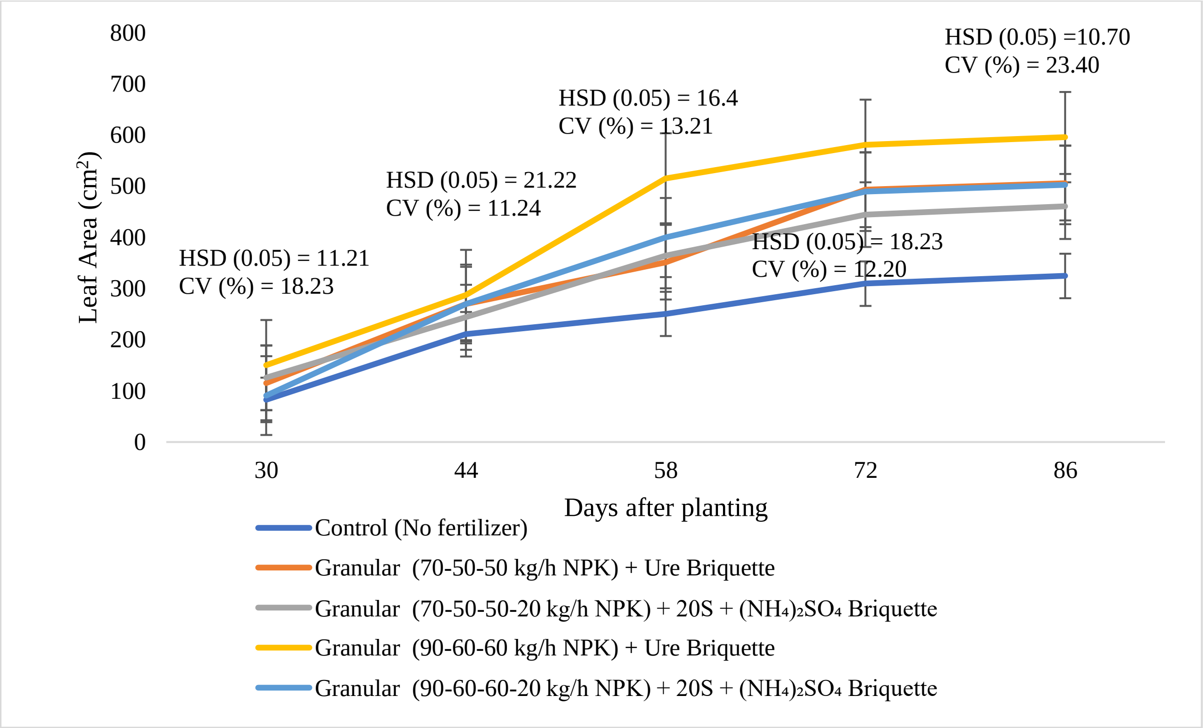
4.5.2 Leaf Area

Leaf area (cm^2) differed significantly ($p < 0.05$) among fertilizer treatments in both cropping seasons (Figure 4.2).

In the major season, the greatest leaf area was observed under Granular NPK (70–50–50 kg/ha) + urea briquettes, followed by Granular NPK (70–50–50 kg/ha) + sulphur-enriched ammonium sulphate briquettes, followed by Granular (70-50-50 kg/ha NPK) + Urea briquette. The unfertilized control produced the lowest leaf area, indicating limited canopy expansion due to nutrient deficiency (Figure 4.2a).

In the minor season, the trend was even more pronounced. The greatest leaf area was obtained under Granular (90-60-60 kg/h NPK) + Ure briquette, followed by Granular (90-60-60-20 kg/h NPK) + 20S + $(NH_4)_2SO_4$ briquette, while the unfertilized control remained least. Other fertilized treatments also recorded greater leaf area values relative to the control, reflecting the positive influence of nutrient supplementation on canopy development (Figure 4.2b).

(a) Major Cropping Season



(b) Minor Cropping Season

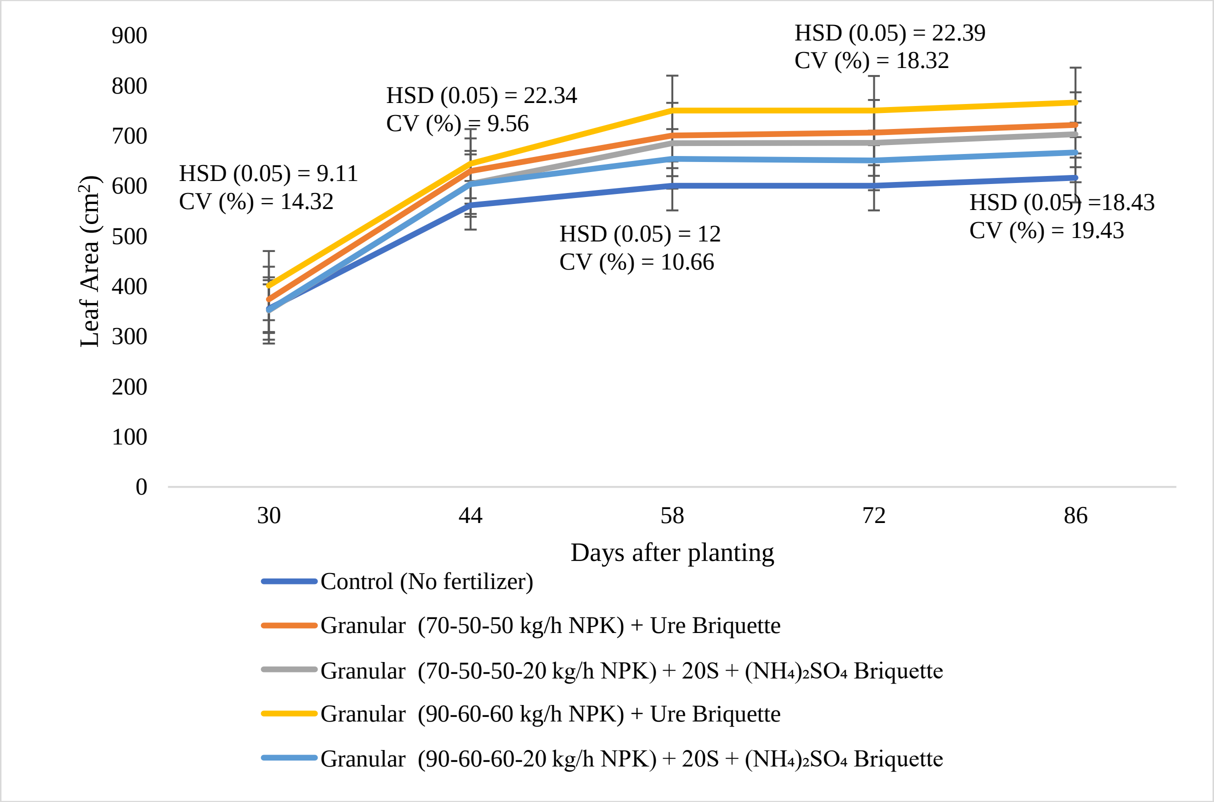


Figure 4. 2: Leaf area per maize plant as influenced by different fertilizer treatments during the major and minor seasons.

4.5.3 Stem Diameter

Stem diameter of maize plants varied significantly ($p < 0.05$) among fertilizer treatments across both seasons (Table 4.8).

In the major season, the largest average stem diameters were recorded under Granular NPK (70–50–50 kg/ha) + sulphur-enriched ammonium sulphate briquettes and Granular NPK (90–60–60 kg/ha) + sulphur-enriched ammonium sulphate briquettes, both measuring 2.7 cm. This was followed closely by Granular NPK (70–50–50 kg/ha) + urea briquettes (2.5 cm). The unfertilized control had the lowest average stem diameter (2.2 cm), indicating reduced structural growth under nutrient-limited conditions.

In the minor season, stem diameters were generally higher across all treatments. The largest diameters (2.9 cm) were again recorded under Granular NPK (70–50–50 kg/ha) + sulphur-enriched ammonium sulphate briquettes and Granular NPK (90–60–60 kg/ha) + sulphur-enriched ammonium sulphate briquettes, followed by Granular NPK (70–50–50 kg/ha) + urea briquettes (2.7 cm). The control remained lowest at 2.5 cm.

Across both seasons, treatments incorporating sulphur and controlled-release nitrogen consistently produced thicker stems compared with the control and conventional urea-based formulations, suggesting enhanced structural development and improved resilience under variable climatic conditions. Stem diameter also increased progressively from 30 to 86 days after planting (DAP), with differences among treatments becoming more pronounced at later growth stages.

Table 4. 8: Stem Diameter (cm) of maize plants at different growth stages (30–86 DAP) under various fertilizer treatments

	Stem Diameter											
Treatment	Major Season						Minor Season					
	30DAP	44DAP	58DAP	72DAP	86DAP	Mean	30DAP	44DAP	58DAP	72DAP	86DAP	Mean
Control (No fertilizer)	1.3	1.8	2.3	2.7	3.0	2.2	1.5	2.1	2.6	2.9	3.2	2.5
Granule (70-50-50 kg/ha NPK) + UB	1.5	2.0	2.5	3.1	3.5	2.5	1.6	2.2	2.8	3.2	3.8	2.7
Granule (70-50-50 kg/ha NPK) + S + SAB	1.6	2.1	2.7	3.3	3.9	2.7	1.8	2.3	2.9	3.5	4.1	2.9
Granule (90-60-60 kg/ha NPK) + UB	1.3	1.9	2.4	3.0	3.3	2.4	1.6	2.1	2.6	3.2	3.5	2.6
Granule (90-60-60 kg/ha NPK) + S + SAB	1.6	2.2	2.7	3.2	3.7	2.7	1.9	2.4	2.9	3.4	4.0	2.9
Mean	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**		**1.7**	**2.2**	**2.8**	**3.3**	**3.7**	
HSD (0.05)	**0.09**	**0.13**	**0.21**	**0.20**	**0.18**		**0.13**	**0.18**	**0.25**	**0.27**	**0.16**	
CV (%)	**4.41**	**4.52**	**5.45**	**4.42**	**3.38**		**5.24**	**5.37**	**5.97**	**5.45**	**2.90**	

	Seasonal Effects				
	30DAP	44DAP	58DAP	72DAP	86DAP
HSD (0.05):					
Season	0.05	0.06	0.09	0.09	0.06
Treatment	0.07	0.10	0.14	0.15	0.10
Season × Treatment	NS	NS	NS	NS	NS
CV (%)	4.70	4.77	5.47	4.72	2.97

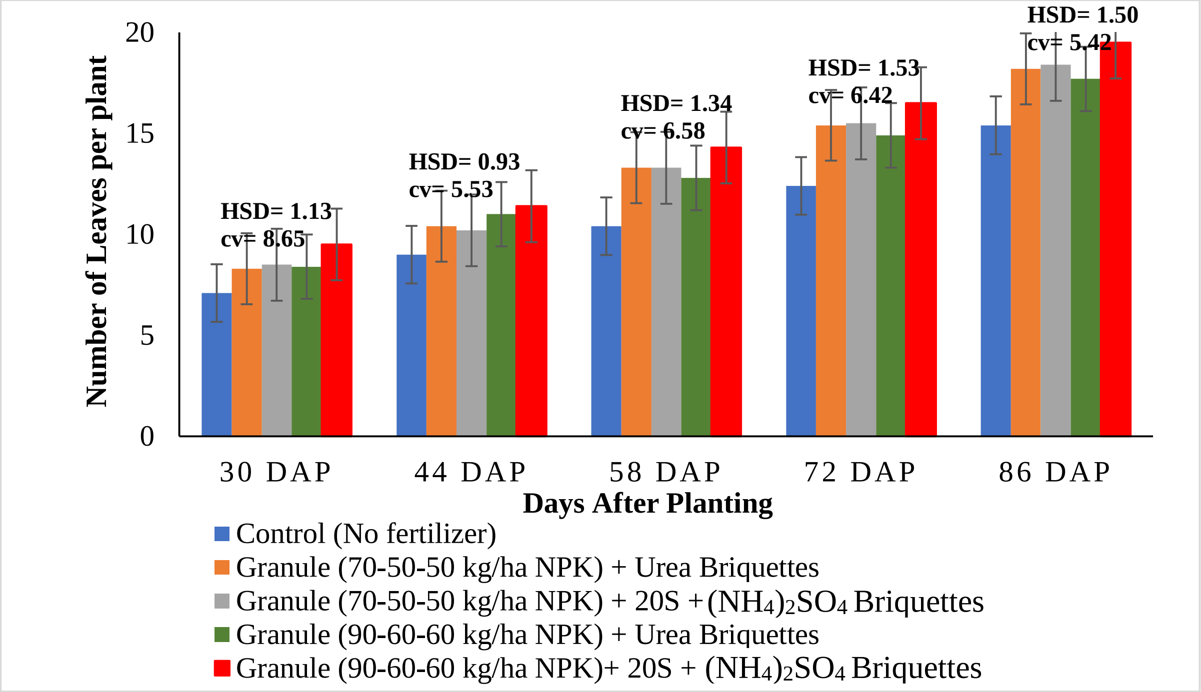
HSD=least significant difference at 5% probability, CV (%) = Coefficient of variation

4.5.4 Number of Leaves Per Plant

The number of leaves per plant increased steadily with days after planting (DAP) across all treatments in both major and minor seasons (Figure 4.3). In the major season, generally, the treatment with NPK (70-50-50) + urea briquettes recorded the highest leaf count at 86 DAP (19.6 leaves), followed by NPK (70-50-50) + sulphur-enriched ammonium sulphate briquettes (18.4 leaves). The control recorded the lowest leaf count at all stages, reaching 18.1 leaves at 86 DAP (Figure 4.3a).

In the minor season, generally, the same trend was observed, with NPK (70-50-50) + urea briquettes leading at 86 DAP (18.3 leaves), while the control had the lowest number (16.7 leaves). Treatments with higher NPK rates and sulphur amendments (T3 and T5) consistently produced more leaves than the control and low-NPK treatments, particularly at later growth stages (Figure 4.3b)

(a) Major Cropping Season



(b) Minor Cropping Season

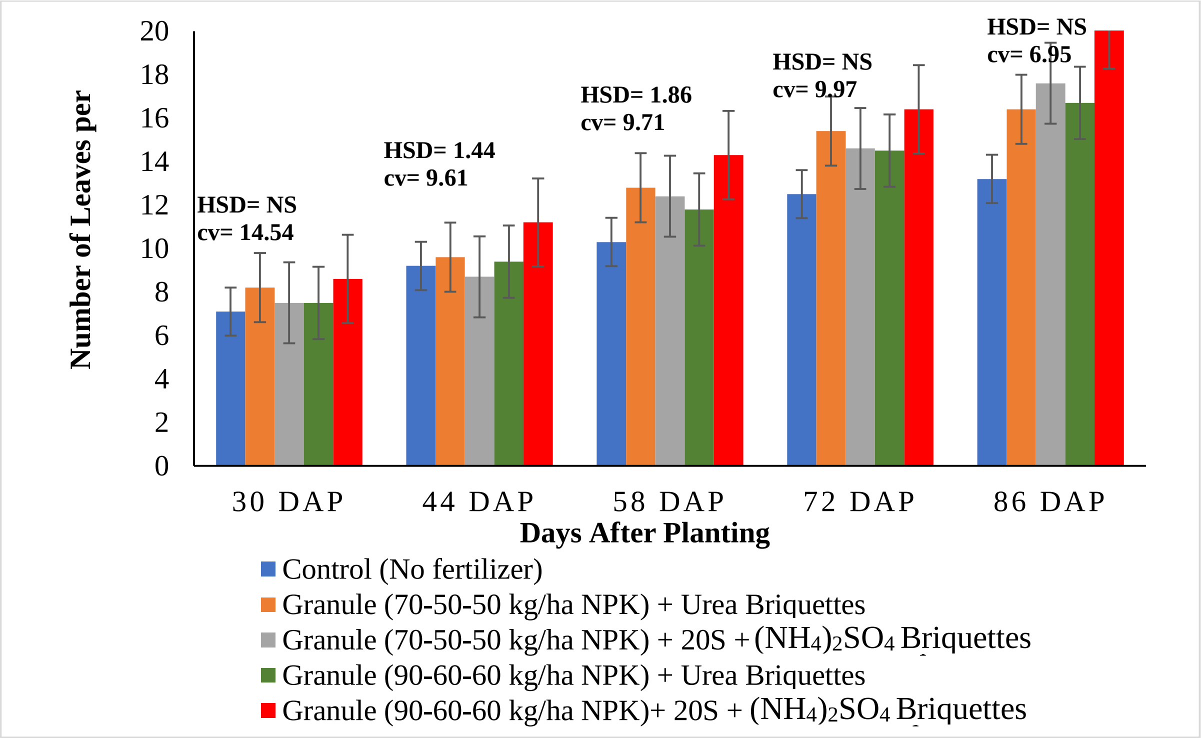


Figure 4. 3 Number of maize leaves per plant as affected different fertilizer treatments during the major and minor seasons.

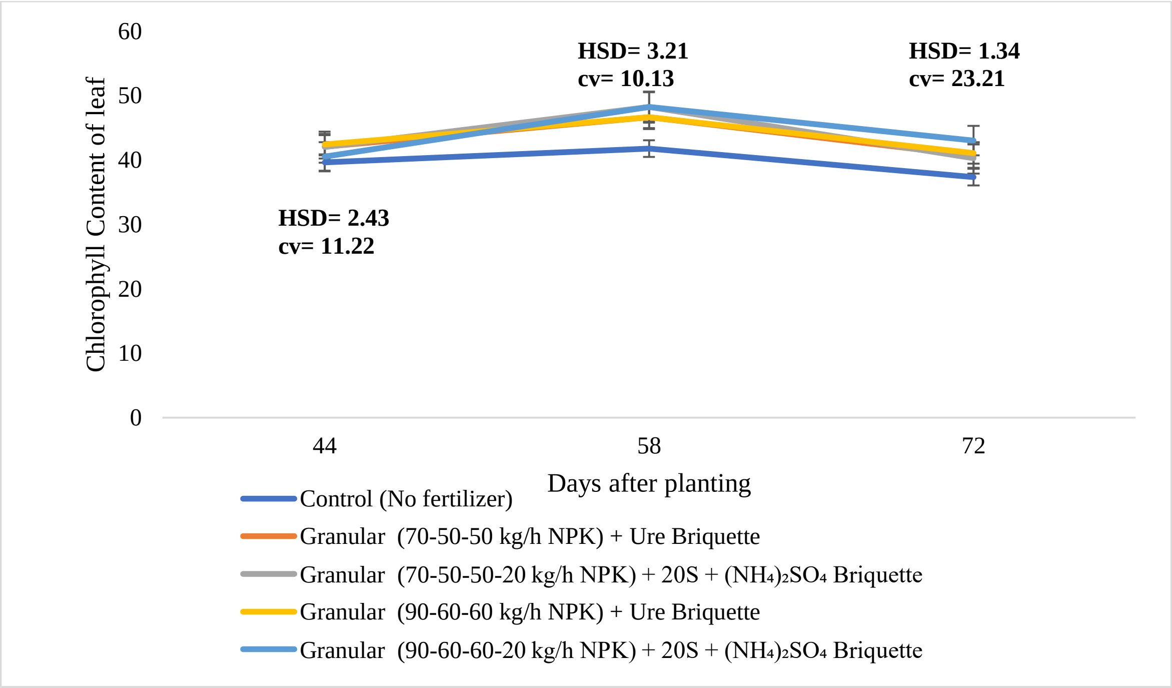
4.5.5 Chlorophyll Content of Leaf

Chlorophyll content of leaf, differed significantly across treatments in both major and minor seasons (Figure 4.4). In the major season, the highest leaf chlorophyll content (53.29spad) was recorded under the application of granular NPK (70-50-50) + urea briquettes, followed by granular NPK (90-60-60) + sulphur-enriched ammonium sulphate briquettes at 52.67 (Figure 4.4a). The lowest value (44.63spad) was observed in the control (no fertilizer) treatment.

In the minor season, the highest leaf chlorophyll content (53.61spad) occurred under granular NPK (90-60-60) + sulphur-enriched ammonium sulphate briquettes, with granular NPK (70-50-50) + urea briquettes closely following at 52.30. The control treatment again recorded the lowest leaf chlorophyll content of (42.63spad) (Figure 4.4b).

Across both seasons, treatments containing controlled-release nitrogen (urea briquettes) and sulphur-enriched formulations significantly increased leaf chlorophyll content compared to the control and conventional granular urea. These improvements suggest enhanced nitrogen use efficiency and better photosynthetic activity under varying climatic conditions.

(a) Major Cropping Season



(b) Minor Cropping Season

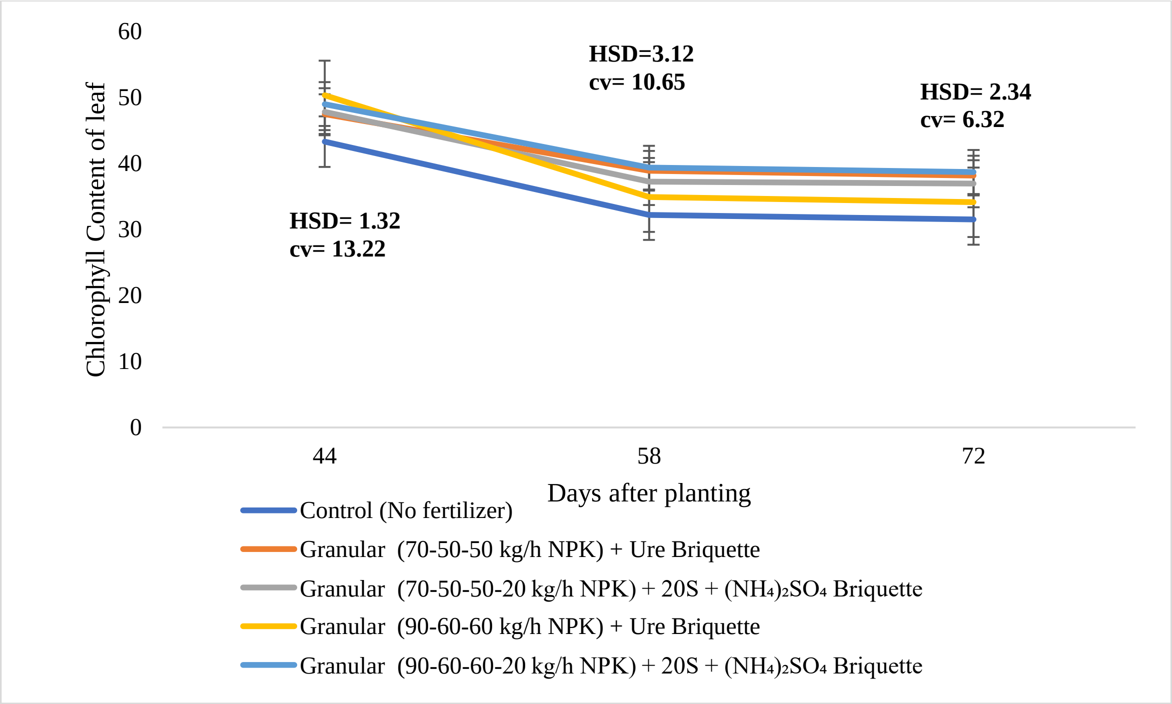


Figure 4. 3: Chlorophyll content of leaf as affected different fertilizer treatments during the major and minor seasons.

4.6 Yield and Yield Components of Maize

4.6.1 Grain Yield and 100-Seed Weight

Grain yield varied significantly among treatments across both major and minor seasons (Table 4.9). The highest grain yield was recorded under the application of granular NPK (90-60-60 kg/ha) + 20S + NH_4SO_4 briquettes, yielding 4.8 t/ha in the major season and 4.5 t/ha in the minor season, with an overall mean of 4.6 t/ha. This was closely followed by granular NPK (70-50-50 kg/ha) + 20S + NH_4SO_4 briquettes, which produced 4.7 t/ha and 4.3 t/ha in the major and minor seasons respectively, with a mean of 4.5 t/ha. The control treatment recorded the lowest yield (2.7 t/ha in the major and 2.6 t/ha in the minor season).

Similarly, 100-seed weight was significantly influenced by treatment. The highest 100-seed weight was observed under granular NPK (70-50-50 kg/ha) + 20S + NH_4SO_4 briquettes, with a mean of 43.9 g, followed closely by granular NPK + urea briquettes (41.6 g). The control plot had the lowest seed weight (31.8 g). These findings underscore the benefits of combining controlled-release nitrogen and sulphur in enhancing both grain yield and seed quality (Table 4.9).

Table 4. 9: Grain yield and 100-seed weight of maize as affected by different fertilizer treatments during the major and minor seasons

Treatment	**Grain Yield(t/ha)**			**100-Seed Weight(g)**		
	Major	Minor	Mean	Major	Minor	Mean
Control (No fertilizer)	2.7	2.6	2.6	32.0	31.6	31.8
Granule (70-50-50 kg/ha NPK) + UB	3.7	3.3	3.5	41.7	41.5	41.6
Granule (70-50-50 kg/ha NPK) + S + SAB	4.7	4.3	4.5	44.1	43.8	43.9
Granule (90-60-60 kg/ha NPK) + UB	3.9	3.5	3.7	33.3	32.9	33.1
Granule (90-60-60 kg/ha NPK) + S + SAB	4.8	4.5	4.6	38.0	37.7	37.9
Mean	3.9	3.7		37.8	37.5	
HSD (0.05)	0.47	0.65		6.02	6.02	
CV (%)	7.80	11.57		10.33	10.43	
Season (HSD=0.05) =		0.22			NS	
Treatment (HSD=0.05) =		0.36			3.78	
Season × Treatment (HSD=0.05) =		NS			NS	

HSD=Tukey's Honesty significant difference at 5% probability, CV (%) = Coefficient of variation

4.6.2 Number of Cobs Per Plant, Number of Plants Harvested, Number of Lodged Plants and Total Biomass at harvest

In the major season, cob number per plot ranged from 34 to 53 per plot. The highest number of cobs was recorded under the high NPK + sulphur-enriched ammonium sulphate briquettes, while the lowest was under the control. In the minor season, the values ranged from 31 to 49, following a similar trend (Table 4.10). The overall mean number of cobs per plot ranged from 32 to 51. The number of harvested plants per plot in the major season ranged from 32.0 to 51.8, with the highest under high NPK + sulphur-enriched ammonium sulphate briquettes. In the minor season, the range was 29 to 49. The overall mean ranged from 31 to 50 plants per plot.

Lodging varied considerably across treatments. In the major season, lodged plants ranged from 1.0 to 2.3, while in the minor season, the range was 3 to 4. The mean number of lodged plants across seasons ranged from 2 to 3 per plot. Total aboveground biomass at harvest in the major season ranged from (12.0 kg to 18.6 kg) with the highest recorded under high NPK + sulphur-enriched ammonium sulphate briquettes. In the minor season, values ranged from (11.5 kg to 18.2kg.)

Table 4. 10: Number of Cobs Per Plot, Number of Plants Harvested, Number of Lodged Plants and Total Biomass

Treatment	Number of Cobs Per Plot			Number of Plants Harvested			Number of Lodged Plants			Total Biomass at harvest (kg)		
	Major	Minor	Mean	Major	Minor	Mean	Major	Minor	Mean	Major	Minor	Mean
Control (No fertilizer)	45	42	43	44	40	42	1	3	2	12.0	11.5	11.7
Granule (70-50-50 kg/ha NPK) + UB	48	46	47	48	45	46	2	3	3	15.3	15.1	15.2
Granule (70-50-50 kg/ha NPK) + S + SAB	40	38	39	40	37	38	1	3	2	18.0	17.6	17.8
Granule (90-60-60 kg/ha NPK) + UB	53	49	51	52	49	50	2	4	3	13.4	13.2	13.3
Granule (90-60-60 kg/ha NPK) + S + SAB	44	41	42	43	40	41	2	3	2	18.6	18.2	18.4
Mean	34	31	32	32	29	31	2	3	2	15.5	15.1	
HSD (0.05)	4.83	5.10		5.58	5.70		NS	NS		2.70	2.93	
CV (%)	7.18	8.10		8.45	9.26		55.44	42.1		11.36	12.60	

Season (HSD=0.05) =	1.97	2.24	0.69	NS
Treatment (HSD=0.05) =	3.12	3.54	NS	1.77
Season × Treatment (HSD=0.05) =	NS	NS	NS	NS

HSD=Tukey's Honesty significant difference at 5% probability, CV (%)= Coefficient of variation

4.6.3 Cost Benefit Analysis

Partial benefit analysis revealed that the highest grain yield and net benefit were recorded under the treatment involving high NPK rate (90-60-60 kg/ha) combined with sulphur enriched ammonium sulphate briquettes for both seasons (Table 4.11 and 4.12). This was closely followed by the moderate NPK + sulphur treatment. The control recorded the lowest yield but incurred no cost, resulting in a lowest net benefit. Among treatments, the highest benefit-cost ratio was associated with moderate NPK + sulphur, while the lowest among fertilized treatments was observed in high NPK + urea briquettes. These results indicate that integrating sulphur with NPK, particularly at moderate rates, optimizes economic returns under the conditions of the study.

The marginal rate of return (MRR) analysis revealed that applying NPK (70-50-50) + Urea Briquettes yielded an MRR of over 500.0% for both seasons as compared to the control, indicating that every additional GHS 1 invested returned over GHS 5.00. Further inclusion of sulphur and ammonium sulphate briquettes increased the MRR to over 700% for both seasons (Table 4.11and Table 4.12).

Table 4. 11: Partial Benefit Analysis (PBA) of Fertilizer Treatments on Maize Grain Yield during Major Cropping Season

Variable	**Control (No fertilizer)**	**NPK (70-50-50) + Urea Briquettes**	**NPK (70-50-50) + S + SAB**	**NPK (90-60-60) + Urea Briquettes**	**NPK (90-60-60) + S + SAB**
Grain Yield (t/ha)	2.6	3.5	4.5	3.7	4.6
Total Gross Benefit (GHC)	13000	17500	22500	18500	23000
Total Variable Cost (GHC)	0	1,400	1,400	1,400	1,660
Net Benefit (GHC)	13,000	16,100	21,100	17,100	21,340
Benefit: Cost Ratio (BCR)	–	11.50	15.07	12.21	12.86
MRR	**Control (No fertilizer)**	**NPK (70-50-50) + Urea Briquettes**	**NPK (90-60-60) + Urea Briquettes**	**NPK (70-50-50) + S + SAB**	**NPK (90-60-60) + S + SAB**
TVC	0	1400	1400	1400	1660
NB	13,000	16,100	17,100	21,100	21,340
MRR ([ΔNB/ΔTVC] × 100)	-	221.43	D*	D*	92.31

D=Dominate

Table 4. 12: Partial Benefit Analysis (PBA) of Fertilizer Treatments on Maize Grain Yield during Minor Cropping Season

Variable	**Control (No fertilizer)**	**NPK (70-50-50) + Urea Briquettes**	**NPK (70-50-50) + S + SAB**	**NPK (90-60-60) + Urea Briquettes**	**NPK (90-60-60) + S + SAB**
Grain Yield (t/ha)	2.6	3.3	4.3	3.5	4.5
Total Gross Benefit (GHC)	13,000	16,500	21,500	17,500	22,500
Total Variable Cost (GHC)	0	1,400	1,400	1,400	1,660
Net Benefit (GHC)	13,000	15,100	20,100	16,100	20,840
Benefit: Cost Ratio (BCR)	–	10.79	14.36	11.50	12.55
MRR	**Control (No fertilizer)**	**NPK (70-50-50) + Urea Briquettes**	**NPK (90-60-60) + Urea Briquettes**	**NPK (70-50-50) + S + SAB**	**NPK (90-60-60) + S + SAB**
TVC	0	1400	1400	1400	1660
NB	13,000	15,100	16,100	20,100	20,840
MRR ([ΔNB/ΔTVC] × 100)		150.00	D*	D*	284.62

D=Dominate

CHAPTER FIVE: DISCUSSION

5.1 Soil Chemical Properties

Soil fertility is a dynamic property influenced by nutrient inputs, cropping intensity, and environmental factors. In this study, the application of blended basal Fertilizer and nitrogen briquettes demonstrated varying impacts on the chemical composition of Chromic Luvisols following maize cultivation. The observed differences in post-harvest soil properties (Figures 4.1 to 4.5 and Table 4.3) can be better understood when interpreted in relation to the initial soil status (Table 4.2), prevailing climatic conditions (Table 4.1), and the nature and rate of nutrient applications across the experimental treatments.

The slight increase in soil pH across all fertilised plots, particularly in those receiving ammonium sulphate briquettes, may be attributed to acidifying effects associated with ammoniacal nitrogen transformation. The consistent rainfall patterns observed during the minor season likely exacerbated leaching losses and hydrogen ion accumulation, contributing to this acidification. However, the maintained pH values within agronomically acceptable ranges suggest that the buffering capacity of the soil was not exceeded. This indicates that while nitrogen briquettes may induce mild acidification, especially when applied at higher doses, their impact remains manageable within a single cropping season.

Available phosphorus concentrations improved significantly under fertilised treatments, especially with the combination of NPK (90-60-60) and ammonium sulphate briquettes. This trend suggests that strategic nutrient synchronisation not only enhances P uptake by the crop but also leaves residual amounts in the soil. Nevertheless, the effectiveness of phosphorus retention may have been partly diminished by seasonal rainfall variations, especially during the minor season where higher rainfall may have contributed to P leaching and fixation in acidic microenvironments. These findings align with earlier reports by

Adjei-Nsiah *et al*. (2021), who observed that phosphorus availability in Ghanaian soils is highly sensitive to both pH and seasonal moisture conditions.

Total nitrogen content improved in all fertilised plots compared to the control, with ammonium sulphate briquette treatments recording the highest values. This is consistent with the gradual release pattern of briquettes, which likely reduced nitrogen losses and improved synchrony with plant uptake. The data further suggest that the residual nitrogen effect was more pronounced under high-dose ammonium sulphate application, possibly due to reduced volatilisation compared to conventional urea. However, this nitrogen retention must be weighed against the acidifying effects associated with sulphate release, as evidenced by the lower pH in the same plots. These dual effects underscore the importance of balancing nutrient supply and soil health when recommending Fertilizer strategies.

Organic carbon and organic matter levels increased modestly in fertilised treatments, particularly where urea briquettes were used in combination with basal NPK. This improvement may be attributed to higher biomass input through root exudates and crop residue return, which are known to stimulate microbial activity and contribute to the organic matter pool (Palm *et al*., 2001). Despite the short duration of the experiment, these findings indicate that intensive maize cropping, when supported with adequate fertilisation, can enhance carbon cycling within the soil. Yet, the relatively minor differences between treatments also suggest that longer-term studies would be required to confirm trends in soil organic matter accumulation.

Sulphur concentrations (Figure 4.5) were significantly enhanced in treatments that received ammonium sulphate briquettes, which is expected given the S-containing formulation of the Fertilizer. This improvement is agronomically relevant, as sulphur plays a key role in protein synthesis and enzymatic functions in maize, yet is often deficient in tropical soils (FAO, 2020). The statistical separation of treatments in Figure 4.5 confirms that the sulphur contribution from ammonium sulphate was not only effective but also residual, persisting beyond immediate plant uptake. In contrast, treatments lacking sulphur inputs showed low post-harvest S levels, reinforcing the value of multi-nutrient sources for comprehensive soil fertility improvement.

Exchangeable bases presented in Table 4.3 exhibited marginal responses to fertilisation. Potassium levels remained relatively stable or slightly improved across treatments, consistent with direct K supplementation through NPK formulations. Calcium and magnesium, on the other hand, showed slight reductions in high nitrogen plots, possibly due to cation exchange competition and leaching under mildly acidic conditions. Sodium levels remained low across all treatments, suggesting minimal risk of sodicity development. The general trend of base saturation mirrored these changes, indicating a moderate nutrient uptake by maize and limited nutrient replenishment through the short-term fertilisation regime.

Climatic conditions, particularly rainfall and temperature variations between the major and minor seasons, influenced the observed chemical changes. Higher rainfall in the minor season likely increased leaching losses, especially for mobile nutrients such as nitrogen and sulphur. This could explain the relatively lower concentrations observed in some treatments during that period. These seasonal fluctuations must be considered when recommending Fertilizer types and application timings, as nutrient availability is not solely a function of application rate but also of environmental interactions.

Overall, the combined application of NPK (90-60-60) with ammonium sulphate briquettes was most effective in enhancing nitrogen, phosphorus, and sulphur concentrations, though with a concurrent decline in soil pH. Urea briquettes provided a more balanced response, improving organic matter and maintaining a favourable pH range. These outcomes support the use of site-specific, integrated Fertilizer strategies that match crop demands while safeguarding long-term soil health. The results further confirm that controlled-release nitrogen sources, when appropriately paired with basal Fertilizers, can improve nutrient use efficiency and sustain soil fertility beyond a single cropping season.

5.2 Influence of Fertilizer Treatments on Maize Growth Parameters

The application of Fertilizer treatments significantly influenced key vegetative and phenological growth parameters of maize, including plant height, leaf area, stem Diameter, and the duration to tasselling, silking, and physiological maturity. These growth indicators are critical determinants of maize productivity, as they directly reflect the plant's ability to efficiently capture light, assimilate nutrients, and transition through developmental stages. Maize plants grown on fertilised plots exhibited superior plant height compared to the control. Notably, the tallest plants were observed in plots treated with NPK (90-60-60) + ammonium sulphate briquettes, closely followed by those that received NPK (90-60-60) + urea briquettes. This result is attributed to the synergistic effects of balanced nutrient supply, particularly nitrogen and sulphur, which are essential for cell elongation and chlorophyll formation. Nitrogen availability enhances vegetative vigor, while sulphur supports protein synthesis, both of which are critical for internode elongation. The relatively shorter plants under control and lower-N treatments underscore the limiting effect of nutrient deficiency on maize growth, consistent with findings by Vanlauwe *et al*. (2015). The leaf area followed a similar trend, with higher values recorded in the high-dose fertilised plots. The increase in leaf area is indicative of improved leaf expansion and canopy development under optimal nutrient conditions. This is significant because leaf area correlates strongly with photosynthetically active radiation interception and carbon assimilation rates. Treatments with controlled-release nitrogen sources (urea and ammonium sulphate briquettes) maintained more stable nitrogen availability, allowing for sustained leaf growth and delayed senescence. This observation supports earlier studies by

Bationo *et al*. (2018), which showed that split or slow-release nitrogen improves leaf area and biomass in maize.

Stem Diameter was also enhanced under fertilised conditions, especially with ammonium sulphate briquettes. Thicker stems suggest greater mechanical support for the developing cobs and improved vascular efficiency for nutrient transport. The data show that the combination of high NPK rates and sulphur-rich nitrogen sources contributed to stronger plant architecture, which is beneficial in reducing lodging risks and supporting higher yields.

The timing of tasseling, silking, and physiological maturity was moderately affected by Fertilizer treatments. In general, fertilised plots exhibited slightly earlier tasselling and silking compared to the control. This may reflect the influence of nitrogen in accelerating vegetative development and promoting timely floral initiation. However, plots treated with NPK + urea briquettes reached physiological maturity more synchronously and efficiently than others. This synchrony is critical for grain filling, as it ensures optimal nutrient allocation to reproductive organs. Interestingly, ammonium sulphate briquette treatments showed a marginal delay in physiological maturity, which could be attributed to prolonged vegetative growth supported by residual nitrogen and sulphur availability. This delayed maturity might be advantageous in extending the grain-filling period, provided environmental conditions remain favourable.

Seasonal climatic variability also played a role in modulating growth responses. The higher rainfall and lower average temperatures in the minor season may have influenced nutrient solubility and uptake efficiency. For instance, excessive rainfall may have led to some nitrogen losses in the major season, reducing its early-season impact on vegetative growth. Conversely, the controlled-release nature of the briquettes likely mitigated these losses, sustaining nutrient supply and stabilising growth rates across both seasons.

In summary, the application of NPK (90-60-60) in combination with either urea or ammonium sulphate briquettes led to the most favourable maize growth outcomes. These treatments improved plant height, leaf area, stem thickness, and promoted synchronised development. Their performance underscores the agronomic advantage of using site-specific Fertilizer combinations that not only address macronutrient needs but also synchronise nutrient release with crop demand. The control treatment, by contrast, demonstrated the consequences of nutrient limitation, with stunted growth, thinner stems, and delayed maturity, ultimately constraining yield potential.

5.3 Response of Maize Yield and Yield Components to Fertilizer Treatments

Fertilizer treatments significantly influenced maize yield and its associated components, including cob length, cob diameter, number of cobs per plant, biomass accumulation, and harvest index. These yield parameters provide a direct reflection of the crop's physiological response to nutrient availability, photosynthetic efficiency, and partitioning of assimilates under varying fertility regimes.

Maize grain yield was markedly higher in plots that received NPK (90-60-60) combined with ammonium sulphate briquettes, followed closely by those treated with NPK (90-60-60) plus urea briquettes. The superior performance of these treatments can be attributed to enhanced and synchronised nutrient availability throughout the crop's growth cycle. Controlled-release nitrogen sources such as urea and ammonium sulphate briquettes ensured a steady supply of nitrogen during critical stages of grain development, reducing losses due to leaching or volatilisation, especially under the high rainfall conditions observed in the minor season. This finding corroborates the work of Savant *et al*. (1991) and Hu et al. (2023), who reported improved grain yield in cereals under deep-placed or slow-release nitrogen formulations due to enhanced nitrogen use efficiency.

Cob length and diameter also showed significant improvement under high-NPK treatments with briquettes. These enhancements are a function of effective pollination, carbohydrate allocation, and overall plant vigour, all of which are directly influenced by nutrient supply. Nitrogen, phosphorus, and potassium play synergistic roles in promoting ear development, grain filling, and kernel size. According to Bationo *et al*. (2018), adequate nitrogen not only improves vegetative growth but also increases the translocation of assimilates to the cobs during reproductive stages, thereby enhancing cob size and kernel weight.

The number of cobs per plant, a key yield determinant, was significantly higher in plots treated with NPK + ammonium sulphate briquettes, as well as those with NPK + urea briquettes, compared to the control and standard NPK-alone treatments. This result indicates that balanced and sustained nutrient availability not only supports main cob development but may also stimulate the formation of productive secondary ears. The increased cob number can also be linked to enhanced leaf area index and photosynthetic capacity. Similar trends have been reported by Vanlauwe *et al*. (2015), where integrated Fertilizer applications resulted in both yield stability and increased cob formation in maize across sub-Saharan Africa.

Total biomass accumulation reflected the cumulative effect of nutrient uptake, growth duration, and assimilate production. Plots under NPK (90-60-60) with either urea or ammonium sulphate briquettes recorded the highest biomass yields, highlighting their role in maximising both vegetative and reproductive output. High nitrogen availability, particularly in synchrony with moisture availability, tends to prolong vegetative growth, which in turn supports higher dry matter accumulation (Ali *et al*., 2022). Biomass data also showed that control plots, which lacked Fertilizer input, exhibited significantly lower biomass, indicating severe nutrient limitation and suboptimal photosynthesis.

The harvest index (HI), which reflects the proportion of economic yield (grain) to total above-ground biomass, varied moderately among treatments. Treatments with urea briquettes generally showed a slightly higher HI, suggesting more efficient partitioning of assimilates toward grain production rather than vegetative tissue. This may be linked to better synchronisation of nitrogen supply with grain-filling stages, thereby enhancing nitrogen remobilisation into kernels. In contrast, treatments with ammonium sulphate briquettes, while having high biomass and grain yield, exhibited slightly lower HI, possibly due to longer vegetative phases delaying grain maturity.

Environmental conditions during the growing seasons also influenced yield responses. The major season, with relatively lower rainfall, may have limited nutrient movement and root absorption, especially in treatments lacking controlled-release Fertilizers. In contrast, the minor season, characterised by higher rainfall (Table 4.1), potentially improved nutrient dissolution and mobility but also increased the risk of leaching. Controlled-release nitrogen sources demonstrated resilience under both conditions by maintaining nutrient availability and ensuring consistent yield performance across seasons.

Overall, the results confirm that fertilizer treatments significantly influence yield components of maize. The combined application of high-dose NPK with controlled-release nitrogen sources, especially ammonium sulphate briquettes, proved most effective in enhancing cob formation, grain development, and total biomass. These treatments improved nutrient synchrony, reduced losses, and supported yield stability under variable rainfall conditions. The findings align with principles of Integrated Soil Fertility Management (ISFM), which emphasise the right Fertilizer source, rate, timing, and placement to optimise crop productivity and resource use efficiency (Vanlauwe *et al.*, 2015; SARI, 2020).

5.4 Economic Viability of Fertilizer Treatments on Maize Production

The choice of Fertilizer strategies in maize production is influenced not only by agronomic effectiveness but also by their economic viability. In this study, the evaluation of Fertilizer treatments using cost–benefit ratio (CBR), marginal rate of return (MRR), and input–output efficiency provided critical insights into the profitability and sustainability of each input option.

The cost-benefit analysis revealed that while all fertilised plots outperformed the control in terms of economic return, the treatment involving NPK (90-60-60) + urea briquettes recorded the highest cost–benefit ratio. This suggests that the yield increase from this treatment more than compensated for its input cost, delivering the greatest profit margin per cedi invested. The controlled release nature of urea briquettes likely contributed to improved nitrogen use efficiency, minimising nutrient losses and ensuring that a greater proportion of applied nitrogen was converted into grain yield. This aligns with findings from Giller *et al*. (2011), who reported that synchronised nitrogen availability enhances grain yield without incurring excessive input cost.

In contrast, NPK (90-60-60) + ammonium sulphate briquettes, though agronomically superior in terms of grain yield and nutrient enhancement, incurred higher Fertilizer costs, which slightly reduced its relative economic advantage. The inclusion of sulphur and the higher formulation cost of ammonium sulphate briquettes contributed to this effect. Nonetheless, the treatment still presented a favourable MRR, exceeding the minimum acceptable threshold of 100%, suggesting that every additional cedi invested in this Fertilizer combination yielded more than one cedi in return. This indicates economic viability, particularly for farmers with access to capital and a focus on long-term soil nutrient balance.

The input–output efficiency, defined as the ratio of grain output (kg) per cedi of Fertilizer invested, was highest for the NPK + urea briquettes treatment, reflecting its balanced cost structure and consistent yield performance. The control treatment, while incurring no Fertilizer cost, produced the lowest grain yield and biomass, highlighting the risk of low-input systems in nutrient-depleted soils. Although it avoided direct expenditure, its opportunity cost in terms of foregone yield and revenue was high. This supports previous research by Bationo *et al*. (2018) and Adzawla *et al*. (2024), which demonstrated that minimal-input maize systems in sub-Saharan Africa often trap farmers in cycles of low productivity and economic stagnation.

Seasonal variations also influenced the cost-effectiveness of Fertilizer use. In the major season, moderate rainfall and favourable temperatures likely supported higher Fertilizer use efficiency, reducing losses and enhancing grain conversion. Conversely, the minor season, with higher rainfall (Table 4.1), may have contributed to nutrient leaching, particularly for treatments lacking controlled-release Fertilizers. However, the economic returns of briquette-based treatments remained robust, as their sustained nutrient release buffered the effects of seasonal weather variability.

Importantly, this analysis highlights the trade-off between short-term profitability and long-term soil health. While urea briquettes delivered the highest immediate return, ammonium sulphate briquettes improved both yield and residual sulphur content, contributing to soil fertility sustainability — a critical factor for regions experiencing progressive nutrient mining. As such, the choice of Fertilizer package should be informed not only by current market prices and yield potential, but also by the strategic goal of enhancing soil capital over time.

In conclusion, both NPK + urea briquettes and NPK + ammonium sulphate briquettes are economically viable, but they serve different purposes. Urea briquettes offer optimal return on investment and are more suitable for resource-constrained farmers, while ammonium sulphate briquettes, despite slightly lower immediate profits, support nutrient sustainability and long-term productivity. Policymakers and extension agents should therefore promote integrated Fertilizer strategies that balance profitability, risk management, and agroecological sustainability — particularly in smallholder systems vulnerable to economic and climatic shocks.

CHAPTER SIX: CONCLUSION AND RECOMMENDATIONS

6.1 Conclusion

The conclusions below are drawn in direct response to the specific objectives of the study.

1. The application of fertilizer treatments significantly influenced final soil chemical properties compared to initial levels. Soils treated with NPK (90-60-60) combined with ammonium sulphate briquettes exhibited the most substantial improvements in available phosphorus, sulphur, organic matter, and exchangeable bases. Despite this, the acidic conditions remained within an acceptable range for maize cultivation, suggesting that the inclusion of sulphur-rich nitrogen sources enhances soil fertility when complemented with appropriate liming strategies. Conversely, NPK + urea briquettes improved nutrient levels while maintaining a more stable soil pH, reflecting balanced nutrient dynamics.
2. Maize growth parameters, including plant height, stem diameter, leaf area, and phenological development (tasselling, silking, and physiological maturity), were significantly improved in plots treated with fertilizer compared to the control. The best vegetative performance was observed in treatments involving NPK + urea and NPK + ammonium sulphate briquettes, indicating that synchronised nitrogen release plays a critical role in sustaining vegetative vigour and accelerating developmental milestones.
3. Yield and yield components, such as grain yield, number of cobs per plot and total biomass at harvest, also responded positively to Fertilizer applications. The highest grain yield and biomass accumulation were recorded in plots treated with NPK + ammonium sulphate briquettes, followed closely by NPK + urea briquettes. These treatments provided adequate nutrients during critical grain-filling stages, and more efficient partitioning of assimilates.

4. From an economic perspective, Fertilizer application was profitable across all treatments compared to the unfertilised control. The NPK + urea briquette treatment recorded the highest cost–benefit ratio and marginal rate of return, making it the most economically attractive option for smallholder farmers seeking short-term profit. Although the NPK + ammonium sulphate briquette treatment delivered higher physical yields, its relatively higher input cost slightly reduced its economic advantage.

6.2 Recommendations

Based on the outcomes of this study, the following recommendations are proposed to guide farmers, policymakers, and future researchers:

1. Farmers in the transition agro-ecological zone of Ghana are encouraged to adopt NPK (90-60-60) in combination with urea or ammonium sulphate briquettes, as these treatments significantly enhance soil fertility, crop growth, and yield while ensuring efficient nutrient use.

2. For resource-constrained farmers aiming for higher short-term returns, NPK + urea briquettes are recommended due to their superior cost–benefit ratio and marginal rate of return.

3. Where long-term soil fertility is a priority, NPK + ammonium sulphate briquettes are advisable, given their ability to improve sulphur levels and enhance nutrient reserves, despite slightly lower short-term profitability.

4. Regular soil testing and liming are recommended, particularly for plots receiving ammonium-based fertilizers, to mitigate potential soil acidification and sustain crop productivity.

5. Government and agricultural extension agencies should support the dissemination and subsidisation of controlled-release fertilizer technologies, especially in areas with high nutrient depletion and rainfall variability.

Further long-term studies should explore the cumulative effects of briquette Fertilizers across multiple seasons and cropping systems, as well as their integration with organic amendments for sustainable intensification.

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LIST OF APPENDICES

Appendix 1: Guide to interpretation of soil analytical data in Ghana

Nutrient	Rank/Grade			
Phosphorus, P (ppm), (Bray 1)				
< 10	Low			
10 – 20	Moderate			
> 20	High			
Potassium, K (pmm)				
< 50	Low			
50 – 100	Moderate			
> 100	High			
Calcium, Ca (ppm)/Meg = 0.25 Ca				
< 5.0	Low			
5.0 – 10.0	Moderate			
> 10.0	High			
ECEC (cmol (+)/kg)				
< 10	Low			
10 - 20	Moderate			
> 20	High			
Soil pH (Distilled Water Method)				
< 5.0	Very Acidic			
5.1 – 5.5	Acidic			
5.6 – 6.0	Moderately Acidic			
6.0 – 6.5	Slightly Acidic			
6.5 – 7.0	Neutral			
7.0 – 7.5	Slightly Alkaline			
7.6 – 8.5	Alkaline			
> 8.5	Very Alkaline			
% Organic Carbon	**% Organic Carbon**	**Interpretation**		
< 1.0	< 1.5	Low		
1.0– 2.0	1.6 – 3.0	Moderate		
2.0-4.0	3.0	Adequate		
> 4.0	>3.0	High		
Nitrogen (%)				
< 0.1	Low			
0.1 – 0.2	Moderate			
> 0.2	High			
Exchangeable cations (cmol (+)/kg)	**Units**	**low**	**moderate**	**High**
Sodium (Na)	(cmol (+)/kg)	-	0-2	> 2.0
Potassium (K)	(cmol (+)/kg)	<0.2	0.2 – 0.4	> 0.4
Calcium (Ca)	(cmol (+)/kg)	< 2.0	2.0-10	> 10
Magnesium (Mg)	(cmol (+)/kg)	< 1.0	1.0-3.0	> 3.0

Source: (KNUST, Soil Science department 2023).