YIELD, TOTAL CAROTENOID CONTENT, DRY MATTER AND GENETIC DIVERSITY OF YELLOW-FLESH CASSAVA *(Manihot esculenta)* VARIETIES

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DECLARATION

I hereby declare that this thesis is the result of my own original research undertaken under supervision and that no part of it or in whole has been presented for another degree in this university or elsewhere.

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DEDICATION

Primarily, this work is dedicated to Almighty God for His protection and guidance, as well as to my late father, Mr. Kwabena Asiedu. It is also dedicated to my devoted and loving mother, Mrs. Margret Agyei, and my siblings, Asiedu Abigail, Ebenezer Asiedu, Asiedu Amoako Patrick, Millicent Asiedu, Richmond Asiedu, and Rita Asiedu, for their prayers and support in all of my endeavors. Lastly, this work is dedicated to my respected supervisor, Dr. Godwin Amenorpe, as well as Mr. Solomon Out and Mrs. Rhoda Gyinae Diawuoh, for their tremendous assistance in my education.

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LIST OF ABBREVIATIONS

ABBREVIATIONS	MEANING
ANOVA	Analysis of variance
CV%	Coefficient of variation
FAO	Food and Agriculture Organization
FAOSTAT	Food and Agriculture Organization Corporate Statistical Database
GAEC	Ghana Atomic Energy Commission
QTLs	quantitative trait loci
LSD	Least significant difference
CRI	Crops Research Institute
SARI	Savanna Agricultural Research Institute
MOFA	Ministry of Agriculture
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
SSA	Sub-Saharan Africa
MVD	FAO and IAEA Mutant Varieties Database
BNARI	Biotechnology and Nuclear Agriculture Research Institute

DAP	Days after planting

ABSTRACT

Yellow-flesh cassava varieties are crucial for their potential nutritional benefits in addressing vitamin A deficiency and enhancing dietary diversity. To achieve our objective of identifying the root yield in kg/plant, total carotenoid in ug/g and dry matter in percentage profiles of four varieties of yellow-flesh cassava, varieties—Kpornu, Tetteh Bankye, Nyonku, and Genotype D—were evaluated over two years using a Randomised Complete Block Design with five replicates. Kpornu exhibited a yield range of 3.1 to 11.2 kg per plant, peaking at 11.2 kg in December, with an average of 7.15 kg. Tetteh Bankye showed a yield range from 3.2 to 16.1 kg, peaking at 16.1 kg in December, with an average of 9.65 kg. Nyonku's yield ranged from 2.2 to 8.4 kg, peaking at 8.4 kg in December, with an average of 5.3 kg, while Genotype D had the lowest yield range of 2.3 to 4.9 kg, peaking at 4.9 kg in December, with an average of 3.6 kg. Peak carotenoid content for all varieties was observed in December, with Genotype D showing the highest value of 18.7 µg/g, followed by Kpornu (14.3 µg/g), Tetteh Bankye (14.1 µg/g), and Nyonku (11.8 µg/g). The average dry matter content for all varieties peaked in June, with Nyonku recording the highest value of 38.5%, followed by Tetteh Bankye (31.8%), Kpornu (27.5%), and Genotype D (31.1%). To achieve our second objective of determining genetic diversity using cluster analyses, principal components analyses, and correlation of variables from the four yellow flesh cassava varieties. The study found positive correlations between yield and total carotenoids, suggesting opportunities to improve both productivity and nutritional quality, while negative correlations between yield and dry matter content pointed to trade-offs in processing suitability. Cluster analysis showed that Nyonku and Kpornu were the most similar, sharing 80% of traits, while Tetteh Bankye showed 50% similarity with them.

Genotype D was the most distinct, clustering at 90% dissimilarity, sharing only 10% of traits. Principal Component Analysis (PCA) revealed that PC1 explained 53.09%, PC2 accounted for 31.74%, and PC3 explained 15.17%, together capturing 100% of the total variation in the crop varieties. The PCA biplot analysis highlighted distinct genetic profiles influenced by traits such as leaf lobe number, petiole length, and leaf retention, with Genotype D showing unique contributions from these traits. Key traits like apical leaf colour and leaf lobe number shaped Kpornu and Nyonku, while Tetteh Bankye was dominated by petiole length, emphasising the importance of these traits in plant vigour and adaptability. The varieties exhibited moderate to high genetic diversity, with Genotype D offering unique traits valuable for breeding.

CHAPTER ONE

1.0 INTRODUCTION

Cassava (Manihot esculenta), commonly known as cassava, serves as a primary food source for over 800 million people globally, especially in regions where food security is a critical concern Oguntoye, m. a. (2021). The main product of cassava is its starchy root, while its foliage offers high nutritional quality for both human and animal consumption, presenting significant potential (Imran *et al*., 2024). According to a report, cassava ranks as the fourth most important staple food globally, following rice, wheat, and maize. Interestingly, in terms of calorie consumption, it holds the second position among staple foods in Sub-Saharan Africa (Ceballos *et al*., 2017). Often referred to as 'Africa insurance,' cassava demonstrates resilience by consistently yielding under challenging conditions such as drought, poor soil fertility, and minimal management intensity, making it highly adaptable to climate change impacts. From 2010 to 2014, an average of 22 million hectares of cassava were cultivated annually worldwide, with 70% in Africa, 18% in Asia, and approximately 12% in the Americas (Parma *et al*., 2017).

In Sub-Saharan Africa, an estimated 980,000 pre-school children showed clinical signs of Vitamin A deficiency, with 480,000 residing in West and Central Africa (Badewa, 2023). As many as 17.4 million people in West and Central Africa show sub-clinical and clinical vitamin A deficiency; sub-clinical and clinical deficiency rates in 19 countries of West and Central Africa are estimated at 1.1% and 20.4%, respectively (Anyango, 2007). Cassava is an important starchy staple crop in Ghana with per capita consumption of 152.9 kg/year. Besides being a staple food crop, cassava can be used as raw material for the production of industrial starch and ethanol (Adjei-Nsiah &

Sakyi-Dawson, 2012). In Ghana, cassava is cultivated as a monocrop or intercropped with other food crops, either as the dominant or subsidiary crop. In terms of quantity produced, cassava is the most important root crop in Ghana followed by yams and cocoyam, but cassava ranks second to maize in terms of area planted. The production of cassava in Ghana ranged from 10,217,929 MT to 12,260,330 MT in the period 2007–2009 covering an area of 800,531 ha to 885,800 ha. Ghana currently produces about 12,260,000 MT of cassava annually. Out of this, 8,561,700 MT is available for human consumption while national consumption is estimated at only 3,672,700 MT resulting in a surplus of about 4,889,000 MT which can be exploited for the production of industrial starch or ethanol (Adjei-Nsiah *et al*., 2019; Jones, 2016).

Beta-carotenoids are precursors to vitamin A, a crucial nutrient for human health. Consumption of beta-carotene-rich foods like yellow-flesh cassava can help prevent vitamin A deficiency-related health problems, particularly in vulnerable populations like children and pregnant women (Aslam, 2024). Yellow-flesh cassava provides an additional source of dietary diversity. This helps in creating balanced and nutritious meals, which is essential for overall health and well-being. Cassava is a staple crop in many developing regions or countries. Enhancing its nutritional content contributes to improved food security and resilience, especially in areas where other sources of vitamin A are limited. The natural enrichment of cassava with beta-carotenoids reduces the need for artificial vitamin A supplementation programs, which can be logistically challenging and costly to implement. Introducing beta-carotenoids through conventional breeding techniques, rather than relying on synthetic supplements, is a more sustainable approach. It reduces the environmental footprint associated with the production and distribution of supplements.

The promotion of beta-carotenoid-enriched cassava can stimulate local economies by creating demand for improved varieties. Much of the research on cassava has centered on yield improvement and disease resistance, while the nutritional aspects have received comparatively less attention.

1.2 Problem Statement:

Despite the potential of yellow-flesh cassava to combat malnutrition, there is a significant gap in understanding the growth patterns of total carotenoid levels in these varieties. This research aims to fill this critical knowledge gap and emphasize the importance of harvesting yellow-flesh cassava at optimal periods to maximize carotenoid yields.

1.3 Justification:

Understanding when total carotenoid peaks in yellow-flesh cassava is essential for several reasons: it allows for assessing nutritional quality, optimizing harvest schedules, informing breeding strategies, maximizing the impact of biofortification efforts, and guiding consumer education initiatives (Grune *et al.*, 2010) at the right time. Carotenoids, particularly beta-carotene, are vital for vitamin A synthesis, crucial for vision, immune function, and overall health. Identifying peak carotenoid periods informs dietary planning and aids in combating vitamin A deficiency, contributing to food security in cassava-dependent populations at the right time (Latham *et al.*, 2011). Strategic planning around peak carotenoid periods is crucial for maximizing the health impact of biofortified yellow-flesh cassava, particularly in regions with high vitamin A deficiency rates. Addressing these research gaps is critical for advancing agricultural practices, supporting breeding efforts, and addressing global health challenges related to malnutrition and food security.

1.4. Main Objective

The main objective of this study is to evaluate the yield, dry matter content, and total carotenoid profiles of yellow-flesh cassava varieties.

1.5. Specific Objectives:

a. Identifying the root yield, total carotenoid and dry matter profiles of four varieties of yellow-flesh cassava over a span of 12 months.
b. To determine genetic diversity using cluster analyses, principal components analyses, and correlation of variables from the four yellow-flesh cassava varieties.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 Centre of Origin, Domestication and Taxonomy of Cassava

Cassava (Manihot esculenta Crantz), also known as manioc or yuca, has its origins in Latin America, where it has been cultivated by indigenous populations for over 4000 years. After the discovery of the Americas, European traders introduced cassava to Africa and later to Asia, where it became essential for food security and starch extraction. By the 19th century, cassava had become a staple crop in southern India, Java Island in Indonesia, and the southern Philippines, with additional use for starch extraction in Malaysia and parts of Indonesia. Following World War II, Thailand adopted cassava as an industrial crop, producing starch for local consumption and animal feed pellets for the European market. In Indonesia, cassava remains primarily a food crop, integral to various culinary traditions, although in southern Sumatra, its cultivation focuses on starch extraction (Hahn, 1997). Believed to have originated in South America, specifically in present-day Brazil and Paraguay, cassava spread throughout the continent before being introduced globally during the European exploration and colonization era. The Portuguese brought cassava to Africa around 1558, initially in the Congo Basin, marking its introduction to Sub-Saharan Africa. Today, cassava is crucial for over 300 million Africans, serving as a staple food for 800 million people, particularly in regions where it is a primary source of carbohydrates. Its ability to thrive in diverse climates, withstand low rainfall, and tolerate poor soil quality contributes significantly to its widespread cultivation and importance as a staple crop (Jones *et al.*, 2019).

In Ghana, cassava occupies a central role in agriculture, enhancing food security and economic development. Historically introduced through trade and exploration routes, cassava adapted well to Ghana's diverse agro-ecological zones, supporting its adoption by local communities. Research underscores its high caloric yield and resilience to harsh conditions, making it invaluable during times of crop failure (Owusu-Ansah & Asante, 2020). The introduction of improved cassava varieties and efficient farming techniques has further integrated cassava into Ghanaian agriculture, facilitated by agricultural extension programs that disseminate knowledge on high-yielding varieties and sustainable practices (Quaye *et al*., 2018). However, challenges such as pest and disease outbreaks threaten sustainable cassava production, prompting ongoing research efforts to enhance its resilience in Ghana's agricultural landscape (Adu-Gyamfi *et al*., 2021).

Taxonomically, the genus Manihot belongs to the Euphorbiaceae family, with M. esculenta being the cultivated and economically significant species (Hahn, 1997). Early classifications by taxonomists like Linnaeus laid foundational understanding, yet the complexity of cassava's taxonomy became apparent with subsequent research advancements (Morales, 2006). Molecular techniques, including SSRs (Simple Sequence Repeats) and SNPs (Single Nucleotide Polymorphisms), have greatly improved our understanding of cassava diversity and phylogenetic relationships (Olsen *et al*., 2004). These techniques have been crucial in deciphering genetic variability related to morphological traits such as leaf shape, tuber characteristics, and growth habits among different cassava varieties (de Oliveira, 2019). Despite these advancements, challenges remain in reconciling morphological and molecular classifications (Ferguson *et al*., 2019). Integrating genomic data with traditional taxonomy promises to refine our understanding of cassava diversity further, enhancing breeding efforts and the development of resilient varieties suited to diverse environments.

2.2 Food, Medicinal and Industrial Importance of Cassava

Cassava is a versatile crop with significant importance across food, medicinal, and industrial sectors. It serves as a staple food in tropical and subtropical regions, providing essential carbohydrates crucial for food security (Montagnac *et al*., 2009). The roots are processed into various products such as flour and starch, while its leaves, rich in vitamins and phytochemicals, are utilized in traditional medicine for their antimicrobial and antioxidant properties (Adelakun *et al*., 2017; Quartey *et al*., 2016). Cassava also contributes to modern medicine, showing promise in combating diseases like cancer due to its cytotoxic effects on cancer cells (Silva *et al*., 2016).

In addition to its nutritional benefits, cassava plays a vital role in industrial applications. Cassava starch, known for its viscosity and adhesive properties, is used extensively in food processing, paper production, textiles, and pharmaceuticals (Wheatley, 2015). It also serves as a feedstock for bioethanol production, offering a renewable energy source (Li *et al*., 2020). Cassava's by-products, including peel and pomace, contribute to animal feed formulations, enhancing livestock nutrition (Akinola *et al*., 2019).

2.3 Climatic Requirements for Cassava Production

Cassava is well-adapted to a wide range of climatic conditions, but optimal growth occurs within specific temperature and rainfall ranges. Generally, cassava thrives in tropical and subtropical climates with temperatures between 25°C and 30°C, although it can tolerate temperatures up to 40°C for short periods (Ezui *et al.*, 2017). Prolonged exposure to temperatures below 18°C inhibits growth and can lead to physiological disorders such as leaf bronzing and root rot. Adequate rainfall is crucial during the growing season, with an ideal range of 1,000 to 1,500 mm evenly distributed throughout the year (Howeler *et al.*, 2013). Cassava is relatively drought-tolerant, but prolonged dry spells can significantly reduce yields land affect root quality. Additionally, cassava requires sufficient sunlight for photosynthesis, making it unsuitable for cultivation in heavily shaded areas.

2.4 Soil Requirements for Cassava Cultivation

Cassava cultivation is adaptable to various soil types, with optimal growth observed in well-drained loamy soils within a pH range of 5.5 to 6.5 (Howeler *et al.*, 2013). Soil compaction and waterlogging adversely affect root development, leading to reduced yields and increased vulnerability to pests and diseases. Sandy soils, though well-drained, may require additional organic matter and fertilization to enhance fertility and water retention capabilities. Conversely, heavy clay soils can restrict root expansion, necessitating soil amendments for improved drainage and aeration. Cassava exhibits moderate tolerance to acidic soils, although excessive acidity can hinder nutrient availability and root growth, necessitating lime application to adjust pH levels (George *et al.*, 2012). Adequate soil fertility management, including nitrogen, phosphorus, and potassium supplementation, is crucial for sustaining cassava root development and maximizing crop productivity.

2.5 Agronomic Practices for Cassava Cultivation

Successful cassava cultivation hinges on strategic agronomic practices aimed at enhancing yields while minimizing environmental impact. Selection of healthy stem cuttings from disease-free plants is paramount for propagation, ensuring robust growth (Ezui *et al*., 2017). Planting these cuttings at appropriate spacings of 1 m × 1 m to 1.5 m × 1.5 m, adjusted for soil fertility and variety, optimizes growth conditions. Weed management is critical during early growth stages to mitigate competition for nutrients and moisture; methods like mechanical weeding and mulching are effective (George *et al*., 2012). Proper fertilizer application, tailored through soil testing, balances nutrient needs without causing environmental harm, focusing on nitrogen, phosphorus, and potassium (Yahaya *et al*., 2023).

Pest and disease control are integral to sustaining cassava production. Integrated pest management strategies, encompassing cultural, biological, and chemical controls, are essential against threats like cassava mosaic disease and bacterial blight (Beed, F. D. (2014). Climate factors, such as temperature, rainfall, and sunlight, profoundly influence cassava growth and yield, necessitating optimal environmental conditions. Suitable soil attributes—good drainage, fertility, and pH levels—foster robust root development and nutrient absorption, underpinning successful cultivation practices (Ezui *et al*., 2017).

2.6 Enhancing Cassava Production for Global Food Security and Sustainability

Cassava is a globally significant crop, cultivated widely across tropical and subtropical regions, particularly in Africa, Asia, and Latin America. It serves as a staple food for over 800 million people and plays a key role in poverty reduction across many nations (FAO, 2021). In 2022, Ghana's gross production index for roots and tubers reached 144.44, representing a 44.44% increase from the baseline period of 2014-2016, signalling notable growth in the agricultural sector (FAO, 2023; Tridge, 2024). Renowned for its resilience, cassava thrives in low-input farming systems, is drought-tolerant, and can grow in poor soils, making it an essential crop for climate change adaptation. Its potential for bioenergy production, particularly through bioethanol and biogas, further enhances its importance in sustainable agriculture (FAO, 2021).

However, despite these advantages, cassava production faces several challenges. Low productivity, limited market access, pest and disease outbreaks, and the impacts of climate change hinder its potential. Overcoming these obstacles requires concerted efforts from governments, research institutions, development organisations, and the private sector. In Ghana, while cassava remains vital to food security and economic development, challenges such as inadequate access to quality planting materials, pest pressures, and market constraints limit its full potential. Globally, enhancing cassava production involves improving value chain efficiency and expanding market opportunities for smallholder farmers (FAO, 2021).

2.7 Addressing Constraints in Cassava Production for Enhanced Food Security

Cassava production plays a critical role in ensuring food security and sustaining livelihoods across tropical and subtropical regions. However, several significant constraints hinder optimal cultivation, affecting productivity, quality, and profitability. Pests and diseases such as cassava mosaic disease (CMD), cassava brown streak disease (CBSD), and cassava bacterial blight (CBB) present major threats, causing substantial yield losses and reduced crop quality (Legg *et al*., 2014). Effective control strategies include the use of resistant varieties, integrated pest management (IPM), and biopesticide applications. Access to quality planting materials also remains a crucial limitation, especially in remote areas, where farmers often depend on traditional varieties that are susceptible to pests and diseases or have low yield potential (Alvarez *et al*., 2016). To improve access, initiatives such as establishing cassava multiplication centres, implementing farmer training programs, and fostering partnerships between research institutions and extension services are essential.

Post-harvest losses further undermine cassava production, often resulting from poor harvesting techniques, inadequate storage facilities, and limited access to processing technologies. These issues necessitate investments in infrastructure and training in good agricultural practices (GAPs) (Lynam *et al*., 2016). Additionally, limited market access exacerbates these challenges. Cassava is frequently undervalued and faces market inefficiencies, including inadequate transportation and insufficient market information, which reduces farmers' profitability (Nweke *et al*., 2002). Improving market access requires enhancing rural infrastructure and developing robust market information systems to strengthen market linkages for farmers. Furthermore, climate change poses significant risks to cassava production, with rising temperatures, erratic rainfall patterns, and extreme weather events threatening growth and yield stability (Amelework *et al*., 2021). Addressing these constraints is crucial for ensuring cassava's role in global food security and rural development.

2.8 Abiotic Constraints in Cassava Production for Resilience and Sustainability

Despite cassava’s deep root structure that aids in withstanding some drought, extreme drought conditions lead to reduced root development and lower yields. Physiological issues such as leaf wilting also occur during severe droughts (Farooq *et al*., 2009). With climate change intensifying droughts, it is essential for farmers to adopt drought-resistant farming techniques and efficient water management strategies to safeguard cassava yields. On the other hand, challenges such as waterlogging and flooding limit the roots’ ability to breathe and absorb nutrients, leading to diseases like root rot (Legg *et al*., 2014). Sustainable management of these soils requires techniques like gypsum application, leaching, and the cultivation of salt-tolerant cassava varieties. Climate-smart practices such as selecting temperature-tolerant varieties and employing shading and mulching techniques are critical for mitigating the effects of temperature extremes.

2.9 Managing Cassava Diseases to Sustain Productivity and Food Security

Cassava is highly vulnerable to a range of diseases that threaten its productivity and economic value for farmers. Cassava mosaic disease (CMD), caused by begomoviruses transmitted by whiteflies, is particularly destructive. It results in mosaic patterns, leaf yellowing, stunted growth, and reduced root yields (Ghimirey *et al*., 2024). Effective management strategies for CMD include the use of resistant varieties, vector control, the removal of infected plants, and planting disease-free materials. Another significant threat is cassava brown streak disease (CBSD), caused by Cassava brown streak virus (CBSV) and Ugandan cassava brown streak virus (UCBSV). This disease causes necrotic lesions on stems, leaf mottling, and brown streaks in roots, making the roots unmarketable

(Ghimirey *et al*., 2024). Control measures for CBSD involve using resistant varieties, managing vectors, and enforcing strict phytosanitary practices.

Cassava bacterial blight (CBB), caused by *Xanthomonas axonopodis pv. manihotis*, affects leaves, stems, and tubers. Symptoms include water-soaked lesions, cankers, and premature defoliation, which significantly reduce yields (Verdier *et al*., 2012). Managing CBB requires sanitation practices, copper-based treatments, and cultural methods to limit its spread. Additionally, cassava anthracnose disease, caused by *Colletotrichum gloeosporioides*, leads to stem lesions, leaf blight, and tuber rot. Control strategies include the use of resistant varieties, fungicide applications, and crop rotation (Gomez *et al*., 2010).

2.10 Enhancing Cassava Production Through Improved Cultivation and Disease Management Techniques

Cassava is a vital staple crop in many tropical regions, prized for its versatility and ability to thrive in diverse environments. One of the most common cultivation methods involves planting stem cuttings. Studies by Sheat *et al*., (2024) highlight the importance of using healthy, disease-free cuttings to ensure successful establishment. Researchers, including Akinboe *et al*. (2020), have explored the minisett technique, a rapid multiplication method that uses small stem cuttings, known as minisetts, to promote early root development. Soil quality plays a critical role in cassava yield, with investigations by Ogunrinde *et al*. (2019) emphasizing the need for well-drained soils with good organic matter content for optimal growth. Fertilization strategies are also crucial, as findings from Ajayi *et al*. (2015) suggest that a balanced application of nitrogen, phosphorus, and potassium enhances plant development and boosts tuber yields. Cassava mosaic disease (CMD) is a significant threat to production. Research by Adams *et al*. (2017) underscores the importance of developing disease-resistant varieties and implementing early detection and control measures. Furthermore, various studies, including those by Mbanzibwa *et al*. (2011), emphasize the need for integrated pest management strategies to combat root rot diseases. These strategies include proper sanitation, crop rotation, and the use of resistant varieties. Given cassava's susceptibility to climatic variations, research by Devi *et al*. (2022) focuses on breeding resilient varieties that can withstand changing climate conditions, thereby ensuring food security in the face of environmental challenges.

2.11 The Nutritional and Agricultural Potential of Yellow-Flesh Cassava

Yellow-flesh cassava is a distinct cultivar recognized for its vibrant yellow roots (Rafique, 2019). This variety has garnered significant attention due to its enhanced nutritional profile, particularly its high pro-vitamin A content compared to traditional white-flesh varieties (Neela & Fanta, 2019). Vitamin A is essential for healthy vision, skin, and immune function. Research by Kumar, *et al*., (2024) highlight that micronutrient deficiencies, especially vitamin A deficiency, remain a critical public health issue in many regions. The pro-vitamin A-rich yellow-flesh cassava offers a sustainable and accessible solution to combat these deficiencies. A study by Talsma *et al*. (2019) emphasizes the potential of biofortified cassava varieties, such as yellow-flesh cassava, to significantly alleviate vitamin A deficiency in populations dependent on cassava as a staple food. However, despite its nutritional advantages, consumer acceptance plays a vital role in the successful integration of yellow-flesh cassava into local diets (Lawal, 2022). Research by Tomlins *et al*. (2017) stresses that sensory attributes, including taste and texture, are critical factors influencing consumer preferences. Addressing these factors is essential for the widespread adoption of yellow-flesh cassava. Agronomically, yellow-flesh cassava shares similar cultivation practices with traditional cassava varieties, making it a feasible option for farmers. However, ongoing research focuses on optimizing specific agronomic practices tailored to biofortified varieties. Studies by Ukpabi & Maziya-Dixon (2018) explore strategies to improve the yield and resilience of yellow-flesh cassava under various environmental conditions. Integrating yellow-flesh cassava into both agricultural and dietary systems can play a significant role in global efforts to combat malnutrition.

2.11 Beta-Carotenoids in Cassava: Nutritional Benefits, Bioavailability, and Implications for Vitamin A Deficiency

Beta-carotenoids are powerful pigments with significant antioxidant properties, found in numerous fruits and vegetables. They are critical to human health as a precursor to vitamin A, which is essential for vision, immune function, and skin health (Tanumihardjo, 2013). Research has shown that beta-carotenoids may reduce the risk of chronic diseases like age-related macular degeneration and certain cancers (Tufail *et al*., 2024). They neutralize free radicals, offering protection against oxidative stress, which is a key factor in disease prevention. The bioavailability of beta-carotenoids—how well they are absorbed and utilized by the body—is crucial for maximizing these health benefits. Studies have indicated that bioavailability is influenced by factors like the food matrix, preparation methods, and the presence of dietary fats (Jones *et al*., 2019). Innovations such as nano-emulsions and encapsulation technologies are improving beta-carotenoid absorption, making them more effective (Garcia *et al*., 2021).

While beta-carotenoids are known for their antioxidant effects, research suggests that synthetic vitamin A can act as a pro-oxidant in high concentrations or under oxidative stress (Brown *et al*., 2018). This is a key distinction between natural beta-carotenoids and synthetic vitamin A, as the natural forms are released gradually based on the body's needs, avoiding the risks of avitaminosis and toxicity. This controlled release makes natural beta-carotenoids a safer and more effective option. Emerging research on genetic variations in beta-carotenoid metabolism highlights that individual genetic differences can significantly influence their absorption and utilization (Miller *et al*., 2013). This could lead to more personalized dietary recommendations, optimizing beta-carotenoid intake for individual health needs.

Beta-carotenoids are crucial for addressing vitamin A deficiency, a global public health issue, particularly in developing countries. Adequate intake can prevent conditions like night blindness and improve immune function by enhancing lymphocyte production (Sommer, 2008; Bendich, 1991). Beta-carotenoids also provide photoprotection against ultraviolet (UV) radiation, further supporting skin health (Stahl & Sies, 2007). Research has demonstrated a link between higher beta-carotenoid intake and a reduced risk of cardiovascular diseases (Li *et al*., 2012).

In cassava, a staple food for millions in Sub-Saharan Africa and parts of Asia, beta-carotenoids add nutritional value by serving as a precursor to vitamin A. Breeding programs and genetic modification efforts are focusing on enhancing the beta-carotenoid content in yellow-flesh cassava varieties, which can help combat vitamin A deficiency (Badewa, 2023; Sayre *et al*., 2011). The synthesis of beta-carotenoids in cassava is influenced by environmental factors such as nutrient availability, particularly nitrogen, phosphorus, and potassium, as well as irrigation and light intensity (Njoku *et al*., 2014;

Lopez *et al*., 2004). Moderate temperatures also enhance carotenoid biosynthesis through enzymatic activity (Chávez *et al*., 2005).

Preserving beta-carotenoid content post-harvest is essential, with practices like cool storage and optimized processing methods playing a critical role (Woolfe, 1992; Chávez *et al*., 2007). Cassava is a major source of carbohydrates, but its beta-carotenoid content makes it even more valuable, particularly in regions with limited access to diverse foods. Incorporating beta-carotenoid-rich cassava into diets can help address vitamin A deficiency and improve overall health by promoting eye health, reducing the risk of certain cancers, and boosting immune function.

Research indicates that beta-carotenoid levels in cassava can vary among different varieties, and selecting high-beta-carotenoid varieties can significantly enhance the crop's nutritional impact. Further studies on varietal differences and innovative processing techniques could optimize the health benefits of cassava consumption, making it a key contributor to solving vitamin A deficiency in many parts of the world.

2.12. Factors Influencing Beta-Carotenoid Content in Cassava: Genetic, Environmental, and Post-Harvest Considerations

Beta-carotenoid content in cassava varies due to genetic differences among varieties. Some cassava varieties are naturally high in beta-carotene, while others accumulate lower levels, particularly those not bred for high carotenoid content (Iglesias *et al*., 1997). The expression of genes involved in carotenoid biosynthesis can differ across varieties, and downregulation of key biosynthetic genes can result in lower beta-carotene levels (Welsch *et al*., 2010). Insufficient soil nutrients, such as nitrogen, phosphorus, and potassium, can hinder carotenoid synthesis (Njoku *et al*., 2014b). Drought conditions, which cause water stress, further limit carotenoid accumulation in cassava (Sayre *et al*., 2011). Additionally, low light conditions can reduce beta-carotene synthesis, as carotenoid production is light-dependent (Lopez *et al*., 2004). Temperature extremes can disrupt the enzymatic processes required for carotenoid biosynthesis, and optimal temperatures are essential for maintaining high beta-carotene levels (Chávez *et al*., 2005).

Post-harvest conditions also significantly influence beta-carotenoid retention. Exposure to light, heat, and oxygen during storage can cause degradation of carotenoids, leading to significant losses (Woolfe, 1992). Traditional processing methods like boiling, frying, and fermenting can degrade carotenoids, with high temperatures and prolonged cooking times being particularly detrimental (Chávez *et al*., 2007). Oxidative stress caused by environmental factors, such as drought or high temperatures, can also result in carotenoid degradation (Foyer & Noctor, 2005). Moreover, metabolic pathways within cassava plants compete for precursors and energy, which can divert resources away from carotenoid biosynthesis and reduce beta-carotene accumulation (Fraser & Bramley, 2004).

2.11.4 Optimizing Carotenoid Content in Yellow-Flesh Cassava

Carotenoids are synthesised via the isoprenoid pathway, starting from isopentenyl diphosphate (IPP) and dimethylallyl diphosphate (DMAPP), leading to the formation of geranylgeranyl diphosphate (GGPP). GGPP is converted into phytoene, lycopene, and eventually beta-carotene and other carotenoids. Traditional breeding methods select and cross-breed varieties with naturally high carotenoid content. Yellow-flesh cassava varieties developed by the IITA exhibit increased carotenoid levels (Iglesias *et al*., 1997). Gene introduction has also enhanced carotenoid biosynthesis, such as introducing the phytoene synthase (psy) gene from maize into cassava (Arango *et al*., 2010). CRISPR-Cas9 tools allow for precise modifications in carotenoid biosynthetic genes, improving their expression and carotenoid accumulation. Adequate nitrogen, phosphorus, and potassium levels are essential for carotenoid biosynthesis, while proper fertilisation practices enhance carotenoid accumulation (Saini *et al*., 2018). Consistent irrigation prevents water stress, which is vital for maintaining carotenoid synthesis. Carotenoid synthesis is light-dependent, with higher light intensity promoting carotenoid production (Pizarro & Stange, 2009). Moderate temperatures favour the enzymatic activities involved in carotenoid biosynthesis, ensuring optimal carotenoid accumulation (Zhao *et al*., 2022).

Storing cassava roots in conditions that minimise exposure to light, heat, and oxygen helps maintain carotenoid levels (Saini *et al*.,2018). Cooking techniques like gentle boiling and steaming, rather than prolonged or high-temperature cooking, help preserve carotenoid content (Zhao *et al*., 2022b). Antioxidants protect carotenoids from oxidative degradation, and breeding or agronomic practices can enhance plant antioxidant capacity (Foyer & Noctor, 2005). Optimising metabolic pathways ensures efficient precursor use and minimises competition with other metabolic processes (Fraser & Bramley, 2004). The most prominent carotenoid in yellow-flesh cassava is beta-carotene, responsible for its yellow to orange colour.

The intensity and hue of cassava root colour depend on the concentration of carotenoids, especially beta-carotene, with higher content producing deeper orange shades (Iglesias *et al*., 1997). Different cassava varieties exhibit varying carotenoid profiles, resulting in diverse root flesh colours. Selective breeding and genetic modifications aim to enhance carotenoid content and achieve desired colour traits Bradshaw, J. E. (2019). Adequate light exposure during growth promotes carotenoid synthesis, intensifying root flesh colour, while shaded or low-light conditions lead to paler root flesh Aldarkazali, M. (2020). Optimal soil fertility and nutrient availability, particularly nitrogen, phosphorus, and potassium, support carotenoid biosynthesis, influencing root flesh colour (Milošević & Milošević, 2020). Consistent irrigation and avoidance of water stress are crucial for maintaining carotenoid levels and ensuring vibrant root flesh colour (Sabir *et al*., 2024). Post-harvest exposure to light and heat can degrade carotenoids, leading to faded root flesh colour. Proper storage in cool, dark conditions preserves carotenoid content and colour intensity Ramaswamy, H. S. (2014). Rising awareness of the health benefits of carotenoids, particularly their role in combating vitamin A deficiency, has led to increased demand for biofortified, carotenoid-rich cassava varieties (Sabir *et al*., 2024).

2.13 Genetic and Environmental Factors Influencing Dry Matter Content in Cassava

Cassava, a key crop in tropical and subtropical regions, has dry matter content (DMC) as an important determinant of its nutritional and industrial value. The DMC varies between varieties, typically ranging from 30% to over 40% (Ceballos *et al*., 2004), and is influenced by genetic factors. Breeding programmes utilise molecular biology to target genes involved in starch biosynthesis, such as ADP-glucose pyrophosphorylase and starch synthase (Zhang *et al*., 2014), and marker-assisted selection (MAS) to enhance DMC.

Climatic factors, including optimal temperatures (25-30°C) and adequate rainfall, enhance photosynthesis and carbohydrate accumulation, promoting higher DMC (El-Sharkawy, 2007). However, extreme temperatures and prolonged drought reduce DMC due to plant stress (Burns *et al*., 2010). Soil fertility and organic matter also affect DMC, with well-drained, fertile soils supporting better root development and starch accumulation (Pellet & El-Sharkawy, 1997).

The spacing and planting density of cassava influence DMC by ensuring plants receive adequate light and nutrients, which enhances root development (Kawano, 2003). Water management is crucial, as excessive irrigation can cause waterlogging, reducing DMC, while proper irrigation during growth stages aids starch accumulation (El-Sharkawy, 2007). The timing of harvest also impacts DMC, as early or late harvesting can reduce starch content (Alves, 2002). Post-harvest storage in cool, dry conditions helps maintain DMC (Nuwamanya *et al*., 2011).

Genetic variability impacts dry matter partitioning in cassava, with high-yielding cultivars demonstrating better biomass allocation to storage roots, linked to improved photosynthetic efficiency and delayed senescence (Okogbenin *et al*., 2013). Soil moisture and temperature play a key role in partitioning, with moderate temperatures promoting root development and starch accumulation (El-Sharkawy, 2012; Rojas *et al*., 2015).

Enzymes such as sucrose synthase and ADP-glucose pyrophosphorylase are critical for starch synthesis and accumulation in cassava storage roots (Hunt *et al*., 2013). Agronomic practices, including balanced fertilisation and appropriate planting densities, enhance dry matter accumulation (Howeler *et al*., 2013; Igbokwe *et al*., 2014). DMC is vital for fresh consumption and industrial applications, such as flour, starch, and bioethanol production.

Accurate DMC estimation is crucial for breeding and crop management. Methods like oven-drying, the specific gravity (SG) method, refractometry, and non-destructive techniques such as near-infrared spectroscopy (NIRS) offer rapid, accurate DMC assessments (Belalcazar *et al.*, 2016). Recent advancements, including portable NIRS devices, enable field-based, real-time DMC data collection, improving accessibility for farmers and researchers.

The relationship between DMC and carotenoid content in cassava is complex and influenced by genetic and environmental factors. Some studies indicate a positive correlation between carotenoid and DMC (Peprah, B. B. (2020). while others report a negative correlation due to metabolic trade-offs between carotenoid biosynthesis and starch accumulation (Delgado *et al.*, 2024). Akinwale *et al.* (2010) noted variability in the correlation depending on breeding populations and environmental factors, suggesting that genetic background and environmental conditions influence both traits.

Environmental factors, including soil type, temperature, and water availability, also affect both carotenoid and DMC content. Stress conditions, such as drought, can impair both carotenoid and starch accumulation. Post-harvest practices, including proper handling and storage, are essential to preserve carotenoid levels without significantly affecting DMC. Breeding programmes and research focused on improving DMC and carotenoid content under diverse conditions will be crucial for enhancing cassava's nutritional and industrial potential.

2.14. Factors Influencing Storage Root Formation and Yield in Cassava

Storage root formation in cassava is driven by hormonal signals, primarily auxins, cytokinins, and gibberellins, which regulate root initiation and differentiation (Zhang *et al.*, 2014). During bulking, cell division in the cambium, followed by expansion, leads to root thickening. Cytokinins promote cell division, while gibberellins stimulate cell elongation

(Nuwamanya *et al*., 2011b). Secondary growth, involving the vascular cambium, produces xylem and phloem to support nutrient transport (Lebot, 2009). Starch accumulation in roots depends on enzymes like ADP-glucose pyrophosphorylase (AGPase), which catalyses starch synthesis (Santisopasri *et al*., 2001).

Genetic and environmental factors regulate starch biosynthesis, with hormonal signals and environmental conditions influencing enzyme activity (Oparka *et al*., 1999). High temperatures and fertile, well-drained soils enhance starch accumulation, while poor soil and temperature extremes hinder root bulking (Ceballos *et al*., 2004). Genetic diversity among cassava cultivars affects bulking, with varieties high in starch and disease resistance demonstrating better performance (Hershey & Jennings, 2012). Modern breeding techniques, including marker-assisted and genomic selection, improve root bulking traits (Collard *et al*.,2008).

Balanced fertilisation supports root bulking by ensuring the availability of nitrogen, phosphorus, and potassium, promoting root growth and starch accumulation (Pellet & El-Sharkawy, 1997). Planting density is crucial for optimising space for root expansion, reducing competition for nutrients and water (Howeler, 2002. However, environmental stressors, such as drought and poor soil fertility, remain challenges in optimising bulking (Haussman *et al*., 2012).

Cassava yield is influenced by genetic variation, with disease-resistant varieties, such as those resistant to cassava mosaic disease (CMD) and cassava brown streak disease (CBSD), showing higher yields (Legg *et al*., 2015). Nutrient management, particularly nitrogen, phosphorus, and potassium, is vital for optimal root growth (Howeler, 2002). Cassava thrives in slightly acidic to neutral soils (pH 5.5-7.0), and soil pH management improves nutrient uptake (CIAT, 1991). Adequate water supply during bulking stages is essential for maximising yield (Esilaba *et al*., 2023). Optimal temperatures of 25°C to 30°C are required for maximum yield (Lebot, 2009).

Cassava's growth depends on consistent rainfall, with excessive rainfall causing waterlogging and drought limiting root bulking (Cock *et al*., 2021). Pest management strategies, including the control of cassava mealybug and green mite, are crucial for maintaining high yields (Bellotti *et al*., 2012). Disease control through resistant varieties and good agricultural practices is essential for yield maintenance (Legg *et al*., 2015).

Farmer training in best agronomic practices, pest management, and resource use can improve cassava yields (Nweke *et al*., 2002). Additionally, access to markets and fair pricing encourages the adoption of yield-enhancing practices (Haggblade *et al*., 2012). Root formation and bulking are influenced by auxins, cytokinins, and other genetic factors (Ravi *et al*., 2014), with optimal conditions enhancing starch accumulation (Santisopasri *et al*., 2001). Research into drought-tolerant varieties and effective crop management practices is needed to overcome environmental stress (Ray *et al*., 2020). Integrated pest management and disease control, as well as balanced fertilisation and soil management, are crucial to improving cassava yield and quality.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Location of the experiment

The research was conducted at the Biotechnology and Nuclear Agriculture Research Institute (BNARI) field, under the Ghana Atomic Energy Commission (GAEC) at Kwabenya, near Accra. The experimental site is located at 05˚ 40’ N and longitude 0˚ 13’ W at an elevation of 76 m above sea level within the coastal Savannah agro-ecological zone.

3.2 Field Establishment

The study was conducted over two years, comprising an initial 12-month evaluation phase, which was repeated in the subsequent year to enhance data reliability. The research site featured well-drained savanna ochrosol (Ferric Acrisol) soils, derived from quartzite schist, as described by FAO/UNESCO (1994). Land preparation, planting, and crop management adhered to established agronomic practices to optimise cassava growth and productivity.

3.3 Plant Material

Four cassava varieties—Kpornu, Tettey Bankye, Nyonku, and Genotype D—were included in the trials to assess their performance under the study conditions. There varieties were part of varieties released through GAEC and UCC collaboration in 2019 (Amenorpe, 2019).

3.4 Experimental Design

Field trials utilised a randomised complete block design (RCBD) with five replications to reduce spatial variability and enhance experimental precision. Each cassava variety was planted in a 6-metre by 5-metre plot containing 41 stem cuttings, arranged with a 1-metre spacing between rows and columns. From the 4th to the 12th month, four plants were harvested every two months, totalling 20 harvested plants, while the remaining 21 served as border rows.

3.5 Data Collection

3.5.1 Morphological data

Both qualitative and quantitative morphological data of four varieties were collected following the procedure of Fukuda *et al*., (2010).

3.5.2 Yield Assessment

At harvest maturity, total root yield per plot was determined by harvesting all plants within the boarder rows. The total fresh weight of harvested roots per plot was recorded, and representative samples were collected for further analysis in the laboratory.

3.5.3 Dry Matter Content

Root samples were oven-dried to constant weight at a predetermined temperature (e.g., 78°C) to determine dry matter content. - Dry matter content (%) was calculated as the ratio of dry weight to fresh weight multiplied by 100.

3.5.4 Total Carotenoid Analysis

Carotenoids were extracted from cassava root samples using an appropriate solvent system (e.g., acetone or hexane). - Extracted carotenoids were quantified using spectrophotometric methods based on absorbance at specific wavelengths (e.g., 450 nm for total carotenoids). Total carotenoid content was expressed as micrograms per gram of dry weight (µg/g DW) of cassava roots.

The icheck method was used to measure total carotenoids only. The portable device consists of a hand-held photometer icheck carotene (Bio Analyst GmbH, Teltow, Germany), and the disposable reagent vials in which the extraction was performed. Five grams of homogenized sample were pounded in a mortar, 5mL of distilled water was added and grinding was performed until a smooth paste was obtained. The mashed root paste was transferred into the 50-mL centrifuge tube and the mortar and pestle were washed with 10mL of distilled water, followed by pouring into the centrifuge tube. The volume was adjusted to 25mL with distilled water and the tube was shaken thoroughly until a homogenous slurry was obtained. A total of 0.4mL of slurry was taken with a syringe and injected into the reagent vial. After shaking the vial vigorously for seconds, the sample was left to rest for 5 to 10 minutes and measured in the icheck carotene device. the device displayed all the readings that were used to determine the total carotenoid content of each sample.

3.6 Data Analysis:

Analysis of variance (ANOVA) was conducted to assess the significance of varietal effects on yield, dry matter content, and total carotenoid profile. Mean separation tests (e.g., Tukey's HSD) were performed to compare differences among cassava varieties for each trait.

Correlation analysis was conducted to explore relationships between yield, dry matter content, and total carotenoid profile. Statistical analyses were performed using appropriate software packages (SPSS), and significance was declared at $p < 0.05$.

3.7 Quality Control

Field experiments were conducted following good agricultural practices to ensure the reliability and reproducibility of results. Proper sample collection, processing, and storage procedures were followed to minimize experimental errors and maintain sample integrity. Standard analytical methods and protocols were used for all measurements to ensure consistency and accuracy of data.

CHAPTER FOUR

4.0 RESULT

4.1 Average yield in kg per plant profile of four yellow-flesh cassava varieties

Figure 1 presents the average yield profiles of four yellow-flesh cassava varieties throughout the year 2022 and 2023. The analysis of the yield data for the four yellow-flesh cassava varieties reveals distinct patterns in terms of their range, mean yield, and peak productivity from four to 12 months after planting. Kpornu variety shows a yield range from 3.1 to 11.2 kg per plant, with a mean yield of 7.15 kg per plant. It demonstrates steady growth, peaking at 11.2 kg per plant in month 12, making it a reliable choice for farmers seeking consistent production over time. Tettey Bankye, with a range from 3.2 to 16.1 kg per plant and a mean yield of 9.65 kg per plant, also shows a strong upward trend in productivity, reaching its highest yield of 16.1 kg per plant in month 12. This variety offers the highest overall yield among the four, making it ideal for those aiming for high-end season productivity. Nyonku has a more variable yield, ranging from 2.2 to 8.4 kg per plant, with a mean yield of 5.3 kg per plant. Although its yield fluctuates throughout the year, it likely reaches its peak towards the mid-to-late harvest period, though the exact month is unspecified. Lastly, Genotype D, with the lowest yield range of 2.3 to 4.9 kg per plant and a mean yield of 3.6 kg per plant, maintains relatively stable but lower yields across the growing season, with its peak likely occurring mid-to-late in the harvest period. While Tettey Bankye leads in productivity, Genotype D stands out for its stability, making it suitable for conditions where yield consistency is more important than peak output.

Overall, the yield profiles suggest that Kpornu and Tettey Bankye are well-suited for farmers targeting higher yields by the end of the season, while Nyonku and Genotype D may be chosen for their specific traits such as variable or stable performance.

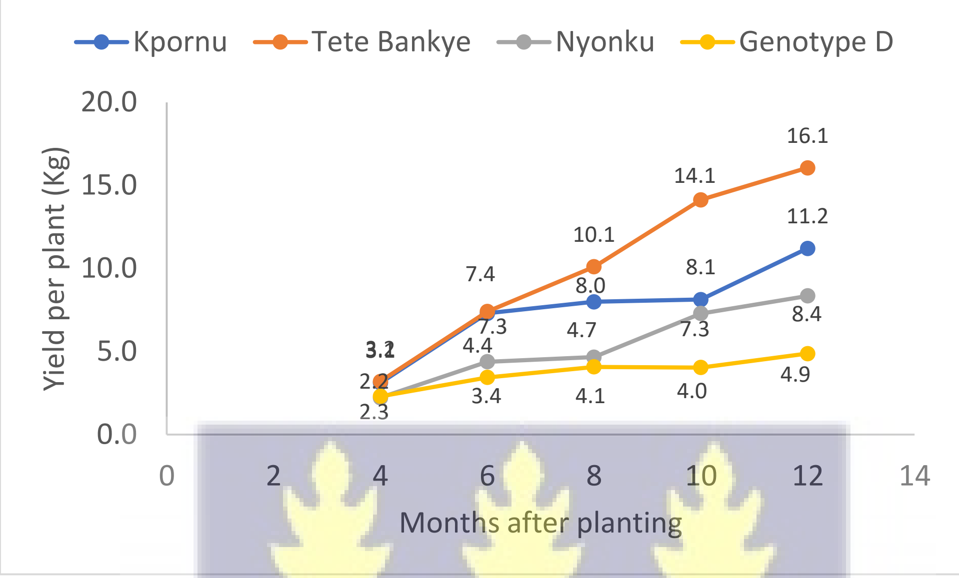

Figure 1: Average of 2022 and 2023 yield data per plant profile of four yellow-flesh cassava varieties

4.2 Total carotenoid profile of four yellow-flesh cassava varieties over a 12 month period

Figure 2 provides a visual representation of the total carotenoid profiles of four yellow-flesh cassava varieties throughout the year 2022, offering insights into their nutritional content and potential health benefits. Examining the data depicted in the figure reveals distinct patterns and variations among the varieties over different months. Notably, there are differences in total carotenoid content across the varieties, with each exhibiting unique trends. Monthly fluctuations indicate changes in carotenoid accumulation, with some varieties showing increases while others decrease over time. Additionally, different varieties reach their peak total carotenoid content at varying times throughout the year. Understanding these profiles is crucial for consumers, nutritionists, and food scientists, as it provides insights into the nutritional value and potential health benefits of yellow-flesh cassava varieties.

For example, Kpornu demonstrates moderate levels of total carotenoid content throughout the year, with values ranging from 4.1 to 11.7. It exhibits an increase in total carotenoid content from month 4 to month 12, indicating potential health benefits associated with consuming this variety. Tetteh Bankye starts with lower total carotenoid content at 5.1 in month 4 but shows fluctuations throughout the year, reaching a peak at 8.6 in month 6 before declining slightly. Nyonku maintains relatively stable total carotenoid content, ranging from 5.4 to 10.6, showing consistency in its nutritional profile. Genotype D stands out with the highest total carotenoid content among all varieties, peaking at 18.7 in month 12, indicating its potential as a highly nutritious option. Each variety presents unique characteristics in terms of total carotenoid content over the course of the year 2022, highlighting the importance of understanding these profiles for consumers seeking to make healthy dietary choices.

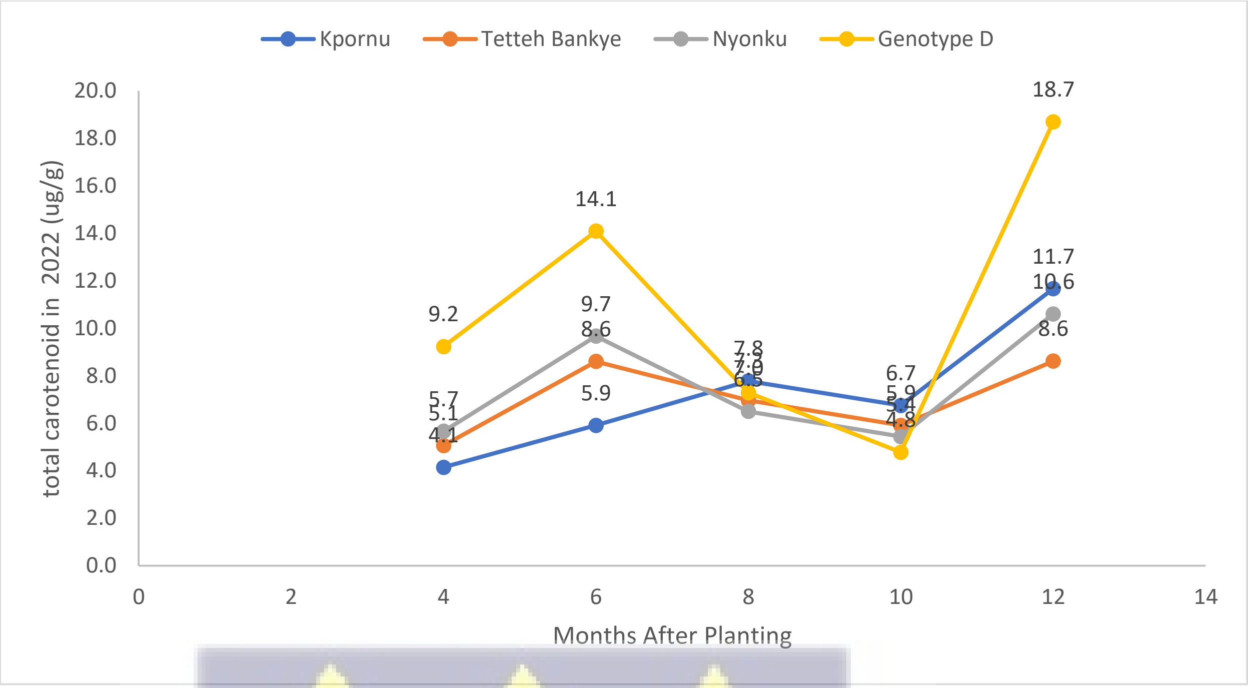

Figure 2: Total carotenoid profile of four yellow-flesh cassava varieties over a 12 month period

4.3 Total carotenoid profile of four yellow-flesh cassava varieties over a 12 month period

Figure 3 illustrates the total carotenoid profiles of four yellow-flesh cassava varieties throughout the year 2023, offering valuable insights into their nutritional content and potential health benefits.

Kpornu exhibits moderate to high levels of total carotenoid content throughout the year, ranging from 6.7 to 17.0. It demonstrates a steady increase in total carotenoid content from month 4 to month 12, indicating potential health benefits associated with consuming this variety. Tetteh Bankye starts with relatively high total carotenoid content at 10.2 in month 4 and shows consistent increases throughout the year, peaking at 19.6 in month 12. Nyonku maintains variable total carotenoid content, ranging from 6.9 to 13.0, with fluctuations observed from four to 12 months after planting. Genotype D stands out with consistently high total carotenoid content among all varieties, ranging from 11.5 to 18.6. It maintains relatively stable levels over the year, showcasing its potential as a highly nutritious option. Each variety presents unique characteristics in terms of total carotenoid content, highlighting the importance of understanding these profiles for consumers seeking to make informed dietary choices.

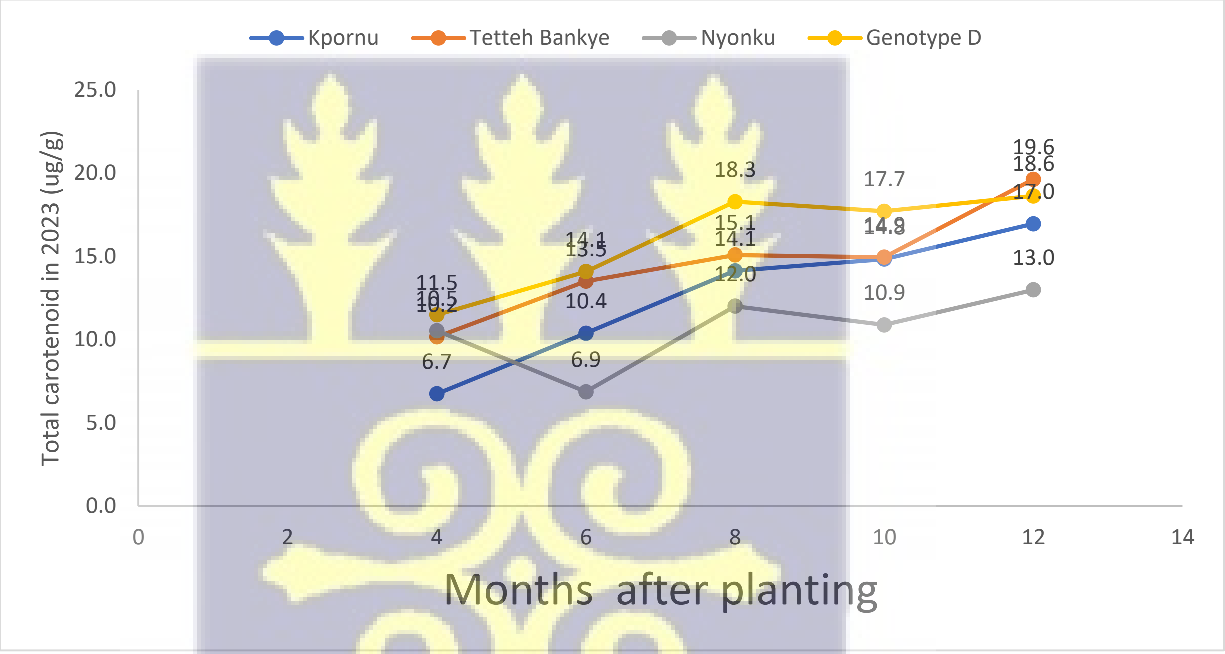

Figure 3: Total carotenoid profile of four yellow-flesh cassava varieties over a 12 month period

4.4. Average Total carotenoid profile of four yellow-flesh cassava varieties for 2022 and 2023

The average 2022 and 2023 otal carotenoid profile of four yellow-flesh cassava varieties, including Kpornu, Tetteh Bankye, Nyonku, and Genotype D, was analyzed across five different months (April, June, August, October, and December) is shown in Figure 4. The total carotenoid values were measured in micrograms per gram (µg/g). The analysis shows that the carotenoid content in Kpornu ranged from 5.4 µg/g in April to 14.3 µg/g in December, with a peak in December. For Tetteh Bankye, the values ranged from 7.6 µg/g in April to 14.1 µg/g in December, peaking in December as well. Nyonku's carotenoid content varied from 8.1 µg/g in April to 11.8 µg/g in December, with the highest value observed in December. Genotype D showed a range from 10.4 µg/g in April to 18.7 µg/g in December, with the peak also occurring in December. In conclusion, for all four varieties, December recorded the highest total carotenoid content, with Genotype D exhibiting the highest overall carotenoid levels, peaking at 18.7 µg/g.

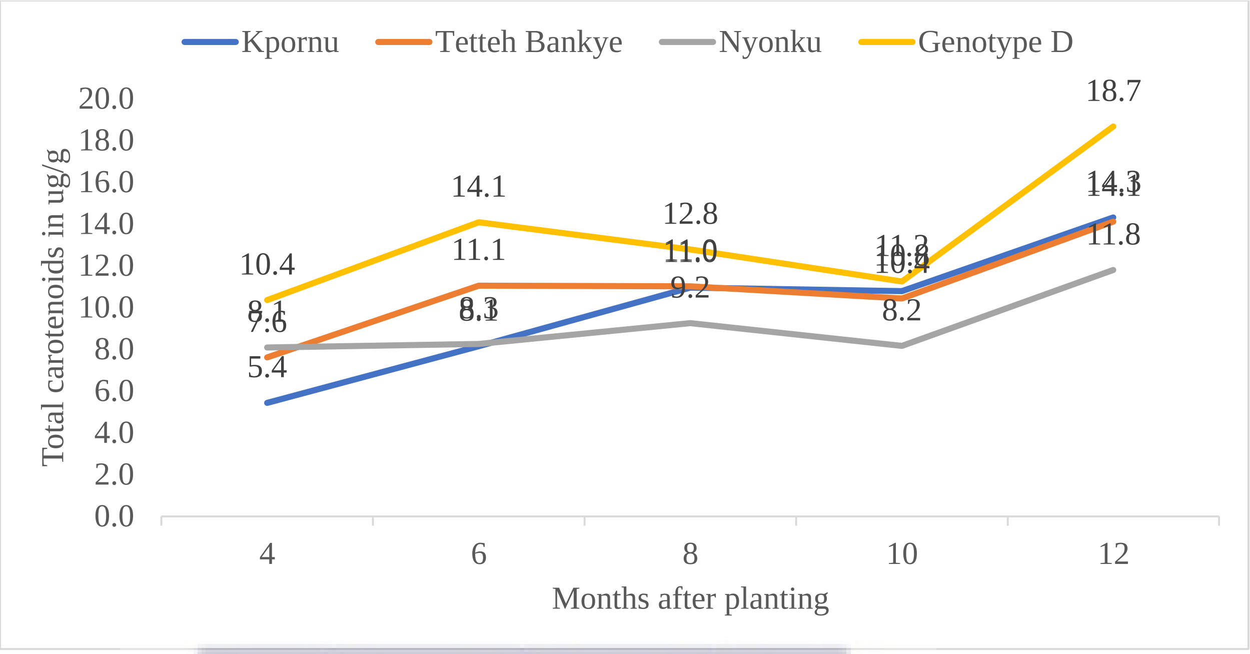

Figure 4: Average total carotenoid profile of four yellow-flesh cassava varieties for 2022 and 2023

4.4 Dry matter profile of four yellow-flesh cassava varieties over a 12 month period

Figure 5 provides the dry matter profiles of four yellow-flesh cassava varieties harvested throughout the year 2022. Kpornu demonstrates moderate to high dry matter content throughout the year, with values ranging from 26.3% to 33.3%. It shows a notable increase in dry matter content from month 4 to month 10, indicating potential maturity and starch accumulation during this period. Tetteh Bankye initially starts with high dry matter content at 33.1% in month 4 but experiences a significant decline to 18.7% in month 8 before a slight recovery at month 10. This variety displays considerable variability from four to 12 months after planting. Nyonku maintains relatively stable dry matter content throughout the year, ranging from 22.6% to 26.1%. It exhibits consistency in dry matter content, suggesting potential reliability for processing purposes. Genotype D consistently exhibits high dry matter content across the months, starting at 33.9% in month 4 and maintaining values above 28% throughout the harvesting period. This variety demonstrates stability in dry matter content, indicating its suitability for processing and product consistency.

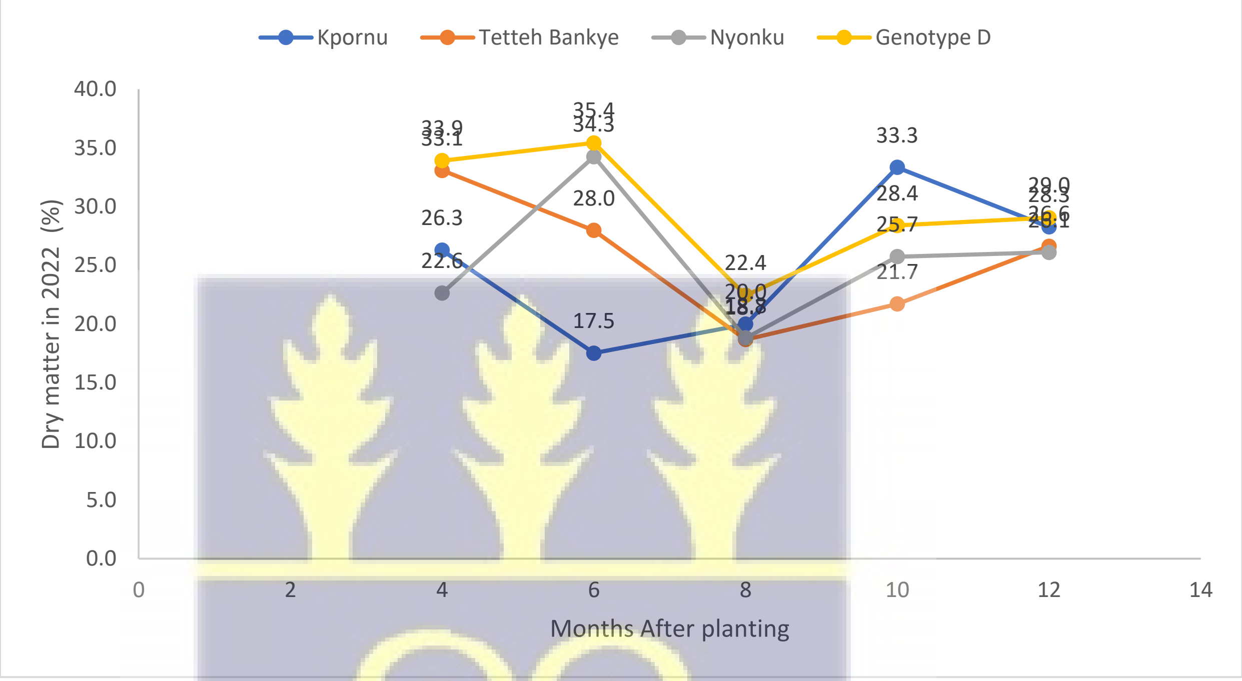

Figure 5: Dry matter profile of four yellow-flesh cassava varieties over a 12 month period

4.5 Dry matter profile of four yellow-flesh cassava varieties over a 12 month period

Figure 6 offers a comprehensive overview of the dry matter profiles of four yellow-flesh cassava varieties throughout the year 2023. Analyzing the data reveals variability in dry matter content across the varieties, with each displaying unique trends. Monthly fluctuations indicate changes in maturity and starch accumulation, with some varieties experiencing significant fluctuations while others remain relatively stable. Additionally, different varieties reach their peak dry matter content at varying times throughout the year. Kpornu demonstrates moderate dry matter content levels throughout the year, ranging from 23.8% to 26.0%. It maintains relatively consistent dry matter content, showing only minor fluctuations from four to 12 months after planting. Tetteh Bankye starts strong with high dry matter content of 31.1% in month 4 but experiences a significant decline to 18.9% in month 8, followed by slight fluctuations thereafter. Nyonku stands out with the highest dry matter content among all varieties, peaking at 38.5% in month 6, although it undergoes a slight decrease to 24.8% by month 12. Genotype D displays relatively consistent dry matter content, ranging from 27.7% in month 4 to 26.5% in month 12. Overall, each genotype exhibits distinct characteristics in terms of dry matter content over the course of the year 2023, highlighting the importance of understanding these profiles for informed decision-making in cassava cultivation and processing.

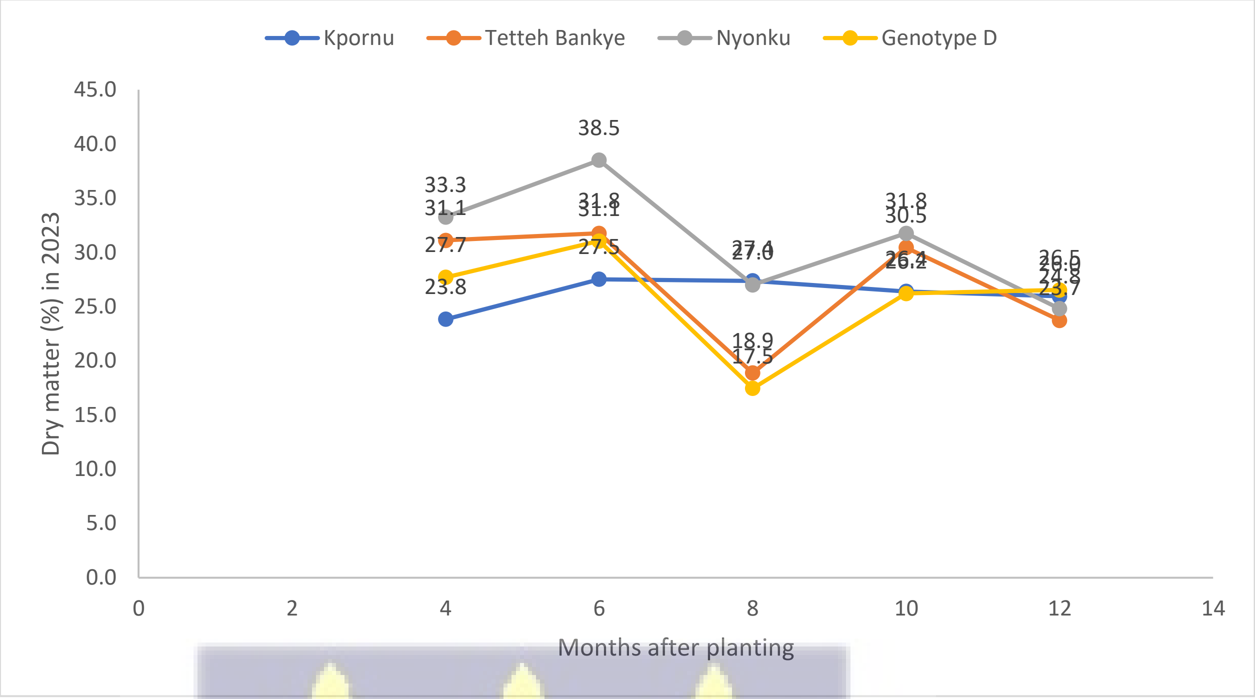

Figure 6: Dry matter profile of four yellow-flesh cassava varieties over a 12 month period

4.6. Average Dry matter profile of four yellow-flesh cassava varieties for 2022 and 2023

Figure 7 shows the average dry matter content (measured as a percentage) of four yellow-flesh cassava varieties—Kpornu, Tetteh Bankye, Nyonku, and Genotype D—was analysed over five months in 2022 and 2023. For Kpornu, the dry matter ranged from 23.8% in April to 27.5% in June, with the peak dry matter value of 27.5% observed in June. The mean dry matter content for Kpornu was approximately 25.8%. Tetteh Bankye's dry matter ranged from 18.9% in August to 31.8% in June, with June being the peak month of 31.8%. The mean dry matter for Tetteh Bankye was 27.2%. Nyonku showed a range from 24.8% in

December to 38.5% in June, with June marking the peak dry matter at 38.5%. The mean dry matter content for Nyonku was 30.7%. Genotype D had a dry matter range from 17.5% in August to 31.1% in June, with June again being the peak month of 31.1%. The mean dry matter for Genotype D was 26.7%. In summary, June was the month when all four varieties reached their highest dry matter content, with Nyonku exhibiting the highest overall dry matter percentage of 38.5%, followed by Tetteh Bankye, Kpornu, and Genotype D.

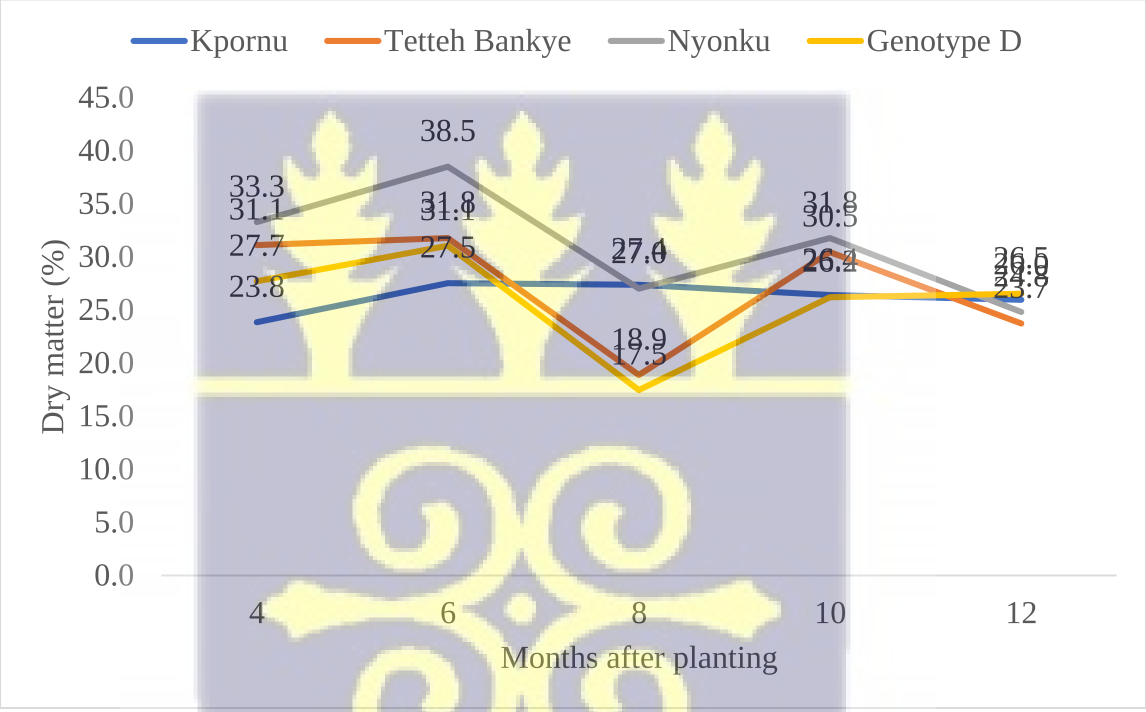

Figure 7. Average dry matter profile of four yellow-flesh cassava varieties for 2022 and 2023

4.7 Correlation profile of Average yield per plant, dry matter and total carotenoid of four yellow-flesh cassava varieties

Figure 8 provides a correlation profile of average yield in kg per plant, dry matter in percentages, and total carotenoid content in ug/g for four yellow-flesh cassava varieties across different months. The data reveals that the an average yield per plant increases over the months, there appears to be a corresponding increase in total carotenoid content, suggesting a positive correlation between these two factors. Conversely, there seems to be a negative correlation between average yield and dry matter content, with higher yields associated with lower dry matter percentages. Example, Kpornu variety demonstrates moderate average yields per plant, ranging from 2.71 kg to 10.12 kg across the months. It exhibits relatively high levels of dry matter content, ranging from 26.38% to 27.04%, indicating its potential for producing nutritious cassava with good storage qualities. The average total carotenoid content in Kpornu ranges from 10.83 ug/gug/g to 14.72 ug/gug/g, suggesting its potential health benefits due to the presence of carotenoids. Tettey Bankye shows average yields per plant ranging from 2.71 kg to 10.12 kg. It has slightly lower dry matter content compared to Kpornu, ranging from 25.24% to 26.55%. The total carotenoid content varies from 10.83 ug/g to 14.72 ug/g, indicating a similar nutritional profile to Kpornu. Nyonku exhibits average yields per plant ranging from 2.71 kg to 10.12 kg, similar to the other varieties. It has moderate dry matter content, ranging from 25.24% to 27.19%. The total carotenoid content ranges from 10.83 ug/g to 14.72 ug/g, indicating a consistent nutritional profile across the months. Genotype D demonstrates comparable average yields per plant, ranging from 2.71 kg to 10.12 kg. It has slightly lower dry matter content compared to Nyonku, ranging from 25.24% to 27.04%. The total carotenoid content ranges from 10.83 ug/g to 14.72 ug/g, suggesting a similar nutritional profile to the other varieties.

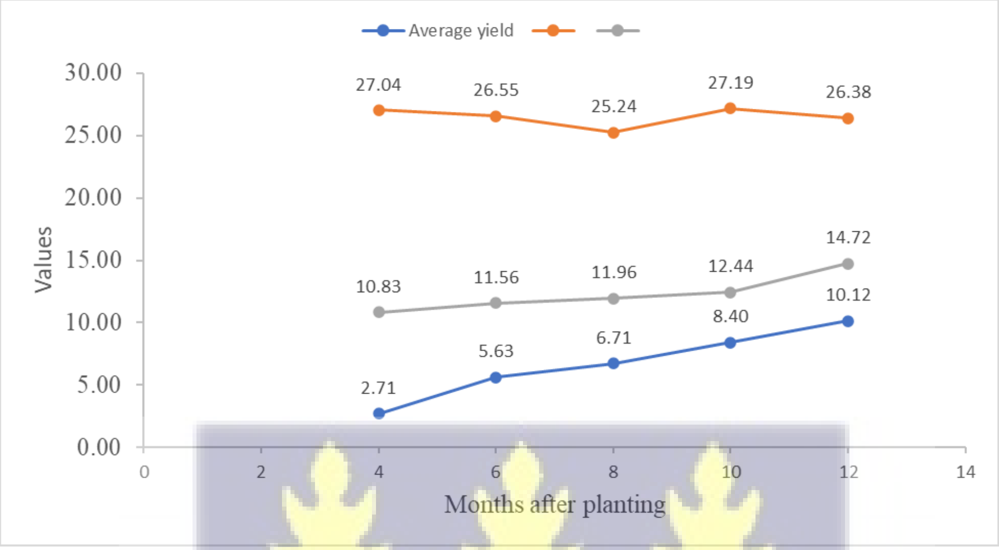

Figure 8. Correlation profile of average yield (kg per plant), dry matter (%) and total carotenoid (ug/g) of four yellow-flesh cassava varieties

4.8 Pearson correlation coefficients between each pair of variables

Table 1 presents Pearson correlation coefficients between yield (Kg), dry matter (%), and total carotenoids (ug/g). The Pearson correlation coefficient ranges from -1 to 1, where: 1 indicates a perfect positive linear relationship, 0 indicates no linear relationship, and -1 indicates a perfect negative linear relationship. In this study, the correlation between yield and dry matter is moderate and positive (0.555), indicating that as yield increases, dry matter content tends to rise, although the relationship is not very strong. The yield and total carotenoids correlation is strong and positive (0.792), suggesting that higher-yielding crops have significantly higher carotenoid content, which is beneficial for both yield and nutritional value. The correlation between dry matter and total carotenoids is weak and negative (-0.332), implying that as dry matter increases, carotenoid content tends to decrease slightly. This inverse relationship between dry matter and carotenoids may reflect a trade-off between structural composition and nutritional quality. The positive correlation between yield and dry matter (0.555) suggests a modest link that may influence crop breeding. The strong positive correlation between yield and carotenoids (0.792) highlights an opportunity to breed high-yielding crops with enhanced nutritional value. On the other hand, the negative correlation between dry matter and carotenoids (-0.332) may require careful balancing in breeding strategies. Overall, these correlations reveal important interactions that can guide crop improvement decisions for yield, dry matter, and carotenoids.

Table 1: Pearson correlation coefficients between each pair of variables

	Average yield (Kg)	Average Dry matter (%)	Average Total Carotenoids (ug/g)
Yield	1		
Dry Matter	0.555	1	
Carotenoids	0.792	-0.332	1

5.7 Genetic Diversity with Cluster Analyses of Four varieties

The dendrogram illustrates the clustering of four varieties (Nyonku, Tetteh Bankye, Knornu, and Genotype D) based on their shared characteristics, with the percentage of dissimilarity increasing at each point of combination (Figure 9). Nyonku and Knornu were the most similar varieties, clustering together at a relatively low dissimilarity of approximately 20%, which indicates that they shared around 80% similarity in traits such as apical leaf colour, pubescence, leaf retention, leaf colour, leaf lobe margins, stem cortex colour, stem epidermis colour, and colour of the end branch. Minor differences in the shape of the central leaf lobe, petiole orientation, and stem exterior colour contributed to their initial merging.

Following this, Tetteh Bankye combined with the Nyonku-Knornu cluster at a dissimilarity level of about **50%**, meaning that Tetteh Bankye shared approximately **50% similarity** with the previously merged cluster. **Tetteh Bankye** had similarities in traits such as leaf retention, leaf lobe margins, petiole orientation, stem cortex colour, and the colour of the end branch, but differed significantly in apical leaf colour, pubescence (being the only variety with pubescence), shape of the central leaf lobe, petiole colour, and stem exterior colour, which resulted in its later merger.

Lastly, **Genotype D** merged with the others at a high dissimilarity level of around **90%**, reflecting that it only shared about **10% similarity** with the previously formed cluster. **Genotype D** exhibited distinct differences, such as having the highest apical leaf colour, the most distinct shape of the central leaf lobe, petiole colour, leaf colour, and stem exterior colour, which set it apart from the other varieties. As such, it did not cluster with the rest until the final stage, underscoring its unique characteristics. Overall, the dendrogram demonstrates a hierarchy of similarity, with **Nyonku** and **Knornu** being the most similar (around **80% similarity**), followed by **Tetteh Bankye** (**50% similarity**), and **Genotype**

D, which stood out as the most distinct variety, sharing only **10% similarity** with the others.

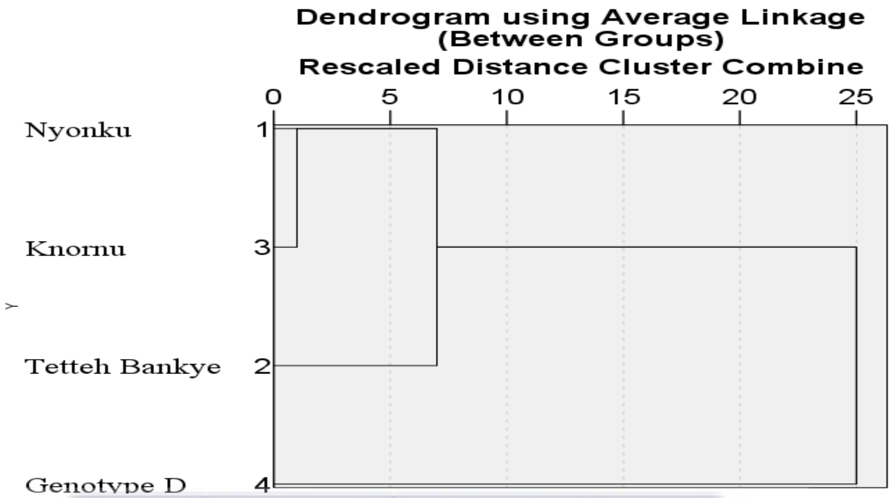

Figure 9: Cluster of four yellow-flesh varieties based on 12 qualitative traits

5.8 Principal Component Analysis

Principal Component Analysis (PCA) examines the relationship between various morphological and nutritional traits of the crop varieties (Table 2). It provides loadings for each trait across three principal components (PC1, PC2, and PC3), and also shows the percentage of variance each component explains.

PC1 (53.09% variance): This component is the most significant, capturing over half of the variation in the dataset. Traits with positive loadings, such as the ratio of lobe length to lobe width (0.456), total carotenoid content (0.343), and distance between leaf scars (0.288), contribute to this principal component. These traits suggest that PC1 is primarily driven by a combination of morphological (leaf structure) and nutritional (carotenoid content) features. The negative loadings of yield (-0.410) and width of leaf lobe (-0.451) suggest that as these traits increase, they are associated with lower values on PC1.

PC2 (31.74% variance): PC2 explains a significant portion of the variation in the dataset. The major contributors to this component include dry matter profile (0.476) and length of leaf lobe (0.506). These traits indicate that PC2 represents structural growth traits. Interestingly, traits like petiole length (-0.312) and total carotenoid content (-0.268) have negative loadings, highlighting an inverse relationship with PC2.

PC3 (15.17% variance): PC3 explains a smaller proportion of the variance but still provides valuable insights. Petiole length (0.718) has the highest positive loading in PC3, suggesting that this trait plays a dominant role in distinguishing this component. Total carotenoid content (0.414) also contributes positively, while distance between leaf scars (-0.403) has a negative loading, further demonstrating the variety of traits influencing PC3.

The cumulative percentage variation column reveals that the three principal components together explain 100% of the variance in the dataset, ensuring that all the major patterns in the data are captured. The latent roots for each principal component (14.335 for PC1, 8.571 for PC2, and 4.095 for PC3) further emphasize the relative importance of each component in the analysis. Overall, the PCA effectively reduces the dimensionality of the dataset while preserving the key information. The first two components, PC1 and PC2, capture the majority of the variability, offering insights into the relationships between physical traits (like leaf morphology) and nutritional characteristics (like carotenoid content), which could be useful for crop improvement efforts.

Table 2. Principal Component Analysis of Morphological and Nutritional Traits in Crop Varieties

Latent vectors (loadings)	PC1	PC2	PC3
Dry_matter_profile_in_%	0.243	0.476	0.228
Total_carotenoid_in_ug/g	0.343	-0.268	0.414
Yield_kg_plant	-0.410	-0.223	0.198
distance_btn_leaf_scars_in_cm	0.288	-0.365	-0.403
length_of_leaf_lobe_in_cm	-0.218	0.506	0.178
length_of_stipules_in_mm	0.332	0.404	0.066
petiole_length_in_cm	0.061	-0.312	0.718
ratio_of_lobe_length_to_lobe_wid	0.456	0.011	0.074
width_of_leaf_lobe_in_cm	-0.451	0.045	0.134
Latent roots	14.335	8.571	4.095
Percentage variation	53.09	31.74	15.17
Cum percentage variation	53.09	84.83	100

s

5.9 PCA biplot of five varieties based on 9 latent roots loading vectors

The PCA biplot showed genotypes with varying degrees of influence by specific traits (Figure 10). For instance, Kpornu is predominantly influenced by traits such as apical leaf colour, leaf retention and orientation of the petiole, along with a leaf lobe number. Similarly, Nyonku is highly influenced by apical leaf colour, leaf retention, leaf lobe number and a moderate petiole length. Tetteh Bankye is strongly influenced by a leaf lobe number and petiole length (24 cm), while Genotype D is notably impacted by its leaf lobe number (9 lobes), petiole length (24 cm), and leaf retention. Across the genotypes, leaf lobe number emerges as a central trait, especially influencing Kpornu, Tetteh Bankye, and Genotype D, indicating its importance in distinguishing these varieties. Other significant traits include apical leaf colour, which primarily affects Kpornu and Nyonku, and petiole length, which plays a role in differentiating Nyonku and Tetteh Bankye. Additionally, leaf retention is a key trait for Kpornu and Nyonku, linking it to plant growth and potential yield. These findings highlight the importance of these traits in determining the genetic characteristics and selection criteria for crop improvement and breeding efforts.

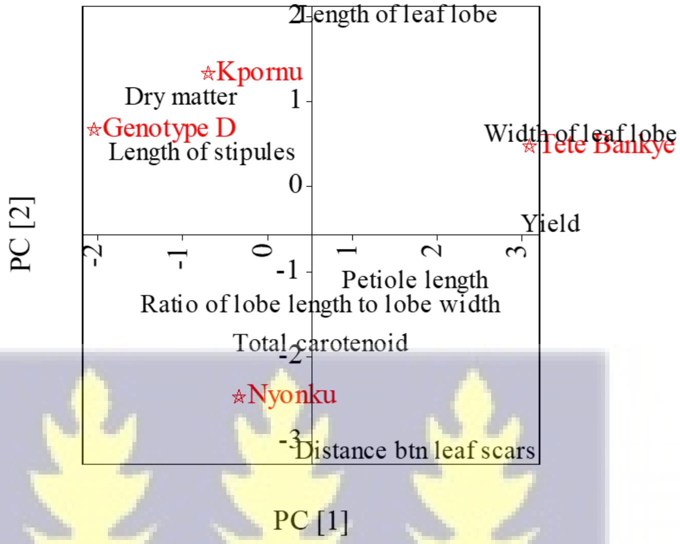

Figure 10: PCA biplot of five varieties based on 9 latent roots loading vectors.

CHAPTER FIVE

5.0 DISCUSSION

5.1 Average Root Yield Accumulation and Harvest Timing in Yellow-flesh Cassava Varieties

The yield profiles of the four yellow-flesh cassava varieties across 2022 and 2023 revealed notable differences in yield accumulation over time, reflecting genetic diversity, environmental factors, and management practices. The analysis of the four yellow-flesh cassava varieties demonstrates clear differences in their yield performance, with varying ranges, means, and peak productivity times, all of which are important for optimizing agricultural practices. Kpornu shows a yield range between 3.1 to 11.2 kg per plant, with an average yield of 7.15 kg per plant. This variety exhibits steady growth, reaching its peak yield of 11.2 kg per plant in month 12, making it a suitable option for farmers looking for consistent productivity over a longer harvest period (Peprah, 2020). In contrast, Tettey Bankye has a much wider yield range, from 3.2 to 16.1 kg per plant, and the highest mean yield of 9.65 kg per plant among all varieties, reaching a peak yield of 16.1 kg per plant in month 12. This variety stands out for its potential to deliver a high-end season harvest, making it ideal for farmers focused on maximizing yield at the end of the cycle.

Nyonku demonstrates more variability in its yield, ranging from 2.2 to 8.4 kg per plant, with a mean yield of 5.3 kg per plant. Although the exact month of peak yield is unspecified, it likely reaches its highest output towards the mid-to-late harvest period, making it less predictable but potentially valuable for farmers who can adapt to its fluctuations (Enesi, 2022). Lastly, Genotype D has the lowest yield, ranging from 2.3 to 4.9 kg per plant, with a mean yield of 3.6 kg per plant. Despite its low productivity, it maintains a stable yield throughout the growing period, making it suitable for regions or conditions where yield stability is more critical than maximizing output. The differences in these profiles are crucial for guiding farmers' decisions on variety selection, planting schedules, and crop management strategies, as they align with specific agricultural goals, whether they prioritize consistency, high yields, or adaptability.

5.2 Average Total Carotenoid Accumulation and Harvest Timing in Yellow-Flesh Cassava Varieties

The average total carotenoid profile of four yellow-flesh cassava varieties (Kpornu, Tetteh Bankye, Nyonku, and Genotype D) was analysed over nine months at two months intervals, namely at April, June, August, October, and December, for the years 2022 and 2023. Carotenoid values were measured in micrograms per gram (µg/g), and the results revealed distinct patterns in carotenoid accumulation across the varieties. Kpornu, for instance, exhibited a range from 5.4 µg/g in April to 14.3 µg/g in December, with a peak observed in December. Similarly, Tetteh Bankye displayed a range between 7.6 µg/g in April and 14.1 µg/g in December, also peaking in December. Nyonku's carotenoid content ranged from 8.1 µg/g in April to 11.8 µg/g in December, showing a clear increase towards the end of the year, with December yielding the highest value for this variety as well. Genotype D demonstrated the highest carotenoid levels overall, with values ranging from 10.4 µg/g in April to 18.7 µg/g in December, reaching its peak in December.

In terms of carotenoid content, all four cassava varieties exhibited an increase in total carotenoids as the year progressed, with December consistently showing the highest concentrations for each variety. This seasonal trend is consistent with previous research suggesting that environmental factors such as temperature, light exposure, and soil conditions can influence carotenoid biosynthesis in root crops, with the accumulation often peaking towards the end of the growing season (Rodrigues *et al*., 2021; Nyabuga *et al*., 2017). Moreover, the higher carotenoid levels observed in Genotype D further support its potential as a high-carotenoid cassava variety, which could be beneficial for addressing micronutrient deficiencies, particularly vitamin A deficiency, in regions where cassava is a staple food (Maroyi, 2022).

The observed variations between varieties may also reflect differences in their genetic makeup, as well as their response to environmental stressors such as drought or pests, which can affect the plant's ability to synthesise carotenoids (Alvarez *et al*., 2020; Adu *et al*., 2023). For instance, Genotype D's robust carotenoid accumulation could be linked to specific genetic traits associated with enhanced antioxidant synthesis, as demonstrated in other crops like sweet potato and maize (Mochizuki *et al*., 2022).

In conclusion, December consistently recorded the highest total carotenoid content across all four varieties, with Genotype D exhibiting the highest overall levels. These findings align with the literature on cassava's carotenoid variation and its potential for biofortification. The increase in carotenoid content towards the end of the growing season further highlights the importance of selecting appropriate harvesting times to maximise nutritional content in cassava (Ochieng *et al*., 2019).

5.3 Average of 2022 and 2023 Dry Matter Accumulation and Harvest Timing in Yellow flesh Cassava Varieties

The average dry matter content, measured as a percentage, of four yellow flesh cassava varieties (Kpornu, Tetteh Bankye, Nyonku, and Genotype D) was analysed across nine months taken at two months intervals from April to December in 2022 and 2023. For Kpornu, the dry matter ranged from 23.8% in April to 27.5% in June, with June recording the peak dry matter of 27.5%. The mean dry matter content for Kpornu over the period was approximately 25.8%. Similarly, Tetteh Bankye's dry matter content varied between 18.9% in August and 31.8% in June, with June also being the peak month for this variety. The mean dry matter for Tetteh Bankye was 27.2%. In the case of Nyonku, the dry matter ranged from 24.8% in December to 38.5% in June, with June marking the highest dry matter percentage of 38.5%. Nyonku also had the highest mean dry matter content among the varieties, at 30.7%. Genotype D exhibited a dry matter range from 17.5% in August to 31.1% in June, with the peak dry matter of 31.1% observed in June. The mean dry matter for Genotype D was 26.7%.

In summary, June was the month when all four varieties achieved their highest dry matter content. Nyonku had the highest overall dry matter percentage at 38.5%, followed by Tetteh Bankye of 31.8%, Kpornu at 27.5%, and Genotype D of 31.1%. These trends are consistent with findings in other cassava studies, where dry matter accumulation often peaks during the mid- to late-growing season, particularly in response to factors such as nutrient availability and environmental conditions (Ochieng *et al*., 2019). The differences in dry matter content between varieties can be attributed to both genetic factors and environmental influences, with varieties like Nyonku showing higher dry matter accumulation due to specific adaptive traits that favour storage root development (Mochizuki *et al*., 2022). Additionally, research by Ospina *et al*. (2020) and Rodrigues *et al*. (2021) suggests that the timing of peak dry matter accumulation can vary depending on the cassava variety's growth cycle and climatic conditions, particularly temperature and rainfall patterns.

The observed variation in dry matter values is also significant for biofortification and commercial production, as higher dry matter content is often associated with improved starch yields and processing qualities (Maroyi, 2022). For instance, Genotype D's lower dry matter content in comparison to Nyonku might suggest less efficient storage root development, which could impact its suitability for specific industrial applications (Alvarez *et al*., 2019). These findings highlight the importance of selecting the appropriate cassava variety based on desired traits such as dry matter content for specific end-uses, whether for direct consumption, industrial processing, or fortification programs (Nyabuga *et al*., 2017).

5.4 Correlation profile of Average yield per plant, dry matter and total carotenoid of four yellow flesh cassava varieties

The correlation profiles of average yield per plant, dry matter content, and total carotenoid content in four yellow-flesh cassava varieties across two years (2022 and 2023) show important trends that influence both agronomic practices and nutritional outcomes. The correlation analysis reveals a positive relationship between average yield and total carotenoid content, suggesting that as yield increases, so does the carotenoid accumulation. This aligns with existing literature indicating that cassava varieties with higher yields tend to accumulate more carotenoids, which can contribute to improved nutritional value, particularly in addressing vitamin A deficiencies (Girón-Calle *et al*., 2016). On the other hand, the negative correlation between yield and dry matter content, where higher yields correspond to lower dry matter percentages, is indicative of a resource allocation trade-off between yield and starch accumulation, which is consistent with the findings of Ceballos *et al*. (2016).

The varieties Kpornu, Tettey Bankye, Nyonku, and Genotype D display differing patterns in their dry matter and carotenoid profiles. Kpornu, which shows moderate yields, also demonstrates high dry matter content and carotenoid levels. These traits suggest its potential for producing nutritious cassava with good storage qualities, which are important for processing and post-harvest shelf life (Ospina *et al*., 2020). Similarly, its carotenoid content offers potential health benefits, such as enhancing vitamin A intake (Sanful *et al*., 2020). Tettey Bankye, while exhibiting slightly lower dry matter content than Kpornu, still maintains a comparable carotenoid profile, suggesting similar nutritional benefits despite its lower starch accumulation. Nyonku and Genotype D show moderate dry matter and carotenoid content, making them suitable for diverse processing applications, but with slightly lower dry matter content in Genotype D, which may affect its processing suitability (Ceballos *et al*., 2016).

Monthly fluctuations in dry matter and carotenoid content reflect changes in the cassava plants' growth stages, with peak values often occurring at different times depending on the genotype. For example, Kpornu reached peak total carotenoid content at month 6 in both 2022 and 2023, coinciding with its peak yield period. This suggests that harvesting at this time would optimize both yield and carotenoid content, enhancing both productivity and nutritional value. Conversely, Tettey Bankye displayed a significant decline in dry matter content from month 4 to month 8, which aligns with a reduction in starch accumulation and reflects the trade-off between starch storage and root growth. In contrast, Nyonku maintained stable dry matter content throughout the year, making it a reliable choice for consistent processing outputs, though its carotenoid content peaked earlier than that of other varieties.

The fluctuations observed in the correlation profiles are consistent with literature, which attributes variability in dry matter and carotenoid accumulation to factors such as genetic differences, environmental conditions, and agronomic practices (Ukpabi & Maziya-Dixon, 2018). The plant's need to allocate resources between root growth, starch accumulation, and carotenoid synthesis can explain these fluctuations, as higher starch accumulation may divert resources from carotenoid production and vice versa. Additionally, environmental factors such as water and nutrient availability play crucial roles in influencing the plants' ability to accumulate dry matter and carotenoids (Juneja *et al.*, 2013).

In terms of harvest timing, the optimal month to harvest Kpornu and Tettey Bankye for peak yield and nutritional content appears to be around month 6. For Nyonku, although it showed consistent dry matter content, its carotenoid content peaked earlier at month 5, indicating that harvesting slightly earlier than for other varieties could maximize its nutritional benefits. Genotype D, with its relatively stable dry matter and carotenoid levels, may be harvested throughout the growing season to maintain consistent product quality.

The Pearson correlation coefficients between average yield, dry matter, and carotenoid content further support these findings. A positive correlation between yield and carotenoid content suggests that enhancing yield in certain varieties could simultaneously improve their nutritional value (Dufour *et al.*, 2019). However, the negative correlation between dry matter and yield emphasizes the need to balance starch accumulation with nutrient enrichment when selecting cassava varieties for different purposes (Sanful *et al*., 2020). By understanding these correlations, breeders and researchers can optimize breeding strategies to enhance both productivity and nutritional content, thus contributing to improved food security and public health outcomes.

5.5 Genetic Diversity study with Cluster Analyses of Four varieties

The genetic diversity of plant varieties plays a critical role in understanding their adaptability, resilience, and potential for breeding improvements. In this discussion, the genetic diversity of four varieties—Nyonku, Tetteh Bankye, Knornu, and Genotype D—is explored through a cluster analysis based on phenotypic traits. The dendrogram shows the hierarchical relationships between the varieties, reveals varying degrees of similarity and dissimilarity, allowing for inferences about their genetic relatedness.

Nyonku and Knornu were the most genetically similar varieties, as indicated by their early clustering in the dendrogram at a dissimilarity level of approximately 20%, which suggests that they share around 80% of their phenotypic traits. Traits such as apical leaf colour, pubescence, leaf retention, leaf colour, and leaf lobe margins are nearly identical between these two varieties. According to Benzécri (1992), phenotypic similarity is often reflective of underlying genetic similarity, particularly when multiple traits are involved. This high level of similarity implies that Nyonku and Knornu likely share a close genetic lineage or have been subject to similar selective pressures, possibly within the same breeding programme or geographic region (Sneath & Sokal, 1973).

Tetteh Bankye demonstrated moderate similarity to Nyonku and Knornu, clustering with them at a 50% dissimilarity level, suggesting a 50% overlap in shared traits. The shared characteristics include leaf retention, leaf lobe margins, petiole orientation, and stem cortex colour, which likely point to some genetic commonality between Tetteh Bankye and the other two varieties. However, distinct differences in key traits, such as pubescence (with Tetteh Bankye being the only variety exhibiting pubescence), apical leaf colour, and stem exterior colour, set it apart (Mohammadi & Prasanna, 2003). These differences suggest that while Tetteh Bankye shares some genetic background with Nyonku and Knornu, it also possesses unique genetic markers, possibly due to different evolutionary pressures or hybridisation events (Nei, 1973).

Genotype D was the most genetically distinct of the four varieties, clustering with the others only at a dissimilarity level of 90%, meaning it shared only 10% similarity with the combined cluster of the other varieties. The distinct characteristics of Genotype D, such as its high apical leaf colour, unique shape of the central leaf lobe, and the most extreme values for petiole colour and stem exterior colour, underscore its genetic uniqueness (Rohlf, 2000). This high level of dissimilarity may indicate that Genotype D either originates from a different breeding programme or has been subject to selective pressures that are markedly different from those of the other varieties (Lowe *et al.*, 2004). Such genetic distance suggests a broader genetic base, which could be beneficial for breeding programmes seeking to introduce new traits such as disease resistance or drought tolerance (Allard, 1999).

The clear differentiation between the varieties in the dendrogram, particularly the distinctiveness of Genotype D, suggests that the four varieties exhibit a moderate to high degree of genetic diversity overall. Genetic diversity within plant species is essential for adaptability to changing environments and for the resilience of crops against pests, diseases, and climate change (Hamrick & Godt, 1990). The genetic similarity between Nyonku and Knornu might suggest that these two varieties are less genetically diverse and therefore could be more vulnerable to similar threats. Conversely, the genetic distinctiveness of Genotype D suggests that it could provide valuable genetic resources for breeding programmes, offering traits that are not present in the other varieties (Frankham *et al*., 2002).

Mohammadi and Prasanna (2003) note that high genetic diversity in breeding populations is a crucial factor in ensuring long-term crop improvement, as it provides a broader base for selection. The clustering of the four varieties indicates that while some varieties, like Nyonku and Knornu, are closely related, the overall genetic diversity across the varieties is sufficient to support effective breeding strategies. Additionally, the presence of distinct phenotypic traits, particularly in Genotype D, offers opportunities for hybridisation to combine desirable traits from genetically diverse backgrounds (Hallauer *et al*., 2010).

In conclusion, the dendrogram analysis of the four varieties reveals varying levels of genetic diversity, with Nyonku and Knornu being the most similar and Genotype D the most distinct. This indicates that the varieties used in the study are genetically diverse, particularly with the presence of Genotype D. Such diversity is essential for the adaptability and improvement of crops, as it provides a broader genetic base for breeding programmes. The moderate similarity of Tetteh Bankye and the distinctiveness of Genotype D further underscore the potential for genetic variation within this group, which is critical for future agricultural sustainability.

5.8 Principal Component Analysis

Principal Component Analysis (PCA) of the morphological and nutritional traits of crop varieties provides an insightful breakdown of the variance within the dataset. The first principal component (PC1) accounts for the largest proportion of the variance, with 53.09% of the total variation explained. The traits contributing most to PC1, such as the ratio of lobe length to lobe width (0.456), total carotenoid content (0.343), and distance between leaf scars (0.288), suggest that this component is primarily driven by a combination of leaf structural and nutritional characteristics. Notably, the negative loadings for yield (-0.410) and width of leaf lobe (-0.451) indicate that higher values of these traits are associated with lower scores on PC1, highlighting an inverse relationship between some morphological traits and carotenoid content. This finding aligns with studies suggesting a trade-off between structural development and nutritional quality in crops (Esuma *et al*., 2016).

The second principal component (PC2), which explains 31.74% of the variance, is mainly influenced by traits related to plant structure, particularly dry matter profile (0.476) and length of leaf lobe (0.506). These strong positive loadings indicate that PC2 represents structural growth traits, such as biomass accumulation and leaf development. However, the negative loadings of petiole length (-0.312) and total carotenoid content (-0.268) suggest an inverse relationship between these traits and the second principal component. This supports previous findings that structural traits like leaf size and petiole length can sometimes detract from the nutritional quality of crops, particularly in terms of carotenoid content (Peprah, 2020).

The third principal component (PC3), while explaining only 15.17% of the total variance, provides further insights into the distinctive traits of the varieties studied. Petiole length

(0.718) has the highest positive loading, making it the primary contributor to this component. Additionally, total carotenoid content (0.414) also plays a role, while distance between leaf scars (-0.403) negatively impacts PC3. This suggests that petiole length and carotenoid content are key factors that differentiate the varieties along this component, which may have implications for crop selection based on both morphological and nutritional traits.

The cumulative percentage variation of 100% confirms that the three principal components together explain all the major patterns in the dataset. The latent roots for each principal component further highlight the relative significance of each component in capturing the data's variance. Overall, PCA has successfully reduced the dimensionality of the dataset, preserving key information that can guide crop improvement efforts, particularly by offering insights into the relationship between physical traits (e.g., leaf morphology) and nutritional characteristics (e.g., carotenoid content), which are crucial for enhancing both yield and nutritional value in crop breeding programmes (Chand *et al*., 2022).

5.9 PCA Biplot Analysis of Genotypic Variation in Crop Varieties

The PCA biplot analysis of the five varieties reveals varying degrees of influence by specific traits, shedding light on the genetic diversity and phenotypic characteristics of these genotypes. In particular, Kpornu appears to be predominantly influenced by apical leaf colour, leaf retention, orientation of the petiole, and leaf lobe number, with these traits forming the basis of its genetic distinctiveness. Nyonku shares similar characteristics, being highly influenced by apical leaf colour, leaf retention, and leaf lobe number, with petiole length also contributing to its phenotypic profile. The influence of these traits on Nyonku and Kpornu suggests their potential importance in breeding for traits related to leaf morphology and plant growth, which have been associated with better adaptability and productivity in various crops (Araus *et al*., 2008).

On the other hand, Tetteh Bankye is strongly influenced by leaf lobe number and petiole length, with the latter trait measuring 24 cm. The dominance of petiole length in this genotype supports previous findings that petiole length can significantly influence plant architecture and nutrient transport, both of which are critical to plant health and yield potential (Sack *et al*., 2013). Similarly, Genotype D is highly impacted by leaf lobe number (9 lobes), petiole length, and leaf retention, further underlining the importance of leaf morphology in distinguishing between varieties.

Across all genotypes, leaf lobe number emerges as a central trait, particularly for Kpornu, Tetteh Bankye, and Genotype D, suggesting its vital role in phenotypic variation and varietal identification. This observation is consistent with studies in other crops, where leaf size and number have been linked to plant vigour and environmental adaptability (Richards *et al*., 2010). Additionally, apical leaf colour and petiole length stand out as important traits for Kpornu, Nyonku, and Tetteh Bankye, supporting their utility in improving crop performance under various environmental conditions (Amenorpe, 2019).

Furthermore, leaf retention is a key trait influencing Kpornu and Nyonku, linking it to plant growth, water retention, and potential yield. Previous studies have shown that higher leaf retention is associated with improved photosynthetic efficiency and greater drought resistance, both of which are essential for sustainable crop production in fluctuating climates (Cock & Connor, 2021). These findings underline the significance of combining morphological traits with nutritional traits in crop improvement strategies, aiming to enhance both yield potential and resilience to environmental stresses.

In conclusion, the PCA biplot provides valuable insights into the relationships between morphological and nutritional traits in these crop varieties, which can inform breeding programmes. By focusing on key traits such as leaf lobe number, petiole length, and leaf retention, breeders can select for desirable characteristics that improve both plant growth and yield potential. These findings contribute to a better understanding of the genetic factors driving crop performance, which is crucial for enhancing agricultural productivity and ensuring food security.

CHAPTER SIX

6.0 CONCLUSION

This study successfully fulfilled the specified objectives by providing detailed insights into the root yield, dry matter, total carotenoid content, and genetic diversity of the four yellow flesh cassava varieties, namely Kpornu, Nyonku, Tetteh Bankye, and Genotype D, over a 12-month period.

The identification of root yield, dry matter, and total carotenoid profiles was comprehensively achieved. This study evaluated the yield, total carotenoid content, and dry matter profiles of four yellow flesh cassava varieties—Kpornu, Tetteh Bankye, Nyonku, and Genotype D—across 2022 and 2023. Kpornu exhibited a yield range of 3.1 to 11.2 kg per plant, with a peak yield of 11.2 kg in month 12, and an average of 7.15 kg. Tetteh Bankye showed a wider yield range from 3.2 to 16.1 kg, peaking at 16.1 kg in month 12, with an average of 9.65 kg. Nyonku's yield ranged from 2.2 to 8.4 kg, with an average of 5.3 kg, while Genotype D had the lowest yield range of 2.3 to 4.9 kg, with an average of 3.6 kg. Peak carotenoid content for all varieties was observed in December, with Genotype D showing the highest value of 18.7 µg/g, followed by Kpornu (14.3 µg/g), Tetteh Bankye (14.1 µg/g), and Nyonku (11.8 µg/g). The average dry matter content for all varieties peaked in June, with Nyonku recording the highest value of 38.5%, followed by Tetteh Bankye (31.8%), Kpornu (27.5%), and Genotype D (31.1%). The study identified positive correlations between yield and total carotenoids, suggesting opportunities to enhance both productivity and nutritional quality. In contrast, negative correlations between yield and dry matter content underscored potential trade-offs affecting processing suitability and product quality. The determination of genetic diversity through cluster analysis, principal component analysis (PCA), and correlation of variables was effectively achieved. PCA revealed distinct patterns of genetic variation among the varieties. Kpornu and Nyonku were found to share a closer genetic relationship, with similar traits such as apical leaf colour, leaf retention, and leaf lobe number influencing their phenotypic profiles. In contrast, Tetteh Bankye and Genotype D, while exhibiting some overlapping traits, were distinguished by unique influences, particularly in petiole length and leaf morphology. These differences were further emphasised in the PCA biplot, where traits such as leaf lobe number, petiole length, and leaf retention were identified as major contributors to the genetic diversity observed among the varieties. This analysis underscores the genetic differentiation between the varieties, with each exhibiting a unique combination of traits that highlight their genetic diversity. This diversity is critical for the selection of cassava varieties with desirable attributes, such as improved yield, enhanced nutritional content, and greater environmental adaptability.

In conclusion, the study successfully achieved both objectives by providing a detailed analysis of the root yield, dry matter, carotenoid content, and genetic diversity of the four cassava varieties. The findings offer valuable insights for future breeding programmes aimed at improving the performance and resilience of cassava crops.

6.1 RECCOMMENDATION

It is recommended to prioritize Genotype D for breeding programmes focused on enhancing carotenoid content and dry matter yield due to its consistent performance.

Genotype D, showing distinct genetic traits, should be tested in different agroecological zones for better environmental adaptability. The genetic diversity observed among the varieties supports the use of PCA and other molecular techniques to refine breeding strategies for optimal traits. Continuous monitoring of these traits over multiple growing seasons is recommended to assess stability and support the selection of the best-performing varieties.

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