UNIVERSIDADE
EDUARDO
MONDLANE

Faculty of Agronomy and Forest Engineering

Department of Crop Production

MSc in Plant Breeding and Seed Systems

Phenotypic Diversity and Genotype × Environment Interaction for yield-related traits in Bambara groundnut [*Vigna subterranea* (L.) Verdc.] Accessions

Author: Marvelline Chifamba

Supervisors:

Prof. Rogerio Chiulele

Prof Michael Abberton

Dr Hapson Mushoriwa

Dr Takudzwa Mandizvo

Dr Olaniyi Oyatomi

August 2026

Declaration

I, **Marvelline Chifamba (20235459)**, do hereby declare that this thesis titled "Phenotypic Diversity and Genotype × Environment Interaction for yield-related traits in Bambara groundnut [*Vigna subterranea* (L.) Verdc.] Accessions" has been composed solely by me. It has neither been presented in part nor in whole for another degree elsewhere.

MChifs

13/04/2026

Marvelline Chifamba Date

MSc. Plant Breeding and Seed Systems/ UEM

Approval page

This is to certify that this research project, carried out by Marvelline Chifamba under our supervision, has been accepted and approved in partial fulfillment of the requirements for the degree of Master of Science in Plant Breeding and Seed Systems from the Department of Crop Production, Faculty of Agronomy and Forestry Engineering at Eduardo Mondlane University.

Signatures:

Supervisor _____ Date 15/04/2026
Prof Rogerio Chiulele

Co-supervisor _____ Date 13/04/2026
Prof Michael Abberton

Co-supervisor _____ Date 14/04/2026
Dr Olaniyi Oyatomi

Co-supervisor _____ Date 14/ 04/ 2026
Dr Hapson Mushoriwa

Co-supervisor _____ Date 14 April 2026
Dr Takudzwa Mandizvo

Acknowledgements

First and foremost, I am eternally grateful to the Lord Almighty, the "I Am that I Am," for I have seen His goodness, mercy, and compassion. In Him, I live, move, and have my being.

I wish to express my profound gratitude to my family for being my greatest support system throughout this journey. Your encouragement and prayers have kept me going. Special thanks to my mother Mrs Emerina Neunze and my sisters: Makanaka, Pamela, and Edina Chifamba; and my brothers: Munyaradzi and Tazvinzwa Chifamba, for their unwavering support.

I am deeply thankful to the Centre of Excellence in Agri-Food Systems and Nutrition (CE-AFSN) for granting me the scholarship for my MSc studies at Universidade Eduardo Mondlane (UEM). I am also grateful to the International Maize and Wheat Improvement Center (CIMMYT) through the Vision for Adapted Crops and Soils (VACS) Capacity Activity for providing the generous research funds that supported this project.

My sincere gratitude goes to the International Institute of Tropical Agriculture (IITA) for the Research Fellowship opportunity, which provided essential human resources, field and laboratory facilities, and the chance to participate in specialized trainings and symposiums.

I wish to sincerely appreciate my supervisors: Prof. Rogerio Marcus Chiulele, Prof. Michael Abberton, Dr. Olaniyi Oyatomi, Dr. Hapson Mushoriwa, and Dr. Takudzwa Mandizvo for their invaluable moral support and the knowledge they shared in developing this project. I am also deeply grateful to Dean Muungani, Dr. Ranjana Bhattacharjee, and Dr. Paliwal for their guidance and mentorship. Special thanks go to Dr. Agre's family for their warm hospitality in hosting me at their residence. My heartfelt thanks also go to Mr. Kunle and Mr. Wole for their dedicated support during my field trials in Ikenne and Kano, Nigeria.

I would also like to acknowledge my dear sisters: Chizaram Oluebube Uzoma, Mrs. Tariro Muungani, Mrs. Judith Mushoriwa, Precious Nwogwugwu, Chiamaka Grace Uzoma Ojoro, Olamide, Dr. Ufuoma, Mrs Mary Diekade and Chioma for making my stay in Nigeria bearable. I also thank the IITA Genetic Resources Centre (GRC) staff and the International Association of Research Scholars and Fellows (IARSAF) for their encouragement. To my colleagues at UEM, thank you for making my time in Mozambique memorable.

Words are not enough to express my sincere gratitude for the massive support I received during my MSc studies.

Dedication

In memory of my beloved father, Mr. Esau Chifamba. Your legacy lives on, and may your soul continue to rest in peace.

Resumo

O amendoim-bambara (BGN) é uma importante cultura de oportunidade para a diversificação das culturas e a produção de alimentos resilientes às mudanças climáticas na África Subsaariana (ASS). Pode apresentar bom desempenho em condições de produção relativamente marginais e possui importante valor nutricional. Apesar dessas características, o BGN continua subutilizado, em parte devido à limitada caracterização sistemática do germoplasma disponível quanto à qualidade das sementes e ao desempenho agronómico em diferentes ambientes. Este estudo teve como objetivo avaliar a diversidade morfométrica das sementes e o desempenho de acessos de BGN em múltiplos ambientes, visando apoiar o melhoramento genético e o desenvolvimento de variedades. As características morfométricas das sementes de 106 acessos foram caracterizadas utilizando imagens multiespectrais (MSI) obtidas por Videometer, gerando descritores de alto rendimento e não destrutivos do tamanho, forma e cor das sementes. Foram quantificadas vinte características, e a análise de variância revelou efeitos significativos dos acessos para todas as características ($p < 0,05$), indicando variação fenotípica substancial. A análise de componentes principais e o agrupamento hierárquico distinguiram grupos fenotípicos e apoiaram uma classificação prática do tamanho das sementes em três classes (pequena, média e grande), permitindo a discriminação rápida dos acessos e a identificação de materiais parentais contrastantes. Posteriormente, 104 acessos foram avaliados em três agroecologias contrastantes da Nigéria (Ibadan, Ikenne e Kano), utilizando um delineamento alfa-látice de 8 × 13 com três repetições. As características agronómicas, fenológicas e relacionadas com o rendimento foram analisadas por ANOVA combinada, GGE, análise de componentes principais e agrupamento hierárquico. Foram observados efeitos significativos dos acessos para nove das onze características, particularmente para emergência, floração, arquitetura da planta e número de vagens por planta, enquanto os efeitos ambientais foram significativos para todas as características. Foi detetada interação genótipo × ambiente significativa para seis características: dias até à primeira emergência, número de plantas, dias até à primeira floração, dias até 50% de floração, expansão da planta e largura do folíolo terminal, mas não para o rendimento por parcela. A análise de biplot GGE forneceu informações exploratórias sobre as respostas dos acessos e a discriminação dos ambientes. De modo geral, os resultados demonstram variação fenotípica substancial nas características das sementes e agronómicas e destacam a importância dos efeitos ambientais e das interações genótipo × ambiente específicas para cada característica na avaliação do BGN. A integração da fenotipagem de alto rendimento das sementes com a avaliação em múltiplos ambientes constitui uma base útil para a caracterização do germoplasma, identificação de materiais parentais contrastantes e futuros programas de melhoramento.

Palavras-chave: amendoim-bambara; cultura de oportunidade; diversidade fenotípica; imagens multiespectrais; morfometria das sementes; interação genótipo × ambiente; avaliação em múltiplos ambientes; fenotipagem de alto rendimento.

Abstract

Bambara groundnut (BGN) is an important opportunity crop with valuable attributes for crop diversification and climate-resilient food production in sub-Saharan Africa (SSA). It can perform under relatively marginal production conditions and offers valuable attributes for climate-resilient food production, while providing important nutritional value. Despite these attributes, BGN remains underutilized, partly due to limited systematic characterization of available germplasm for seed quality and agronomic performance across environments. This study aimed to evaluate seed morphometric diversity and multi-environment performance of Bambara groundnut accessions to support breeding and varietal development. Seed morphometric traits of 106 accessions were characterized using Videometer multispectral imaging (MSI), generating high-throughput, non-destructive descriptors of seed size, shape, and colour. Twenty seed traits were quantified, and analysis of variance revealed significant accession effects across all traits ($p < 0.05$), indicating substantial phenotypic variation. Principal component analysis and hierarchical clustering distinguished phenotypic groups and supported a practical three-class seed size classification scheme (small, medium, and large) for rapid discrimination of accessions and identification of contrasting parental material. Subsequently, 104 accessions were evaluated across three contrasting Nigerian agroecologies (Ibadan, Ikenne, and Kano) using an 8 × 13 alpha-lattice design with three replications. Agronomic, phenological, and yield-related traits were analysed using combined analysis of variance (ANOVA), genotype plus genotype × environment (GGE) biplot analysis, principal component analysis, and hierarchical clustering. Significant accession effects were observed for nine of eleven traits, particularly for emergence, flowering time, plant architecture, and number of pods per plant, while environmental effects were significant for all traits. Significant genotype × environment interaction was detected for six traits: days to first emergence, plant count, days to first flowering, days to 50% flowering, plant spread, and terminal leaflet width. In contrast, genotype × environment interaction was not significant for yield per plot. GGE biplot analysis provided exploratory insights into accession responses and environmental discrimination. Overall, the findings demonstrate substantial phenotypic variation in seed and agronomic traits and highlight the importance of environmental effects and trait-specific genotype × environment interactions in BGN evaluation. Integrating high-throughput seed phenotyping with multi-environment evaluation provides a useful basis for germplasm characterization, identification of contrasting parental material, and future crop improvement.

Keywords: Bambara groundnut; opportunity crop; phenotypic diversity; multispectral imaging; seed morphometrics; genotype × environment interaction; multi-environment evaluation; high-throughput phenotyping.

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Chapter 1: Introduction

1.1 Background

Bambara groundnut [*Vigna subterranea* (L.) Verdc.], often abbreviated as BGN is an important indigenous legume native to Africa. It occupies a strategic role in global food security, especially under climatic change pressures and expanding population demands. Recognized for its remarkable drought and heat resilience (Boraiah et al., 2024; Chandora et al., 2024), BGN thrives on marginal soils where major crops often fail. This positions it as a premier opportunity crop, particularly under conditions of minimal rainfall and limited agricultural inputs like fertilizers and pesticides (Esan et al., 2023a; Tan et al., 2020a).

Nutritionally, BGN seeds are rich in carbohydrates, comprising 55–70% of their composition, along with significant protein content ranging from 17–25%. They also contain moderate amounts of fat (1.4–12%) and dietary fiber (5.2–6.4%) (Maphosa et al., 2022). This nutrient profile makes BGN seeds an important source of energy and protein, particularly in tropical agricultural systems (Mayes et al., 2019). Additionally, BGN supports livelihoods by providing cash income for smallholder farmers in underdeveloped regions. Its resilience and adaptability make it a crucial component of low-input agriculture, promoting food supply diversification and serving as a safeguard against failures of staple crops (Khan et al., 2022).

Despite its potential, the genetic improvement of BGN remains challenging. The crop's improvement efforts are hampered by limited genomic resources, complex abiotic stress tolerance mechanisms, and Genotype-by-Environment interactions (G×E) that obscure uniform breeding gains (Khan et al., 2021). Understanding and exploiting the underlying genetic diversity present within its germplasm is fundamental to overcoming these bottlenecks and achieving sustainable yield improvements (Muhammad et al., 2020).

Generally, in plant breeding, yield and its related traits form the cornerstone of most crop improvement programs, serving as key selection criteria to enhance food production. In BGN, important yield-related traits include the number of pods per plant, pod weight per plant, seed weight per plant, and hundred-seed weight (Esan et al., 2023a). Dissecting these components and their correlations helps understand the biological basis of yield and its stability across environments. This dissection enables breeders to identify traits that contribute significantly to yield, making selection more efficient.

Phenotypic variation associated with yield and related traits is critical for effective breeding. This is because it reflects not only underlying genetic diversity but also the plant's adaptive responses to environmental stresses (Booy et al., 2000; Nevo, 2001). Understanding such variation helps predict breeding gains and develop cultivars with broader adaptation (Khan et al., 2022). Moreover, yield traits are often correlated with climate resilience attributes; for example, traits that confer drought tolerance tend to affect seed productivity, thereby linking yield improvement with the crop's ability to withstand environmental adversity (Linus et al., 2023).

The exploration of yield components thus holds dual significance: improving productivity and ensuring resilience under changing climatic conditions, especially for crops like BGN that are mostly grown in stress-prone areas.

1.2 Problem statement

Bambara groundnut (BGN) is a resilient, nutritionally valuable legume with strong potential for sustainable food production in marginal environments. However, compared to major legumes such as soybean and common bean, it remains underutilized and under-researched (Mayes et al., 2019). Formal breeding efforts have progressed slowly, leaving farmers largely reliant on unimproved landraces and farmer-saved seed, which contributes to low and inconsistent yields (Abberton et al., 2022). A key constraint underlying this slow progress is the limited characterization of BGN germplasm. The extent of phenotypic diversity in seed traits, and the nature and magnitude of Genotype × Environment (G×E) interactions affecting agronomic performance, remain insufficiently documented (Kunene et al., 2024; Linus et al., 2023). Without this information, breeders cannot reliably identify accessions with desirable seed characteristics or with stable, superior performance across environments. As a result, many potentially valuable accessions in existing collections remain unexploited, despite their capacity to contribute to yield stability, climate resilience, and improved seed quality traits (Mayes et al., 2019; Tan et al., 2020). This study therefore addresses this gap by generating high-throughput seed morphometric data and multi-environment field performance data for a set of BGN accessions, to characterize phenotypic diversity and quantify G×E interaction. This information is intended to support more informed selection and utilization of BGN accessions in breeding programs targeting yield stability, seed quality, and climate resilience.

1.3 Justification

This study is justified by the need to enhance the effective utilization of Bambara groundnut genetic resources through improved characterization and evaluation of available germplasm. Understanding variation in seed morphometric traits, yield-related characteristics, and genotype × environment interactions will provide valuable information for identifying promising accessions with desirable attributes for breeding. Integrating high-throughput seed morphometric phenotyping with multi-environment evaluation will strengthen germplasm characterization and support more efficient selection of stable and high-performing genotypes. The findings will contribute to breeding programs by improving the identification of suitable parental materials and supporting the development of improved Bambara groundnut varieties. Ultimately, this will promote better utilization of the crop, enhance farmer adoption, and contribute to resilient and sustainable food systems.

1.4 Aim and objectives

This study aims to assess the phenotypic diversity of Bambara groundnut accessions through advanced seed morphometric imaging systems and multi-environmental field evaluations.

1.4.1 Specific objectives

The specific objectives of the study are:

i. To characterize seed morphometric traits of Bambara groundnut accessions using high-throughput phenotyping.
ii. To assess the phenotypic variability of 104 Bambara groundnut accessions across three test environments.
iii. To quantify Genotype × Environment Interaction among the 104 Bambara groundnut accessions across the test environments.

1.4.2 Hypotheses

i. There is significant diversity among Bambara groundnut accessions, as assessed by seed morphometric traits.
ii. Bambara groundnut accessions exhibit significant variation in performance across environments.
iii. Bambara groundnut accessions exhibit Genotype × Environment Interaction across the test environments.

Chapter 2: Literature review

2.1 Underutilized legumes

Underutilized legumes are crop species that receive limited research and commercial attention despite their potential contribution to food and nutritional security. Unlike major legumes such as soybean and common bean, they are mainly cultivated in traditional and informal farming systems, where they support local livelihoods and preserve cultural heritage (Odeku et al., 2024). Cultivation and seed management are often undertaken by smallholder farmers, particularly women, who rely on indigenous knowledge for seed selection, production, and utilization (Ebert, 2014). Seeds are commonly exchanged within farming communities or passed down through generations, contributing to the conservation of locally adapted germplasm (Ellen & Platten, 2011).

Despite their resilience and adaptability, many underutilized legumes generally produce lower yields than major commercial legumes. This is largely due to limited breeding efforts, the absence of improved varieties, and inadequate agronomic recommendations (Ebert, 2014). Their weak integration into formal markets and value chains has also contributed to their characterization as "poor people's crops," limiting investment in research, commercialization, and wide adoption (Glatzel et al., 2025). Traditional knowledge related to their cultivation, processing, and medicinal uses is often transmitted orally, making them vulnerable to genetic erosion as younger generations increasingly adopt urban lifestyles and modern dietary preferences (Shah et al., 2020). Nevertheless, these crops possess valuable traits that are increasingly relevant in the face of climate change, including tolerance to drought, poor soils, and low-input production systems. Among them, Bambara groundnut has emerged as one of the most promising species because of its remarkable resilience, nutritional value, and capacity to produce under marginal conditions (Khan et al., 2022; Mayes et al., 2019; Olanrewaju et al., 2022), These attributes have renewed interest in the crop as a candidate for genetic improvement, climate-smart agriculture, and food system diversification.

2.2 Origin and domestication

Bambara groundnut [*Vigna subterranea* (L.) Verdc.] is an opportunity crop that is indigenous to Africa. It is widely believed to have originated in West Africa, particularly in the region encompassing northern Nigeria and Cameroon (Soumare et al., 2022). It is considered one of the earliest domesticated African grain legumes, with domestication occurring during a period similar to that of cowpea and other indigenous crops (Smýkal et al., 2015). Archaeological and historical evidence suggests that the crop has been cultivated for several thousand years, and its common name is thought to be derived from the Bambara ethnic group of Mali, where it has long been grown and utilized (Nc, 2018). Following its domestication, Bambara groundnut spread throughout sub-Saharan Africa through trade routes and farmer-to-farmer seed exchange, resulting in the development of diverse landraces adapted to different agroecological conditions (Majola et al., 2021). This long history of cultivation and adaptation has contributed to substantial genetic diversity within the species.

2.3 Morphology of Bambara groundnut

Bambara groundnut is an annual, herbaceous and predominantly self-pollinating legume that exhibits growth habits ranging from compact bunch types to spreading types (Bonny et al., 2019; IPGRI, IITA, BAMNET, 2000). The species is widely cultivated across Africa, where considerable morphological variation has evolved through adaptation to diverse agro-ecological environments (El Bilali et al., 2024; Uba et al., 2023). Botanically, Bambara groundnut is closely related to cowpea [*Vigna unguiculata* (L.) Walp], while its reproductive habit resembles that of groundnut (*Arachis hypogaea* L.)(Azman Halimi et al., 2019; Mayes et al., 2019). The plant develops a strong taproot with lateral branches, trifoliate leaves borne on long petioles, and papilionaceous flowers (characteristic of the Fabaceae family). Following self-fertilization, the flower stalk elongates and pushes the developing pod into the soil, where it matures underground, a phenomenon known as geocarpy (Bertioli et al., 2011; Gulu, 2018) as illustrated in **Figure 2.1.**



Figure 2.1: Morphological characteristics of Bambara groundnut: (a) trifoliate leaves borne on long petioles, (b) flowering and early pod development at the soil surface, (c) harvested plant showing mature underground pods, and (d) mature seeds.

Considerable variation exists among Bambara groundnut accessions for several morphological traits that are commonly used in germplasm characterization. Differences have been reported in growth habit, leaflet shape, petiole pigmentation, pod texture, seed size, and seed coat colour (Basu et al., 2007; IPGRI, IITA, BAMNET, 2000; Ntundu et al., 2006). Terminal leaflets may be oval, round, lanceolate, or elliptic, while petioles range from green to purple in colour. Mature pods are small, wrinkled, and typically contain one or two seeds. Seed characteristics are particularly diverse, with seed coat colours ranging from cream, red, and brown to black, including various mottled, striped, and eye-pattern combinations (IPGRI, IITA, BAMNET, 2000). Variation in seed size and seed weight is also substantial and represents an important source of diversity for breeding and crop improvement programs (Osundare et al., 2023).



Figure 2.2: Variation in selected morphological traits of Bambara groundnut: (a) green petiole pigmentation, (b) purple petiole pigmentation, (c) cream seed coat colour, and (d) black seed coat colour.

2.4 Bambara groundnut production

Bambara groundnut is an important grain legume valued for its ability to produce under low-input conditions, including poor sandy soils and drought-prone environments. Despite these advantages, the crop remains underutilized and is often regarded as a low-value crop, resulting in limited investment and relatively small areas dedicated to its cultivation (Pasipanodya et al., 2025). Production is largely concentrated in smallholder farming systems across sub-Saharan Africa (El Bilali et al., 2024; Majola et al., 2021), where farmers rarely maintain production records, making it difficult to accurately estimate harvested area and total production (Azam-Ali et al., 2001).

Across Africa, Bambara groundnut yields typically range from 0.5 to 3.0 t ha^{-1}, with an average yield of approximately 0.85 t ha^{-1} and annual production of about 0.3 million tonnes (Azam-Ali et al., 2001; Mayes et al., 2019). However, yields below 0.1 t ha^{-1} have been reported in some production environments (Khan et al., 2021; Maphosa et al., 2022). The crop is predominantly grown using local landraces, often planted as mixtures to minimize production risks under variable environmental conditions (Brink et al., 2000). Bambara groundnut is commonly cultivated as a sole crop, in rotation, or intercropped with cereals and other legumes in smallholder farming systems.

West African countries account for the largest share of global Bambara groundnut production, with Niger having the largest harvested area and Burkina Faso recording some of the highest yields (FAO, 2025). The crop is also cultivated in Southern African countries including South Africa, Eswatini, Zimbabwe, Zambia, and Botswana, although production levels are often not fully captured in international databases (Majola et al., 2021; Masindeni, 2006). Beyond Africa, Bambara groundnut is grown on a smaller scale in parts of Southeast Asia, particularly Indonesia and Thailand (Mayes et al., 2019). Although global production and cultivated area have increased over the past few decades, average yields have remained relatively stagnant, highlighting the need for improved varieties, agronomic practices, and crop management strategies (Maphosa et al., 2022).

2.5 Production constraints

Bambara groundnut has an average growth period of 110–150 days (Basu, Roberts, et al., 2007). During this time, production is limited by several factors, although modern management practices offer opportunities to improve yields. Biotic stresses, including diseases caused by fungi, bacteria, viruses, insect pests, and nematodes, can reduce both yield and crop quality (Majola et al., 2021). These stresses may reduce seed germination, disrupt physiological processes, damage plants, and even lead to mycotoxin production, which is harmful to humans and livestock. Some of these diseases can be controlled through good agronomic practices, such as crop rotation, removal or burning of crop residues, treating stored seeds with ash, and using appropriate crop protection chemicals (Maphosa et al., 2022).

Abiotic factors also limit BGN production. Erratic rainfall, extreme temperatures, altitude, and poor soils are major constraints (Gerrano, 2013; Gerrano et al., 2021). Climate change may further affect rainfall patterns, increasing the risk of drought or flooding and disrupting planting calendars for rainfed smallholder farmers (Aliyu et al., 2016; Pasipanodya et al., 2022b; West et al., 2012). Most smallholder farmers grow BGN on poor or degraded soils, often in marginal areas. Stress factors such as heat, drought, or salinity can occur simultaneously, sometimes affecting the same physiological traits (Tricker et al., 2018).

Although Bambara groundnut (BGN) is generally regarded as drought-tolerant (Mayes et al., 2019), water stress can still substantially affect a wide range of its morphological, physiological, and biochemical traits. Drought has been shown to influence canopy development, size, duration, and biomass accumulation and its partitioning within the plant (Jørgensen et al., 2010; Mabhaudhi & Modi, 2013). The crop also exhibits phenological plasticity under drought conditions (Mabhaudhi & Modi, 2013).

The crop requires 600–700 mm of rainfall during the growing season for optimal yield, although minimum rainfall requirements may be as low as 300 mm (Majola et al., 2021). BGN employs drought avoidance, escape, or tolerance strategies, with all three mechanisms observed to varying extents across genotypes (Chai et al., 2016; Jørgensen et al., 2010; Mabhaudhi & Modi, 2013). Excessive rainfall during maturity or harvest can cause waterlogging, damaging underground pods; planting on ridges or mounds helps reduce this risk (Gulu, 2018).

BGN is sensitive to frost at all growth stages, while warm temperatures accelerate development. Ideal growth occurs between 19–30 °C, and temperatures above 30 °C can cause heat stress and reduce yield (Majola et al., 2021; Masindeni, 2006).

Extreme temperatures can cause leaf wilting, reduced biomass, and lower yields. Because fruits develop underground, well-drained, loose sandy loam soils with a pH of 5–6.5 are preferred to avoid seed damage. The crop is also sensitive to flooding or hypoxic conditions (Sesay et al., 2010).

2.6 Genetic Structure and Gene Pools of Bambara Groundnut

Understanding the genetic structure and diversity of a crop is fundamental to guiding effective plant breeding programs. In Bambara groundnut, two distinct genepools with the same chromosome number (2n = 2x = 22) exist: the cultivated *V. subterranea* var. *subterranea* and the wild *V. subterranea* var. *spontanea* (Uba et al., 2021). Its primary gene pool is of African origin, with wild populations confined to parts of Nigeria and Cameroon (Khan et al., 2024), a region widely regarded as the crop's centre of domestication and dispersal (Uba et al., 2021). Molecular studies using SSR and DArT-SNP markers have consistently shown that genetic variation in Bambara groundnut is structured geographically, although a large proportion of the variation occurs within populations rather than among them. (Somta et al., 2011). This pattern of genetic structure is consistent with the crop's predominantly self-pollinating breeding system (Massawe et al., 2005; Mayes et al., 2019; Pasipanodya et al., 2022).

Despite these insights into genetic structure, genomic work in Bambara groundnut remains limited because a fully completed and publicly available reference genome is still lacking (Olanrewaju et al., 2022). As a result, sequence data are commonly aligned to the reference genome of cowpea [*Vigna unguiculata* (L.) Walp.], the closest sequenced relative of Bambara groundnut (Paliwal et al., 2021; Salazar-Licea et al., 2022). Genetic linkage maps have also been developed, such as the one built from an F3 population derived from a cross between two domesticated landraces, Tiga Nicuru × DipC (Ahmad et al., 2016).Because these genomic resources are still developing, phenotypic evaluation of available accessions remains an important way to identify useful variation for breeding (Muhammad et al., 2020b)

2.7 Statistical Approaches in Bambara Groundnut Diversity Studies

The characterization and evaluation of Bambara groundnut germplasm generate large datasets comprising qualitative and quantitative traits. To effectively identify phenotypic variation, determine relationships among accessions, and support breeding decisions, researchers employ both univariate and multivariate statistical techniques (Khan et al., 2021). Among the most commonly used approaches are Analysis of Variance (ANOVA), Principal Component Analysis (PCA), and Cluster Analysis (Esan et al., 2023; Khan et al., 2022).

Analysis of Variance (ANOVA) is a widely used statistical technique for comparing group means by partitioning total observed variation into components attributable to different sources (Allam, 2025; Das et al., 2023; Stahle & Wold, 1989). It enables researchers to determine whether observed differences among genotypes are statistically significant rather than the result of random variation. (Olanrewaju et al., 2021; Sharma, 2006). In Bambara groundnut diversity studies, ANOVA has been applied extensively to evaluate variation in traits such as flowering time, maturity, seed dimensions, and yield components (Ntundu et al., 2006; Olanrewaju et al., 2021; Onwubiko, 2021). The validity of ANOVA depends on several assumptions, including independence of observations, normal distribution of residuals, and homogeneity of variances among treatment groups. Beyond detecting significant differences among genotypes, ANOVA provides the basis for estimating important genetic parameters such as phenotypic which is widely used in crop improvement and selection programs. (Arredondo Montero, 2026).

Principal Component Analysis (PCA) is a powerful, frequently utilized multivariate technique to summarize and categorize phenotypic diversity in Bambara groundnut collections. It effectively condenses vast agro-morphological and physiological datasets into a few key principal components, enabling researchers to identify the most discriminatory traits for crop improvement. (Louis et al., 2025; Mandizvo, 2025). Because morphological traits are often measured in different units and scales, variables are commonly standardized to zero mean and unit variance before PCA is performed. This scaling procedure prevents traits with large numerical values from disproportionately influencing the analysis. In Bambara groundnut studies, the first few principal components generally account for a substantial proportion of total variation and help identify the traits contributing most to accession differentiation (Esan et al., 2023).

Cluster analysis is a multivariate statistical technique used to classify accessions into groups based on their overall similarity or dissimilarity across multiple traits (Azam et al., 2023). The method is widely employed in crop diversity studies to identify patterns of variation within germplasm collections and to facilitate the selection of genetically diverse parental materials for breeding programs. Clustering approaches are broadly categorized into distance-based and model-based methods (Nadeekantha et al., 2024), with distance-based hierarchical clustering being the most commonly applied in morphological characterization studies. In Bambara groundnut research, hierarchical clustering methods such as the Unweighted Pair Group Method with Arithmetic Mean (UPGMA) and Ward's method are frequently used in conjunction with Euclidean distance matrices to group accessions according to their phenotypic similarity (Khan et al., 2021; Osundare et al., 2023). The resulting dendrogram provides a graphical representation of relationships among accessions, where clusters represent groups of relatively similar genotypes. Accessions belonging to different clusters are generally considered more genetically divergent and may offer greater opportunities for generating variability in breeding programs (Khan et al., 2020).

Chapter 3: Materials and methods

3.1.Characterization of seed morphometric traits using videometer Lab Systems

3.1.1 Plant material

A total of 106 BGN accessions were obtained from the Genetic Resources Centre (GRC) of the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria (Figure 3.1). The accessions represented diverse geographical origins across sub-Saharan Africa (SSA), including Benin, Burkina Faso, Cameroon, Ghana, Nigeria, Zambia, and Zimbabwe, thereby providing a diverse set of genetic resources used for the study.

3.1.2 Experimental design

The experiment was arranged in a Completely Randomised Design (CRD), with accession as treatment. From each accession, 10 seeds were randomly selected and analysed individually. Each seed represented replication, yielding 10 per accession and a total of 1060 experimental units. The measured traits were recorded at the individual seed level and used to assess phenotypic variation among accessions. The statistical model used was a one-way ANOVA (Equation 1).

$$Y_{ij} = \mu + G_i + \varepsilon_{ij} \qquad \textbf{Equation 1}$$

Where is Y_{ij}: the observed trait value of the jth seed from the ith accession; μ: overall mean; Gi: fixed effect of the ith accession (genotype); ε_{ij}: residual error associated with each seed.

3.1.3 Sample preparation

Ten individual seeds were randomly selected for each accession. The seeds were cleaned to remove debris and placed in petri dishes, and positioned away from the edges, ensuring they were uniformly spread without overlapping. Seeds were positioned away from the dish edges to minimise distortions during image acquisition and improve image quality.

3.1.4 System calibration

The Videometer system was turned on and allowed to warm up for 15 mins. Geometric calibration was done using the geometric target to correct lens distortion. The radiometric calibration was run using white and dark references to normalize light intensity across wavelengths before imaging.

3.1.5 Image acquisition and data collection

Image acquisition was done using the VideometerLab4™ system (Videometer A/S, Herlev, Denmark), following the methodology described by Bhadmus et al. (2023). Ten seeds were imaged for each of the 106 BGN accessions and the captured images were processed through the VideometerLab software version 3.14.9 (Figure 3.2), which extracted detailed feature information (Table 3.1) from the scans.

Petri dishes containing cleaned, uniformly arranged seeds were loaded into the videometer chamber (Figure 3.2a). The system scanned the samples under controlled multispectral illumination (Figure 3.2b). A reference class was defined to standardize the imaging process. Sample counts were automatically added to the classifier file. The software applied machine learning algorithms to segment and analyze seed images (Figure 3.2e). Relevant morphometric and colour features (blob feature sets) were selected and extracted. Final measurements were exported into Excel sheets for subsequent statistical analysis.

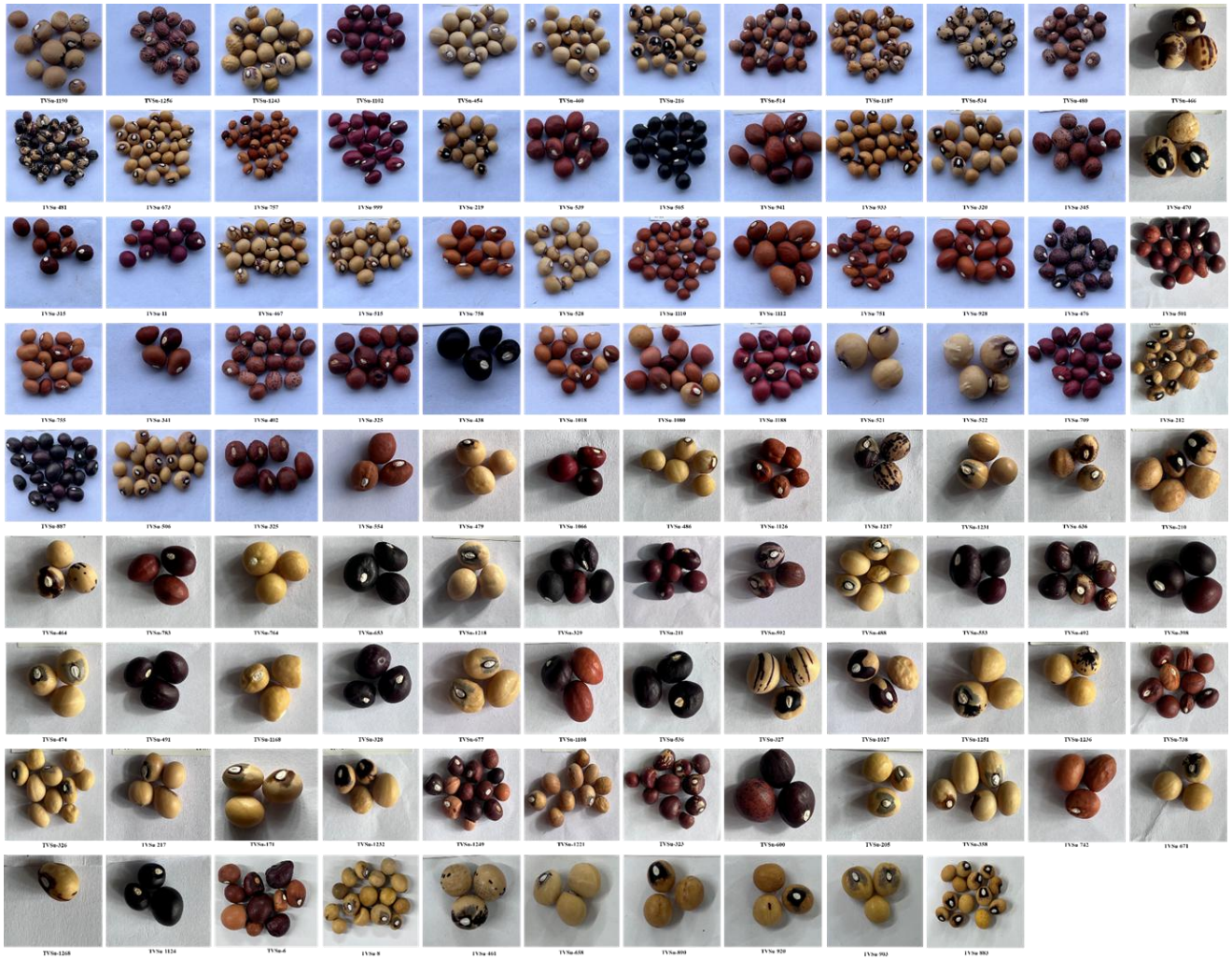

Figure 3.1: Phenotypic diversity of 106 BGN seeds across study accessions. The panel shows representative seed lots illustrating variation in seed coat colour (cream to dark purple/black), seed patterns (plain, mottled, speckled, and bicolour), and size/shape.

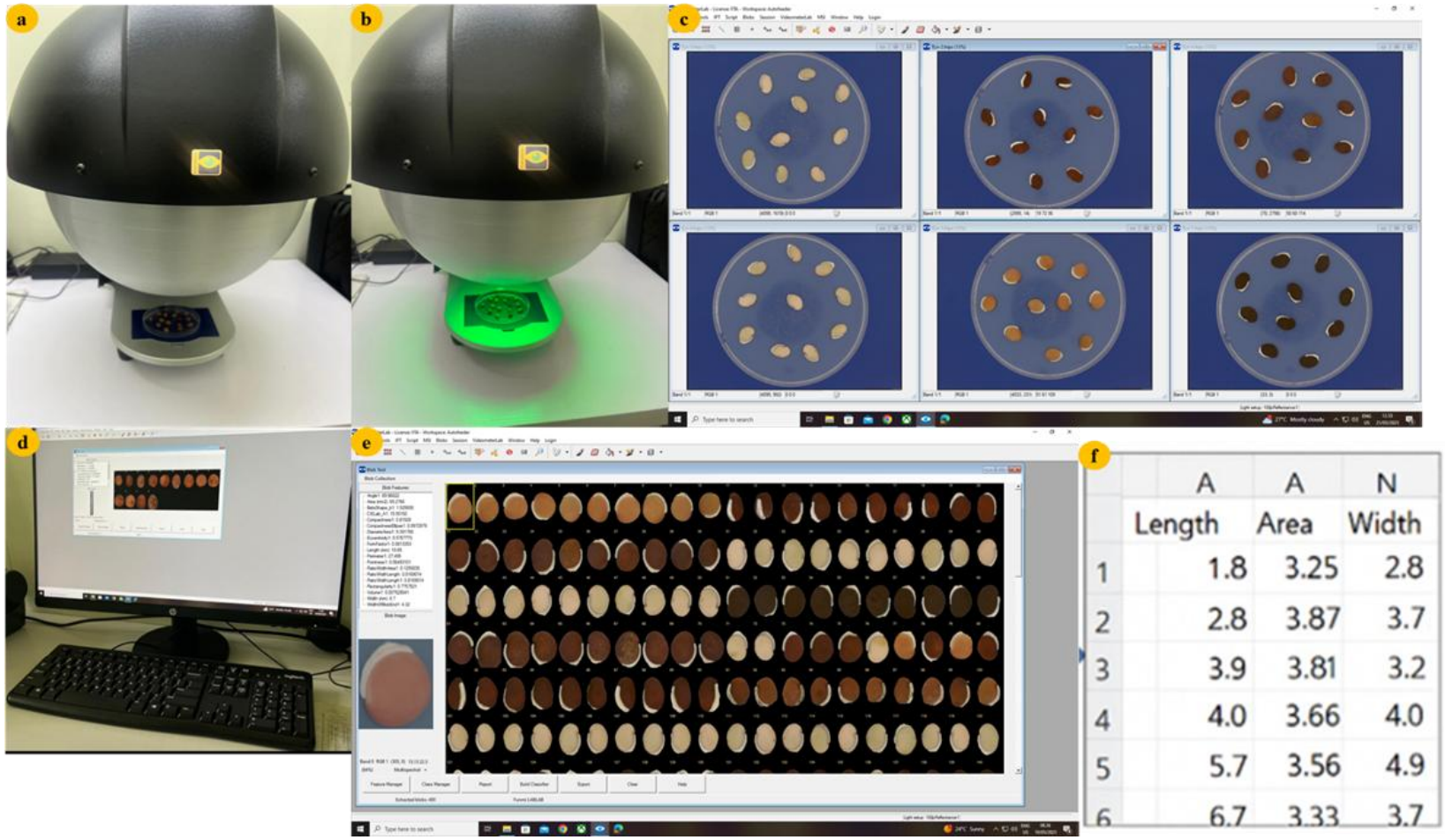

Figure 3.2: Image acquisition and processing workflow for seed phenotyping using an automated imaging system. (**a**) Imaging chamber setup with seed samples placed inside the device. (**b**) Active imaging stage with illumination for sample capture. (**c**) Raw seed images acquired under different orientations. (**d**) Visualization of captured images on the computer interface. (**e**) Seed phenotyping software processing and feature extraction, showing seed images arranged for trait analysis. (**f**) Example of extracted quantitative data (length, area, and width) exported for statistical analysis

Table 3.1: Definitions and units of image-derived Bambara groundnut seed traits.

Trait	Description
Seed area (SA) mm^2	Total area of the blob
Seed length (SL) mm	vertical dimension of the image-oriented bounding box (iob)
Seed width (SW) mm	horizontal dimension of the image oriented bounding box (iob)
Ratio width/length (RWL)	Ratio width to length of an object-oriented box (oob).
Perimeter (P) mm	Length of blob perimeter
Volume (V) mm^3	seed volume based on shape and dimensions
Rectangularity (Rect)	Ratio of blob area to bounding box area for an object-oriented box
Eccentricity (Ecc)	$\sqrt{(1 - y_2 / y_1)}$ of spatial moments: Measure of the elongation (deviation from circularity)
Compactness (Comp)	$4 \times \text{Area} / (\pi \times L^2)$. Measures deviation from circular shape.
Diameter area (DA) mm^2	Area of the smallest circle that can enclose the seed
Form factor (FF)	$4 \times \text{area} / (\text{PI} \times \text{Perimeter}^2)$. Measures deviation from circular shape
Pointness (Pt)	$(2 \times \text{area_H} - \text{area}) / \text{area}$ where area_H is the area of the largest half of the blob obtained by splitting it at length/2 along the object's orientation (oob)
Ratio width/area (RWA)	Ratio of seed width to seed area
Beta shape-b1 (Bb1)	Calculates beta shape parameter
Width of Blob End (WBE) mm	Measures the width of the blob at either the top or bottom end, relative to the width of the object-oriented box.
CIELab-A1 (CA1)	A colour measurement in the CIELab colour space (colour parameter)
Compactness Ellipse (CE)	$4 \times \text{Area} / (\pi \times L \times W)$. Measures the elliptical shape
Seed colour	Exact colour values (RGB/Hex)
Seed hue (°)	Colour appearance parameter (position on the colour wheel, degrees 0–360°)
Lightness	Brightness (0 = dark, 100 = bright)

Measurements were computed from each seed's binary "blob" and its bounding boxes; units are shown in parentheses (mm, mm^2, mm^3) and ratio indices are unitless. **IOB** = image-oriented bounding box; **OOB** = object-oriented (major-axis–aligned) bounding box

3.1.6 Statistical analysis

The collected data were subjected to Analysis of Variance using Genstat 23rd Edition (VSN International, Hempstead, United Kingdom). Means were separated using Fisher's protected least significant difference (LSD) test when accessions showed significant differences in the measured parameters at the 5% significance level. Descriptive statistics, including means, standard deviations, and coefficients of variation, were computed to summarize trait variation, while Pearson's correlation coefficients were calculated to determine relationships among seed morphometric and agronomic traits. Agglomerative Hierarchical Clustering (AHC) was performed on seed morphometric data using Ward's method and squared Euclidean distance to measure similarity, following OriginLab (OriginLab Corporation. OriginPro, Version 2025 [software], Northampton, MA: OriginLab Corporation; 2025). Principal Component Analysis (PCA) and the biplot diagrams were exploited to identify genotypes using XLSTAT software (Data Analysis and Statistical Solution for Microsoft Excel, Addinsoft, Paris, France, 2025).

3.2 Evaluation of the performance of 104 Bambara groundnut accessions across test environments

3.2.1 Experimental sites

Field trials were conducted across three agro-ecologically distinct locations in Nigeria namely: Ikenne (Humid forest), Ibadan (Derived Savanna), and Kano (Sudan Savanna). The geographical coordinates, planting dates, and environmental characteristics for each site are summarized in Table 3.2. These sites were selected for their contrasting climatic conditions and their importance as major agricultural production zones.

Table 3.2: Geographical coordinates and environmental characteristics of the experimental sites in Ikenne, Ibadan, and Kano, Nigeria

Location	Latitude	Longitude	Altitude	Planting date	Rainfall (mm)	Soil class
Ikenne	6°50'58.37"N	3°41'56.18"E	74	08/05/2025	1020–1150	Vertisols
Ibadan	7°29'14.21"N	3°54'15.43"E	227	23/05/2025	1200–1450	Lixisols
Kano	12° 8'22.93"N	8°40'8.03"E	430	29/05/2025	600–800	Acrisols



Figure 3.3: Map of Nigeria showing the locations of the experimental sites used in the study: Ibadan and Ikenne in the south-western region, and Kano in the northern region. (Source: Generated using Google Earth, 2026).

3.2.2 Plant materials

The study used 104 BGN accessions obtained from the Genetic Resource Centre (GRC) at the International Institute of Tropical Agriculture (IITA) in Ibadan, Nigeria. These accessions represent diverse geographical origins, capturing a broad genetic base for evaluation. The list of accessions, including their origin, is presented in Table 3.2

Table 3.3: List of Bambara groundnut accessions used in the study, showing accession serial number, accession name, digital object identifier and country of origin

Code	Name	DOI	Country of origin	Code	Name	DOI	Country of origin	Code	Name	DOI	Country of origin	Code	Name	DOI	Country of origin	Code	Name	DOI	Country of origin
G1	TVSu-1018	10.18730/GC29	Zimbabwe	G21	TVSu-1243	10.18730/GJCT	Nigeria	G41	TVSu-329	10.18730/FQJK	Nigeria	G61	TVSu-488	10.18730/FWCS	Cameroon	G81	TVSu-653	10.18730/G1E2	Nigeria
G2	TVSu-1027	10.18730/GCBJ	Zimbabwe	G22	TVSu-1249	10.18730/GJJ*	Nigeria	G42	TVSu-341	10.18730/FQYZ	Nigeria	G62	TVSu-491	10.18730/FWFW	Cameroon	G82	TVSu-658	10.18730/G1K7	Nigeria
G3	TVSu-1066	10.18730/GDGJ	Zimbabwe	G23	TVSu-1251	10.18730/GJM$	Nigeria	G43	TVSu-345	10.18730/FR2=	Nigeria	G63	TVSu-492	10.18730/FWGX	Cameroon	G83	TVSu-671	10.18730/G1YJ	Nigeria
G4	TVSu-1080	10.18730/GDWY	Zimbabwe	G24	TVSu-1256	10.18730/GJS2	Nigeria	G44	TVSu-358	10.18730/FRFB	Nigeria	G64	TVSu-501	10.18730/FWS1	Cameroon	G84	TVSu-673	10.18730/G20M	Nigeria
G5	TVSu-11	10.18730/FG10	Nigeria	G25	TVSu-171	10.18730/FKC~	Nigeria	G45	TVSu-398	10.18730/FSNC	Cameroon	G65	TVSu-506	10.18730/FWY6	Cameroon	G85	TVSu-677	10.18730/G24R	Zambia
G6	TVSu-1102	10.18730/GEEB	Zimbabwe	G26	TVSu-205	10.18730/FM2J	Benin	G46	TVSu-402	10.18730/FSSG	Cameroon	G66	TVSu-514	10.18730/FX6E	Cameroon	G86	TVSu-709	10.18730/G33J	Zambia
G7	TVSu-1108	10.18730/GEJF	Zimbabwe	G27	TVSu-210	10.18730/FM5N	Ghana	G47	TVSu-438	10.18730/FTVD	Cameroon	G67	TVSu-515	10.18730/FX7F	Cameroon	G87	TVSu-738	10.18730/G3Y8	Zambia
G8	TVSu-1110	10.18730/GEMH	Zimbabwe	G28	TVSu-211	10.18730/FM6P	Ghana	G48	TVSu-454	10.18730/FVAW	Cameroon	G68	TVSu-521	10.18730/FXDN	Cameroon	G88	TVSu-742	10.18730/G42C	Zambia
G9	TVSu-1112	10.18730/GEPK	Zimbabwe	G29	TVSu-212	10.18730/FM7Q	Ghana	G49	TVSu-460	10.18730/FVG$	Cameroon	G69	TVSu-522	10.18730/FXEP	Cameroon	G89	TVSu-751	10.18730/G4BN	Zambia
G10	TVSu-1126	10.18730/GF3*	Zimbabwe	G30	TVSu-216	10.18730/FMBV	Ghana	G50	TVSu-461	10.18730/FVH=	Cameroon	G70	TVSu-528	10.18730/FXMW	Cameroon	G90	TVSu-755	10.18730/G4FS	Zambia
G11	TVSu-1168	10.18730/GG8*	Burkina Faso	G31	TVSu-217	10.18730/FMCW	Ghana	G51	TVSu-464	10.18730/FVM1	Cameroon	G71	TVSu-534	10.18730/FXS~	Cameroon	G91	TVSu-757	10.18730/G4HV	Zambia
G12	TVSu-1187	10.18730/GGVE	Burkina Faso	G32	TVSu-219	10.18730/FMEY	Ghana	G52	TVSu-466	10.18730/FVP3	Cameroon	G72	TVSu-536	10.18730/FXV=	Cameroon	G92	TVSu-758	10.18730/G4JW	Zambia
G13	TVSu-1188	10.18730/GGWF	Burkina Faso	G33	TVSu-3	10.18730/FFSX	Nigeria	G53	TVSu-467	10.18730/FVQ4	Cameroon	G73	TVSu-539	10.18730/FXY1	Cameroon	G93	TVSu-764	10.18730/G4R$	Zambia
G14	TVSu-1190	10.18730/GGYH	Burkina Faso	G34	TVSu-315	10.18730/FQ45	Burkina Faso	G54	TVSu-470	10.18730/FVT7	Cameroon	G74	TVSu-553	10.18730/FYCF	Cameroon	G94	TVSu-783	10.18730/G59E	Zambia
G15	TVSu-1217	10.18730/GHS7	Burkina Faso	G35	TVSu-320	10.18730/FQ9A	Burkina Faso	G55	TVSu-474	10.18730/FVYB	Cameroon	G75	TVSu-554	10.18730/FYDG	Cameroon	G95	TVSu-8	10.18730/FFY$	Nigeria
G16	TVSu-1218	10.18730/GHT8	Nigeria	G36	TVSu-323	10.18730/FQCD	Nigeria	G56	TVSu-476	10.18730/FW0D	Cameroon	G76	TVSu-565	10.18730/FYRV	Cameroon	G96	TVSu-883	10.18730/G83Y	Zambia
G17	TVSu-1221	10.18730/GHWA	Nigeria	G37	TVSu-325	10.18730/FQEF	Nigeria	G57	TVSu-479	10.18730/FW3G	Cameroon	G77	TVSu-592	10.18730/FZJG	Nigeria	G97	TVSu-887	10.18730/G87$	Zambia
G18	TVSu-1231	10.18730/GJ3H	Nigeria	G38	TVSu-326	10.18730/FQFG	Nigeria	G58	TVSu-480	10.18730/FW4H	Cameroon	G78	TVSu-6	10.18730/FFW*	Nigeria	G98	TVSu-890	10.18730/G8A0	Zambia
G19	TVSu-1232	10.18730/GJ4J	Nigeria	G39	TVSu-327	10.18730/FQGH	Nigeria	G59	TVSu-481	10.18730/FW5J	Cameroon	G79	TVSu-600	10.18730/FZTR	Nigeria	G99	TVSu-903	10.18730/G8NB	Zambia
G20	TVSu-1236	10.18730/GJ7N	Nigeria	G40	TVSu-328	10.18730/FQHJ	Nigeria	G60	TVSu-486	10.18730/FWAQ	Cameroon	G80	TVSu-636	10.18730/G0YQ	Nigeria	G100	TVSu-920	10.18730/G95V	Zambia
G101	TVSu-928	10.18730/G9D=	Zambia	G102	TVSu-933	10.18730/G9J3	Zambia	G103	TVSu-941	10.18730/G9TB	Zambia	G104	TVSu-999	10.18730/GBGW	Zimbabwe				

TVSu: Tropical Vigna subterranea; **S/N:** Serial Number

3.2.3 Experimental design and field management

An Alpha lattice design (8 × 13) with three replications was implemented at each location. Each plot consisted of a single 4m row, with a spacing of 1 m between rows and 0.25 m between plants. Standard agronomic practices were followed to simulate low-input farming systems typical of smallholder production, including manual weeding, earthing up and supplementary irrigation during prolonged dry spells. Foliar insecticides were applied as needed to control pest infestations, ensuring uniform growing conditions across all accessions.

3.2.4 Data collection and trait measurement

Eleven agronomic traits (Table 3.4) were measured during the morphological characterization of the BGN accessions following the BGN descriptors (IPGRI, IITA, BAMNET, 2000). Phenological traits included DTFE, DT50E, DTFF and DT50F. Morphological measurements comprised PH, PS, TLL and TLW recorded 10 weeks after planting. Yield-related traits included the total number of pods per plant (NPPP) and yield per plot (YPP), adjusted to 12% moisture content. Data were collected from five randomly selected plants per plot, with means used for statistical analysis.

Table 3.4: Agronomic traits evaluated in Bambara groundnut and their corresponding modes of observation, including phenological, morphological and yield-related parameters

Agronomic trait	Mode of observation
Days to 1st emergence (DTFE)	Number of Days from sowing to first emergence
Days to 50% emergence (DT50E)	Number of Days from sowing to 50% emergence
Plant count (PC)	Number of surviving plants in a plot
Days to 1st flowering (DTFF)	Number of Days from sowing to first flower emergence
Days to 50% flowering (DT50F)	Number of Days from sowing to when 50% of plants begin to flower
Plant height (PH)	Recorded 10 weeks after planting; average height of 5 plants
Plant spread (PS)	Average widest length between 2 opposite points of 5 plants
Terminal leaflet length (TLL)	Average length of 3 leaves at the 4th node of 5 healthy plants
Terminal leaflet width (TLW)	Average width of 3 leaves at the 4th node of 5 healthy plants
Number of pods per plant (NPPP)	Mean number of pods in 5 plant stands
Yield per plot (YPP)	Weight of dried seed (at 12% moisture content)

Source: *Descriptors for Bambara Groundnut*, 2000; IPGRI, IITA, BAMNET, 2000)

3.2.5 Statistical analysis

Statistical analyses were conducted to evaluate the effects of genotype, environment, and genotype × environment (G × E) interaction on the measured traits of BGN accessions across the 3 test environments. A combined analysis of variance (ANOVA) was performed using a linear model in which genotype, environment, and G × E interaction were treated as fixed effects. The model used is presented in Equation 2.

$$Y_{ijk} = \mu + G_i + E_j + (GE)_{ij} + \varepsilon_{ijk} \qquad \text{Equation 2}$$

$\boldsymbol{Y_{ijk}}$: observed value of the ith genotype in the jth environment and k^{th} replication; $\boldsymbol{\mu}$: overall mean; $\boldsymbol{G_i}$: effect of the ith genotype; $\boldsymbol{E_j}$: effect of the jth environment; $\boldsymbol{(GE)ij}$: genotype × environment interaction; $\boldsymbol{\varepsilon_{ijk}}$: residual error. The significance of the sources of variation was determined using F-tests at the 5% and 1% significance levels.

Violin plots with embedded boxplots were generated to visualize the distribution and variability of the traits across environments. Genotype performance and stability across environments were further evaluated using Genotype plus Genotype-by-Environment Interaction (GGE) biplot analysis based on the Average Environment Coordination (AEC) method in GenStat 2023 (VSNi, UK). To identify the main traits contributing to variation among accessions within each environment, Principal Component Analysis (PCA) was conducted separately for Ibadan, Ikenne, and Kano using standardized trait data in ORIGINPRO®2026 (OriginLab Corporation, Northampton, MA, USA). Trait relationships were further explored using Pearson's correlation coefficients, and the results were visualized in correlation matrices and PC biplots in R (RStudio 2026.01.1 + 403). Agglomerative hierarchical clustering (AHC) was performed to classify accessions based on yield per plot across environments XLSTAT (Addinsoft, Paris, France, 2026).

Chapter 4: Results and discussion

4.1 Characterization of seed morphometric traits using Videometer Lab Systems

4.1.1 Analysis of variance

The accession effect was significant ($p < 0.05$) for SA, SL, SW, RWL, Pr, Vol, Rect, Ecc and Comp (Table 4.1). The consistently high genotype mean squares (MS) relative to residual MS indicate that genetic differences among accessions contributed strongly to observed seed size, shape, and variation in seed geometry.

Accession differences were also highly significant ($p < 0.05$) for DA, FF, Pt, RWA, Bb1, WBE, CA1 and CE. In particular, traits such as CA1 [genotype mean square (418.817) vs. residual (4.751)] and WBE (2.023 vs. 0.218) showed substantial genotype effects, indicating strong variation in seed colour intensity and terminal width.

Table 4.1 confirmed that genotypic variation was highly significant across all seed traits, encompassing size (SA, SL, SW, Vol, DA), shape indices (RWL, Rect, Ecc, Comp, FF, Pt, RWA, CE, Bb1, WBE), and colour (CA1). The relatively low residual MS compared to genotype mean squares further demonstrated that the observed differences are primarily explained by genetic factors rather than random error, underscoring the potential for selecting and classifying genotypes based on distinct seed morphological and colour characteristics.

Table 4.1: Analysis of variance showing mean squares and significant tests for seed morphometric traits of 106 Bambara groundnut accessions measured using a videometer

Source of variation	d.f	SA	SL	SW	RWL	Pr	Vol	Rect	Ecc	Comp
Genotype	105	1951.3**	9.580**	7.149**	0.020**	61.607**	4.787 ×10^{-6**}	1.60×10^{-4**}	0.065**	0.020**
Residual	954	180.6	0.983	0.664	0.003	5.836	4.91×10^{-7}	7.027×10^{-5}	0.009	0.002
Total	1059	-	-	-	-	-	-	-	-	-

Source of variation	d.f	DA	FF	Pt	RWA	Bb1	WBE	CA1	CE
Genotype	105	7.522**	8.591×10^{-4**}	5.594×10^{-4**}	0.001**	0.003**	2.023**	418.817**	1.576×10^{-5**}
Residual	954	0.705	3.17×10^{-4}	2.630×10^{-4}	1.229×10^{-4}	0.002	0.218	4.751	8.480×10^{-6}
Total	1059	-	-	-	-	-	-	-	-

: Significant difference at 5% probability level;SA**: seed area; **SL**: seed length; **SW**: seed width; **RWL**: ratio width/length; **Pr**: perimeter; **Vol**: volume; **Rect**: rectangularity; **Ecc**: eccentricity, **Comp**: compactness; **DA**: diameter area; **FF**: form factor; **Pt**: pointness; **RWA**: ratio width/area; **Bb1**: beta shape-b1; **WBE**: width of blob end; **CA1**: CIELab-A1; **CE**: compactness ellipse

Figure 4.1 presents the frequency distribution of seed coat colour (SCC) among 106 BGN accessions, classified according to the Reichs-Ausschuß für Lieferbedingungen und Gütesicherung (RAL) colour system. The upper panel depicts the occurrence of each RAL colour category, while the lower panel illustrates the corresponding visual shades, highlighting both the diversity and relative abundance of seed coat colours within the germplasm.

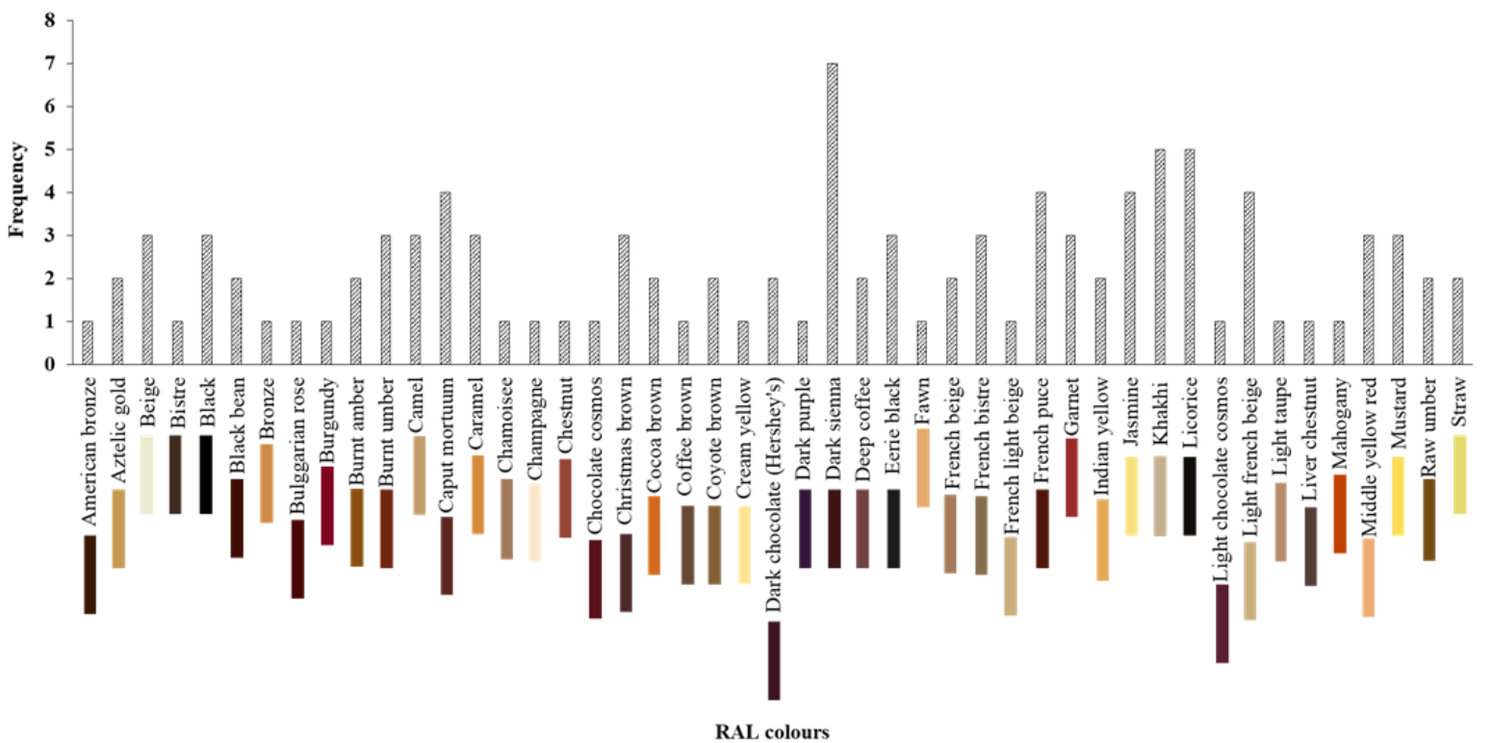

Figure 4.1: Frequency distribution of seed coat colour among 106 Bambara groundnut accessions, classified according to the Reichs-Ausschuß für Lieferbedingungen und Gütesicherung (RAL) colour system.

Seed size traits showed substantial differences. For example, TVSu-600 (SA = 117.89 mm², SL = 13.41 mm) and TVSu-320 (SA = 115.29 mm^2, SL = 13.14 mm) represented some of the largest-seeded accessions. In contrast, smaller-seeded types such as TVSu-466 (SA = 58.55 mm^2, SL = 9.2 mm) and TVSu-890 (SA = 57.61 mm^2, SL = 9.28 mm) cluster at the lower end, highlighting evident genetic variability for seed area and length. Interestingly, seed width (SW) is relatively less variable, with many accessions clustering around 9–11 mm, though some, such as TVSu-1018 (11.319 mm), are significantly broader.

Seed shape indices further distinguished accessions. RWL (ratio of width to length) varied markedly: highly elongated types such as TVSu-999 (0.728) contrasted with more rounded forms like TVSu-636 (0.952) and TVSu-1249 (0.947), which are among the most compact. Similarly, eccentricity (Ecc) and compactness (Comp) mirror this contrast: elongated genotypes (low Comp, high Ecc) versus rounder genotypes (high Comp, low Ecc). Traits like form factor (FF) and pointness (Pt) also showed fine-scale shape distinctions.

Some accessions stood out for colour and appearance. CA1 (CIELab-A1) and Hue varied widely, with TVSu-600 displaying a relatively high saturation (96%) but moderate hue, while others, such as TVSu-1243 and TVSu-521 showed stronger colour values. Brightness (%) also differed, with some seeds (TVSu-1124, 0%) being very dark, while others (TVSu-1027, 100%) were highly bright, indicating large phenotypic variation in seed coat pigmentation. The volumetric trait (Vol) and derived indices such as DA (diameter area) and WBE (width of blob end) also followed the seed size trend, being largest in accessions like TVSu-210 (Vol = 0.009 mm^3; DA = 11.98 mm) and smallest in TVSu-890 (Vol = 6.559×10^{-3} mm^3; DA = 8.52 mm.

4.1.2 Data visualization

The distributions of seed morphometric traits among BGN accessions are presented using violin plots (Figure 4.2). The plots revealed considerable variability across accessions for size-related observations (SA, SL, SW, Pr and Vol), with relatively wide density distributions indicating heterogeneity within the population (Figure 4.2a, b, c, e and f). Ratios such as width-to-length (Figure 4.2d) and width-to-area (Figure 4.2m) showed narrower distributions, suggesting more conserved geometric proportions than absolute size measures.

Shape descriptors, including rectangularity (Figure 4.2g), eccentricity (Figure 4.2h), compactness (Figure 4.2i), diameter-area (Figure 4.2j), form factor (Figure 4.2k), pointness (Figure 4.2l), and beta shape parameter (Figure 4.2n), exhibited moderate variation, with the majority of accessions clustering around median values but with extended tails highlighting the presence of extreme phenotypes. Notably, eccentricity and pointness showed longer tails, suggesting the presence of outlier accessions with distinct seed characteristics.

For seed-end traits such as the width of the blob end (Figure 4.2o), variation was more constrained, whereas colour metric parameters—CIELab-A1 (Figure 4.2p), hue, saturation, and brightness—showed distinct, broader distributions, reflecting the underlying diversity in seed coat pigmentation. Hue and saturation showed a wider spread than brightness, suggesting that seed colour intensity variation is greater than that of lightness. The violin plots highlight conserved and divergent traits across BGN accessions, emphasizing substantial phenotypic diversity that can be exploited for trait-specific selection in breeding programs.

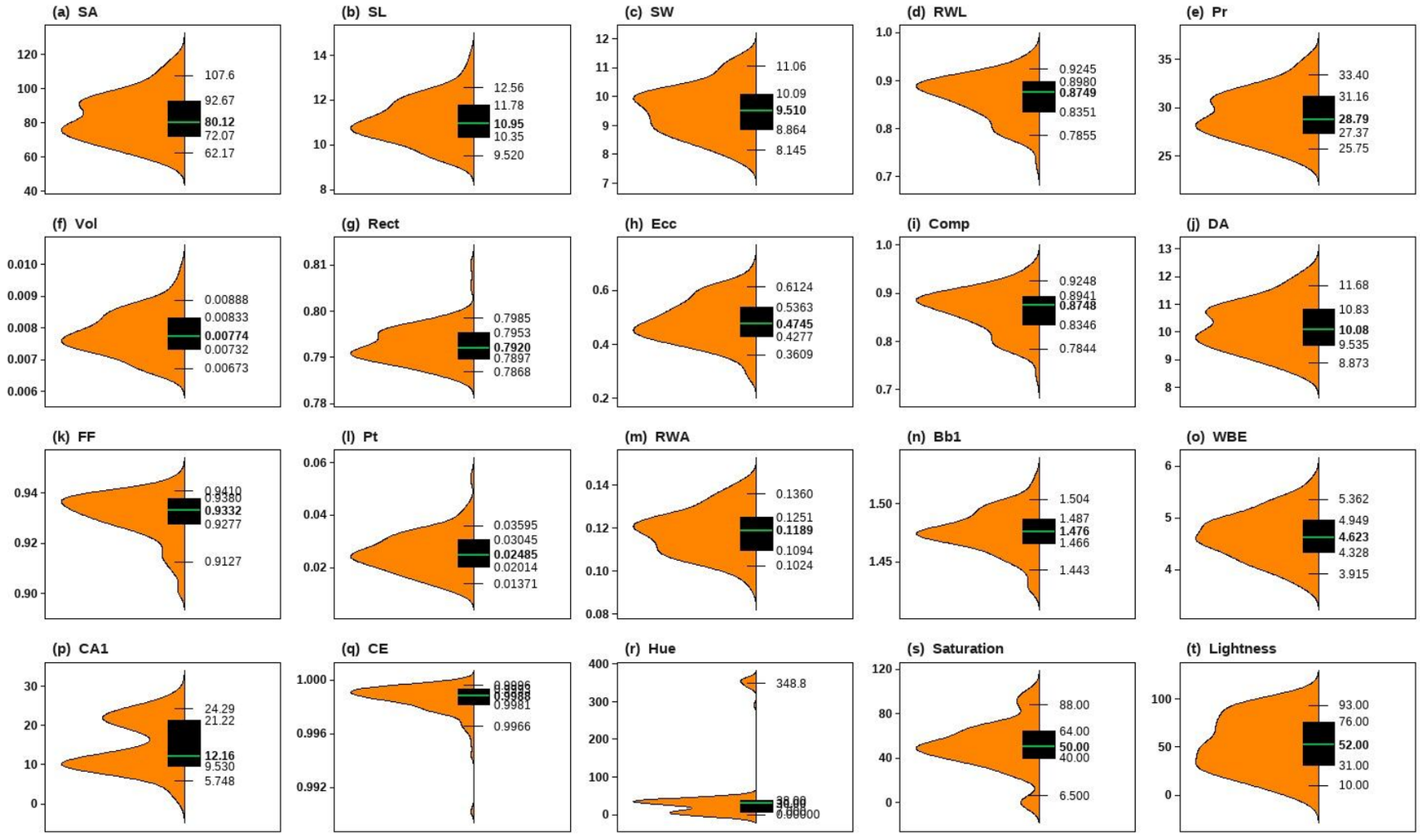

Figure 4.2: Violin plots showing the distribution and variability of seed morphometric traits across BGN accessions. Each subplot represents a distinct trait, with the imbedded black box plot indicating the interquartile range, the central line denoting the median, and the orange shape reflecting kernel density estimation of trait distribution. (**a**) seed area, (**b**) seed length, (**c**) seed width, (**d**) ratio width/length, (**e**) perimeter, (**f**) volume, (**g**) rectangularity, (**h**) eccentricity, (**i**) compactness, (**j**) diameter area, (**k**) form factor, (**l**) pointness, (**m**) ratio width/area, (**n**) beta shape-b1, (**o**) width of blob end, (**p**) CIELab-A1, (**q**) compactness ellipse, (**r**) hue, (**s**) saturation, (**t**) lightness

4.1.3 Principal component analysis (PCA)

The first principal component (PC1) is primarily associated with seed size. Traits such as SA, SL, SW, Pr, Vol, DA and WBE all load strongly and positively, indicating that this axis represents overall seed dimensionality (Table 4.2). Larger, bulkier seeds therefore characterize genotypes with high PC1 scores. In contrast, the negative loading of the RWA highlights a trade-off, where elongated or narrow seeds with proportionally less area fall on the opposite end of this axis.

PC2 represented accessions based on seed shape and form variation, contrasting compact and rounded seeds with elongated ones. High positive loadings for the ratio RWL, Comp and FF emphasized short, broad, and compact seed forms, while the strong negative contribution of Ecc, together with moderate negative loadings for Pt, SL, and Vol, indicated that elongated, narrow seeds occupy the opposite side of this axis. Thus, PC2 distinguished between rounded and more elongated seed shapes (Table 4.2).

Similarly, PC3 captured a combination of shape irregularities and colour variations. Positive loadings for Rect, Pt, hue, CA1 and saturation indicated that seeds scoring highly on this axis tend to be more angular, pointed, and strongly pigmented, with darker or more intense coat colours. Conversely, negative loadings for Bb1, CE and lightness revealed that seeds with smoother outlines, higher symmetry, and lighter colours are positioned at the opposite end of this component (Table 4.2).

PC4 is dominated by colour and fine structural traits. High positive loadings for beta shape (Bb1), CA1, saturation, CE and hue suggested that seeds with high scores on this axis are characterized by more intense pigmentation and irregular or less uniform outlines. Negative contributions from Rect indicated more rectangular and lighter-coloured seeds fall at the opposite extreme (Table 4.2).

Overall, the principal component structure showed that variation among the seeds is represented first by size (PC1), then by shape (PC2), with subsequent components capturing irregularity and colour differences (PC3 and PC4). This indicated that while seed size is the dominant source of variation in BGN, differences in shape and colour also play an important role in distinguishing genotypes (Table 4.2).

Table 4.2: Extracted eigenvectors showing the coefficients of the first four principal components derived from PCA of 106 Bambara groundnut seed morphometric and colour traits

Traits	PC1	PC2	PC3	PC4
SA	0.358	-0.026	0.012	0.038
SL	0.337	-0.154	-0.042	0.012
SW	0.346	0.102	0.047	0.083
RWL	0.021	0.422	0.168	0.110
Pr	0.358	-0.041	0.013	0.010
Vol	0.337	-0.154	-0.042	0.012
Rect	0.063	0.179	0.373	-0.266
Ecc	-0.022	-0.411	-0.187	-0.122
Comp	0.025	0.423	0.157	0.127
DA	0.359	-0.019	0.008	0.036
FF	0.064	0.360	0.033	0.224
Pt	0.015	-0.260	0.319	-0.061
RWA	-0.343	0.123	0.049	0.013
Bb1	-0.026	0.018	-0.449	0.464
WBE	0.340	0.097	0.137	-0.018
CA1	-0.084	-0.260	0.302	0.441
CE	0.102	0.109	-0.350	0.301
Hue	0.005	-0.090	0.340	0.264
Saturation	-0.086	-0.184	0.251	0.497
Lightness	0.012	0.195	-0.223	-0.065

SA: seed area; **SL**: seed length; **SW**: seed width; **RWL**: ratio width/length; **Pr**: perimeter; **Vol**: volume; **Rect**: rectangularity; **Ecc**: eccentricity, **Comp**: compactness; **DA**: diameter area; **FF**: form factor; **Pt**: pointness; **RWA**: ratio width/area; **Bb1**: beta shape-b1; **WBE**: width of blob end; **CA1**: CIELab-A1; **CE**: compactness ellipse

The PCA biplot assessed the genetic relationship among BGN accessions based on evaluated traits (Figure 4.3). TVSu-636, TVSu-1256, TVSu-219, TVSu-486, TVSu-1243 and TVSu-1251 grouped based on high FF, lightness, Rect and CE. Similarly, accessions TVSu-402, TVSu-738, TVSu-783, TVSu-883, TVSu-480, TVSu-210, TVSu-320, and TVSu-481 were grouped because they consistently exhibited large seed morphological dimensions, particularly in terms of diameter area, overall volume, and seed surface area. This clustering suggests that these accessions represent a class of BGN lines characterized by superior seed size attributes (Figure 4.3).

Accessions TVSu-476, TVSu-1188, TVSu-742, TVSu-341, TVSu-1102, TVSu-941 and TVSu-1018 are grouped based on high saturation, CIELab-A1 and eccentricity while accessions TVSu-933, TVSu-11, TVSu-764, TVSu-464, TVSu-205, TVSu-515 and TVSu-1217 are grouped together based on high RWA and Bb1 (Figure 4.3).

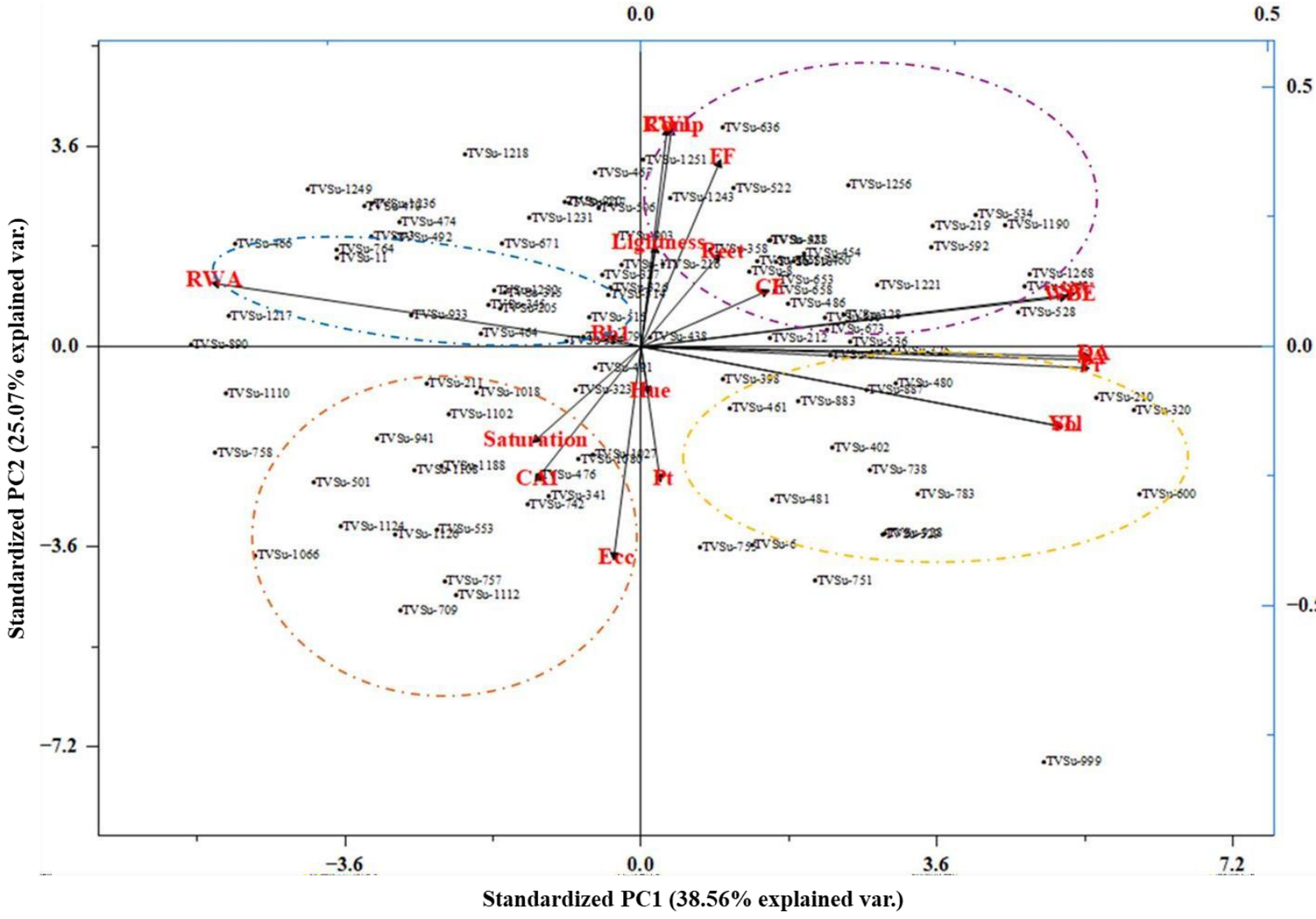

Figure 4.3: Principal component analysis (PCA) biplot of 106 Bambara groundnut accessions based on seed morphometric traits

4.1.4 Pearson correlation among seed morphometric traits

The strongest positive correlations are observed among seed-size-related traits. Seed area and SL are significantly positively correlated (r = 0.95), as are SA and SW (r = 0.95), and SA and Pr (r = 0.96). Diameter area is positively correlated with SA (r = 0.96) Pr (r = 0.95), while Vol shows equally strong associations with SA (r = 0.95) and SW (r = 0.82) (Figure 4.4a).

However, shape-related indices showed contrasting relationships. Eccentricity is significantly and negatively correlated with Comp (r = –0.99), reflecting that more elongated seeds are necessarily less compact. Likewise, form factor and eccentricity are negatively correlated (r = –0.73), while FF and compactness are positively associated (r = 0.78), supporting the interpretation of these traits as roundness versus elongation types (Figure 4.4a).

Some indices showed inverse relationships with size. The width-to-area ratio was negatively correlated with SA (r = –0.95), SL (r = –0.97), and Pr (r = –0.99), suggesting that as seeds get larger, the width-to-area ratio declines. Similarly, the width of blob end showed strong positive correlations with size parameters such as SA (r = 0.92) and DA (r = 0.94), but a strong negative association with RWA (r = –0.82) (Figure 4.4a).

For seed colour, saturation and compactness ellipse (CE) were positively correlated (r = 0.66), while lightness and Pt were negatively correlated (r = –0.42). These relationships suggest that colour dimensions interact subtly with shape characteristics but are not strongly dependent on size traits (Figure 4.4a).

The chord diagram (Figure 4.4b) illustrated a web of relationships among seed traits, with the thickness and colour of the ribbons indicating the strength and nature of these associations. Size-related traits such as SA, SL, SW, Pr, Vol, and DA dominated the network, interconnected by numerous thick ribbons that highlighted strong positive correlations and a central role in defining overall seed size. Similarly, shape descriptors, including RWL, Ecc, Comp, FF, and RWA, form a contrasting cluster, in which strong connections reveal a trade-off between elongated and compact seed forms. In contrast, colour attributes such as hue, CA1, CE, saturation, and lightness occupied a more peripheral position in the network, displaying fewer and thinner links. However, these traits still maintained moderate associations with shape traits. Overall, the network diagram demonstrated that seed variation is structured around three interrelated dimensions, with size traits forming the central hub, shape traits highlighting morphological contrasts, and colour traits contributing complementary variation at the periphery (Figure 4.4b)

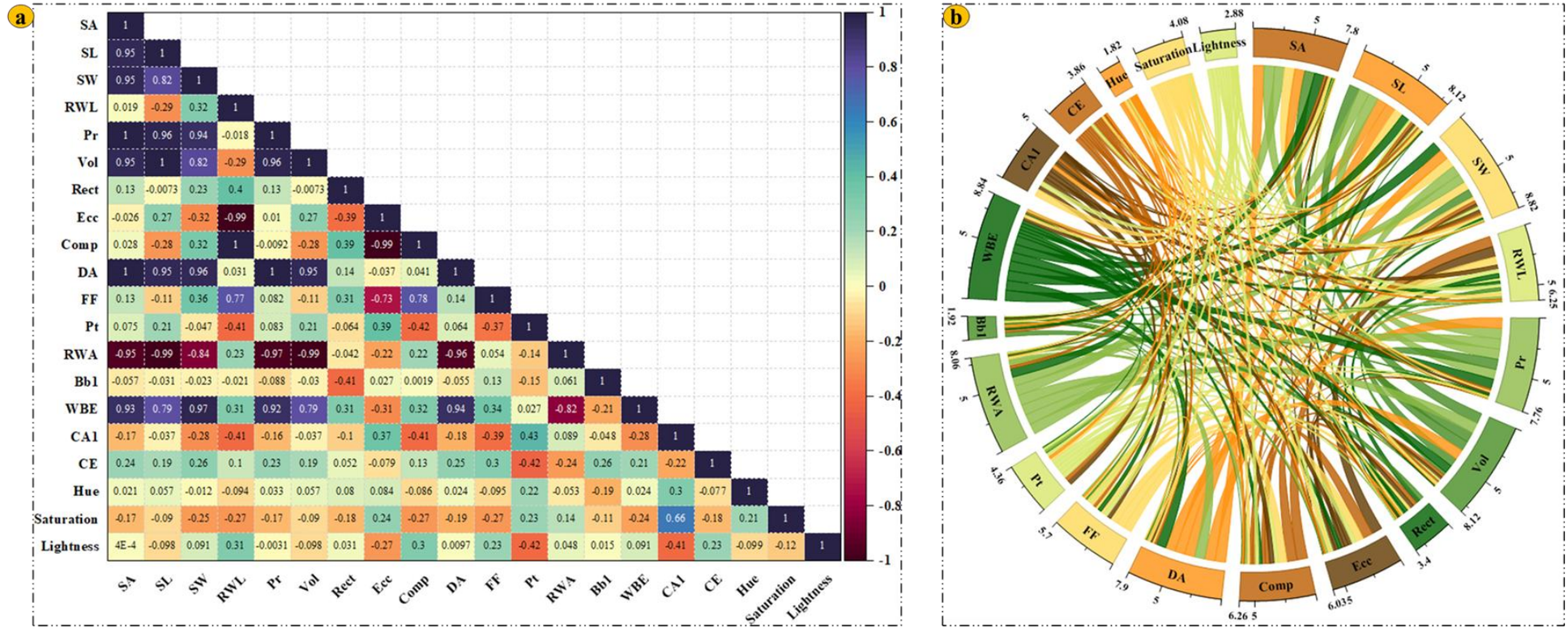

Figure 4.4: Correlations among Bambara groundnut seed traits. (**a**) lower-triangular Pearson correlation heatmap, (**b**) circos/chord diagram **SA**: seed area; **SL**: seed length; **SW**: seed width; **RWL**= ratio width/length; **Pr**: perimeter; **Vol**: volume; **Rect**: rectangularity; **Ecc**: eccentricity, **Comp**: compactness; **DA**: diameter area; **FF**: form factor; **Pt**: pointness; **RWA**: ratio width/area; **Bb1**: beta shape-b1; **WBE**: width of blob end; **CA1**: CIELab-A1; **CE**: compactness ellipse

4.1.5 Agglomerative Hierarchical Clustering (AHC)

The AHC dendrograms grouped 106 BGN accessions into three distinct clusters based on (i) seed size and dimensional traits (Figure 4.5a), (ii) seed shape and form traits (Figure 4.5b) and (iii) seed coat colour attributes (Figure 4.5c). Based on seed size and dimensional traits (SA, SL, SW, DA, Vol, and Pr), BGN accessions were clustered according to overall seed bulkiness. This cluster grouped accessions based on size-related variations (large and small seeds) (Figure 4.5a). Small-seeded accessions such as TVSu-171, TVSu-1066, TVSu-1110, TVSu-758 grouped together, while large-seeded accessions including TVSu-928, TVSu-534, TVSu-592, TVSu-887, TVSu-576, TVSu-136 grouped together (Figure 4.5a).

Similarly, BGN accessions were grouped based on seed shape and form traits (RWL, Rect, Ecc, Comp, FF, Pt, RWA, CE and Bb1). This group distinguished (i) elongated and round seeds, (ii) compact and irregular seeds and (iii) smooth and angular seeds (Figure 4.5b). Accessions TVSu-1218, TVSu-467, TVSu-1251, TVSu-1249, TVSu-1256 and TVSu-666 represented as elongated or irregular-shaped seeds, often with a narrow width relative to length (Figure 4.5b). TVSu-382, TVSu-476, TVSu-531, TVSu-941, TVSu-461, TVSu-341, TVSu-600 and TVSu-1018 are grouped as medium/elliptical-shaped seeds, with balanced geometry, not too round nor too elongated, while TVSu-454, TVSu-1221, TVSu-320, TVSu-491, TVSu-526 and TVSu-237 round/compact-shaped seeds, with greater uniformity and less elongation (Figure 4.5b).

Seed coat colour attributes (hue, saturation and lightness) clustered the accessions based on SCT pigmentation and consumer perception traits (Figure 4.5c). TVSu-1218, TVSu-474, TVSu-486, TVSu-1243, TVSu-506, TVSu-3, TVSu-358, TVSu-171, TVSu-11, TVSu-890 and TVSu-883 were grouped based on light-coloured seeds, typically lower in saturation, giving a softer or faded appearance. Similarly, accessions TVSu-928, TVSu-783, TVSu-941, TVSu-553, TVSu-112, TVSu-315, TVSu-758, TVSu-1080, TVSu-126 and TVSu-323, represented by dark, intensely pigmented seeds, formed one cluster. This cluster also exhibited darker hues with stronger saturation. Medium-brown to mottled seeds with moderate saturation and lightness, including the accessions TVSu-476, TVSu-539, TVSu-514, TVSu-325, TVSu-751, TVSu-999, and TVSu-1188 (Figure 4.5c).

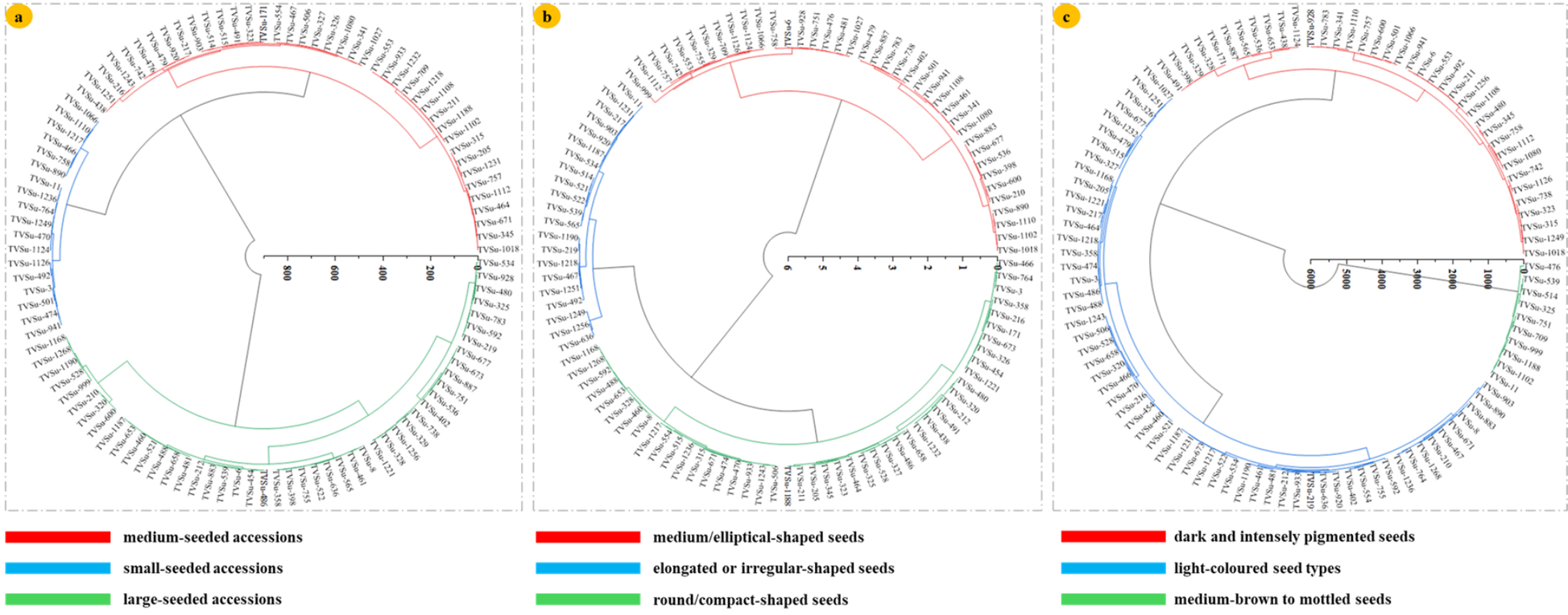

Figure 4.5: Comparative AHC of 106 BGN accessions based on different sets of seed traits. (**a**) cluster generated from size-related traits (seed area, seed length, seed width, diameter area, volume and perimeter), (**b**) cluster generated from shape descriptors (ratio width/length, rectangularity, eccentricity, compactness, form factor, pointness and ratio width/area) and (**c**) cluster generated from colour attributes (hue, saturation and lightness)

4.1.6 Discussion

This study used videometer-based multispectral phenotyping to quantify seed morphometric diversity in Bambara groundnut. Highly significant differences were observed across all traits ($P < 0.05$; Table 4.1) among the 106 BGN accessions evaluated, indicating substantial phenotypic variation in seed size, shape, and colour. This aligns with findings in other underutilized legumes such as winged bean, where phenotypic diversity enabled the strategic selection of accessions from contrasting clusters for hybridization to obtain desirable trait combinations(Adebayo and Shonde, 2024).

Seed size descriptors (area, volume, perimeter) are known to relate to germination potential, seedling vigour, and market grading standards (Mandizvo and Odindo, 2019). Based on this, large-seeded accessions such as TVSu-320, TVSu-600, and TVSu-999 are likely suited to markets and end-uses that favour larger seeds, where size is linked to consumer preference and grading value. In contrast, smaller-seeded accessions such as TVSu-466 and TVSu-890 may be better suited to contexts where smaller seed size is preferred.

Shape descriptors (rectangularity, eccentricity, and compactness) discriminated accessions into elongated versus round seed types. Seed geometry is known to influence processing efficiency, dehulling behaviour, and cooking quality (Kiebre et al., 2025; Massawe et al., 2005); rounded, more compact seeds are typically preferred in markets valuing uniformity and ease of processing. Based on this, the round-seeded accessions identified in this study are likely suited to such consumer and processing contexts, while the more elongated accessions may be better suited to settings where seed geometry carries ecological or adaptive relevance rather than processing convenience.

Colour parameters revealed variation from very dark to cream-coloured seed coats, consistent with known regional preferences: cream-coloured seeds are preferred in Southern Africa (Pasipanodya et al., 2025), while red or darker types are valued in West Africa for their nutritional and processing qualities (Uba et al., 2022). Since market acceptance of new varieties is closely tied to visible seed traits(Fwanyanga et al., 2024; Mayes et al., 2019), the colour range captured here indicates that accessions in this panel may already align with preferences in different regional markets, depending on their specific seed coat colour.

AHC clustering grouped accessions by seed size, shape, and colour, producing groups broadly consistent with the market and use-related associations discussed above: accessions with large, round, light-coloured seeds clustered toward high-value consumer-preferred profiles, while smaller or darker-seeded accessions clustered toward profiles more relevant to local adaptation and nutritional use. These groupings offer a practical starting point for selecting contrasting parents in future crossing work, based on complementary seed trait profiles.

4.1.7 Conclusion

The study showed that the 106 BGN accessions evaluated exhibited substantial phenotypic variability in seed size, shape, and colour. The resulting descriptors distinguished accessions and revealed phenotypic structure useful for germplasm characterization and identification of contrasting parental material. The AHC groups are exploratory and dataset-specific and should not be interpreted as fixed classes or decision thresholds for new accessions. Integration of these descriptors into genomic selection, agronomic evaluation, or market-oriented selection will require further work using molecular data, replicated field trials, and consumer or end-user assessments. The findings therefore establish a standardized phenotyping foundation for identifying variability among BGN accessions, to be built on by future genetic and applied breeding work.

4.2 Evaluation of the performance of 104 Bambara groundnut accessions across test environments

4.2.1 Analysis of variance (ANOVA)

The ANOVA (Table 4.3) revealed significant effects of genotype, environment, and genotype × environment interaction on several agronomic and morphological traits of BGN. Genotypic effects were highly significant for most traits (DFE, D50E, PC, DTFF, DT50F, PH, PS, TLW and NPPP). However, genotype had no significant effect on TLL and YPP, indicating limited genetic variability for these traits among the evaluated genotypes.

Environmental effects were highly significant for all measured traits, demonstrating that environmental conditions strongly influenced crop performance. Particularly large environmental mean squares were observed for PH (3190.080), PS (70115.170), NPPP (31210.9), and YPP (14694.9), highlighting the strong influence of location or seasonal conditions on plant growth and productivity (Table 4.3).

The G × E interaction was significant for DFE, PC, DTFF, DT50F, PS, and TLW, indicating that the relative performance of genotypes for these traits varied across environments. In contrast, the interaction effect was not significant for D50E, PH, TLL, NPPP, and YPP, suggesting relatively stable genotypic responses across the test environments.

The ANOVA indicate substantial genetic variability among the evaluated BGN accessions for several key traits, while also emphasizing the strong influence of environmental conditions and the importance of multi-environment testing for reliable accession evaluation

Table 4.3: Analysis of Variance showing mean squares and significant tests for agronomic and morphological traits of 104 BGN accessions, including genotype, environment and genotype × environment interaction

Source of variation	d.f	DFE	D50E	PC	DTFF	DT50F	PH	PS	TLL	TLW	NPPP	YPP
Genotype (G)	103	2.770*	2.799*	91.120*	52.770*	77.840*	80.690*	120.090**	2.470ns	0.7445*	142.3*	299.300ns
Environment (E)	2	48.474**	30.167**	215.570**	497.030**	890.370**	3190.080**	70115.170**	439.202**	140.600**	31210.9**	14694.9**
G × E	206	1.132*	1.540ns	22.650*	27.240*	46.470*	65.150ns	95.690**	2.098ns	0.643*	119.4ns	315.9ns
Residual	624	0.925	1.392	13.840	12.180	19.710	56.460	48.400	2.297	0.521	101.100	290.500
Total	935											

*: Significant difference at the 5% probability level; **ns**: not significant; **d.f**.: degrees of freedom; **DFE**: days to first emergence; **D50E**: days to 50% emergence; **PC**: plant count; **DTFF**: days to first flowering; **DT50F**: days to 50% flowering; **PH**: plant height; **PS**: plant spread; **TLL**: terminal leaflet length; **TLW**: terminal leaflet width; **NPPP**: number of pods per plant; **YPP**: yield per plot.

4.2.2 Accessions performance across environments

The distribution of agronomic and morphological traits of BGN across the three test environments is illustrated using violin plots (Figure 4.6). These plots display the spread and central tendency of each trait, with the embedded boxplots indicating the median and interquartile ranges. Emergence traits showed narrow variability across environments. The mean DFE was 6.79 days in Ibadan, 6.50 days (Ikenne) and 6.01 days (Kano), indicating earlier emergence in Kano (Figure 4.6a). Similarly, D50E averaged 8.31 days in Ibadan, 8 days (Ikenne) and 8.67 days (Kano), reflecting variation among locations (Figure 4.6b).

The mean plant count (PC) was 9.65 plants in Ibadan, 11.33 in Ikenne, and 11.56 in Kano, suggesting better establishment in Ikenne and Kano than in Ibadan (Figure 4.6c). Flowering traits showed environmental influence. The mean days to first flowering (DTFF) was approximately 42.33 days in Ibadan, 40.57 days in Ikenne, and 39.64 days in Kano, indicating earlier flowering under the Kano environment (Figure 4.6d). Similarly, days to 50% flowering (DT50F) averaged 46.85 days in Ibadan, 46.33 days in Ikenne, and 44.67 days in Kano, suggesting faster reproductive development in Kano (Figure 4.6e).

Growth-related traits also varied across environments. The mean plant height (PH) was approximately 25.43 cm in Ibadan, 19.58 cm in Ikenne, and 23.06 cm in Kano, indicating taller plants in Ibadan (Figure 4.6f). In contrast, plant spread (PS) was greatest in Ibadan (56.15 cm), followed by Ikenne (35.33 cm) and Kano (28.35 cm), demonstrating wider canopy development at Ibadan (Figure 4.6g).

Leaf morphological traits showed moderate variation. The mean TLL (Figure 4.6h) was 7.15 cm in Ibadan, 4.95 cm in Ikenne, and 6.09 cm in Kano, while TLW (Figure 4.6i) averaged 3.13 cm in Ibadan, 1.94 cm in Ikenne, and 2.55 cm in Kano, indicating generally larger leaves under the Ibadan environment. Yield-related traits exhibited considerable variation among locations. The mean number of pods per plant (NPPP) was highest in Ibadan (≈24.55 pods), compared with 4.91 pods in Ikenne and 9.46 pods in Kano (Figure 4.6j). Similarly, YPP was greatest in Ibadan (≈22.52), followed by Kano (≈14.73) and Ikenne (≈10.71) (Figure 4.6k).

The distributions indicate clear environmental effects on plant growth and yield performance, with Ibadan generally supporting superior vegetative growth and productivity, while Ikenne showed comparatively lower performance for several yield-related traits

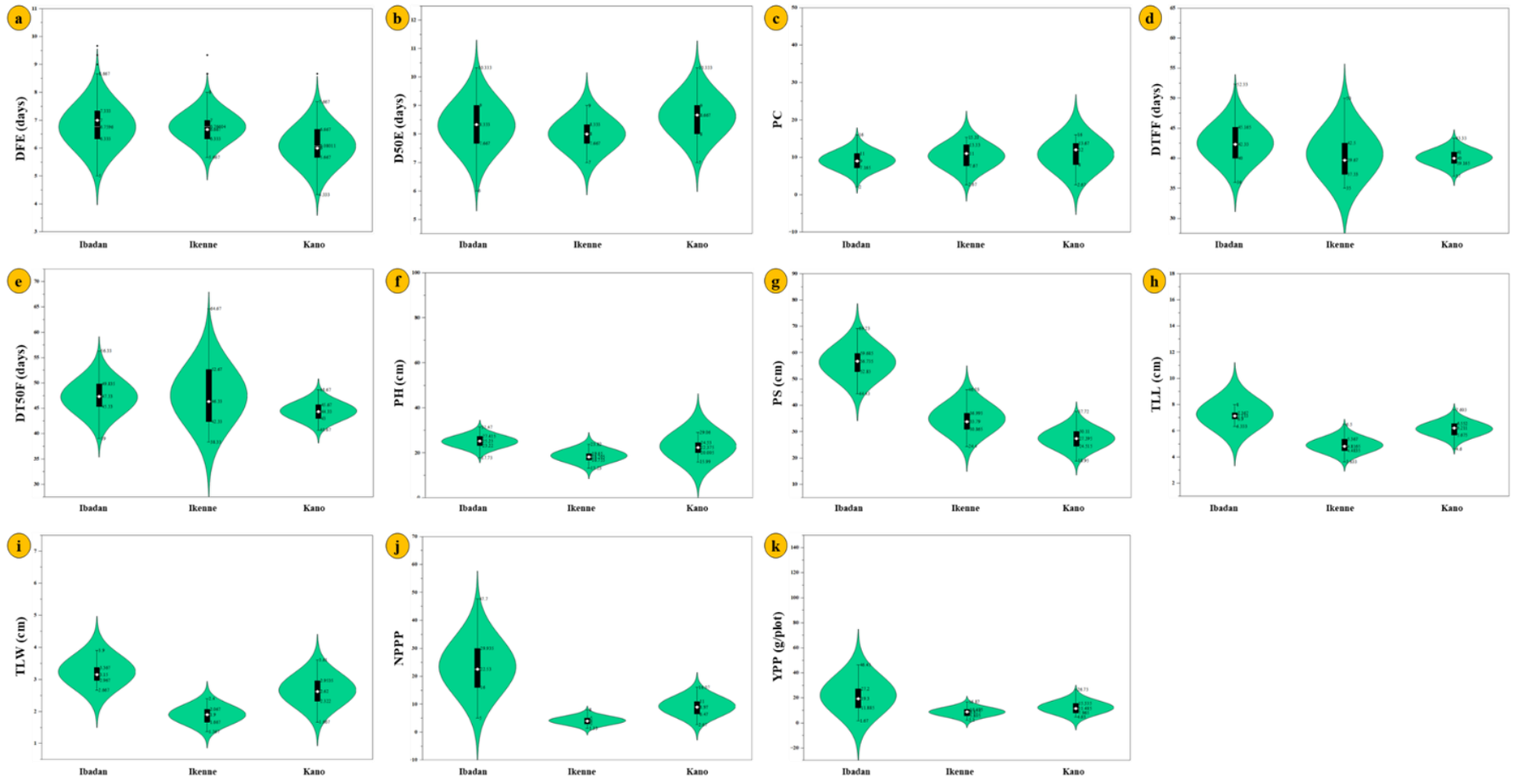

Figure 4.6: Violin plots showing the distribution of agronomic and morphological traits of Bambara groundnut accessions evaluated across three environments (Ibadan, Ikenne, and Kano). Panels represent: (a) days to first emergence (DFE), (b) days to 50% emergence (D50E), (c) plant count (PC), (d) days to first flowering (DTFF), (e) days to 50% flowering (DT50F), (f) plant height (PH), (g) plant spread (PS), (h) terminal leaflet length (TLL), (i) terminal leaflet width (TLW), (j) number of pods per plant (NPPP)s and (k) yield per plot (YPP).

4.2.3 GGE biplots

The GGE biplots based on the Average Environment Coordination (AEC) method were used to evaluate genotype performance and stability across the three environments (Ibadan, Ikenne, and Kano), D50E, DT50F, NPPP and YPP (Figure 4.7). In these plots, the AEC abscissa indicates the direction of higher mean trait values across environments, and the AEC ordinate represents genotype stability, with genotypes closer to the axis being more stable.

For D50E (Figure 4.7a), most genotypes were clustered around the origin, indicating relatively small genotype × environment interaction effects for this trait. Environments (Ibadan and Ikenne) were positioned in a similar direction along the positive side of the AEC axis, suggesting a positive correlation between these locations in discriminating genotypes for emergence. In contrast, Kano was in a different direction, suggesting that it provided distinct environmental conditions that influenced emergence behaviour. A few genotypes located farther along the positive end of the AEC axis exhibited higher mean D50E values, whereas those positioned at the negative end showed relatively earlier emergence.

For DT50F (Figure 4.7b), a similar clustering pattern of genotypes around the origin was observed, suggesting moderate stability of most genotypes across environments. Ibadan showed a longer vector than the other environments, indicating a stronger discriminating ability for days to flowering. Ikenne was positioned farther from the origin along the horizontal axis, but in a slightly different direction from Ibadan, suggesting variation in the environmental influence on flowering time. Kano, which was positioned closer to the origin, appeared less discriminating for this trait.

In the case of NPPP (Figure 4.7c), most genotypes again clustered near the origin, indicating relatively small differences in genotype performance across environments. The environment in Ibadan was located farther along the AEC axis than those in Ikenne and Kano, suggesting that it made a stronger contribution to genotype differentiation for pod production. Ikenne and Kano were positioned closer to the origin and exhibited similar orientations, indicating comparable environmental influences on pod number.

For YPP (Figure 4.7d), the distribution of genotypes around the origin suggests that most genotypes exhibited moderate stability across environments for yield per plot. Ibadan was positioned far from the origin along the positive direction of the AEC axis, indicating that it was the most discriminating environment for identifying high-yielding genotypes. In contrast, Ikenne and Kano were located closer to the origin, suggesting relatively lower discriminating ability for yield evaluation. A few genotypes positioned toward the positive end of the AEC axis demonstrated superior mean yield performance, whereas those positioned toward the negative end showed relatively lower yield across environments.

The AEC-based GGE biplots indicate that Ibadan generally showed stronger discrimination across most traits, while Ikenne and Kano exhibited relatively moderate or similar environmental effects. The clustering of most genotypes near the origin across all traits suggests relatively stable genotype performance with limited crossover genotype × environment interaction, although some genotypes showed specific adaptation to particular environments.

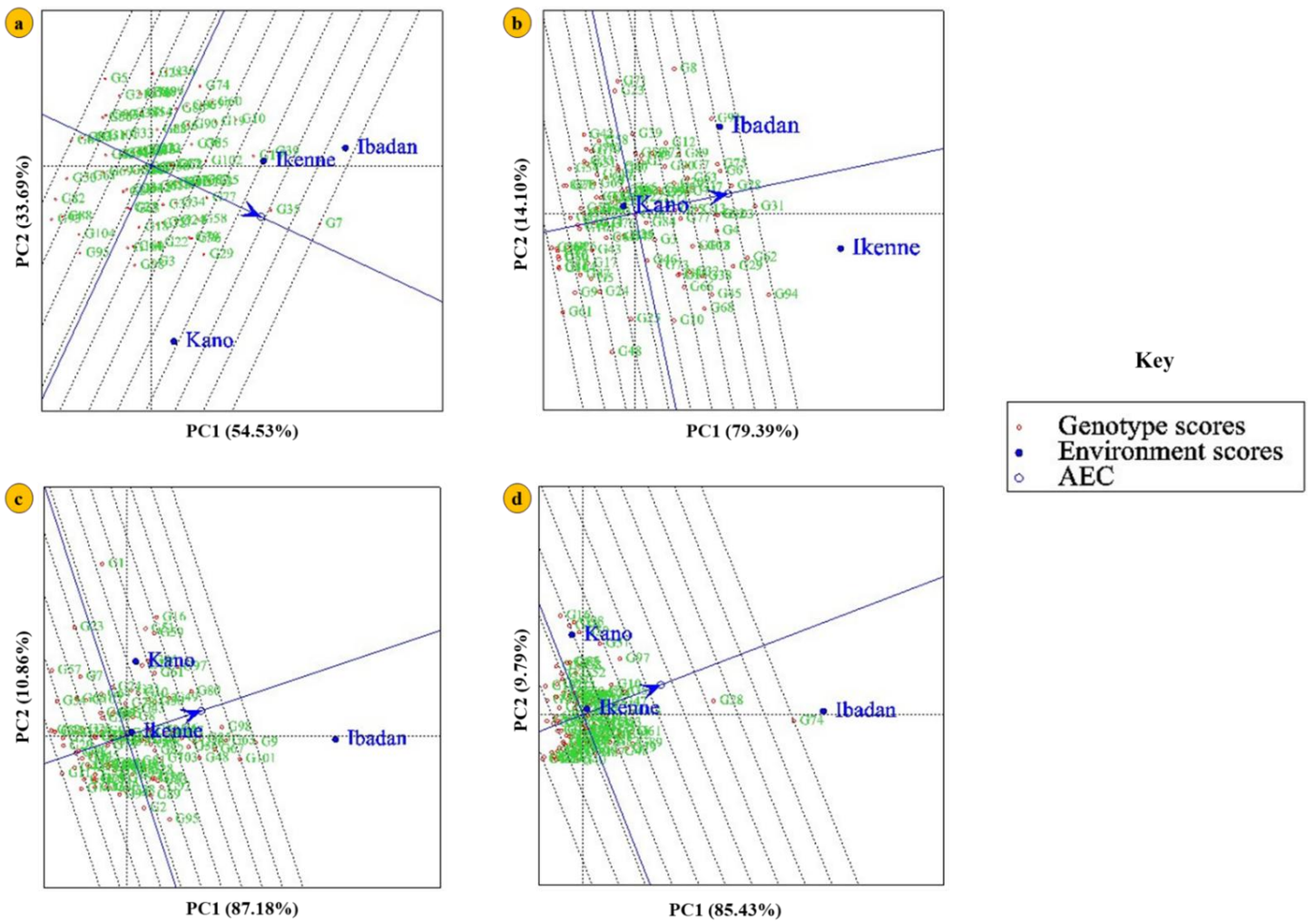

Figure 4.7: GGE biplots based on the average environment coordination (AEC) method showing the mean performance and stability of Bambara groundnut accessions across three environments (Ibadan, Ikenne and Kano) for different agronomic traits. Panels represent (**a**) days to 50% emergence (D50E), (**b**) days to 50% flowering (DT50F), (**c**) number of pods per plant (NPPP) and (**d**) yield per plot (YPP).

4.2.1 Principal Component Analysis (PCA) and Pearson correlation

Principal component analysis (PCA) was conducted separately for the agronomic traits measured in Ibadan, Ikenne and Kano to determine the major traits contributing to variation among BGN accessions. At Ibadan, the first four principal components (PC1–PC4) had eigenvalues of 2.789, 1.617, 1.507, and 1.185, explaining 25.35%, 14.70%, 13.70%, and 10.77% of the total variation, respectively, with a cumulative contribution of 64.53%. PC1 was mainly influenced by DFE (0.340), D50E (0.346), DTFF (0.442) and DT50F (0.384), indicating that phenological traits contributed strongly to the first component. PC2 was largely associated with PC (0.468), PH (0.442), PS (0.385) and DT50F (0.477). PC3 was mainly influenced by DFE (0.553) and DK50E (0.513), while TLL (0.674) and YPP (0.453) contributed strongly to PC4 (Table 4.4).

At Ikenne, the first four PCs accounted for 66.08% of the total variation, with eigenvalues of 2.556, 1.967, 1.471, and 1.274, respectively, explaining 23.24%, 17.88%, 13.37%, and 11.59% of the variation. PC1 was primarily associated with DFE (0.478), D50E (0.417), DTFF (0.471), and DT50F (0.483), indicating that emergence and flowering traits were the main drivers of variation. PC2 showed strong contributions from the NPPP (0.563) and YPP (0.557). PC3 was mainly influenced by PH (0.465) and PS (0.498), whereas TLL (0.516) and D50E (0.400) contributed substantially to PC4 (Table 4.4).

In Kano, the first four PCs had eigenvalues of 2.512, 1.624, 1.512, and 1.365, accounting for 22.83%, 14.76%, 13.75%, and 12.41% of the total variation, respectively, with a cumulative contribution of 63.75%. PC1 was mainly associated with PC (0.329), DTFF (0.323), NPPP (0.280) and YPP (0.271), while emergence traits DFE (-0.461) and D50E (-0.484) had strong negative contributions. PC2 was strongly influenced by PH (0.601) and plant count PC (0.565). PC3 was dominated by NPPP (0.626) and YPP (0.598), indicating that yield-related traits contributed strongly to this component. PC4 was mainly associated with TLL (0.671) and TLW (0.568) (Table 4.4).

The PCA results indicate that phenological traits (emergence and flowering) were the major contributors to variation at Ibadan and Ikenne, whereas yield-related traits (NPPP and YPP) and plant architecture traits contributed more strongly to variation at Kano, highlighting differences in trait expression across environments

Table 4.4: Principal component analysis (PCA) loadings of agronomic traits for Bambara groundnut genotypes evaluated at three environments (Ibadan, Ikenne and Kano)

	Ibadan				Ikenne				Kano			
Trait(s)	**PC1**	**PC2**	**PC3**	**PC4**	**PC1**	**PC2**	**PC3**	**PC4**	**PC1**	**PC2**	**PC3**	**PC4**
DFE	0.340	0.004	0.553	-0.006	0.478	-0.064	0.114	0.349	-0.461	0.268	0.329	0.223
D50E	0.346	0.033	0.513	0.031	0.417	-0.198	0.005	0.400	-0.484	0.310	0.235	0.194
PC	-0.236	0.468	-0.142	-0.098	-0.306	0.023	-0.293	-0.050	0.329	0.565	-0.016	-0.047
DTFF	0.442	0.323	-0.203	0.226	0.471	0.036	0.092	-0.400	0.323	0.184	0.063	0.245
DT50F	0.384	0.477	-0.194	0.190	0.483	0.063	-0.034	-0.350	0.130	0.184	-0.127	-0.122
PH	-0.315	0.442	0.172	-0.051	-0.166	-0.394	0.465	0.039	0.246	0.601	0.036	-0.031
PS	-0.332	0.385	0.239	0.032	-0.104	-0.389	0.498	0.142	0.236	-0.100	-0.105	-0.245
TLL	-0.040	-0.037	-0.253	0.674	0.025	0.056	-0.376	0.516	0.151	-0.117	-0.134	0.671
TLW	-0.174	-0.310	0.014	0.404	0.081	0.118	-0.062	0.338	0.180	-0.065	-0.192	0.568
NPPP	-0.352	0.041	0.277	0.275	-0.050	0.563	0.388	0.121	0.280	-0.127	0.626	0.008
YPP	-0.035	0.067	0.323	0.453	-0.029	0.557	0.361	0.130	0.271	-0.202	0.598	0.032
Eigenvalue	2.789	1.617	1.507	1.185	2.556	1.967	1.471	1.274	2.512	1.624	1.512	1.365
Variability (%)	25.350	14.704	13.700	10.772	23.237	17.882	13.372	11.585	22.832	14.761	13.745	12.407
Cumulative (%)	25.350	40.054	53.754	64.526	23.237	41.119	54.491	66.075	22.832	37.594	51.339	63.746

DFE: days to first emergence; **D50E**: days to 50% emergence; **PC**: plant count; **DTFF**: days to first flowering; **DT50F**: days to 50% flowering; **PH**: plant height; **PS**: plant spread; **TLL**: terminal leaflet length; **TLW**: terminal leaflet width; **NPPP**: number of pods per plant; **YPP**: yield per plot

PC biplots and correlation matrices were used to examine the relationships among agronomic traits of BGN accession across the three environments (Figure 4.8). In Ibadan (Figures 4.8a and 4.8b), the PC biplot revealed clear clustering of traits. Phenological traits, including DFE, D50E, DTFF and DT50F, were closely aligned, indicating strong positive (+ve) associations among these traits. This relationship was supported by the correlation matrix, which showed strong positive correlations between DFE and D50E (r = 0.66) and between DTFF and DT50F (r = 0.83). Plant architectural traits (PH, PS and PC) formed another cluster, while yield-related traits (NPPP and YPP) showed relatively weak correlations with most phenological traits.

At Ikenne (Figures 4.8c and 4.8d), the PC biplot indicated a similar grouping pattern, with emergence and flowering traits clustering together. The correlation matrix further confirmed strong positive relationships between DFE and D50E (r = 0.68) and between DTFF and DT50F (r = 0.78). Yield per plot (YPP) showed a strong positive association with NPPP (r = 0.74), indicating that pod number was the major contributor to yield performance in this environment. Plant height (PH) was moderately correlated with plant spread (PS; r = 0.56), suggesting coordinated expression of plant architecture traits.

In Kano (Figures 4.8e and 4.8f), the PC biplot showed a clearer separation of trait groups. Emergence traits (DFE and D50E) were strongly associated and showed opposite relationships with several yield-related traits, indicating contrasting relationships. The correlation matrix confirmed a strong positive correlation between DFE and D50E (r = 0.87). Yield per plot (YPP) was strongly correlated with NPPP (r = 0.63), again highlighting the importance of pod number in determining yield. Additionally, PC showed a strong +ve association with PH (r = 0.67).

Both PC biplots and correlation matrices consistently indicated strong associations among emergence traits and flowering traits across environments, while yield per plot was mainly driven by the number of pods per plant. Differences in trait associations among environments further suggest that environmental conditions influenced the expression and relationships of key agronomic traits among the BGN accessions.

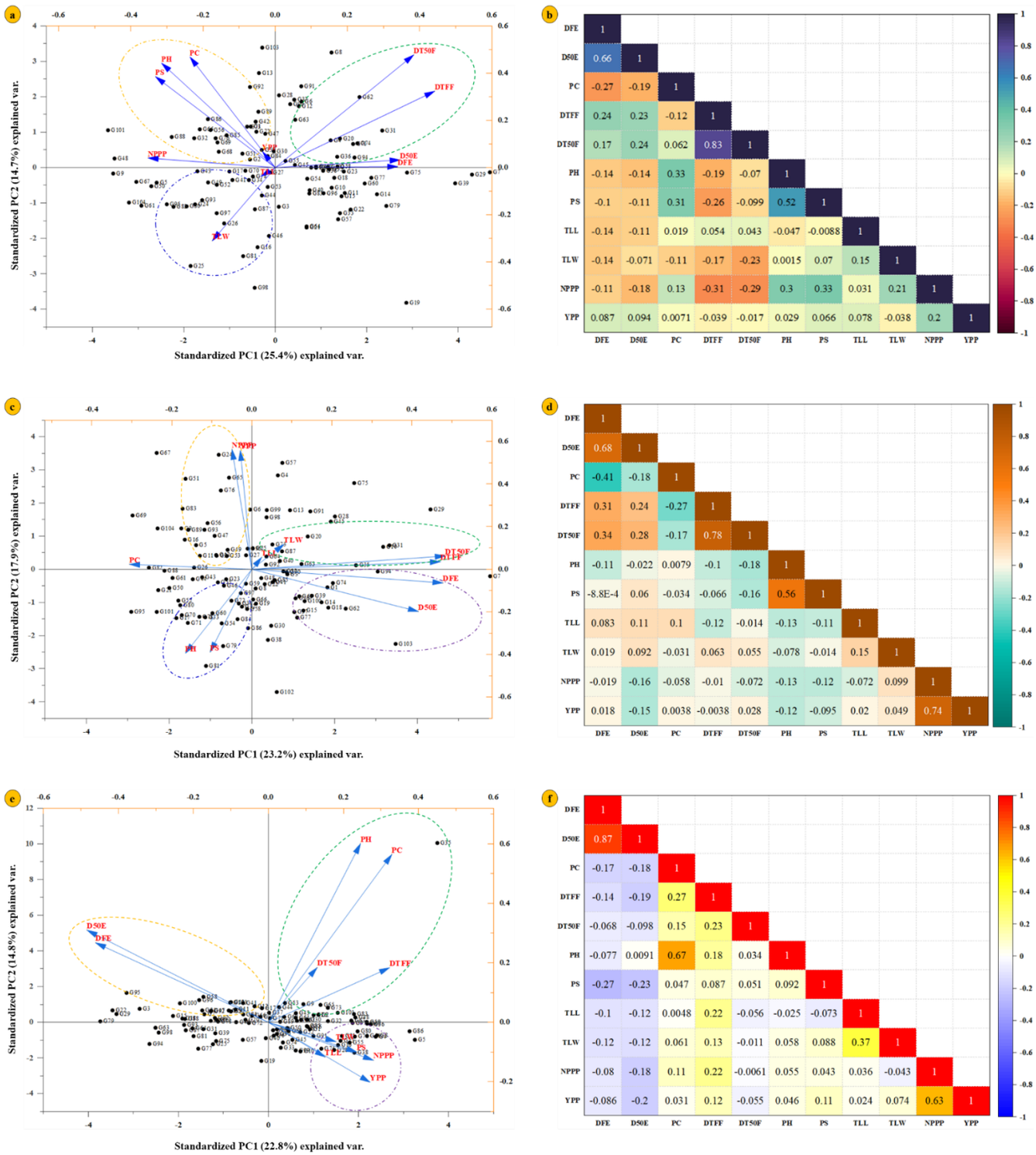

Figure 4.8: Principal component (PC) biplots and correlation matrices illustrating the relationships among agronomic traits of Bambara groundnut accessions evaluated across three environments. Panels (**a**), (**c**) and (**e**) show the principal component biplots for Ibadan, Ikenne and Kano, respectively. Panels (**b**), (**d**) and (**f**) present the corresponding correlation matrices for Ibadan, Ikenne and Kano, respectively, showing the pairwise relationships among measured traits.

4.2.2 Agglomerative hierarchical clustering (AHC)

Based on yield per plot across three environments, the accessions were classified into five groups (Figure 4.9). Group A (highest yielding) comprised of 28 accessions, including TVSu-1018, TVSu-205, TVSu-460, TVSu-521, TVSu-3, TVSu-474, TVSu-486, TVSu-1112, TVSu-358, TVSu-501, TVSu-1249, TVSu-6, TVSu-738 and TVSu-515)

Group B (high yielding) comprised of 18 accessions (TVSu-11, TVSu-438, TVSu-887, TVSu-1217, TVSu-758, TVSu-454, TVSu-600, TVSu-345, TVSu-488, TVSu-751, TVSu-1126, TVSu-1256, TVSu-464, TVSu-1221, TVSu-329, TVSu-467, TVSu-658 and TVSu-323) (Figure 4.9). Similarly, group C included 2 accessions (TVSu-211 and TVSu-553) with intermediate yield per plot and is considered intermediate yielding (Figure 4.9).

Group D comprised of 25 accessions including TVSu-1027, TVSu-327, TVSu-212, TVSu-341, TVSu-1102, TVSu-476, TVSu-883, TVSu-402, TVSu-8, TVSu-1168, TVSu-492, TVSu-1066, TVSu-653, TVSu-216, TVSu-673, TVSu-755, TVSu-783, TVSu-928, TVSu- 1187, TVSu-480 and TVSu-315, and they are clustered as low yielding accessions.

Group E (Figure 4.9) comprised 31 accessions including TVSu-1108, TVSu-325, TVSu-470, TVSu-536, TVSu-1243, TVSu-491, TVSu-709, TVSu-326, TVSu-1251, TVSu-528, TVSu-933, TVSu-506, TVSu-764, TVSu-757 and TVSu-999; they are clustered as lowest yielding accessions.

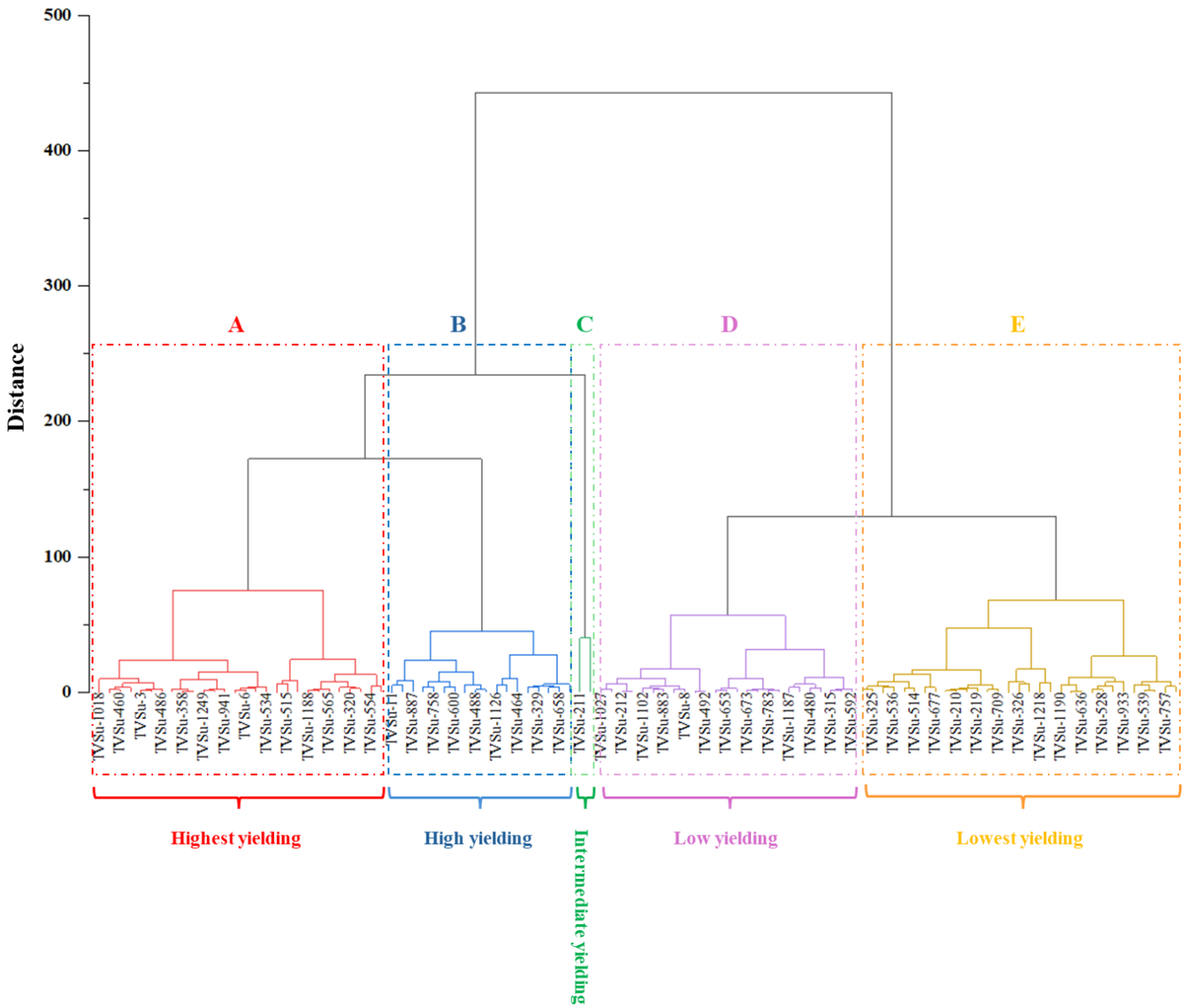

Figure 4.9: Hierarchical cluster dendrogram showing the grouping of Bambara groundnut accessions based on yield performance across three environments

4.3 Discussion

This study provides a comprehensive multi-environment trial (MET) evaluation of 104 BGN accessions across three contrasting agroecological zones in Nigeria. The results demonstrate substantial phenotypic variation among accessions and an association between environment and trait expression, including yield performance. These findings reinforce the importance of METs in identifying accessions with broad or specific phenotypic adaptation for breeding programs targeting climate-resilient cropping systems in SSA.

The ANOVA revealed significant accession effects for agronomic traits, indicating substantial phenotypic diversity within evaluated germplasm. Traits such as days to emergence, flowering time, plant architecture, and pod number displayed significant variation among accessions. This is consistent with previous studies reporting substantial phenotypic diversity among BGN landraces and germplasm collections (Aliyu et al., 2014; Louis et al., 2025; Ntundu et al., 2006; Siwale et al., 2022). This diversity is a useful starting point for breeding programs seeking to improve yield stability, stress tolerance and agronomic performance.

Environmental effects were highly significant for all measured traits, indicating that the growing locations strongly influenced BGN growth and development. The large environmental mean squares observed for PS, PH, NPPP, and YPP (Table 4.3) indicate their sensitivity to environmental variation. This observation aligns with previous findings indicating that BGN productivity is influenced by environmental conditions, particularly rainfall patterns and soil fertility (Mabhaudhi et al., 2018; Olanrewaju et al., 2021) The environmental influence observed in this study underscores the need to evaluate germplasm across diverse agro ecological conditions to ensure reliable genotype selection.

Significant G × E interactions were detected for several traits, including emergence time, flowering traits, plant count, plant spread, and leaflet width, indicating that the relative ranking of accessions differed across environments. Such interactions complicate selection because relative performance was not consistent across sites. Similar observations have been reported in BGN and other legumes, where G × E interactions influenced yield stability and trait expression (Linus et al., 2023; Mametja et al., 2025; Ruzive et al., 2025).

In contrast, NPPP and YPP did not show a significant G × E interaction, indicating relatively consistent ranking of accessions for these two traits across the three environments tested. This consistency suggested that certain accessions possessed comparatively stable performance across the environments evaluated (Kunene et al., 2024). From a breeding perspective, traits with low G × E interaction were valuable, as they enabled more reliable selection of superior accessions across multiple environments. The results therefore suggested that pod production and overall yield performance could serve as relatively stable selection criteria in BGN breeding programs targeting broad adaptation.

The contrasting agroecological conditions of the test locations were associated with clear differences in trait expression and yield performance. The violin plot analysis showed that Ibadan generally supported greater vegetative growth and productivity, with higher values for PH, PS, NPPP, and YPP than the other environments, likely reflecting its higher rainfall and more favourable soil conditions.

The Kano environment, characterized by lower rainfall and higher temperatures, was associated with earlier emergence and flowering. Early flowering under water-limited conditions is often considered a drought-escape mechanism, allowing plants to complete their reproductive cycle before severe moisture deficits occur (Mandizvo et al., 2022); the accelerated phenology observed at Kano was consistent with this adaptive response.

Ikenne generally recorded lower yields than the other environments, likely reflecting its humid forest agroecology. Because BGN produces small, fragile flowers close to the soil surface, the heavy rainfall at Ikenne may have caused mechanical damage to flowers or disrupted pollination and pegging before fertilization. Excessive soil moisture in this high-rainfall zone can also promote root-zone anoxia and nutrient leaching, both of which limit pod development and seed yield.

GGE biplot analysis provided further insight into accession performance, stability, and environmental discriminating ability. The clustering of most accessions near the biplot origin indicated relatively small G × E effects for several traits, consistent with moderate stability across environments. Accessions positioned closer to the average environment coordination (AEC) axis showed greater stability, while those further from the axis were more environment-sensitive.

The test environments also differed in discriminating ability. Ibadan showed the longest environmental vector for several traits, indicating strong discriminating power and suggesting it may be a particularly useful location for selecting superior BGN accessions. Ikenne and Kano, positioned closer to the origin, showed lower discriminating power for certain traits. These patterns aligned with the GGE biplot framework, which emphasizes identifying environments that are both discriminating and representative for effective genotype evaluation(Esan et al., 2023; Mullualem et al., 2024; Olanrewaju et al., 2021). In practical breeding terms, discriminating environments are valuable for identifying high-performing accessions, while representative environments are useful for selecting broadly adapted material.

Principal component analysis and correlation analysis revealed clear associations among agronomic traits across environments. Phenological traits, including emergence and flowering parameters, consistently clustered together and were strongly positively correlated, indicating coordinated timing of developmental events: accessions that emerged earlier also tended to flower earlier. Similar phenological associations have been reported in BGN and other legumes (Esan et al., 2023).

Yield per plot was strongly positively correlated with NPPP, particularly at Ikenne and Kano, supporting pod number as a major component of yield in BGN. Previous studies have also identified pod number as a key yield component in the crop (Mohammed et al., 2018). This association suggested that selecting for increased pod production could be an effective breeding strategy for improving yield. Yield traits showed relatively weak correlations with phenological traits in some environments, suggesting that reproductive output was shaped by additional factors such as resource allocation and plant architecture, highlighting the complexity of yield determination in BGN.

Hierarchical clustering based on yield performance grouped the evaluated accessions into five clusters, ranging from highest- to lowest-yielding. Accessions in the highest- and high-yielding clusters represented promising candidates for direct varietal development or as parental lines in breeding programs. The presence of multiple yield clusters also reflected substantial phenotypic diversity within the germplasm collection, valuable for maintaining a broad genetic base and enhancing the long-term adaptability of improved cultivars. The intermediate- and low-yielding clusters provided further insight into trait variation and potential constraints on productivity.

These findings have practical implications for developing climate-resilient BGN varieties. Accessions with stable performance across environments offer opportunities for broadly adapted cultivars, while accessions with strong site-specific performance may be exploited for targeted breeding in particular agroecological zones.

Given the increasing challenges posed by climate change, including drought and soil degradation, BGN offers considerable potential for enhancing food security in SSA. Its ability to produce reasonable yields under marginal conditions makes it an attractive crop for diversifying agricultural systems and improving nutritional security (Soumare et al., 2022; Tan et al., 2020)

4.4 Conclusion

This study evaluated 104 BGN accessions across three contrasting agroecological environments in Nigeria to assess agronomic performance, G × E interactions, and yield stability. Substantial phenotypic variability was observed among accessions for most agronomic traits, indicating valuable genetic resources for BGN improvement. Environmental effects were also highly significant, indicating that location strongly influenced crop growth and productivity. Although G × E interactions were significant for several traits, key yield components: NPPP and YPP showed relatively stable performance across environments, suggesting the potential for selecting accessions with broad adaptation.

Multivariate analyses showed that phenological traits contributed most strongly to variation at the southern sites (Ibadan and Ikenne), while yield-related traits contributed more strongly at the northern site (Kano). Correlation analysis confirmed pod number as the primary determinant of yield in BGN.

Hierarchical clustering identified distinct accession groups based on yield performance, including several high-yielding accessions that represented promising breeding candidates. These findings offer valuable insight into BGN improvement and underscore the importance of METs for identifying stable, high-performing accessions. The study contributes to the growing evidence supporting BGN as a climate-resilient crop with significant potential to enhance food security and agricultural sustainability in SSA. Future breeding efforts should integrate the identified high-performing accessions into breeding programs and expand multi-location evaluation to further refine selection across diverse agroecological environments.

Chapter 5: General Conclusions and Recommendations

4.5 General Conclusion

This study demonstrated that videometer-based multispectral imaging provided a rapid, precise, and non-destructive approach for characterizing BGN seed traits. The technology generated reproducible multidimensional measurements of seed size, shape, and colour, revealing substantial phenotypic variation among the evaluated accessions. These results highlighted the potential of MSI as a high-throughput phenotyping tool that could complement conventional breeding methods by providing standardized, objective seed descriptors an approach that could be integrated into breeding pipelines to improve selection accuracy, facilitate trait mapping, and support breeding objectives around seed quality, consumer preference, and market competitiveness.

The multi-environment evaluation of 104 BGN accessions across three contrasting agroecological environments in Nigeria revealed substantial phenotypic variability for most agronomic traits, indicating valuable genetic resources for crop improvement. Environmental effects were also highly significant, demonstrating that location strongly influenced BGN growth and productivity. Although G × E interactions were observed for several traits, key yield components: NPPP and YPP showed relatively stable responses across environments, suggesting the feasibility of selecting accessions with broad adaptation.

Overall, these findings highlight the value of combining advanced phenotyping tools with multi-environment evaluation to accelerate genetic improvement in this climate-resilient crop. The high-performing accessions and phenotypic data identified here provide valuable resources for BGN breeding programs aimed at developing high-yielding, stable, and market-preferred varieties across diverse agroecological conditions in sub-Saharan Africa.

4.6 General Recommendations

(i) Videometer-based multispectral imaging (MSI) should be incorporated into Bambara groundnut breeding programs as a standardized, high-throughput phenotyping tool for seed traits.

(ii) The high-yielding and relatively stable accessions identified in this study should be further evaluated and incorporated into Bambara groundnut breeding programs as potential parental lines.

(iii) Future research should focus on genotypic characterization of the evaluated germplasm using molecular markers, to facilitate trait mapping, strengthen selection strategies, and accelerate genetic improvement in Bambara groundnut.

References

Abberton, M., Paliwal, R., Faloye, B., Marimagne, T., Moriam, A., Oyatomi, O., 2022. Indigenous African Orphan Legumes: Potential for Food and Nutrition Security in SSA. Front. Sustain. Food Syst. 6. https://doi.org/10.3389/fsufs.2022.708124

Adebayo, M.A., Shonde, T.E., 2024. Phenotypic diversity within winged bean (Psophocarpus tetragonolobus L.) accessions. J. Underutilized Legum. 6, 31–42.

Ahmad, N.S., Redjeki, E.S., Ho, W.K., Aliyu, S., Mayes, K., Massawe, F., Kilian, A., Mayes, S., 2016. Construction of a genetic linkage map and QTL analysis in bambara groundnut. Genome 59, 459–472. https://doi.org/10.1139/gen-2015-0153

Aliyu, S., Massawe, F., Mayes, S., 2014. Beyond landraces: developing improved germplasm resources for underutilized species – a case for Bambara groundnut. Biotechnol. Genet. Eng. Rev. 30, 127–141. https://doi.org/10.1080/02648725.2014.992625

Bhadmus, A., Abberton, M., Idehen, E., Ekanem, U., Paliwal, R., Oyatomi, O., 2023. Genetic Diversity Assessment of Winged Bean [Psophocarpus tetragonolobus (L.) DC.] Accessions Using Agronomic and Seed Morphometric Traits. Crops 3, 170–183. https://doi.org/10.3390/crops3020017

Booy, G., Hendriks, R.J.J., Smulders, M.J.M., Groenendael, J.M.V., Vosman, B., 2000. Genetic Diversity and the Survival of Populations. Plant Biol. 2, 379–395. https://doi.org/10.1055/s-2000-5958

Boraiah, K.M., Shendekar, S., Shinde, C., Basavaraj, P.S., Pradhan, A., Harisha, C.B., Halli, H.M., Pal, K.K., Reddy, K.S., 2024. Bambara Groundnut (Vigna subterranea (L.) Verdc.), in: Potential Pulses, CABI Books. pp. 217–240. https://doi.org/10.1079/9781800624658.0012

Chandora, R., Basavaraja, T., Pratap, A., 2024. Potential Pulses: Genetic and Genomic Resources. CABI.

Descriptors for Bambara Groundnut: Vigna Subterranea, 2000. . Bioversity International.

Esan, V.I., Oke, G.O., Ogunbode, T.O., 2023a. Genetic variation and characterization of Bambara groundnut [Vigna subterranea (L.) verdc.] accessions under multi-environments considering yield and yield components performance. Sci. Rep. 13, 1498. https://doi.org/10.1038/s41598-023-28794-8

Esan, V.I., Oke, G.O., Ogunbode, T.O., Obisesan, I.A., 2023b. AMMI and GGE biplot analyses of Bambara groundnut [Vigna subterranea (L.) Verdc.] for agronomic performances under three environmental conditions. Front. Plant Sci. 13. https://doi.org/10.3389/fpls.2022.997429

Fwanyanga, F.M., Horn, L.N., Sibanda, T., Reinhold-Hurek, B., 2024. Bambara groundnuts [Vigna subterranea (L.)Verdc] Production Systems in Kavango East Region, Northern Namibia. Indian J. Agric. Res. 58, 1087. https://doi.org/10.18805/IJARe.AF-838

IPGRI, IITA, BAMNET, 2000. Descriptors for bambara groundnut (Vigna subterranea). International Plant Genetic Resources Institute, International Institute of Tropical Agriculture, & International Bambara Groundnut Network. (Rome, Italy: IPGRI; Ibadan, Nigeria: IITA; Germany: BAMNET).

Khan, M.H., Rafii, M.Y., Ramlee, S.I., Jusoh, M., 2022. Bambara Groundnut (Vigna Subterranea L. Verdc): A Model Underutilized Legume, its Resiliency to Drought and Excellency of Food & Nutrient values -A Review 2.

Khan, M.M.H., Rafii, M.Y., Ramlee, S.I., Jusoh, M., Al Mamun, M., 2021. Genetic analysis and selection of Bambara groundnut (Vigna subterranea [L.] Verdc.) landraces for high yield revealed by qualitative and quantitative traits. Sci. Rep. 11, 7597. https://doi.org/10.1038/s41598-021-87039-8

Khan, M.M.H., Rafii, M.Y., Ramlee, S.I., Jusoh, M., Al-Mamun, M., 2024. Bambara groundnut (Vigna subterranea L.): A climate-resilient crop to address food and nutritional security. J. Underutil. Crops Res. 3, 12. https://doi.org/10.4102/jucr.v3i1.2

Khan, M.M.H., Rafii, M.Y., Ramlee, S.I., Jusoh, M., Oladosu, Y., Al Mamun, M., Khaliqi, A., 2022. Unveiling Genetic Diversity, Characterization, and Selection of Bambara Groundnut (Vigna subterranea L. Verdc) Genotypes Reflecting Yield and Yield Components in Tropical Malaysia. BioMed Res. Int. 2022, 6794475. https://doi.org/10.1155/2022/6794475

Kiebre, Z., Kiebre, M., Nanema, R.K., Tietiambou, F.R.S., Zerbo, C., Tonde, I., De Muro, P., El Bilali, H., Acasto, F., Nanema, J., 2025. Participatory Selection of Bambara Groundnut Landraces in Burkina Faso: Effects of Gender and Participant Diversity. Agriculture 15, 1769. https://doi.org/10.3390/agriculture15161769

Kunene, S., Gerrano, A.S., Odindo, A.O., 2024. Stability and performance of Bambara groundnut (Vigna subterranea (L.) Verdc.) genotypes in different South African environments. South Afr. J. Plant Soil 41, 83–94. https://doi.org/10.1080/02571862.2024.2420109

Linus, R.A., Olanrewaju, O.S., Oyatomi, O., Idehen, E.O., Abberton, M., 2023. Assessment of Yield Stability of Bambara Groundnut (Vigna subterranea (L.) Verdc.) Using Genotype and Genotype–Environment Interaction Biplot Analysis. Agronomy 13, 2558. https://doi.org/10.3390/agronomy13102558

Louis, Y., Moses, M., Michael, C., Davis, G., Abel, S., Lawrent, P., Vicki, M., Peter, S., Wisdom, C., 2025. Diversity among Bambara groundnut (Vigna subterranea L. Verdc) accessions using agro-morphological traits and diversity array technologies sequence low density markers in Malawi. Genet. Resour. Crop Evol. 72, 3219–3233. https://doi.org/10.1007/s10722-024-02158-1

Mabhaudhi, T., Chibarabada, T.P., Chimonyo, V.G.P., Modi, A.T., 2018. Modelling climate change impact: A case of bambara groundnut (Vigna subterranea). Phys. Chem. Earth 105, 25–31. https://doi.org/10.1016/j.pce.2018.01.003

Mametja, S., Mandizvo, T., Shayanowako, A., Musimwa, T., Chai, H.H., Massawe, F., Sibiya, J., Mabhaudhi, T., 2025. Agro-morphological diversity and yield potential of Bambara groundnut (*Vigna subterranea* L. Verdc.) recombinant inbred lines evaluated across multiple environments in KwaZulu-Natal, South Africa. CABI Agric. Biosci. 0074. https://doi.org/10.1079/ab.2025.0074

Mandizvo, T., Odindo, A.O., 2019. Seed mineral reserves and vigour of Bambara groundnut (Vigna subterranea L.) landraces differing in seed coat colour. Heliyon 5. https://doi.org/10.1016/j.heliyon.2019.e01635

Mandizvo, T., Odindo, A.O., Mashilo, J., Magwaza, L.S., 2022. Drought tolerance assessment of citron watermelon (*Citrullus lanatus* var. *citroides* (L.H. Bailey) Mansf. ex Greb.) accessions based on morphological and physiological traits. Plant Physiol. Biochem. 180, 106–123. https://doi.org/10.1016/j.plaphy.2022.03.037

Maphosa, Y., Jideani, V.A., Maphosa, L., 2022. Bambara groundnut production, grain composition and nutritional value: opportunities for improvements. J. Agric. Sci. 160, 448–458. https://doi.org/10.1017/S0021859622000521

Massawe, F.J., Mwale, S.S., Azam-Ali, S.N., Roberts, J.A., 2005. Breeding in bambara groundnut (Vigna subterranea (L.) Verdc.): strategic considerations. Afr. J. Biotechnol. 4, 463–471.

Mayes, S., Ho, W.K., Chai, H.H., Gao, X., Kundy, A.C., Mateva, K.I., Zahrulakmal, M., Hahiree, M.K.I.M., Kendabie, P., Licea, L.C.S., Massawe, F., Mabhaudhi, T., Modi, A.T., Berchie, J.N., Amoah, S., Faloye, B., Abberton, M., Olaniyi, O., Azam-Ali, S.N., 2019. Bambara groundnut: an exemplar underutilised legume for resilience under climate change. Planta 250, 803–820. https://doi.org/10.1007/s00425-019-03191-6

Mohammed, M., Jaiswal, S.K., Sowley, E.N.K., Ahiabor, B.D.K., Dakora, F.D., 2018. Symbiotic N2 Fixation and Grain Yield of Endangered Kersting's Groundnut Landraces in Response to Soil and Plant Associated Bradyrhizobium Inoculation to Promote Ecological Resource-Use Efficiency. Front. Microbiol. 9. https://doi.org/10.3389/fmicb.2018.02105

Muhammad, I., Rafii, M.Y., Ramlee, S.I., Nazli, M.H., Harun, A.R., Oladosu, Y., Musa, I., Arolu, F., Chukwu, S.C., Sani Haliru, B., Silas Akos, I., Halidu, J., Arolu, I.W., 2020a. Exploration of Bambara Groundnut (Vigna subterranea (L.) Verdc.), an Underutilized Crop, to Aid Global Food Security: Varietal Improvement, Genetic Diversity and Processing. Agronomy 10, 766. https://doi.org/10.3390/agronomy10060766

Muhammad, I., Rafii, M.Y., Ramlee, S.I., Nazli, M.H., Harun, A.R., Oladosu, Y., Musa, I., Arolu, F., Chukwu, S.C., Sani Haliru, B., Silas Akos, I., Halidu, J., Arolu, I.W., 2020b. Exploration of Bambara Groundnut (Vigna subterranea (L.) Verdc.), an Underutilized Crop, to Aid Global Food Security: Varietal Improvement, Genetic Diversity and Processing. Agronomy 10, 766. https://doi.org/10.3390/agronomy10060766

Mullualem, D., Tsega, A., Mengie, T., Fentie, D., Kassa, Z., Fassil, A., Wondaferew, D., Gelaw, T.A., Astatkie, T., 2024. Genotype-by-environment interaction and stability analysis of grain yield of bread wheat (Triticum aestivum L.) genotypes using AMMI and GGE biplot analyses. Heliyon 10. https://doi.org/10.1016/j.heliyon.2024.e32918

Nevo, E., 2001. Evolution of genome–phenome diversity under environmental stress. Proc. Natl. Acad. Sci. 98, 6233–6240. https://doi.org/10.1073/pnas.101109298

Ntundu, W.H., Shillah, S.A., Marandu, W.Y.F., Christiansen, J.L., 2006. Morphological Diversity of Bambara Groundnut [Vigna subterranea (L.) Verdc.] Landraces in Tanzania. Genet. Resour. Crop Evol. 53, 367–378. https://doi.org/10.1007/s10722-004-0580-2

Olanrewaju, O.S., Oyatomi, O., Babalola, O.O., Abberton, M., 2022. Breeding Potentials of Bambara Groundnut for Food and Nutrition Security in the Face of Climate Change. Front. Plant Sci. 12. https://doi.org/10.3389/fpls.2021.798993

Olanrewaju, O.S., Oyatomi, O., Babalola, O.O., Abberton, M., 2021a. Genetic Diversity and Environmental Influence on Growth and Yield Parameters of Bambara Groundnut. Front. Plant Sci. 12. https://doi.org/10.3389/fpls.2021.796352

Olanrewaju, O.S., Oyatomi, O., Babalola, O.O., Abberton, M., 2021b. GGE Biplot Analysis of Genotype × Environment Interaction and Yield Stability in Bambara Groundnut. Agronomy 11, 1839. https://doi.org/10.3390/agronomy11091839

Paliwal, R., Adegboyega, T.T., Abberton, M., Faloye, B., Oyatomi, O., 2021. Potential of genomics for the improvement of underutilized legumes in sub-Saharan Africa. Legume Sci. 3, e69. https://doi.org/10.1002/leg3.69

Pasipanodya, J.T., Horn, L.N., Achigan-Dako, E.G., Musango, R., Sibiya, J., 2022. Utilization of Plant Genetic Resources of Bambara Groundnut Conserved Ex Situ and Genetic Diversification of Its Primary Genepool for Semi-Arid Production. Agriculture 12, 492. https://doi.org/10.3390/agriculture12040492

Pasipanodya, J.T., Horn, L.N., Togarepi, C., Sibiya, J., Musango, R., Achigan-Dako, E.G., 2025. Exploring farmer perspectives on Bambara groundnut [Vigna subterranea (L.) Verdc]: production constraints, preferred varietal traits and implications for varietal development in northern Namibia. Front. Sustain. Food Syst. 9. https://doi.org/10.3389/fsufs.2025.1520677

Ruzive, A., Govender, L., Mandizvo, T., Shayanowako, A.I., Musimwa, T., Chai, H.H., Massawe, F., Mayes, S., Sibiya, J., Mabhaudhi, T., 2025. Agro-morphological diversity and breeding potential of Bambara groundnut (*Vigna subterranea* L. Verdc): Insights from recombinant inbred lines evaluation. South Afr. J. Bot. 185, 315–330. https://doi.org/10.1016/j.sajb.2025.07.061

Salazar-Licea, L., Mateva, K.I., Gao, X., Azman Halimi, R., Andrés-Hernández, L., Chai, H.H., Ho, W.K., King, G.J., Massawe, F., Mayes, S., 2022. The Bambara Groundnut Genome, in: Chapman, M.A. (Ed.), Underutilised Crop Genomes. Springer International Publishing, Cham, pp. 189–215. https://doi.org/10.1007/978-3-031-00848-1_11

Siwale, J., Labuschagne, M., Gerrano, A.S., Mbuma, N.W., 2022. Phenotypic Diversity and Characterization of the Southern African Bambara Groundnut Germplasm Collection for Grain Yield and Yield Components. Agronomy 12. https://doi.org/10.3390/agronomy12081811

Somta, P., Chankaew, S., Rungnoi, O., Srinives, P., 2011. Genetic diversity of the Bambara groundnut (Vigna subterranea (L.) Verdc.) as assessed by SSR markers. Genome 54, 898–910. https://doi.org/10.1139/g11-056

Soumare, A., Diedhiou, A.G., Kane, A., 2022. Bambara groundnut: a neglected and underutilized climate-resilient crop with great potential to alleviate food insecurity in sub-Saharan Africa. J. Crop Improv. 36, 747–767. https://doi.org/10.1080/15427528.2021.2000908

Tan, X.L., Azam-Ali, Susan, Goh, E.V., Mustafa, M., Chai, H.H., Ho, W.K., Mayes, S., Mabhaudhi, T., Azam-Ali, Sayed, Massawe, F., 2020a. Bambara Groundnut: An Underutilized Leguminous Crop for Global Food Security and Nutrition. Front. Nutr. 7. https://doi.org/10.3389/fnut.2020.601496

Tan, X.L., Azam-Ali, Susan, Goh, E.V., Mustafa, M., Chai, H.H., Ho, W.K., Mayes, S., Mabhaudhi, T., Azam-Ali, Sayed, Massawe, F., 2020b. Bambara Groundnut: An Underutilized Leguminous Crop for Global Food Security and Nutrition. Front. Nutr. 7. https://doi.org/10.3389/fnut.2020.601496

Uba, C.U., Oselebe, H.O., Tesfaye, A.A., Abtew, W.G., 2021. Genetic diversity and population structure analysis of bambara groundnut (Vigna subterrenea L) landraces using DArT SNP markers. PLOS ONE 16, e0253600. https://doi.org/10.1371/journal.pone.0253600

Uba, C.U., Oselebe, H.O., Tesfaye, A.A., Agbo, C.U., Abtew, W.G., 2022. Comparative analysis of variation in African Bambara groundnut [*Vigna subterranea* (L) Verdc.] landraces assessed through seed traits. South Afr. J. Bot. 150, 48–57. https://doi.org/10.1016/j.sajb.2022.06.060

Appendices

Appendix 1: Proof of Publication

Citation:

Chifamba, M., Chiulele, R., Abberton, M., Mushoriwa, H., Mandizvo, T., Muungani, D., Paliwal, R., Bhatacharjee, R., & Oyatomi, O. (2026). High-throughput phenotyping of Bambara groundnut [*Vigna subterranea* (L.) Verdc.] seed morphometrics using videometer. *CABI Reviews*. https://doi.org/10.1079/ab.2026.0064

DOI Link: https://www.cabidigitallibrary.org/doi/10.1079/ab.2026.0064

Chifamba et al.
CABI Agriculture and Bioscience (2026) 7:1, 0064
https://doi.org/10.1079/ab.2026.0064

CABI Agriculture and Bioscience

RESEARCH

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High-throughput phenotyping of Bambara groundnut [*Vigna subterranea* (L.) Verdc.] seed morphometrics using videometer

Marvelline Chifamba[1,2*], Rogerio Chiulele[1,2], Michael Abberton[3], Hapson Mushoriwa[3], Takudzwa Mandizvo[4], Dean Muungani[3], Rajneesh Paliwal[3], Ranjana Bhatacharjee[3] and Olaniyi Oyatomi[3]

Abstract

Background: Seed size, shape, and colour are key determinants of Bambara groundnut (BGN) seed quality, processing efficiency, and market value. However, conventional assessment methods are slow, subjective, and poorly suited to large-scale characterisation. There is a need for standardised, non-destructive, high-throughput phenotyping methods to support breeding, seed quality assessment, and germplasm evaluation for this resilient yet underutilised crop. *Methods*: Videometer multispectral imaging (MSI) was used to generate reproducible seed morphometric descriptors for 106 BGN accessions. Twenty seed traits were quantified, including size (area, length, width, perimeter, and volume), shape indices (rectangularity, eccentricity, compactness, form factor, pointness, beta shape, diameter area, width of blob end, and compactness ellipse), and colour metrics (hue, saturation, lightness, and CIELab-A1). Data were analysed using analysis of variance, agglomerative hierarchical clustering, and principal component analysis to assess phenotypic variation. *Results*: Significant genotypic effects were detected across all measured traits ($p < 0.05$), indicating substantial phenotypic diversity among the 106 accessions. Seed size and shape traits exhibited wide variation (area ≈ 35–148 mm^2; length ≈ 7.3–15.5 mm; and width ≈ 6.5–12.7 mm). Multivariate analyses identified exploratory, dataset-specific phenotypic groupings that broadly reflected relative differences in seed size, shape, and colour among accessions, supporting germplasm characterisation and the identification of contrasting parental material for pre-breeding. *Conclusions*: MSI-based phenotyping provides a rapid, non-destructive, and high-throughput approach for quantifying seed morphometric variation in BGN. The generated seed trait data provide a standardised basis for germplasm characterisation, the identification of contrasting parental material, and early-stage screening, establishing MSI as a valuable phenotyping foundation for future BGN improvement.

Keywords: agglomerative hierarchical clustering (AHC), high-throughput phenotyping, precision phenotyping, seed morphometrics, videometer, vision for adapted crops and soils (VACS)

Appendix 2: Mean values of Seed morphometric traits

Table S1: Mean values of 106 Bambara groundnut accessions for seed size, shape and colour traits

Accession	SA (mm^2)	SL (mm)	SW (mm)	RWL	Pr (mm)	Vol (mm^3)	Rect	Ecc	Comp	DA (mm)	FF	Pt	RWA (mm^{-1})	Bb1	RWL	WBE (mm)	CA1	Hue (°)	Saturation (%)	Brightness (%)
TVSu-1018	73.49^{wxyzABCDEFGHIJKL}	10.57^{vwxyzABCDEFGHIJ}	**11.319^{a}**	0.848^{lmnopqrstuvwxyzABCD}	27.630^{xyzABCDEFGHIJK}	7.475×10$^{-3vwxyzABCDEFGHIJ}$	0.789^{fghijklm}	0.521^{cdefghijklmnopqrstuv}	0.846^{opqrstuvwxyzABCDE}	9.65^{wxyzABCDEFGHIJK}	0.932^{abcdefghijkl}	0.023^{cdefghijklmnop}	0.123^{efghijklmnopqrstuvw}	1.505^{abc}	0.848^{lmnopqrstuvwxyzABCD}	4.197^{yzABCDEFGHIJ}	21.07^{hijklmno}	2	63	41
TVSu-1027	77.9^{stuvwxyzABCDEFGHI}	11.03^{klmnopqrstuvwxyzABCD}	**11.307^{a}**	0.8017^{ABCDEFGHI}	28.7^{opqrstuvwxyzABCDEFG}	7.795×10$^{-3klmnopqrstuvwxyzABCD}$	0.796^{cdefghijk}	0.590^{abcdefgh}	0.798^{BCDEFGHI}	9.9^{stuvwxyzABCDEFGHI}	0.917^{ghijklmnopq}	0.032^{bcdefghijklm}	0.116^{nopqrstuvwxyzABCDEFGHIJ}	1.428^{ijk}	0.802^{ABCDEFGHI}	4.539^{nopqrstuvwxyzABCDE}	11.53^{vwxyzABC}	35	40	100
TVSu-1066	61.47^{JKLM}	9.99^{DEFGHIJKLMNO}	11.25^{ab}	0.792^{EFGHI}	25.72^{JKLMNO}	7.059×10$^{-3DEFGHIJKLMNO}$	0.792^{cdefghijklm}	0.604^{abcde}	0.787^{GHI}	8.82^{JKLMNO}	0.909^{nopq}	0.026^{bcdefghijklmnop}	0.130^{abcdefghijkl}	1.446^{efghijk}	0.792^{EFGHI}	3.822^{IJKL}	24.34^{cde}	10	97	24
TVSu-1080	78.99^{pqrstuvwxyzABCDEFGHI}	11.11^{klmnopqrstuvwxyzABCD}	11.103^{abc}	0.826^{uvwxyzABCDEFGH}	28.8^{nopqrstuvwxyzABCDEFG}	7.85×10$^{-3klmnopqrstuvwxyzABCD}$	0.790^{cdefghijklm}	0.553^{bcdefghijklm}	0.825^{vwxyzABCDEFGH}	10.01^{opqrstuvwxyzABCDE}	0.925^{bcdefghijklmno}	0.029^{bcdefghijklmnop}	0.117^{nopqrstuvwxyzABCDEFGHI}	1.477^{abcdefghijk}	0.826^{uvwxyzABCDEFGH}	4.410^{stuvwxyzABCDEFGH}	20.53^{klmnop}	1	54	45
TVSu-11	64.5^{HIJKLM}	9.45^{KLMNO}	11.091^{abcd}	0.917^{abcdefghi}	25.84^{IJKLMNO}	6.682×10$^{-3KLMNO}$	0.797^{bcdefgh}	0.389^{ABCDEFGHIJ}	0.914^{abcdefghij}	9.03^{IJKLMNO}	0.939^{abcd}	0.026^{bcdefghijklmnop}	0.137^{abcd}	1.462^{bcdefghijk}	0.917^{abcdefghi}	4.305^{vwxyzABCDEFGHI}	23.43^{defgh}	340	68	24
TVSu-1102	70.94^{ABCDEFGHIJKLM}	10.36^{xyzABCDEFGHIJKLMN}	11.067^{abcd}	0.849^{lmnopqrstuvwxyzABC}	27.19^{CDEFGHIJKLMN}	7.322×10$^{-3xyzABCDEFGHIJKLMN}$	0.792^{cdefghijklm}	0.525^{cdefghijklmnopqrst}	0.851^{lmnopqrstuvwxyzABC}	9.49^{BCDEFGHIJKLMN}	0.934^{abcdefghi}	0.027^{bcdefghijklmnop}	0.124^{defghijklmnopqrst}	1.478^{abcdefghij}	0.849^{lmnopqrstuvwxyzABC}	4.251^{xyzABCDEFGHIJ}	24.98^{bcd}	340	68	24
TVSu-1108	70.75^{ABCDEFGHIJKLM}	10.55^{vwxyzABCDEFGHIJK}	11.022^{abcde}	0.822^{vwxyzABCDEFGH}	26.91^{DEFGHIJKLMNO}	7.007^{vwxyzABCDEFGHIJK}	0.789^{efghijklm}	0.563^{bcdefghijkl}	0.825^{vwxyzABCDEFGH}	9.41^{BCDEFGHIJKLMNO}	0.926^{abcdefghijklmno}	0.032^{bcdefghijkl}	0.127^{cdefghijklmnop}	1.513^{ab}	0.822^{vwxyzABCDEFGH}	4.080^{CDEFGHIJKL}	22.25^{efghijklm}	0	67	24
TVSu-1110	60.17^{KLM}	9.52^{JKLMNO}	10.854^{abcdef}	0.851^{klmnopqrstuvwxyzAB}	24.99^{KLMNO}	0.007^{JKLMNO}	0.790^{cdefghijklm}	0.518^{cdefghijklmnopqrstuvw}	0.854^{klmnopqrstuvwxyzAB}	8.72^{KLMNO}	0.933^{abcdefghijkl}	0.028^{bcdefghijklmnop}	0.137^{abcd}	1.498^{abcde}	0.851^{klmnopqrstuvwxyzAB}	3.816^{IJKL}	23.08^{defghi}	11	88	31
TVSu-1112	72.99^{xyzABCDEFGHIJKL}	11.02^{klmnopqrstuvwxyzABCD}	10.848^{abcdef}	0.764^{IJ}	27.68^{xyzABCDEFGHIJK}	0.008^{klmnopqrstuvwxyzABCD}	0.785^{m}	**0.640^{ab}**	0.764^{IJ}	9.55^{cABCDEFGHIJKL}	0.913^{lmnopq}	0.031^{bcdefghijklmn}	0.119^{lmnopqrstuvwxyzABCDEFG}	1.486^{abcdefgh}	0.764^{IJ}	3.999^{FGHIJKL}	23.29^{defgh}	1	54	45
TVSu-1124	64.72^{GHIJKLM}	10.42^{wxyzABCDEFGHIJKLM}	10.761^{abcdefg}	0.778^{HI}	26.12^{GHIJKLMNO}	0.007^{wxyzABCDEFGHIJKLM}	0.790^{cdefghijklm}	0.617^{abcd}	0.780^{HI}	9.07^{EFGHIJKLMNO}	0.914^{jklmnopq}	0.025^{cdefghijklmnop}	0.125^{defghijklmnopqrs}	**1.523^{a}**	0.778^{HI}	3.669^{L}	22.49^{efghijkl}	0	0	0
TVSu-1126	68.89^{CDEFGHIJKLM}	10.64^{uvwxyzABCDEFGHI}	10.665^{abcdefgh}	0.784^{FGHI}	26.94^{DEFGHIJKLMNO}	0.008^{uvwxyzABCDEFGHI}	0.791^{cdefghijklm}	0.614^{abcd}	0.783^{GHI}	9.34^{BCDEFGHIJKLMNO}	0.915^{ijklmnopq}	0.025^{cdefghijklmnop}	0.122^{efghijklmnopqrstuvwx}	1.497^{abcde}	0.784^{FGHI}	3.906^{HIJKL}	22.64^{defghijkl}	9	74	54
TVSu-1168	107.82^{abcde}	12.46^{bcdefgh}	10.494^{abcdefghi}	0.889^{cdefghijklmnopqr}	33.4^{abcdef}	0.009^{bcdefgh}	0.796^{cdefghijk}	0.448^{mnopqrstuvwxyzABCDEFGHI}	0.886^{defghijklmnopqrst}	11.69^{abcdef}	0.939^{abcd}	0.022^{cdefghijklmnop}	0.104^{JKLMNOP}	1.483^{abcdefghi}	0.889^{cdefghijklmnopqr}	5.4^{abcd}	11.58^{vwxyzAB}	35	62	89
TVSu-1187	89.45^{ijklmnopqrstuv}	11.27^{ijklmnopqrstuvwxyzAB}	10.488^{abcdefghi}	0.904^{abcdefghijklm}	30.46^{ghijklmnopqrstuvw}	0.008^{ijklmnopqrstuvwxyzAB}	0.793^{cdefghijklm}	0.385^{BCDEFGHIJK}	0.901^{abcdefghijklmnop}	10.66^{hijklmnopqrstuv}	0.939^{abcd}	0.032^{bcdefghijkl}	0.114^{pqrstuvwxyzABCDEFGHIJKLM}	1.476^{abcdefghijk}	0.904^{abcdefghijklm}	5.121^{cdefghijk}	13.62^{uv}	26	44	63
TVSu-1188	70.98^{ABCDEFGHIJKLM}	10.3^{yzABCDEFGHIJKLMN}	10.488^{abcdefghi}	0.868^{efghijklmnopqrstuv}	27.3^{BCDEFGHIJKLM}	0.007^{yzABCDEFGHIJKLMN}	0.796^{cdefghijk}	0.480^{jklmnopqrstuvwxyzABCDE}	0.865^{hijklmnopqrstuvwxy}	9.49^{BCDEFGHIJKLMN}	0.923^{cdefghijklmno}	0.054^{a}	0.127^{cdefghijklmnop}	1.455^{cdefghijk}	0.868^{efghijklmnopqrstuv}	4.437^{pqrstuvwxyzABCDEFG}	26.88^{ab}	351	69	34
TVSu-1190	106.71^{abcdefg}	12.25^{cdefghij}	10.428^{bcdefghij}	0.924^{abcde}	33.08^{abcdefg}	0.009^{cdefghij}	0.797^{bcdefgh}	0.354^{HIJKL}	0.923^{abcdefg}	11.65^{abcdefg}	0.939^{abcd}	0.026^{bcdefghijklmnop}	0.106^{HIJKLMNO}	1.504^{abc}	0.924^{abcde}	5.271^{abcdefgh}	12.49^{vwxyz}	34	42	52
TVSu-1217	59.55^{KLM}	9.34^{MNO}	10.332^{cdefghijk}	0.884^{cdefghijklmnopqrst}	24.89^{LMNO}	0.007^{MNO}	0.790^{cdefghijklm}	0.428^{rstuvwxyzABCDEFGHI}	0.881^{defghijklmnopqrstuv}	8.68^{LMNO}	0.928^{abcdefghijklmn}	0.035^{bcdefg}	**0.140^{ab}**	1.472^{abcdefghijk}	0.884^{cdefghijklmnopqrst}	4.044^{DEFGHIJKL}	12.42^{vwxyz}	27	43	60
TVSu-1218	70.95^{ABCDEFGHIJKLM}	9.88^{EFGHIJKLMNO}	10.329^{cdefghijk}	0.922^{abcdef}	26.98^{DEFGHIJKLMNO}	0.007^{EFGHIJKLMNO}	0.794^{cdefghijklm}	0.377^{DEFGHIJKL}	0.922^{abcdefgh}	9.46^{BCDEFGHIJKLMN}	**0.945^{ab}**	0.020^{fghijklmnop}	0.131^{abcdefghijkl}	1.474^{abcdefghijk}	0.922^{abcdef}	4.419^{qrstuvwxyzABCDEFGH}	11.08^{vwxyzABCDEFG}	43	50	92
TVSu-1221	95.82^{efghijklm}	11.74^{efghijklmnopqrstu}	10.293^{cdefghijkl}	0.882^{cdefghijklmnopqrstu}	31.75^{efghijklm}	0.008^{efghijklmnopqrstu}	0.799^{bcde}	0.460^{lmnopqrstuvwxyzABCDEFGH}	0.880^{efghijklmnopqrstuv}	11.03^{defghijkl}	0.932^{abcdefghijkl}	0.023^{cdefghijklmnop}	0.108^{BCDEFGHIJKLMNO}	1.441^{ghijk}	0.882^{cdefghijklmnopqrstu}	5.241^{abcdefghi}	10.9^{xyzABCDEFGH}	30	50	93
TVSu-1231	75.35^{vwxyzABCDEFGHIJ}	10.3^{yzABCDEFGHIJKLMN}	10.236^{cdefghijklm}	0.906^{abcdefghijkl}	27.94^{uvwxyzABCDEFGHIJ}	0.007^{yzABCDEFGHIJKLMN}	0.797^{bcdefghi}	0.399^{zABCDEFGHIJ}	0.903^{abcdefghijklmno}	9.77^{vwxyzABCDEFGHI}	0.933^{abcdefghij}	0.016^{hijklmnop}	0.125^{defghijklmnopqrs}	1.466^{bcdefghijk}	0.906^{abcdefghijkl}	4.491^{opqrstuvwxyzABCDEF}	9.52^{ABCDEFGHIJ}	26	45	65
TVSu-1232	71.83^{yzABCDEFGHIJKLM}	10.32^{xyzABCDEFGHIJKLMN}	10.215^{defghijklm}	0.861^{hijklmnopqrstuvwxy}	27.36^{BCDEFGHIJKLM}	0.007^{xyzABCDEFGHIJKLMN}	0.793^{cdefghijklm}	0.499^{efghijklmnopqrstuvwxyz}	0.857^{jklmnopqrstuvwxyzA}	9.53^{ABCDEFGHIJKLM}	0.933^{abcdefghijkl}	0.023^{cdefghijklmnop}	0.125^{defghijklmnopqrs}	1.472^{abcdefghijk}	0.861^{hijklmnopqrstuvwxy}	4.386^{uvwxyzABCDEFGH}	9.53^{ABCDEFGHIJ}	38	27	91
TVSu-1236	64.56^{GHIJKLM}	9.52^{JKLMNO}	10.167^{efghijklm}	0.897^{abcdefghijklmn}	26.12^{GHIJKLMNO}	0.007^{JKLMNO}	**0.810^{a}**	0.425^{stuvwxyzABCDEFGHI}	0.894^{bcdefghijklmnop}	9.04^{GHIJKLMNO}	0.933^{abcdefghijkl}	0.021^{defghijklmnop}	0.133^{abcdefg}	1.43^{ijk}	0.897^{abcdefghijklmn}	4.344^{uvwxyzABCDEFGH}	10.39^{yzABCDEFGHIJ}	38	57	76
TVSu-1243	82.79^{klmnopqrstuvwxyzABC}	10.81^{nopqrstuvwxyzABCDEF}	10.14^{ghijklm}	0.900^{abcdefghijklmn}	29.341^{tmnopqrstuvwxyzABCD}	0.008^{nopqrstuvwxyzABCDEF}	0.797^{bcdefghi}	0.415^{uvwxyzABCDEFGHIJ}	0.898^{bcdefghijklmnop}	10.24^{jklmnopqrstuvwxyzAB}	0.939^{abcd}	0.011^{p}	0.119^{lmnopqrstuvwxyzABCDEFGH}	1.472^{abcdefghijk}	0.900^{abcdefghijklmn}	4.728^{ijklmnopqrstuvwxy}	9.6^{ABCDEFGHIJ}	38	37	78
TVSu-1249	65.3^{FGHIJKLM}	9.37^{LMNO}	10.107^{fghijklmn}	**0.947^{ab}**	25.95^{IJKLMNO}	0.007^{LMNO}	0.790^{cdefghijklm}	0.312^{JKL}	0.946^{abc}	9.07^{EFGHIJKLMNO}	0.936^{abcdefgh}	0.017^{ghijklmnop}	0.139^{abc}	1.464^{bcdefghijk}	0.947^{ab}	4.236^{yzABCDEFGHIJ}	19.04^{opqr}	7	64	35
TVSu-1251	82.06^{lmnopqrstuvwxyzABCD}	10.66^{stuvwxyzABCDEFGHI}	10.101^{fghijklmn}	0.931^{abcd}	29.02^{mnopqrstuvwxyzABCDEF}	0.008^{stuvwxyzABCDEFGHI}	0.790^{cdefghijklm}	0.360^{GHIJKL}	0.931^{abcd}	10.2^{klmnopqrstuvwxyzAB}	0.943^{abc}	0.021^{defghijklmnop}	0.122^{fghijklmnopqrstuvwxy}	1.497^{abcde}	0.931^{abcd}	4.644^{klmnopqrstuvwxyzA}	9.52^{ABCDEFGHIJ}	35	40	100
TVSu-1256	96.1^{efghijkl}	11.39^{ghijklmnopqrstuvwxy}	10.098^{fghijklmn}	**0.947^{ab}**	31.51^{efghijklmn}	0.008^{ghijklmnopqrstuvwxy}	0.796^{cdefghij}	0.287^{KL}	**0.948^{ab}**	11.03^{defghijkl}	0.939^{abcd}	0.021^{defghijklmnop}	0.113^{rstuvwxyzABCDEFGHIJKLM}	1.476^{abcdefghijk}	0.947^{ab}	5.238^{abcdefghi}	16.24st	0	67	24
TVSu-1268	108.15^{abcde}	12.46^{bcdefgh}	10.092^{fghijklmno}	0.892^{bcdefghijklmnopq}	33.4^{abcdef}	0.009^{bcdefgh}	0.796^{cdefghijk}	0.441^{opqrstuvwxyzABCDEFGHI}	0.890^{cdefghijklmnopqrs}	11.71^{abcde}	0.940^{abcd}	0.020^{fghijklmnop}	0.104^{JKLMNOP}	1.487^{abcdefg}	0.892^{bcdefghijklmnopq}	5.37^{01}	11.26^{wxyzABCDE}	35	52	69
TVSu-171	79.9^{opqrstuvwxyzABCDEFG}	10.7^{rstuvwxyzABCDEFGHI}	10.092^{fghijklmno}	0.885^{cdefghijklmnopqrs}	28.74^{opqrstuvwxyzABCDEFG}	0.008^{stuvwxyzABCDEFGHI}	0.794^{cdefghijklm}	0.462^{lmnopqrstuvwxyzABCDEFGH}	0.885^{defghijklmnopqrstu}	10.06^{mnopqrstuvwxyzABCD}	0.941^{abcd}	0.020^{fghijklmnop}	0.120^{ijklmnopqrstuvwxyzABCD}	1.471^{abcdefghijk}	0.885^{cdefghijklmnopqrs}	4.623^{klmnopqrstuvwxyzAB}	8.4^{IJ}	6	38	10
TVSu-205	74.54^{vwxyzABCDEFGHIJK}	10.42^{wxyzABCDEFGHIJKLM}	10.086^{fghijklmno}	0.880^{cdefghijklmnopqrstu}	27.79^{vwxyzABCDEFGHIJ}	0.007^{wxyzABCDEFGHIJKLM}	0.786^{klm}	0.470^{klmnopqrstuvwxyzABCDEF}	0.880^{defghijklmnopqrstuv}	9.73^{vwxyzABCDEFGHIJ}	0.934^{abcdefghij}	0.024^{cdefghijklmnop}	0.124^{efghijklmnopqrstuv}	1.499^{abcde}	0.880^{cdefghijklmnopqrstu}	4.464^{pqrstuvwxyzABCDEFG}	10.17^{zABCDEFGHIJ}	35	62	89
TVSu-210	113.42^{abc}	13.06^{abcd}	10.086^{fghijklmno}	0.852^{klmnopqrstuvwxyzAB}	34.48^{abcd}	0.009^{abcd}	0.789^{defghijklm}	0.513^{defghijklmnopqrstuvwx}	0.851^{lmnopqrstuvwxyzABCD}	11.98^{abc}	0.930^{abcdefghijkl}	0.024^{cdefghijklmnop}	0.099^{NOP}	1.478^{abcdefghij}	0.852^{klmnopqrstuvwxyzAB}	5.451^{abc}	12.42^{vwxyz}	35	52	69
TVSu-211	70.76^{BCDEFGHIJKLM}	10.21^{ABCDEFGHIJKLMNO}	10.083^{fghijklmno}	0.865^{fghijklmnopqrstuvw}	27.08^{DEFGHIJKLMNO}	0.007^{ABCDEFGHIJKLMNO}	0.798^{bcdef}	0.485^{ghijklmnopqrstuvwxyzABC}	0.869^{fghijklmnopqrstuvwx}	9.41^{BCDEFGHIJKLMNO}	0.929^{abcdefghijklmn}	0.041^{abc}	0.129^{bcdefghijklm}	1.469^{abcdefghijk}	0.865^{fghijklmnopqrstuvw}	4.251^{xyzABCDEFGHIJ}	20.78^{ijklmnop}	0	67	24
TVSu-212	92.12^{ghijklmnopqrs}	11.54^{efghijklmnopqrstuvw}	10.077^{fghijklmno}	0.864^{efghijklmnopqrstuvw}	30.81^{efghijklmnopqrst}	0.008^{efghijklmnopqrstuvw}	0.799^{bc}	0.485^{ghijklmnopqrstuvwxyzABCD}	0.861^{ijklmnopqrstuvwxyz}	10.67^{hijklmnopqrstuv}	0.932^{abcdefghijkl}	0.026^{bcdefghijklmnop}	0.115^{opqrstuvwxyzABCDEFGHIJKL}	1.455^{cdefghijk}	0.864^{fghijklmnopqrstuvw}	4.857^{fghijklmnopqrstuv}	13.41^{uvw}	32	53	51
TVSu-216	82.83^{klmnopqrstuvwxyzABC}	10.94^{tmnopqrstuvwxyzABCDE}	10.062^{fghijklmnop}	0.886^{cdefghijklmnopqrs}	29.22^{mnopqrstuvwxyzABCDE}	0.008^{mnopqrstuvwxyzABCDE}	0.791^{cdefghijklm}	0.458^{lmnopqrstuvwxyzABCDEFGH}	0.885^{defghijklmnopqrstu}	10.24^{klmnopqrstuvwxyzAB}	0.939^{abcd}	0.025^{cdefghijklmnop}	0.118^{lmnopqrstuvwxyzABCDEFGH}	1.486^{abcdefgh}	0.886^{cdefghijklmnopqrs}	4.665^{klmnopqrstuvwxyzA}	10.89^{vwxyzABCDEFGH}	37	26	76
TVSu-217	77.06^{stuvwxyzABCDEFGHI}	10.36^{xyzABCDEFGHIJKLMN}	10.062^{fghijklmnop}	0.912^{abcdefghij}	28.24^{stuvwxyzABCDEFGHIJ}	0.007^{yzABCDEFGHIJKLMN}	0.795^{cdefghijklm}	0.397^{zABCDEFGHIJ}	0.907^{abcdefghijkl}	9.85^{stuvwxyzABCDEFGHI}	0.938^{abcdef}	0.024^{cdefghijklmnop}	0.125^{defghijklmnopqrs}	1.472^{abcdefghijk}	0.912^{abcdefghij}	4.668^{klmnopqrstuvwxyzA}	10.8^{yzABCDEFGHI}	20	50	93
TVSu-219	100.72^{cdefghij}	11.82^{efghijklmnopqr}	10.032^{fghijklmnopq}	0.919^{abcdefg}	32.28^{bcdefghij}	0.008^{efghijklmnopqr}	0.794^{cdefghijklm}	0.364^{FGHIJKL}	0.918^{abcdefgh}	11.3^{bcdefghi}	0.938^{abcd}	0.021^{defghijklmnop}	0.109^{BCDEFGHIJKLMNO}	1.469^{abcdefghij}	0.919^{abcdefg}	5.34^{abcdefg}	11.41^{vwxyzABCD}	28	49	46
TVSu-3	65.74^{EFGHIJKLM}	9.74^{FGHIJKLMNO}	10.032^{fghijklmnopq}	0.881^{cdefghijklmnopqrstu}	26.17^{GHIJKLMNO}	0.007^{FGHIJKLMNO}	0.793^{cdefghijklm}	0.461^{lmnopqrstuvwxyzABCDEFGH}	0.882^{defghijklmnopqrstuv}	9.12^{DEFGHIJKLMNO}	0.937^{abcdef}g	0.016^{hijklmnop}	0.132^{abcdefghij}	1.47^{abcdefghijk}	0.881^{cdefghijklmnopqrstu}	4.11^{BCDEFGHIJKL}	10.44^{yzABCDEFGHIJ}	42	50	91
TVSu-315	74.17^{wxyzABCDEFGHIJK}	10.24^{zABCDEFGHIJKLMNO}	10.011^{fghijklmnopqr}	0.898^{abcdefghijklmn}	27.73^{wxyzABCDEFGHIJ}	0.007^{zABCDEFGHIJKLMNO}	0.792^{cdefghijklm}	0.428^{rstuvwxyzABCDEFGHI}	0.890^{cdefghijklmnopqrs}	9.68^{wxyzABCDEFGHIJ}	0.935^{abcdefghi}	0.023^{cdefghijklmnop}	0.126^{defghijklmnopqr}	1.449^{defghijk}	0.898^{abcdefghijklmn}	4.617^{klmnopqrstuvwxyzAB}	21.34^{hijklmno}	7	64	35
TVSu-320	**115.29^{ab}**	13.14^{abc}	10.011^{fghijklmnopqr}	0.862^{ghijklmnopqrstuvwx}	34.62^{abc}	0.009^{abc}	0.793^{cdefghijklm}	0.497^{fghijklmnopqrstuvwxyzA}	0.858^{jklmnopqrstuvwxyzA}	12.09^{ab}	0.931^{abcdefghijkl}	0.044^{ab}	0.099^{NOP}	1.477^{abcdefghijk}	0.862^{ghijklmnopqrstuvwx}	5.688^{a}	11.84^{vwxyzA}	33	45	76
TVSu-323	79.77^{opqrstuvwxyzABCDEFGH}	10.78^{opqrstuvwxyzABCDEFGH}	10.011^{fghijklmnopqr}	0.877^{cdefghijklmnopqrstuv}	28.74^{opqrstuvwxyzABCDEFG}	0.008^{opqrstuvwxyzABCDEFGH}	0.791^{cdefghijklm}	0.472^{klmnopqrstuvwxyzABCDE}	0.869^{fghijklmnopqrstuvwx}	10.02^{opqrstuvwxyzABCDE}	0.929^{abcdefghijklmn}	0.034^{bcdefghij}	0.121^{ghijklmnopqrstuvwxyz}	1.456^{cdefghijk}	0.877^{cdefghijklmnopqrstuv}	4.653^{klmnopqrstuvwxyzA}	24.3^{cde}	7	64	35

TVSu-325	98.77^{defghij}	12.03^{defghijklm}	9.909^{ghijklmnopqrs}	0.874^{defghijklmnopqrstuv}	32.1^{bcdefghijk}	0.009^{defghijklm}	0.794^{cdefghijklm}	0.477^{jklmnopqrstuvwxyzABCDE}	0.874^{defghijklmnopqrstuvw}	11.21^{bcdefghi}	0.938^{abcde}	0.020^{fghijklmnop}	0.107^{GHIJKLMNO}	1.475^{abcdefghijk}	0.874^{defghijklmnopqrstuv}	5.076^{cdefghijklm}	20.83^{ijklmnop}	359	54	54
TVSu-326	78.59^{rstuvwxyzABCDEFGHI}	10.68^{stuvwxyzABCDEFGHI}	9.894^{ghijklmnopqrstu}	0.879^{cdefghijklmnopqrstu}	28.66^{opqrstuvwxyzABCDEFGH}	0.008^{stuvwxyzABCDEFGHI}	0.797^{bcdefgh}	0.460^{lmnopqrstuvwxyzABCDEFGH}	0.876^{defghijklmnopqrstuv}	9.98^{qrstuvwxyzABCDEFGH}	0.929^{abcdefghijklmno}	0.029^{bcdefghijklmnop}	0.120^{ijklmnopqrstuvwxyzABC}	1.447^{efghijk}	0.879^{cdefghijklmnopqrstu}	4.788^{hijklmnopqrstuvw}	10.43^{pxABCDEFGHIJ}	35	40	100
TVSu-327	78.69^{qrstuvwxyzABCDEFGHI}	10.75^{qrstuvwxyzABCDEFGH}	9.879^{ghijklmnopqrst}	0.871^{efghijklmnopqrstuv}	28.63^{opqrstuvwxyzABCDEFGH}	0.008^{qrstuvwxyzABCDEFGH}	0.792^{cdefghijklm}	0.486^{ghijklmnopqrstuvwxyzABC}	0.869^{efghijklmnopqrstuvwx}	10^{pqrstuvwxyzABCDEF}	0.938^{abcdef}	0.021^{defghijklmnop}	0.119^{klmnopqrstuvwxyzABCDE}F	1.482^{abcdefghi}	0.871^{efghijklmnopqrstuv}	4.587^{lmnopqrstuvwxyzABC}	9.1^{CDEFGHIJ}	46	67	100
TVSu-328	95.58^{efghijklm}	11.78^{efghijklmnopqrs}	9.873^{ghijklmnopqrst}	0.893^{bcdefghijklmnop}	31.3^{efghijklmnop}	0.008^{efghijklmnopqrs}	0.798^{bcd}	0.441^{opqrstuvwxyzABCDEFGHI}	0.891^{cdefghijklmnopqrs}	11.01^{defghijklm}	0.940^{abcd}	0.033^{bcdefghijk}	0.111^{wxyzABCDEFGHIJKLMN}	1.514^{ab}	0.893^{bcdefghijklmnop}	5.025^{cdefghijklmno}	18.54^{pqr}	6	38	10
TVSu-329	97.63^{defghijk}	12.59^{bcde}	9.831^{hijklmnopqrstu}	0.784^{FGHI}	32.14^{bcdefghijk}	0.009^{bcde}	0.791^{cdefghijklm}	0.615^{abcd}	0.783^{GHI}	11.1^{cdefghij}	0.918^{efghijklmnopq}	0.029^{bcdefghijklmnop}	0.103^{KLMNOP}	1.483^{abcdefghi}	0.784^{FGHI}	4.926^{defghijklmnopqrs}	5^{K}	6	38	10
TVSu-341	78.22^{rstuvwxyzABCDEFGHI}	11.09^{klmnopqrstuvwxyzABCD}	9.804^{hijklmnopqrstu}	0.821^{vwxyzABCDEFGH}	28.59^{opqrstuvwxyzABCDEFGH}	0.008^{klmnopqrstuvwxyzABCD}	0.791^{cdefghijklm}	0.553^{bcdefghijklmn}	0.817^{xyzABCDEFGHI}	9.91^{tstuvwxyzABCDEFGHI}	0.924^{cdefghijklmno}	0.033^{bcdefghij}	0.119^{lmnopqrstuvwxyzABCDEFGH}	1.463^{bcdefghijk}	0.821^{vwxyzABCDEFGH}	4.386^{tuvwxyzABCDEFGH}	22.19^{efghijklm}	11	88	31
TVSu-345	72.78^{xyzABCDEFGHIJKL}	10.32^{xyzABCDEFGHIJKLMN}	9.711^{ijklmnopqrstu}	0.876^{cdefghijklmnopqrstuv}	27.41^{ABCDEFGHIJKLMN}	0.007^{xyzABCDEFGHIJKLMN}	0.794^{cdefghijklm}	0.472^{klmnopqrstuvwxyzABCDE}	0.877^{defghijklmnopqrstuv}	9.6^{yzABCDEFGHIJKL}	0.935^{abcdefghi}	0.025^{bcdefghijklmnop}	0.125^{defghijklmnopqrs}	1.487^{abcdefg}	0.876^{cdefghijklmnopqrstuv}	4.332^{rwxyzABCDEFGHI}	17.8^{qrs}	1	42	44
TVSu-358	85.92^{jklmnopqrstuvwxyzAB}	11.11^{klmnopqrstuvwxyzABCD}	9.687^{ijklmnopqrstu}	0.885^{cdefghijklmnopqrs}	29.89^{klmnopqrstuvwxyzABC}	0.008^{klmnopqrstuvwxyzABCD}	0.792^{cdefghijklm}	0.464^{mnopqrstuvwxyzABCDEF}G	0.884^{defghijklmnopqrstu}	10.44^{ijklmnopqrstuvwxyzA}	0.937^{abcdefg}	0.013^{lmnop}	0.115^{opqrstuvwxyzABCDEFGHIJK}	1.476^{abcdefghijk}	0.885^{cdefghijklmnopqrs}	4.749^{hijklmnopqrstuvwx}	8.47^{HIJ}	43	50	92
TVSu-398	86.07^{ijklmnopqrstuvwxyzA}	11.32^{ijklmnopqrstuvwxyzAB}	9.681^{ijklmnopqrstuv}	0.853^{klmnopqrstuvwxyzA}	30.14^{hijklmnopqrstuvwxyzA}	0.008^{ijklmnopqrstuvwxyzAB}	0.796^{bcdefghij}	0.516^{cdefghijklmnopqrstuvwx}	0.853^{klmnopqrstuvwxyzAB}	10.45^{ijklmnopqrstuvwxyzA}	0.932^{abcdefghijkl}	0.026^{bcdefghijklmnop}	0.113^{stuvwxyzABCDEFGHIJKLM}	1.442^{fghijk}	0.853^{klmnopqrstuvwxyzA}	4.872^{efghijklmnopqrstu}	17.46^{rs}	14	38	44
TVSu-402	95.13^{efghijklmn}	12.1^{cdefghijkl}	9.672^{ijklmnopqrstu}	0.833^{tstuvwxyzABCDEFGH}	31.57^{efghijklmn}	0.009^{cdefghijkl}	0.789^{efghijklm}	0.548^{bcdefghijklmno}	0.834^{stuvwxyzABCDEFGH}	10.99^{defghijklmn}	0.926^{abcdefghijklmno}	0.026^{bcdefghijklmnop}	0.107^{HIJKLMNO}	1.47^{abcdefghijk}	0.833^{tstuvwxyzABCDEFGH}	4.875^{defghijklmnopqrstu}	20.12^{mnop}	0	47	92
TVSu-438	81.99^{klmnopqrstuvwxyzABCD}	11.07^{klmnopqrstuvwxyzABCD}	9.666^{ijklmnopqrstuv}	0.860^{ijklmnopqrstuvwxyz}	29.09^{mnopqrstuvwxyzABCDEF}	0.008^{klmnopqrstuvwxyzABCD}	0.789^{fghijklm}	0.495^{ghijklmnopqrstuvwxyzA}	0.859^{jklmnopqrstuvwxyz}	10.14^{klmnopqrstuvwxyzABC}	0.933^{abcdefghijk}	0.031^{bcdefghijklm}	0.119^{lmnopqrstuvwxyzABCDEFG}	1.488^{abcdefg}	0.860^{ijklmnopqrstuvwxyz}	4.569^{lmnopqrstuvwxyzABCD}	2.96^{KL}	37	0	0
TVSu-454	90.82^{hijklmnopqrst}	11.45^{fghijklmnopqrstuvwx}	9.66^{ijklmnopqrstuv}	0.881^{cdefghijklmnopqrstu}	30.84^{efghijklmnopqrst}	0.008^{fghijklmnopqrstuvwx}	0.796^{cdefghijk}	0.460^{lmnopqrstuvwxyzABCDEFGH}	0.880^{efghijklmnopqrstuv}	10.75^{ghijklmnopqrst}	0.938^{abcde}	0.017^{fghijklmnop}	0.111^{vwxyzABCDEFGHIJKLMN}	1.466^{bcdefghijk}	0.881^{cdefghijklmnopqrstu}	4.962^{cdefghijklmnop}	8.79^{FGHIJ}	37	26	76
TVSu-460	90.4^{hijklmnopqrstu}	11.36^{hijklmnopqrstuvwxyz}	9.633^{ijklmnopqrstuv}	0.894^{bcdefghijklmnop}	30.6^{ghijklmnopqrstu}	0.008^{hijklmnopqrstuvwxyz}	0.792^{cdefghijklm}	0.431^{rstuvwxyzABCDEFGHI}	0.891^{cdefghijklmnopqr}	10.7^{hijklmnopqrstu}	0.935^{abcdefghi}	0.026^{bcdefghijklmnop}	0.114^{qrstuvwxyzABCDEFGHIJKLM}	1.466^{bcdefghijk}	0.894^{bcdefghijklmnop}	5.1^{cdefghijkl}	8.58^{HIJ}	34	26	76
TVSu-461	87.86^{ijklmnopqrstuvwx}	11.68^{efghijklmnopqrstuv}	9.573^{ijklmnopqrstuvw}	0.828^{tuvwxyzABCDEFGH}	30.3^{hijklmnopqrstuvwx}	0.008^{efghijklmnopqrstuv}	0.788^{hijklm}	0.559^{bcdefghijkl}	0.829^{tuvwxyzABCDEFGH}	10.56^{hijklmnopqrstuvwx}	0.930^{abcdefghijklm}	0.021^{efghijklmnop}	0.111^{wxyzABCDEFGHIJKLMN}	1.496^{abcdef}	0.828^{tuvwxyzABCDEFGH}	4.566^{lmnopqrstuvwxyzABCD}	9.18^{BCDEFGHIJ}	30	42	52
TVSu-464	72.79^{xyzABCDEFGHIJKL}	10.32^{xyzABCDEFGHIJKLMN}	9.537^{klmnopqrstuvwx}	0.872^{efghijklmnopqrstuv}	27.89^{uvwxyzABCDEFGHIJ}	0.007^{yzABCDEFGHIJKLMN}	0.791^{cdefghijklm}	0.482^{ijklmnopqrstuvwxyzABCD}	0.875^{defghijklmnopqrstuvw}	9.6^{yzABCDEFGHIJKL}	0.907^{opq}	0.018^{fghijklmnop}	0.125^{defghijklmnopqrs}	1.477^{abcdefghijk}	0.872^{efghijklmnopqrstuv}	4.327^{rwxyzABCDEFGHI}	9.29^{BCDEFGHIJ}	33	50	93
TVSu-466	58.55^{LM}	9.2^{O}	9.483^{klmnopqrstuvwxy}	0.883^{cdefghijklmnopqrstu}	24.58^{NO}	0.007^{O}	0.791^{cdefghijklm}	0.459^{lmnopqrstuvwxyzABCDEFGH}	0.879^{defghijklmnopqrstuv}	8.59^{NO}	0.937^{abcdefg}	0.024^{cdefghijklmnop}	**0.142^{a}**	1.492^{abcdefg}	0.883^{cdefghijklmnopqrstu}	3.942^{GHIJKL}	8.96^{EFGHIJ}	36	45	76
TVSu-467	78.84^{qrstuvwxyzABCDEFGHI}	10.45^{wxyzABCDEFGHIJKL}	9.477^{klmnopqrstuvwxy}	0.925^{abcde}	28.44^{rstuvwxyzABCDEFGHIJ}	0.007^{wxyzABCDEFGHIJKL}	0.795^{cdefghijkl}	0.372^{EFGHIJKL}	0.927^{abcde}	10^{pqrstuvwxyzABCDEF}	0.941^{abcd}	0.018^{fghijklmnop}	0.123^{efghijklmnopqrstuvw}	1.491^{abcdefg}	0.925^{abcde}	4.599^{klmnopqrstuvwxyzABC}	11.34^{vwxyzABCDE}	30	51	69
TVSu-470	65.07^{FGHIJKLM}	9.58^{IJKLMNO}	9.471^{klmnopqrstuvwxy}	0.906^{abcdefghijkl}	25.92^{HIJKLMNO}	0.007^{IJKLMNO}	0.791^{cdefghijklm}	0.421^{tuvwxyzABCDEFGHI}	0.904^{abcdefghijklmn}	9.09^{EFGHIJKLMNO}	0.941^{abcd}	0.023^{cdefghijklmnop}	0.132^{abcde}	1.479^{abcdefghij}	0.906^{abcdefghijkl}	4.185^{zABCDEFGHIJK}	9.32^{BCDEFGHIJ}	43	49	73
TVSu-474	67.28^{DEFGHIJKLM}	9.79^{FGHIJKLMNO}	9.453^{klmnopqrstuvwxyz}	0.899^{abcdefghijklmn}	26.38^{FGHIJKLMNO}	0.007^{FGHIJKLMN}O	0.791^{cdefghijklm}	0.435^{qrstuvwxyzABCDEFGHI}	0.896^{bcdefghijklmnop}	9.23^{CDEFGHIJKLMNO}	0.938^{abcdef}	0.021^{defghijklmnop}	0.132^{abcdefghijk}	1.481^{abcdefghij}	0.899^{abcdefghijklmn}	4.239^{yzABCDEFGHIJ}	8.66^{GHIJ}	291	50	92
TVSu-476	76.11^{tuvwxyzABCDEFGHIJ}	10.96^{tmnopqrstuvwxyzABCDE}	9.441^{klmnopqrstuvwxyz}	0.811^{wxyzABCDEFGHI}	28.29^{stuvwxyzABCDEFGHIJ}	0.008^{tmnopqrstuvwxyzABCD}E	0.795^{cdefghijklm}	0.582^{abcdefghij}	0.810^{pzABCDEFGHI}	9.79^{tuvwxyzABCDEFGHI}J	0.926^{abcdefghijklmno}	0.030^{bcdefghijklmnop}	0.119^{lmnopqrstuvwxyzABCDEF}G	1.464^{bcdefghijk}	0.811^{wxyzABCDEFGHI}	4.236^{tyzABCDEFGHIJ}	11.91^{vwxyzA}	38	52	20
TVSu-479	77.19^{stuvwxyzABCDEFGHI}	10.8^{tnopqrstuvwxyzABCDEFG}	9.438^{klmnopqrstuvwxyzA}	0.837^{pqrstuvwxyzABCDEFG}	28.47^{rstuvwxyzABCDEFGHI}	0.008^{tnopqrstuvwxyzABCDEFG}	0.795^{cdefghijkl}	0.536^{bcdefghijklmnopqr}	0.834^{stuvwxyzABCDEFGH}	9.88^{stuvwxyzABCDEFGHI}	0.928^{abcdefghijklmn}	0.018^{fghijklmnop}	0.119^{lmnopqrstuvwxyzABCDEFGH}	1.454^{cdefghijk}	0.837^{pqrstuvwxyzABCDEFG}	4.467^{pqrstuvwxyzABCDEFG}	9.65^{ABCDEFGHIJ}	1	27	91
TVSu-480	98.73^{defghij}	12.23^{cdefghij}	9.417^{klmnopqrstuvwxyzAB}	0.858^{jklmnopqrstuvwxyz}	32.05^{cdefghijkl}	0.009^{cdefghij}	0.798^{bcdefg}	0.512^{defghijklmnopqrstuvwxy}	0.861^{ijklmnopqrstuvwxyz}	11.21^{bcdefghi}	0.933^{abcdefghijk}	0.033^{bcdefghijk}	0.106^{HIJKLMNO}	1.497^{abcde}	0.858^{jklmnopqrstuvwxyz}	4.959^{cdefghijklmnop}	17.44^{rs}	34	42	44
TVSu-481	90.11^{hijklmnopqrstu}	12.09^{cdefghijkl}	9.372^{lmnopqrstuvwxyzABC}	0.796^{BCDEFGHI}	30.91^{efghijklmnopqrst}	0.009^{cdefghijkl}	0.791^{cdefghijklm}	0.590^{abcdefgh}	0.796^{CDEFGHI}	10.68^{hijklmnopqrstu}	0.917^{fghijklmnopq}	0.030^{bcdefghijklmnop}	0.107^{DEFGHIJKLMNO}	1.477^{abcdefghijk}	0.796^{BCDEFGHI}	4.638^{klmnopqrstuvwxyzAB}	7.99^{J}	42	42	52
TVSu-486	91.38^{hijklmnopqrst}	11.58^{efghijklmnopqrstuv}	9.354^{tmnopqrstuvwxyzABC}	0.871^{efghijklmnopqrstuv}	30.76^{fghijklmnopqrst}	0.008^{efghijklmnopqrstuv}	0.790^{cdefghijklm}	0.483^{ijklmnopqrstuvwxyzABCD}	0.870^{efghijklmnopqrstuvwx}	10.77^{fghijklmnopqrs}	0.937^{abcdefg}	0.020^{fghijklmnop}	0.111^{vwxyzABCDEFGHIJKLMN}	1.49^{abcdefg}	0.871^{efghijklmnopqrstuv}	4.872^{defghijklmnopqrstu}	9.62^{ABCDEFGHIJ}	47	50	91
TVSu-488	89.88^{hijklmnopqrstu}	11.32^{ijklmnopqrstuvwxyzAB}	9.345^{tmnopqrstuvwxyzABC}	0.891^{bcdefghijklmnopq}	30.57^{ghijklmnopqrstu}	0.008^{ijklmnopqrstuvwxyzAB}	0.791^{cdefghijklm}	0.445^{nopqrstuvwxyzABCDEFGHI}	0.891^{cdefghijklmnopqr}	10.68^{hijklmnopqrstuv}	0.938^{abcdef}	0.012^{mnop}	0.113^{stuvwxyzABCDEFGHIJKLM}	1.474^{abcdefghijk}	0.891^{bcdefghijklmnopq}	4.905^{defghijklmnopqrst}	8.9^{EFGHIJ}	6	49	97
TVSu-491	79.47^{tnopqrstuvwxyzABCDEFGH}	10.86^{tnopqrstuvwxyzABCDEF}	9.339^{tmnopqrstuvwxyzABCD}	0.863^{ghijklmnopqrstuvwx}	28.78^{opqrstuvwxyzABCDEFG}	0.008^{tnopqrstuvwxyzABCDEFG}	0.797^{bcdefghi}	0.493^{ghijklmnopqrstuvwxyzAB}	0.858^{jklmnopqrstuvwxyzA}	10.02^{opqrstuvwxyzABCDE}	0.933^{abcdefghijk}	0.027^{bcdefghijklmnop}	0.120^{jklmnopqrstuvwxyzABCDE}	1.468^{bcdefghijk}	0.863^{ghijklmnopqrstuvwx}	4.56^{tmnopqrstuvwxyzABCD}	22.73^{defghijk}	0	38	10
TVSu-492	68.88^{CDEFGHIJKLM}	9.69^{GHIJKLMNO}	9.321^{tmnopqrstuvwxyzABCD}	0.932^{abc}	26.75^{DEFGHIJKLMNO}	0.007^{GHIJKLMNO}	0.795^{cdefghijkl}	0.347^{IJKL}	0.925^{abcdef}	9.31^{BCDEFGHIJKLMNO}	0.928^{abcdefghijklmn}	0.024^{cdefghijklmnop}	0.134^{abcdef}	1.453^{cdefghijk}	0.932^{abc}	4.413^{rstuvwxyzABCDEFGH}	20.29^{lmnop}	0	67	24
TVSu-501	65.94^{EFGHIJKLM}	9.99^{DEFGHIJKLMNO}	9.177^{nopqrstuvwxyzABCDE}	0.831^{stuvwxyzABCDEFGH}	26.22^{GHIJKLMNO}	0.007^{DEFGHIJKLMNO}	0.795^{cdefghijklm}	0.543^{bcdefghijklmnopq}	0.820^{wxyzABCDEFGH}	9.05^{FGHIJKLMNO}	0.913^{klmnopq}	0.031^{bcdefghijklmno}	0.133^{abcdefghi}	1.466^{bcdefghijk}	0.831^{stuvwxyzABCDEFGH}	4.137^{ABCDEFGHIJKL}	19.77^{nopq}	10	97	24
TVSu-506	78.58^{qrstuvwxyzABCDEFGHI}	10.56^{vwxyzABCDEFGHIJK}	9.168^{opqrstuvwxyzABCDE}	0.897^{abcdefghijklmn}	28.52^{qrstuvwxyzABCDEFGHI}	0.007^{vwxyzABCDEFGHIJK}	0.792^{cdefghijklm}	0.431^{rstuvwxyzABCDEFGHI}	0.896^{bcdefghijklmnop}	9.99^{pqrstuvwxyzABCDEFG}	0.940^{abcd}	0.012^{op}	0.121^{ghijklmnopqrstuvwxyzA}	1.485^{abcdefgh}	0.899^{abcdefghijklmn}	4.596^{klmnopqrstuvwxyzABC}	9.61^{ABCDEFGHIJ}	38	37	78
TVSu-514	80.87^{tmnopqrstuvwxyzABCDE}	10.73^{rstuvwxyzABCDEFGH}	9.144^{opqrstuvwxyzABCDE}	0.905^{abcdefghijklm}	28.74^{opqrstuvwxyzABCDEFG}	0.008^{rstuvwxyzABCDEFGH}	0.796^{cdefghijk}	0.410^{wxyzABCDEFGHIJ}	0.908^{abcdefghijkl}	10.11^{lmnopqrstuvwxyzABC}	0.935^{abcdefghi}	0.028^{bcdefghijklmnop}	0.122^{fghijklmnopqrstuvwxy}	1.498^{abcde}	0.905^{abcdefghijklm}	4.623^{klmnopqrstuvwxyzAB}	19.81^{nopq}	35	54	36
TVSu-515	79.65^{opqrstuvwxyzABCDEFGHI}	10.65^{tuvwxyzABCDEFGHI}	9.111^{rstuvwxyzABCDEF}	0.898^{abcdefghijklmn}	29.44^{klmnopqrstuvwxyzABCD}	0.006^{tuvwxyzABCDEFGHI}	0.790^{cdefghijklm}	0.432^{rstuvwxyzABCDEFGHI}	0.894^{bcdefghijklmnop}	10.05^{nopqrstuvwxyzABCD}	0.901^{pq}	0.019^{fghijklmnop}	0.121^{hijklmnopqrstuvwxyzAB}	1.472^{abcdefghijk}	0.898^{abcdefghijklmn}	4.599^{klmnopqrstuvwxyzABC}	10.47^{pxABCDEFGHI}	38	27	91
TVSu-521	90.1^{hijklmnopqrstu}	11.3^{ijklmnopqrstuvwxyzAB}	9.102^{rstuvwxyzABCDEF}	0.907^{abcdefghijk}	30.44^{ghijklmnopqrstuvw}	0.008^{ijklmnopqrstuvwxyzAB}	0.798^{bcdef}	0.404^{yzABCDEFGHIJ}	0.906^{abcdefghijklm}	10.68^{hijklmnopqrstuv}	0.940^{abcd}	0.025^{cdefghijklmnop}	0.115^{opqrstuvwxyzABCDEFGHIJKL}	1.498^{abcde}	0.907^{abcdefghijk}	4.908^{defghijklmnopqrst}	24.02^{cdefg}	37	26	76
TVSu-522	86.84^{ijklmnopqrstuvwxy}	11^{lmnopqrstuvwxyzABCDE}	9.078^{stuvwxyzABCDEF}	0.911^{abcdefghij}	29.95^{ijklmnopqrstuvwxyzAB}	0.008^{lmnopqrstuvwxyzABCD}E	0.795^{cdefghijklm}	0.408^{xyzABCDEFGHIJ}	0.910^{abcdefghijk}	10.5^{ijklmnopqrstuvwxyz}	0.942^{abc}	0.014^{lmnop}	0.116^{nopqrstuvwxyzABCDEFGHIJ}	1.474^{abcdefghijk}	0.911^{abcdefghij}	4.887^{defghijklmnopqrst}	8.78^{FGHIJ}	26	39	70
TVSu-528	107.07^{abcdef}	12.55^{bcdef}	9.033^{stuvwxyzABCDEFG}	0.867^{efghijklmnopqrstuv}	33.49^{abcde}	0.009^{bcdef}	0.793^{cdefghijklm}	0.483^{ijklmnopqrstuvwxyzABCD}	0.867^{ghijklmnopqrstuvwx}	11.65^{abcdefg}	0.933^{abcdefghijk}	0.015^{jklmnop}	0.102^{LMNOP}	1.476^{abcdefghijk}	0.867^{efghijklmnopqrstuv}	5.247^{abcdefghi}	8.39^{IJ}	38	37	78
TVSu-534	103.61^{bcdefgh}	12.01^{defghijklm}	9.027^{stuvwxyzABCDEFG}	0.919^{abcdefgh}	32.77^{abcdefgh}	0.008^{defghijklm}	0.790^{cdefghijklm}	0.384^{CDEFGHIJK}	0.917^{abcdefghi}	11.48^{abcdefgh}	0.940^{abcd}	0.017^{ghijklmnop}	0.107^{HIJKLMNO}	1.48^{abcdefghij}	0.919^{abcdefgh}	5.334^{abcdefg}	8.74^{FGHIJ}	26	29	58
TVSu-536	94.58^{efghijklmno}	11.87^{efghijklmnopq}	9^{stuvwxyzABCDEFGH}	0.849^{lmnopqrstuvwxyzABC}	31.26^{efghijklmnopq}	0.008^{efghijklmnopq}	0.796^{bcdefg}	0.523^{cdefghijklmnopqrstuv}	0.851^{lmnopqrstuvwxyzABCD}	10.91^{efghijklmnopq}	0.933^{abcdefghijk}	0.026^{bcdefghijklmnop}	0.109^{yzABCDEFGHIJKLMN}	1.476^{abcdefghijk}	0.849^{lmnopqrstuvwxyzABC}	4.908^{defghijklmnopqrst}	4.88^{K}	0	0	11
TVSu-539	92.1^{ghijklmnopqrs}	11.38^{ghijklmnopqrstuvwxyz}	8.99^{stuvwxyzABCDEFGH}	0.900^{abcdefghijklmn}	31.12^{efghijklmnopqr}	0.008^{ghijklmnopqrstuvwxyz}	0.805^{ab}	0.418^{tuvwxyzABCDEFGHI}	0.898^{abcdefghijklmnop}	10.82^{efghijklmnopqr}	0.933^{abcdefghijk}	0.031^{bcdefghijklm}	0.111^{uvwxyzABCDEFGHIJKLMN}	1.424^{k}	0.900^{abcdefghijklmn}	5.394^{abcde}	23.41^{defgh}	359	54	36
TVSu-553	71.3^{ABCDEFGHIJKLM}	10.75^{qrstuvwxyzABCDEFGH}	8.982^{stuvwxyzABCDEFGH}	0.795^{CDEFGHI}	27.3^{BCDEFGHIJKLM}	0.008^{qrstuvwxyzABCDEFGH}	0.788^{hijklm}	0.603^{abcdef}	0.795^{DEFGHI}	9.49^{BCDEFGHIJKLMN}	0.923^{cdefghijklmno}	0.031^{bcdefghijklmn}	0.122^{fghijklmnopqrstuvwxy}	1.487^{abcdefg}	0.795^{CDEFGHI}	4.032^{EFGHIJKL}	22.33^{efghijklm}	0	67	24
TVSu-554	79^{qrstuvwxyzABCDEFGHI}	10.67^{stuvwxyzABCDEFGHI}	8.973^{stuvwxyzABCDEFGH}	0.891^{bcdefghijklmnopq}	28.52^{qrstuvwxyzABCDEFGHI}	0.008^{stuvwxyzABCDEFGHI}	0.792^{cdefghijklm}	0.438^{pqrstuvwxyzABCDEFGHI}	0.880^{defghijklmnopqrstuv}	9.94^{stuvwxyzABCDEFGHI}	0.930^{abcdefghijklm}	0.036^{bcdef}	0.124^{defghijklmnopqrst}	1.475^{abcdefghijk}	0.891^{bcdefghijklmnopq}	4.632^{klmnopqrstuvwxyzAB}	21.42^{hijklmn}	14	47	53
TVSu-565	87.33^{ijklmnopqrstuvwx}	11.14^{klmnopqrstuvwxyzABC}	8.919^{stuvwxyzABCDEFGH}	0.902^{abcdefghijklm}	30.12^{hijklmnopqrstuvwxyzA}	0.008^{klmnopqrstuvwxyzABC}	0.789^{defghijklm}	0.415^{vwxyzABCDEFGHIJ}	0.899^{abcdefghijklmnop}	10.52^{ijklmnopqrstuvwxy}	0.937^{abcdefg}	0.035^{bcdefgh}	0.116^{nopqrstuvwxyzABCDEFGHIJ}	1.465^{bcdefghijk}	0.902^{abcdefghijklm}	5.034^{cdefghijklmn}	1.79^{L}	0	0	11
TVSu-592	100.17^{cdefghij}	11.92^{efghijklmn}	8.877^{vwxyzABCDEFGH}	0.896^{bcdefghijklmno}	32.22^{bcdefghij}	0.008^{efghijklmn}	0.796^{cdefghij}	0.437^{pqrstuvwxyzABCDEFGHI}	0.895^{bcdefghijklmnop}	11.28^{bcdefghi}	**0.946^{a}**	0.016^{jklmnop}	0.107^{EFGHIJKLMNO}	1.474^{abcdefghijk}	0.896^{bcdefghijklmno}	5.274^{abcdefgh}	9.31^{BCDEFGHIJ}	24	49	24
TVSu-6	92.79^{ghijklmnopqr}	12.11^{cdefghijkl}	8.859^{vwxyzABCDEFGH}	0.808^{vzABCDEFGHI}	31.36^{efghijklmno}	0.009^{cdefghijkl}	0.792^{cdefghijklm}	0.574^{bcdefghijk}	0.805^{zABCDEFGHI}	10.8^{efghijklmnopqrs}	0.910^{mnopq}	0.022^{defghijklmnop}	0.108$^{CDE

TVSu-636	87.03^{ijklmnopqrstuvwxy}	10.82^{nopqrstuvwxyzABCDEF}	8.844^{vwxyzABCDEFGH}	**0.952^{a}**	29.91^{jklmnopqrstuvwxyzABC}	0.008^{nopqrstuvwxyzABCDEF}	0.794^{cdefghijklm}	0.284^{L}	**0.953^{a}**	10.52^{ijklmnopqrstuvwxy}	0.942^{abc}	0.014^{klmnop}	0.119^{lmnopqrstuvwxyzABCDEFGH}	1.495^{abcdef}	**0.952^{a}**	4.92^{defghijklmnopqrst}	12.7^{uvwxy}	28	49	46
TVSu-653	89.58^{hijklmnopqrstuv}	11.34^{ijklmnopqrstuvwxyzA}	8.811^{vwxyzABCDEFGH}	0.888^{cdefghijklmnopqrs}	30.37^{ghijklmnopqrstuvwx}	0.008^{ijklmnopqrstuvwxyzA}	0.790^{cdefghijklm}	0.450^{mnopqrstuvwxyzABCDEFGHI}	0.888^{defghijklmnopqrs}	10.63^{hijklmnopqrstuv}	0.933^{abcdefghijk}	0.025^{cdefghijklmnop}	0.114^{pqrstuvwxyzABCDEFGHIJKLM}	1.471^{abcdefghijk}	0.888^{cdefghijklmnopqrs}	4.962^{cdefghijklmnop}	2.03^{L}	0	0	0
TVSu-658	89.85^{hijklmnopqrstu}	11.52^{efghijklmnopqrstuvw}	8.799^{vwxyzABCDEFGH}	0.872^{efghijklmnopqrstuv}	30.52^{ghijklmnopqrstuv}	0.008^{efghijklmnopqrstuvw}	0.794^{cdefghijklm}	0.484^{hijklmnopqrstuvwxyzABCD}	0.870^{efghijklmnopqrstuvwx}	10.69^{hijklmnopqrstu}	0.935^{abcdefghi}	0.018^{fghijklmnop}	0.112^{tuvwxyzABCDEFGHIJKLM}	1.498^{abcde}	0.872^{efghijklmnopqrstuv}	4.836^{ghijklmnopqrstuvw}	9.06^{DEFGHIJ}	38	37	78
TVSu-671	72.89^{xyzABCDEFGHIJKL}	10.19^{BCDEFGHIJKLMNO}	8.787^{vwxyzABCDEFGH}	0.896^{bcdefghijklmno}	27.55^{yzABCDEFGHIJKL}	0.007^{BCDEFGHIJKLMNO}	0.794^{cdefghijklm}	0.428^{rstuvwxyzABCDEFGHI}	0.894^{bcdefghijklmnop}	9.61^{xyzABCDEFGHIJKL}	0.935^{abcdefghi}	0.022^{defghijklmnop}	0.126^{defghijklmnopq}	1.466^{bcdefghijk}	0.896^{bcdefghijklmno}	4.446^{pqrstuvwxyzABCDEFG}	9.53^{ABCDEFGHIJ}	40	55	65
TVSu-673	94.16^{efghijklmnop}	11.77^{efghijklmnopqrst}	8.784^{vwxyzABCDEFGH}	0.879^{cdefghijklmnopqrstu}	31.28^{efghijklmnop}	0.008^{efghijklmnopqrst}	0.787^{hijklm}	0.458^{lmnopqrstuvwxyzABCDEFGH}	0.877^{defghijklmnopqrstuv}	10.95^{defghijklmnop}	0.935^{abcdefghi}	0.028^{bcdefghijklmnop}	0.110^{xyzABCDEFGHIJKLMN}	1.49^{abcdefg}	0.879^{cdefghijklmnopqrstu}	4.956^{cdefghijklmnop}	11.15^{wxyzABCDEF}	26	45	65
TVSu-677	93.83^{efghijklmnopq}	11.88^{efghijklmno}	8.673^{wxyzABCDEFGHI}	0.850^{klmnopqrstuvwxyzABC}	31.17^{efghijklmnopqr}	0.008^{efghijklmno}	0.789^{efghijklm}	0.524^{cdefghijklmnopqrstu}	0.847^{mopqrstuvwxyzABCDE}	10.91^{efghijklmnopq}	0.935^{abcdefghi}	0.025^{cdefghijklmnop}	0.109^{BCDEFGHIJKLMNO}	1.486^{abcdefgh}	0.850^{klmnopqrstuvwxyzABC}	4.914^{defghijklmnopqrst}	9.81^{ABCDEFGHIJ}	32	37	90
TVSu-709	70.24^{CDEFGHIJKLM}	10.72^{rstuvwxyzABCDEFGH}	8.664^{wxyzABCDEFGHI}	0.782^{GHI}	27.23^{BCDEFGHIJKLMN}	0.008^{rstuvwxyzABCDEFGH}	0.787^{ijklm}	0.622^{abc}	0.783^{GHI}	9.41^{BCDEFGHIJKLMNO}	0.916^{hijklmnopq}	0.034^{bcdefghij}	0.122^{efghijklmnopqrstuvwx}	1.474^{abcdefghijk}	0.782^{GHI}	4.02^{EFGHIJKL}	21.78^{ghijklmn}	359	92	28
TVSu-738	96.68^{defghijkl}	12.14^{cdefghijk}	8.622^{xyzABCDEFGHI}	0.832^{rstuvwxyzABCDEFGH}	31.99^{defghijkl}	0.009^{cdefghijk}	0.795^{cdefghijk}	0.545^{bcdefghijklmnop}	0.831^{tuvwxyzABCDEFGH}	11.08^{defghijk}	0.928^{abcdefghijklmn}	0.034^{bcdefghij}	0.105^{IJKLMNO}	1.433^{hijk}	0.832^{rstuvwxyzABCDEFGH}	5.169^{bcdefghij}	23.45^{defgh}	7	64	35
TVSu-742	76.28^{tuvwxyzABCDEFGHIJ}	11.08^{klmnopqrstuvwxyzABCD}	8.58^{yzABCDEFGHI}	0.793^{DEFGHI}	28.18^{tuvwxyzABCDEFGHIJ}	0.008^{klmnopqrstuvwxyzABCD}	0.792^{cdefghijklm}	0.607^{zabcd}	0.796^{CDEFGHI}	9.81^{tuvwxyzABCDEFGHI}	0.926^{abcdefghijklmno}	0.029^{bcdefghijklmnop}	0.117^{mnopqrstuvwxyzABCDEFGHI}	1.484^{abcdefgh}	0.793^{DEFGHI}	4.185^{rABCDEFGHIJK}	19.98^{mnop}	9	74	54
TVSu-751	94.5^{efghijklmno}	12.29^{cdefghi}	8.547^{zABCDEFGHI}	0.805^{yzABCDEFGHI}	31.59^{efghijklm}	0.009^{cdefghi}	0.787^{ijklm}	0.588^{abcdefghi}	0.807^{rABCDEFGHI}	10.96^{defghijklmno}	0.923^{cdefghijklmno}	0.035^{bcdefg}	0.105^{IJKLMNO}	1.461^{bcdefghijk}	0.805^{yzABCDEFGHI}	4.875^{defghijklmnopqrstu}	25.92^{abc}	352	81	35
TVSu-755	86.77^{ijklmnopqrstuvwxyz}	11.88^{efghijklmnop}	8.532^{zABCDEFGHI}	0.790^{EFGHI}	30.22^{hijklmnopqrstuvwxyz}	0.008^{efghijklmnop}	0.791^{cdefghijklm}	0.609^{abcd}	0.792^{EFGHI}	10.49^{ijklmnopqrstuvwxyz}	0.923^{cdefghijklmno}	0.032^{bcdefghijkl}	0.109^{ABCDEFGHIJKLMNO}	1.477^{abcdefghijk}	0.790^{EFGHI}	4.53^{nopqrstuvwxyzABCDE}	24.26^{cdef}	20	61	49
TVSu-757	72.94^{xyzABCDEFGHIJKL}	10.92^{mnopqrstuvwxyzABCDE}	8.517^{ABCDEFGHI}	0.789^{EFGHI}	27.52^{zABCDEFGHIJKL}	0.008^{mnopqrstuvwxyzABCDE}	0.786^{klm}	0.608^{abcd}	0.790^{FGHI}	9.57^{yzABCDEFGHIJKL}	0.920^{defghijklmnop}	0.040^{abcd}	0.121^{ghijklmnopqrstuvwxyzAB}	1.495^{abcdefg}	0.789^{EFGHI}	4.137^{ABCDEFGHIJKL}	22.83^{defghij}	29	100	42
TVSu-758	58.62^{LM}	9.68^{GHIJKLMNO}	8.499^{BCDEFGHI}	0.806^{yzABCDEFGHI}	24.82^{MNO}	0.007^{GHIJKLMNO}	0.788^{ghijklm}	0.588^{abcdefghi}	0.803^{ABCDEFGHI}	8.62^{MNO}	0.921^{defghijklmno}	0.017^{ghijklmnop}	0.134^{abcde}	1.501^{abcd}	0.806^{yzABCDEFGHI}	3.684^{KL}	1	54	45
TVSu-764	64.29^{IJKLM}	9.67^{HIJKLMNO}	8.478^{CDEFGHI}	0.880^{cdefghijklmnopqrstu}	25.83^{IJKLMNO}	0.007^{HIJKLMNO}	0.789^{fghijklm}	0.458^{lmnopqrstuvwxyzABCDEFGH}	0.878^{defghijklmnopqrstuv}	9.03^{HIJKLMNO}	0.937^{abcdefg}	0.012^{nop}	0.133^{abcdefgh}	1.492^{abcdefg}	0.880^{cdefghijklmnopqrstu}	4.044^{DEFGHIJKL}	11.86^{vwxyzA}	38	57	76
TVSu-783	101.27^{cdefghi}	12.47^{bcdefg}	8.424^{DEFGHI}	0.839^{opqrstuvwxyzABCDEF}	32.67^{abcdefghi}	8.817×10$^{-3bcdefg}$	0.792^{cdefghijklm}	0.534^{cdefghijklmnopqr}	0.836^{rstuvwxyzABCDEFG}	11.34^{bcdefghi}	0.928^{abcdefghijklmn}	0.039^{abcde}	0.104^{JKLMNOP}	1.463^{bcdefghijk}	0.839^{opqrstuvwxyzABCDEF}	5.226^{abcdefghi}	21.27^{hijklmno}	11	88	31
TVSu-8	88.48^{hijklmnopqrstuvw}	11.25^{ijklmnopqrstuvwxyzAB}	8.391^{EFGHI}	0.896^{bcdefghijklmno}	30.27^{hijklmnopqrstuvwxy}	7.950×10$^{-3ijklmnopqrstuvwxyzAB}$	0.794^{cdefghijklm}	0.436^{qrstuvwxyzABCDEFGHI}	0.893^{bcdefghijklmnopq}	10.58^{hijklmnopqrstuvw}	0.936^{abcdefgh}	0.026^{bcdefghijklmnop}	0.115^{opqrstuvwxyzABCDEFGHIJK}	1.483^{abcdefghi}	0.896^{bcdefghijklmno}	4.95^{cdefghijklmnopq}	9.51^{ABCDEFGHIJ}	40	55	65
TVSu-883	92.31^{fghijklmnopqrs}	11.91^{efghijklmn}	8.343^{EFGHI}	0.843^{nopqrstuvwxyzABCDE}	30.95^{efghijklmnopqrs}	8.419×10$^{-3efghijklmn}$	0.790^{cdefghijklm}	0.530^{cdefghijklmnopqrs}	0.845^{pqrstuvwxyzABCDEF}	10.83^{efghijklmnopqr}	0.929^{abcdefghijklmn}	0.029^{bcdefghijklmnop}	0.109^{zABCDEFGHIJKLMNO}	1.505^{abc}	0.843^{nopqrstuvwxyzABCDE}	4.794^{hijklmnopqrstuvw}	10.76^{zABCDEFGHI}	40	55	65
TVSu-887	94.31^{efghijklmno}	12.03^{defghijklm}	8.307^{EFGHI}	0.834^{qrstuvwxyzABCDEFG}	31.55^{efghijklm}	8.506×10$^{-3defghijklm}$	0.799^{klc}	0.536^{bcdefghijklmnopqr}	0.835^{rstuvwxyzABCDEFGH}	10.94^{defghijklmnop}	0.929^{abcdefghijklmn}	0.033^{bcdefghijk}	0.107^{FGHIJKLMNO}	1.453^{cdefghijk}	0.834^{qrstuvwxyzABCDEFG}	4.956^{cdefghijklmnop}	4.68^{K}	0	0	11
TVSu-890	57.61^{M}	9.28^{NO}	8.208^{FGHI}	0.849^{klmnopqrstuvwxyzABC}	24.48^{O}	6.559×10^{-3NO}	0.787^{ijklm}	0.522^{cdefghijklmnopqrstuv}	0.849^{mnopqrstuvwxyzABCD}	8.52^{O}	0.930abcdefghijkl	0.016^{ijklmnop}	0.139ab	1.471^{abcdefghijk}	0.849^{klmnopqrstuvwxyzABC}	3.759^{IJKL}	13.23uvwx	37	69	54
TVSu-903	80.35^{nopqrstuvwxyzABCDEF}	10.61^{uvwxyzABCDEFGHIJ}	8.124^{GHI}	0.911^{abcdefghij}	28.77^{opqrstuvwxyzABCDEFG}	7.500×10$^{-3uvwxyzABCDEFGHIJ}$	0.792^{cdefghijklm}	0.398^{zABCDEFGHIJ}	0.910^{abcdefghijk}	10.1^{lmnopqrstuvwxyzABC}	0.940^{abcd}	0.0242^{cdefghijklmnop}	0.121^{ghijklmnopqrstuvwxyzAB}	1.476^{abcdefghijk}	0.911^{abcdefghij}	4.692^{jklmnopqrstuvwxyz}	9.98^{ABCDEFGHIJ}	37	69	54
TVSu-920	76.79^{tuvwxyzABCDEFGHI}	10.35^{yzABCDEFGHIJKLMN}	8.097^{HI}	0.916^{abcdefghi}	28.18^{tuvwxyzABCDEFGHIJ}	7.316×10$^{-3xyzABCDEFGHIJKLMN}$	0.796^{cdefghijk}	0.396^{zABCDEFGHIJ}	0.914^{abcdefghij}	9.88^{rstuvwxyzABCDEFGHI}	0.939^{abcd}	0.017^{ghijklmnop}	0.124^{efghijklmnopqrstu}	1.478^{abcdefghij}	0.916^{abcdefghi}	4.569^{lmnopqrstuvwxyzABCD}	13.27^{uvw}	28	49	46
TVSu-928	99.69^{cdefghij}	12.56^{bcdef}	8.091^{HI}	0.805^{zABCDEFGHI}	32.47^{bcdefghij}	8.877×10$^{-3bcdef}$	0.791^{cdefghijklm}	0.591^{abcdefg}	0.806^{zABCDEFGHI}	11.25^{bcdefghi}	0.926^{abcdefghijklmno}	0.023^{cdefghijklmnop}	0.102^{MNOP}	1.458^{cdefghijk}	0.805^{zABCDEFGHI}	4.947^{cdefghijklmnopqr}	**27.2^{a}**	**11**	**88**	**31**
TVSu-933	71.56^{zABCDEFGHIJKLM}	10.06^{CDEFGHIJKLMNO}	7.887^{I}	0.902^{abcdefghijklm}	27.21^{BCDEFGHIJKLMN}	7.108×10$^{-3CDEFGHIJKLMNO}$	0.788^{ghijklm}	0.421^{tuvwxyzABCDEFGHI}	0.893^{bcdefghijklmnopq}	9.51^{ABCDEFGHIJKLMN}	0.940^{abcd}	0.029^{bcdefghijklmnop}	0.128^{bcdefghijklmn}	1.454^{cdefghijk}	0.902^{abcdefghijklm}	4.494^{opqrstuvwxyzABCDEF}	14.76^{ui}	32	53	51
TVSu-941	67.09^{DEFGHIJKLM}	10.27^{yzABCDEFGHIJKLMNO}	7.86^{I}	0.828^{tuvwxyzABCDEFGH}	26.51^{EFGHIJKLMNO}	7.257×10$^{-3yzABCDEFGHIJKLMNO}$	0.790^{cdefghijklm}	0.559^{bcdefghijkl}	0.829^{uvwxyzABCDEFGH}	9.23^{CDEFGHIJKLMNO}	0.929^{abcdefghijklmn}	0.028^{bcdefghijklmnop}	0.127^{cdefghijklmno}	1.503^{abcd}	0.828^{tuvwxyzABCDEFGH}	4.05^{DEFGHIJKL}	20.39^{klmnop}	0	67	24
TVSu-999	110.72^{abcd}	**13.97^{a}**	7.797^{I}	0.7282^{J}	**34.67^{ab}**	**9.878×10^{-3a}**	0.787^{jklm}	**0.681^{a}**	0.728^{J}	11.85^{abcd}	0.901^{q}	0.034^{bcdefghij}	0.092^{p}	1.455^{cdefghijk}	0.728^{J}	5.004^{cdefghijklmno}	23.09^{defghi}	342	64	33