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Research Article

Morphological Characterisation of *Panicum maximum* (Guinea Grass) Across Selected Agro-ecological Zones of Tanzania

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Abstract

This study evaluated the morphological variation of Panicum maximum across two agro-ecological zones in Tanzania: Semi-arid (Mpwapwa district) and sub-humid (Moshi rural district). Plant sampling was conducted using $0.5m^2$ quadrants, with one plant per quadrant, as assessed for plant height, leaf-to-stem ratio, leaf size, number of tillers, and fresh weight to estimate biomass. In six villages, four 10 m^2 plots were established, and six quadrant throws per site provided 144 samples. Soil texture, mineral composition, cation exchange capacity, and fertility were also analyzed. The results indicated sandy soils in the semi-arid zone and clay soils in the sub-humid zone. Significant differences ($p < 0.05$) were observed in all measured morphological traits across zones. The average leaf-to-stem ratio varied significantly between districts and terrains, with hilly areas exerting notable effects on forage quality. Leaf length differed significantly between valley and plain areas, while tiller number varied between zones. In the sub-humid zone, plant traits were relatively stable across terrains, whereas in the semi-arid zone, terrain strongly influenced growth. Biomass yield was consistent across all agro-ecological indicating the species' adaptability. Soil and moisture conditions were key determinants of P. maximum performance. These findings emphasize the importance of soil fertility enhancement and moisture conservation as interventions to optimize P. maximum performance and sustain its role as a key forage resource in diverse environments.

Keywords

Panicum Maximum, Agro-ecological Zones, Morphological Variation, Forage Adaptability, Ecotype, Soil and Moisture Conditions

1. Introduction

The primary source of feed for ruminant animals, including cattle, sheep, and goats in Tanzania, is natural pastures from communal rangelands that are practically owned and managed by local communities [1, 2]. Notwithstanding, Tanzania's communal rangelands are generally limited by a number of challenges, such as degradation and bush encroachment [3]. The major indicators of rangelands degradation are a shift in species composition, loss of range biodiversity, reduction in

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biomass production, less plant cover, low livestock productivity, and soil erosion [4]. Currently, Tanzania has 41.2 million livestock units (LU), requiring 103 million hectares of grazing land [5]. Meanwhile, only 3.06 million hectares of grazing land have been set aside as of the year 2022 through the Village Land Use Plan (VLU). The development and management of grazing land is therefore necessary to meet the requirements for pastures to feed the increasing number of livestock.

Common grazing land management practices implemented in Tanzania include planting pasture species, bush clearing to reduce shrubs and bushes, and removing invasive weeds [5]. *Panicum maximum* (Guinea grass) is among the preferred pasture species naturally occurring in Tanzania range lands, and it has a significant potential in rangeland restoration and pasture establishment on private lands.

Panicum maximum was considered in this study due to its unique characteristics, such as high biomass production and nutritive value, its ability to tolerate waterlogging areas, high resistance to pests and diseases and shade tolerance compared to most improved tropical grasses [6]. Moreover, *Panicum maximum* has a certain degree of frost tolerance and stays in a green state longer and can grow on lighter, soft clay and clay loam soils. The grass is most suited to deep alkaline, moderate levels of soil salinity, dark, heavy, cracking clay soils of moderate to high fertility and with poor internal drainage. The seeds of *Panicum maximum* shed as it matures and mature unevenly from the apex of the panicle to the base [7]. When they begin to ripen, they also appear bleached blue and lose their purplish colour.

When irrigation is applied, seed yields of up to 400kg/ha can be produced, while 100 to 180kg/ha are possible under rain conditions [8]. Crude protein level of *Panicum maximum* is about 8 - 12% and digestibility is approximately 60% in the leafy stage at 3-6-week-old old, which makes it a potential fodder [9]. The regrowth occurs after 10 weeks, during which digestibility is moderate and crude protein content declines [10]. Moreover, its crude protein content drops to 5% at maturity. All these characteristics are given at the species level, but different ecotypes can be found to have varying characteristics, which calls for empirical research.

Different studies on characterisation of *P. maximum* exist on the shading, fertilisers and irradiation effects on morphological and biomass production of the grass [11, 12]. However, the gap exists in the effect of agro-ecological zone on the morphological characteristics of *P. maximum*, particularly in Tanzania. There is therefore a need for characterization of *Panicum maximum* (Guinea grass) and contribute to improving feed availability under changing climatic conditions and increasing adaptability, productivity, and nutritional value of the grass. Characterisation of guinea grass for drought-resistant characteristics, including deep root systems and effective water use. These features ensure consistent biomass production regardless of the face of unpredictable rainfall or dry conditions [13]. Long-term availability of guinea grass is primarily due to its ability to regenerate after grazing. According to [9], field tests conducted in tropical areas, cultivars of guinea grass can produce up to 20–30 tons of dry matter per hectare per year.

Panicum maximum ecotypes are reported to withstand water stress and maintain high yield. Ecotypes such as ecotype9, ecotype4 and Mombasa cultivars can maintain high yields even in water stress conditions [14]. Moreover, identifying ecotypes with high yields and rapid growth could guarantee a steady supply of feed resources across different climatic conditions and agroecological zones. Ecotype refers to a genetically distinct population or group within a species that is adapted to a particular environmental condition, such as climate, soil properties, grazing pressure and or altitude [15]. These adaptations help the ecotype survive and reproduce better in its local habitat than other members of the same species living elsewhere. Although they are members of the same species, ecotypes differ in characteristics like plant height, leaf size, leaf to stem ratio, biomass production, flowering time, resistance to drought, etc. Differences arise due to natural selection over generations in different environments. The present study, therefore, characterized *Panicum maximum* from two selected agro-ecological zones of Tanzania with contrasting climatic conditions. The information obtained from this study will help in species selection for breeding purposes and forage production to improve feed availability in the livestock sector amidst changing climatic conditions in Tanzania.

2. Materials and Methods

2.1. Description of the Study Areas

The study was conducted in two selected agro-ecological zones of Tanzania, comprising Dodoma and Kilimanjaro regions, representing the semi-arid and sub-humid zones, respectively. Two districts were purposively selected, from the two regions, i.e., Mpwapwa from Dodoma and Moshi rural from Kilimanjaro regions. Their selection was due to their significance in livestock production, accessibility, availability of the species under study and representation of semi-arid and sub-humid agroecological zones. Mpwapwa District is located 900m - 1200m above sea level in the central part of the country and receives an average rainfall of about 400 -700mm, and the mean annual temperature ranges from 20℃ to 30℃. On the other hand, Moshi rural district is located between 700 to 2000m above sea level in Kilimanjaro region, northern Tanzania. The district lies between latitudes 2°50' S and 3°20' S and longitudes 37°00' E and 37°30' E with an average annual rainfall of about 800 – 1400 mm, and average temperature ranges from 20℃ to 30℃ in the lowland areas and 10℃ to 25℃ in the highland. The soils in Mpwapwa area were generally sandy, while clay soils dominate in Moshi rural.

2.2. Sampling Procedures and Data Collection for Phenotypic Characterisation of *Panicum Maximum*

One ward was selected from each district. From each ward, three villages were purposively sampled based on their differences in agro-ecological characteristics, topography, significant potential in ruminant production and presence of *Panicum maximum.* This was based on the preliminary survey and consultation with the respective district extension offices. The procedures used for selecting the sites for data collection, as described above, were based on the reference study by [16]. Mpwapwa ward was selected from Mpwapwa district, and Marangu ward from Moshi rural district. Three villages sampled from Mpwapwa include Kikombo, representing ecotypes from hill areas, Ilolo, representing ecotypes from plain areas and Chibwechangula, representing ecotypes from valley areas. Villages from Marangu ward were Mbahe kati representing ecotypes from hill areas, Mkuuni representing ecotypes from plain areas and Kileo representing ecotypes from valley areas.

The selection of plants for assessment of phenotypic characteristics involved multistage sampling. The Process started by selecting four sites from each village, and in each site, a plot with an area of 10-meter square meters was made. Plants to be assessed were sampled using a quadrat of 0.5 $m^{2,}$ which was thrown randomly, six times in the plot. One plant within the quadrat was selected to assess plant height, leaf stem ratio, leaf size and tiller number per plant, giving a total of 144 measurements per characteristic in all six villages. *Panicum maximum* within the quadrat was harvested at 30cm height above the ground level, and weighed to estimate forage production, this is a reference to the study of [17]. A detailed assessment of phenotypic characterisation is provided below:

2.3. Variables for Morphological Characterisation

Variables assessed for morphological characterisation of *Panicum maximum* include**:**

Plant height, which was measured in centimeters (cm) from the base of the stem (at the soil's surface) to the top of the canopy or the highest point of the plant using a tape measure [18]. Leaf length and width were measured from the apex of the blade to the base of the petiole, and width was measured at the widest point perpendicular to the longitudinal axis of the leaf [19].

Leaf to stem ratio was determined by counting the number of leaves in a *Panicum maximum* grass, and later the average was calculated [20]. The average number of tillers per plant was determined by counting the number of tillers from each plant within the quadrat, and the average number per plot was calculated [21]. Estimation of forage yield was done using a quadrant of 0.5 $m^{2,}$ whereby a quadrat was thrown randomly in the field within a selected site and Panicum grass within the quadrat was harvested and weighed on its fresh weight [22]. Assessing *Panicum maximum* productivity potential under various environmental conditions required estimating biomass yield. The sustainability of forage systems as a whole, pasture management choices, and livestock feeding efficiency are all directly impacted by the vital information on forage availability that biomass data provides [23]. Additionally, by comparing Panicum maximum's performance in semi-arid and sub-humid zones, it aids in choosing ecotypes that are appropriate for each area.

2.4. Ecological and Environmental Data Collection

Ecological and environmental data were collected by surveying all study sites and observing the topography and general landscape features. All observed aspects were documented, including other species associated with Panicum grass in the field. Geographic coordinates (longitude, latitude and altitude) were recorded using a smartphone equipped with the GPS Altimeter application. Data on average annual rainfall and temperature were obtained from extension officers.

Visual characteristics of the soil were recorded, and soil samples were collected for chemical analysis. Eight soil samples were collected from each village using a Soil Auger driven at a depth of 15cm, resulting in a total of 48 soil samples from 6 villages. The sampling location was cleared of surface litter. A soil sample was taken after the auger was driven to a plough depth of 15 cm. Each sampling unit's samples were kept in special bags to preserve them until the lab analysis, according to [24]. Soil samples were analyzed using the Agro-Care scanner E-Series to determine their mineral composition, texture, fertility and moisture content.

3. Data Analysis

Data on morphological parameters were summarized in an Excel sheet and then exported to Statistical Package Software for Social Sciences (SPSS) version 30 for One-way Analysis of Variance (ANOVA), to find out if there were significant differences in mean values between locations. The least square difference (LSD) was employed to test specific differences between pairs of means. The correlation analysis was performed to determine the interrelatedness among the assessed traits, i.e. plant height, average leaf-stem ratio, leaf length and width, number of tillers and biomass fresh weight.

Statistical general linear model used (equation (1)):

$$Y = \mu + Ei + \varepsilon ij \tag{1}$$

Where: Y = Trait response, μ = General mean, Ei = ecotype effect, Ɛij = Experimental error.

4. Results and Discussion

4.1. Ecological and Environmental Data of the Selected Sites

Two different agro-ecological zones, the semi-arid represented by Mpwapwa district in Dodoma and the sub-humid zone represented by Moshi rural district in Kilimanjaro, provided the ecological and environmental data of the selected sites. These zones provide an ideal foundation for comparing how environmental factors affect pasture performance and livestock management practices because they differ significantly in terms of rainfall patterns, temperature regimes, vegetation types and soil characteristics. The sections that follow present an interpretation of the findings from each zone, with emphasis on how local conditions shape forage species distributions and productivity.

4.2. Semi-arid Zone

Ecological and Environmental data for both semi-arid and sub-humid zone, as presented in Table 1, revealed that The three villages of Chibwechangula, Ilolo and Kikombo are located in different regions: Chibwechangula is in a valley, Ilolo is on a plain, and Kikombo is in the hills. The topography's change from hills to plains and valleys probably affects the soil types, water runoff patterns and local microclimates, all of which are important elements in a semi-arid environment. As is common for a comparatively small geographic area, the three locations have similar climatic conditions. Temperatures of the study sites range between 20 ℃ to 30 ℃, and 400–700 mm of rainfall annually. This range of rainfall is typical of semi-arid regions, where water availability and forage productivity are impacted by seasonal and highly variable rainfall.

4.3. Sub-humid Zone

The geographical characteristics of the villages in sub-humid areas were also on three villages in Moshi rural district. Mkuuni was on a plain, Kileo was in a valley, and Mbahe Kati was found in a hilly region. According to the climate data, Mbahe Kati and Mkuuni village experience temperatures between 10 ℃ - 25 ℃ and 800–1400 mm of rainfall annually. Kileo village, on the other hand, has a warmer temperature range of 20 ℃ to 30 ℃ but receives the same 800–1400 mm of rainfall annually. Compared to semi-arid areas, these villages in a sub-humid climate, which was characterized by higher rainfall and moderate temperatures, can sustain a variety of ecological activities.

Table 1. *Ecological and Environmental data for both semi-arid and sub-humid zone.*

Zone	**District**	**Village name**	**Area**	**Latitude**	**Longitude**	**Elevation (m)**	**Annual rainfall (mm/yr)**	**Temperature (℃)**
Semi-arid	Mpwapwa	Kikombo	Hills	-6.33311	36.49595	26.62	400–700	20–30
Semi-arid	Mpwapwa	Ilolo	Plain	-6.36054	36.469521	0.85	400–700	20–30
Semi-arid	Mpwapwa	Chibwechangula	Valley	-6.36111	36.485282	18.22	400–700	20–30
Sub humid	Moshi rural	Mbahe kati	Hills	-5.903	39.331	32.10	800–1400	10–25
Sub humid	Moshi rural	Mkuuni	Plain	-5.25	38.21	1.41	800–1400	10–25
Sub humid	Moshi rural	Kileo	Valley	-3.369	37.14	0.42	800–1400	20–30

4.4. Anthropogenic Activities Predominantly Influence the Ecological Conditions of the Study Sites

Anthropogenic activities predominantly involved livestock grazing and crop production on both semi-arid and sub-humid. Most of the land in the semi-arid areas of Kikombo and Chibwechangula was utilised for crop production, mainly groundnuts, maize, sunflower, and sorghum, as well as livestock grazing. Ilolo village, on the other hand, was primarily focused on producing forage and animal grazing areas. In the sub-humid zone, the main crops cultivated in Mbahe kati and Mkuuni were perennial crops such as coffee and banana, with small farms also producing beans. In contrast, Kileo village was primarily used for the production of maize, sunflower, groundnuts and beans. Grasslands (savanna) made up almost all of the vegetation type in the semi-arid regions of Kikombo and Chibwechangula, whereas forests with banana and coffee plantations predominated in the sub-humid areas of Moshi Rural, Mkuuni, and Mbahe.

4.5. Other Plant Species Associated with Panicum Grass in the Study Areas

Apart from farmed crops, the semi-arid regions were dominated by weeds like *Cyperus rotundus, Biden Pilosa, Echinochloa species* and *Dactloctenium aegyptium* as well as grass species like *Cenchrus ciliaris, Bothriochloa insculpta, Andropogon gayanus, Chloris gayana*, and *Cynodon species.* Additionally, the dominance of acacia trees was noted in certain regions of Chibwechangula and Kikombo. With their heavily forested landscapes, Mkuuni and Mbahe villages in Moshi Rural's sub-humid regions were mainly used for the production of cash crops, primarily coffee and bananas. On the other hand, Kileo village concentrated on growing food crops like sunflowers, beans, and maize. In addition to farmed crops, weeds like *Commelina benghalensis, Ageratum conyzoides*, and *Bidens pilosa* were the most common plant species in the sub-humid regions.

4.6. Soil Characteristics of the Studied Sites

The soil analysis result, as presented in Table 2, revealed that the Mpwapwa district generally with sandy soils which has low water holding capacity and are less fertile. In contrast, the soils in Moshi rural areas were clay having high water holding capacity and fertile. The soil pH values in all studied sites ranged from 5.8 to 6.9, which is moderately acidic to nearly neutral. These levels are generally favourable for many forages although at the pH range of 5.8 to 6.0, availability of some nutrients may be slightly [25]. Application of lime to the soil can bring the pH up to more ideal levels [14]. According to literature, Panicum grass can tolerate saline conditions [26].

The fertility parameters of the soil varied significantly. Kileo village had an adequate phosphorus level of 19.7 kg per ha, while all other villages' phosphorus levels were generally low, ranging from 5.1 to 12.1 kg per ha. In most places, potassium concentrations were adequate, although the clay soils of Kileo and Mbahe had particularly high levels. Nitrogen availability was consistently low in Mbahe and all Mpwapwa sites, whereas Kileo and Mkuuni showed adequate to high levels. According to the literature, strong forage growth and productivity are best achieved by keeping soil phosphorus at 45–90kg/ha and potassium at 269–381kg/ha [27]. The availability of nitrogen for forages cannot be accurately determined by soil tests, which makes it unique. For grass-dominant stands, performance is instead enhanced by applying 100–200 kg N/ha annually in split applications, whereas legumes can rely on biological nitrogen fixation and thus need little to no nitrogen from fertilisers [28-30].

Significant differences existed between the sites in terms of Cation Exchange Capacity (CEC), which measures the soil's ability to hold important nutrients. Chibwechangula had a particularly low CEC of 35, indicating limited nutrient retention and a higher risk of leaching losses, particularly under sandy clay textures. Kileo, on the other hand, had an exceedingly high CEC of 213, indicating excellent nutrient-holding capacity and greater resilience against nutrient depletion.

Based on the literature, the Cation Exchange Capacity (CEC) of soil is a crucial measure of the soil's ability to hold on and provide vital nutrients for the production of most forages. Soils with very low CEC values, generally less than 10 cmol kg, are usually sandy soils, which tend to have little organic matter and tend to lose nutrients rapidly through leaching. Because of this, maintaining forage productivity without regular fertilizer applications is challenging [31]. The best conditions for forage growth and persistence are found when the CEC is at least 15 cmol (+)/kg. If properly managed, soils above this range are well suited for maintaining high-yielding forage systems; however, below this threshold, nutrient losses and decreased fertility become limiting factors [32].

Another important factor that varied significantly was the moisture content. Data was collected from both zones as the rainy season approached an end with the goal to ensure a comparison that was based on evidence. The soil in Chibwechangula was more vulnerable to drought stress because it had the lowest moisture content (4.8%). Kileo, on the other hand, had the highest moisture content (28.1%), which favours water availability in the soil.

Because it promotes root function, photosynthesis, and nutrient uptake, soil moisture is essential for forage growth. In order to support vigorous forage, particularly in cut-and-carry systems, the literature generally advises keeping soil moisture in the rooting zone between 50% and 70% of Available Water Capacity (AWC) (Irmak *et al.*, 2011). Plant stress increases and yield losses become noticeable when moisture falls below 40% of AWC; at this point, irrigation is recommended to start to prevent drought-induced declines in biomass and quality [33, 34].

The significance of site-specific and soil management techniques is generally highlighted by these soil analysis results across the various agroecological zones under study. The scientific data presented by soil analysis results the idea that site-specific soil management is a more reliable and sustainable approach than uniform approaches [35]. Traditional farming practices, which use consistent treatments throughout a field, are frequently ineffective due to the wide variations in soil characteristics within a single plot of land [36]. Farmers can maximize productivity and preserve soil sustainability by developing interventions to address nutrient deficiencies, acidity and moisture limitations [35].

Table 2. Soil physical and chemical characteristics of the study sites.

District	Village	Texture	pH		mineral, kg				CEC	Moiture%
			results	class	C	N	P	K		
Mpwapwa	Chibwechangula-VA	sandy clay	6.2	MA-adequate	5.1	0.11	12	19	35	4.8
	Ilolo-PA	sandy clay loam	6.2	MA-adequate	12.1	0.46	2.4	32	83	10.3
	Kikombo-HA	sandy clay loam	6.1	MA-adequate	10.6	0.21	2	23	41	10.1
Moshi rural	Kileo-VA	clay	6.9	Neutral	19.7	0.29	8	40	213	28.1
	Mkuuni-PA	sandy loam	5.8	MA-adequate	41.1	0.3	23	38	59	22.1
	Mbahe-HA	clay	6.1	MA-adequate	7.9	0.3	8.4	86	94	23.6

Notes: VA=Valley areas, PA=Plain areas, HA=Hilly areas, pH=potential hydrogen, C=carbon, p=phosphorus, K=potassium, N=nitrogen, CEC=cation exchange capacity, MA=Moderate acidic,

4.7. Landforms, Vegetation and Dominance of Panicum Grass in the Studied Area

Several landforms and vegetation types were present in the study areas, which seemed to have a significant impact on Panicum grass's adaptability and dominance. A clear distinction in land cover was observed between the semi-arid and sub-humid. In the semi-arid zone of Kikombo and Chibwechangula, the primary land cover was grassland (savanna). Conversely, the sub-humid zone of Mkuuni and Mbahe was dominated by forests with notable presence of bananas and coffee plantations. Environmental factors, specifically topography and vegetation cover, were found to be important in determining the distribution patterns of various Panicum ecotypes.

The results showed that Panicum grass was less common in hilly regions and areas with dense tree and shrub cover, a trend that was particularly noticeable in the Mbahe ecotype areas of Moshi Rural, where the landscape was dominated by banana plantations and tree canopies. The findings of this study on the influence of land forms and vegetation types on the distribution of *Panicum maximum* from both agro-ecological zones are in line with research by [37], who found that Panicum species were typically rare in hillside and valley areas with dense vegetation. Similarly to Mbahe in Moshi, where the land was mostly covered in natural forest and perennial crops. Panicum grass was rarely dominant in these kinds of environments and usually appeared in random patches.

The Mkuuni ecotype in Moshi Rural and the Ilolo ecotype in Mpwapwa, on the other hand, were found in open plains with little tree cover, where they showed great adaptability and control over other grass species. C4 grasses like Panicum flourished because of the ideal growth and photosynthesis conditions these open spaces offered. This finding is consistent with research by [38, 39], who observed that C4 grasses flourish in open, sunny settings because of their effective photosynthetic pathway, which is suited to high temperatures and light levels.

4.8. Morphological Characterisation of *Panicum Maximum*

The results of the morphological characteristics, as presented in Table 3, revealed that all measured morphological parameters differed significantly across villages ($p < 0.05$). The average leaf-to-stem ratio showed that VA differed significantly between the two districts. Likewise, significant differences were also observed in PA between the districts. Additionally, HA had a significant effect on the average leaf-to-stem ratio across the agro-ecological zones. Regarding leaf length, significant differences were observed in valley areas (VAs) and plain areas (PAs) between the two districts, but no such variation was found in hilly areas (HAs). Notably, within Moshi Rural District (a sub-humid zone), leaf length did not vary significantly across all terrains, suggesting that growth in this zone is largely terrain independent. This uniformity indicates that the relatively favourable moisture availability and milder environmental conditions in Moshi Rural support consistent leaf development regardless of topography. In contrast, in Mpwapwa, a semi-arid district. Due to limited water availability in the semi-arid zone appear to amplify terrain-related effects, with valleys and plains offering slightly better conditions for leaf growth than hills. These findings align with those of [40], who reported differences in the transpiration rates of *Panicum maximum* between disturbed and undisturbed sites in a semi-arid region of Kenya, highlighting the species' sensitivity to environmental conditions in water-limited areas. Based on the literature, one important factor in determining the quality of forage is the leaf-to-stem ratio. Changes in this ratio can affect nutrient supply and overall forage quality and are associated with biomass allocation [20]. Nutrient reallocation between leaves and stems may cause an increase in the leaf-to-stem ratio, which would have a major impact on plant height and above-ground biomass [41]. Significant genetic variations in leaf-stem ratios across different ecotypes indicate that environmental factors and genetics influence the ratio [41]. Environmental factors such as climate and soil composition, which can differ greatly among various agro-ecological zones, have an impact on the leaf-to-stem ratio [42].

In terms of plant height, significant differences were noted in hilly areas (HA) of Kikombo (semi-arid zone) and Mbahe (sub-humid zone). However, no significant differences were observed in valley areas (VA) across both ecological zones (Chibwechangula in Mpwapwa and Kileo in Moshi Rural). Similarly, plant height did not vary significantly in plain areas (PA) of Ilolo and Mkuuni. Because of the interaction of topographic factors, vegetation composition, soil characteristics, and climate, forage height varies greatly among agro-ecological zones. Forages in AEZs with plenty of rainfall, fertile soil, and adapted species can grow 20–50% taller than those in nutrient-poor, drier areas. Although some variations can be decreased by management techniques like fertilization or species selection, the main causes of forage height variation are still the natural environmental features of AEZs [43, 44].

Leaf width did not show significant differences in either VA or PA, but significant differences were observed in HA between the two districts. These variations in leaf length and width could be attributed to nitrogen content and shading effects, as noted by [11]. The current findings on leaf morphology align with those of Paciullo, who reported significant differences ($p < 0.001$) in leaf and stem elongation rates and leaf blade lengths of *Panicum maximum* (cv. Tanzania and cv. Massai) due to shading, cultivar type, and nitrogen levels. Additionally, most of the literature entails that agro-ecological zones differ significantly in forage leaf size because of the interaction of topography, vegetation, soil, and climate. While drier, nutrient-poor zones have smaller leaves to conserve resources, adapted species in the most humid, fertile AEZs produce forages with larger leaves to optimize photosynthesis. AEZ-specific environmental factors continue to be the primary drivers of these differences, although management strategies such as species selection can help to a certain degree [43].

The number of tillers did not vary significantly in VAs and HAs, but in PAs, significant differences were observed between agro-ecological zones. As with leaf length, tiller number within Moshi Rural showed no significant differences across terrain types. This consistency may be due to environmental influences, as tiller density is known to be affected by both endogenous and environmental factors [45]. Another plausible explanation is the low nitrogen availability in the soils of the study areas (Table 3), since nitrogen plays a key role in tissue development and the formation of carbon skeletons in plants [46]. These findings are consistent with those of [11]. Because of variations in climate, soil, vegetation, and topography, the number of tillers in forage plants varies greatly among agro-ecological zones. Due to improved moisture, fertility, and favourable temperatures, adapted species in the most humid, nutrient-rich AEZs can yield 20–50% more tillers than those in drier, nutrient-poor zones. Although some restrictions can be reduced by management techniques like choosing species that are good for tillers, environmental factors particular to the AEZ remain the main forces influencing tiller production [47].

Fresh weight (bio-mass yield) did not differ significantly across VAs, PAs, or HAs, indicating that *P. maximum* can be cultivated successfully in both humid and arid/semi-arid zones with relatively comparable yields. In Moshi Rural specifically, no significant differences in fresh weight were observed across terrain types. It is important to note that the yield of fresh and dried forages directly reflects economic value and is a primary indicator of *Panicum maximum* (Benggala grass) productivity [45]. As such, fresh and dry forage weights are important parameters for evaluating productivity, more so than indirect traits such as tiller number, plant height, or stem diameter [12]. The current finding contradicts that of [41] who found that high nutrient contents of *P. maximum* were higher in the wet zone and in the dry zone in Sri Lanka. Overall, the findings reveal that morphological parameters vary significantly between different agro-ecological zones (e.g., semi-arid vs. sub-humid). These differences may result from variations in precipitation, moisture, temperature, soil fertility, and vegetation cover. Furthermore, most morphological traits showed no significant variation across different terrains within the sub-humid zone, in contrast to the semi-arid zone. This could be attributed to the relatively abundant rainfall in the sub-humid zone, which appears to mitigate terrain-related differences.

Table 3. *Morphological characteristics of P. maximum (indicate what the numbers in the table represent and what the sample size was)*

Location		Parameters					
District	Village	Plant height (cm)	Average leaf-stem ratio	Leaf length (cm)	Leaf width (cm)	No. tillers	Fresh Weight (Kgs)
Mpwapwa	Chibwechangula-VA	114.1^{c}±34.9	6.3^{d}±1.5	44.5^{c}±15.6	1.6^{d}±0.6	10.7^{b}±6.2	0.5^{b}±0.3
	Ilolo-PA	174.7^{b}±54.8	8.9^{b}±2.8	47.9^{bc}±20.6	2.3^{b}±0.7	28.5^{a}±28.7	0.8^{a}±0.5
	Kikombo-HA	198.3^{a}±41.9	9.9^{a}±2.7	58.4^{a}±14.6	3.1^{a}±0.5	10.4^{b}±4.8	0.8^{a}±0.5
Moshi rural	Kileo-VA	100.0^{c}±44.4	7.5^{c}±2.2	60.2^{a}±9.9	1.8^{cd}±0.5	7.5^{b}±5.2	0.2^{c}±0.3
	Mkuuni-PA	156.7^{b}±53.1	10.1^{a}±2.2	62.2^{a}±13.6	2.0^{bc}±0.6	10.2^{b}±5.4	0.4^{bc}±0.3
	Mbahe-HA	93.5^{c}±25.9	6.9^{cd}±1.4	55.6^{ab}±9.2	2.3^{b}±0.5	13.0^{b}±6.1	0.4^{bc}±0.3
	SEM	11.51	0.21	1.26	0.06	1.19	0.04
	P-value	<.000	<.000	<.000	<.000	<.000	<.000
	F-value	28.161	14.41	6.199	22.530	8.800	8.679

Notes: VA=Valley areas, PA=Plain areas, HA=Hilly areas, SEM=Standard error of the mean

4.9. Correlation Between Morphological Parameters of *P. Maximum*

Table 4 highlights the correlation analysis of forage characteristics, demonstrating that plant height is strongly and positively associated with leaf-to-stem ratio, leaf width, tiller number, and fresh weight across diverse agro-ecological zones. However, its correlation with leaf length was positive but not statistically significant. The leaf-to-stem ratio exhibited a significant positive correlation with leaf width and fresh weight, while its correlation with leaf length and number of tillers was positive but not significant. Leaf length was significantly positively correlated with leaf width but showed an insignificant negative correlation with both the number of tillers and fresh weight. Leaf width demonstrated a significant positive correlation with the number of tillers and fresh weight. In *Festuca arundinacea*, leaf width (LW) was the leaf trait most closely linked to animal preference, likely due to its higher proportion of mesophyll tissue (MES) [16]. Similarly, the current study corroborates [19], who reported that the leaf width of *Panicum maximum* showed the strongest correlation with MES among the leaf morphological traits. Furthermore, the number of tillers showed a significant positive correlation with fresh weight. This result concurs with [12], who found positive correlation in gamma-rays irradiated *P. maximum's* plant height, leaf width, plant height, stem height, width of high flag leaves, as well as length.

Table 4. *Correlation of morphological parameters/traits.*

Morphological traits	Plant height (cm)	Leaf-stem ratio	Leaf length (cm)	Leaf width (cm)	No. of tillers	Fresh weight (Kgs)
Plant height	1					
Leaf-stem ratio	0.561**	1				
Leaf length	0.143	0.115	1			
Leaf width	0.489**	0.293**	0.167*	1		
No. of tillers	0.245**	0.022	-0.001	0.164*	1	
Fresh weight	0.426**	0.344**	-0.102	0.237**	0.279**	1

**= Correlation is significant at the 0.01 level, *= Correlation is significant at the 0.05 level

5. Conclusion and Recommendations

In order to support climate-smart forage development, this study aids in the selection of *Panicum maximum* ecotypes appropriate for either sub-humid zone productivity or semi-arid resilience. This study demonstrates that *P. maximum* exhibits variable morphological responses across agro-ecological zones, particularly between sub-humid (Moshi Rural) and semi-arid (Mpwapwa) regions.

Within the sub-humid zone, most morphological traits, including leaf length, tiller number, and fresh weight, showed no significant variation across different terrains, suggesting that favourable climatic conditions, especially sufficient moisture, promote consistent growth regardless of topography. In contrast, the semi-arid zone exhibited terrain-dependent variations, indicating that limited water availability amplifies the influence of topographic factors on plant development. Leaf width differed significantly in hilly areas between the districts. Although biomass yield did not differ significantly across terrains or between zones, the consistent yield performance in both environments highlights *P. maximum*'s adaptability and potential as a reliable forage crop under varying environmental conditions. These findings underscore the importance of climatic and edaphic factors, particularly moisture availability and soil fertility, in shaping the morphological traits of *P. maximum*. The observed consistency of growth in the sub-humid zone and the sensitivity to terrain in the semi-arid zone provide valuable insight for forage management and site-specific cultivation strategies. The study recommends more studies on the performance of *P. maximum* collected from different zones when established in the same area with the same climatic conditions. Moreover, more studies should be conducted on the genotypic characterisation of *P. Maximum* from different agro-ecological zones.

Abbreviations

HA	Hill Areas
PA	Plain Areas
VA	Valley Areas
AEZ	Agro-Ecological Zone
LW	Leaf Width
SEM	Standard Error of the Mean
CEC	Cation Exchange Capacity
AWC	Available Water Capacity

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Conflicts of Interest

The authors declare that no conflict of interest exists regarding the publication of this manuscript.

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