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Application of principal component analysis to better understand the ecological dynamics of plant species in aquatic ecosystems

[Application de l'analyse en composantes principales pour mieux comprendre les dynamiques écologiques des espèces végétales dans les écosystèmes aquatiques]

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Abstract

The analysis of plant resources, particularly forage species, is crucial for the sustainable management of ecosystems, especially in biodiversity-rich areas such as the M'fini River basin in the Democratic Republic of Congo. This work addresses current challenges related to the use and preservation of natural resources. The main problem studied here concerns the interaction between dry matter mass, water content, and species diversity in aquatic environments, an area still relatively unexplored in the scientific literature. The fundamental objective of this research is to evaluate the agronomic performance of different species, taking these variables into account while identifying the relationships between them. To this end, a rigorous methodology was adopted, involving systematic sampling techniques along the M'fini River and physicochemical analyses of the water. Data were collected using modern tools, and the analysis was performed using Python Anaconda software, employing robust statistical methods such as principal component analysis, as well as Kruskal-Wallis and Wilcoxon tests to determine the variables influencing ecological dynamics. The results reveal that species with significant forage mass, such as Alchornea cordifolia and Ludwigia hyssopifolia, stand out for their high capacity to produce biomass. These species also exhibit high water content, suggesting they are able to maintain favorable moisture conditions, essential for their growth. The analyses show that species with high dry matter mass, such as Vossia cuspidata and Cyperus papyrus, are particularly well-adapted to aquatic environments, playing a crucial role in water retention. This research also highlights the need for integrated approaches to better understand ecological dynamics and suggests optimized agricultural strategies adapted to regional specificities.

Keywords : Biodiversity, plant resources, principal component analysis, agronomic performance, sustainable management

Résumé

L'analyse des ressources végétales, notamment des espèces fourragères, est cruciale pour la gestion durable des écosystèmes, en particulier dans les zones à forte biodiversité comme le bassin du fleuve M'fini en République démocratique du Congo. Ce travail aborde les enjeux actuels liés à l'utilisation et à la préservation des ressources naturelles. Le principal problème étudié ici concerne l'interaction entre la masse de matière sèche, la teneur en eau et la diversité spécifique en milieu aquatique, un domaine encore relativement peu exploré dans la littérature scientifique. L'objectif fondamental de cette recherche est d'évaluer la performance agronomique de différentes espèces, en tenant compte de ces variables et en identifiant les relations qui les unissent. À cette fin, une méthodologie rigoureuse a été adoptée, comprenant des techniques d'échantillonnage systématique le long du fleuve M'fini et des analyses physico-chimiques de l'eau. Les données ont été collectées à l'aide d'outils modernes et analysées avec le logiciel Python Anaconda, en employant des méthodes statistiques robustes telles que l'analyse en composantes principales, ainsi que les tests de Kruskal-Wallis et de Wilcoxon pour déterminer les variables influençant la dynamique écologique. Les résultats révèlent que les espèces à biomasse fourragère importante, telles que Alchornea cordifolia et Ludwigia hyssopifolia, se distinguent par leur forte capacité de production de biomasse. Ces espèces présentent également une teneur en eau élevée, ce qui suggère leur capacité à maintenir des conditions d'humidité favorables, essentielles à leur croissance. Les analyses montrent que les espèces à forte masse de matière sèche, telles que Vossia cuspidata et Cyperus papyrus, sont particulièrement bien adaptées aux milieux aquatiques, jouant un rôle crucial dans la rétention d'eau. Cette recherche souligne également la nécessité d'approches intégrées pour mieux comprendre les dynamiques écologiques et propose des stratégies agricoles optimisées et adaptées aux spécificités régionales.

Mots-clés: Biodiversité, ressources végétales, analyse en composantes principales, performance agronomique, gestion durable

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1. Introduction

La The analysis of plant resources, and more specifically forage species, is a fundamental challenge for the sustainable management of ecosystems. Natural areas, such as the M'fini basin in the Democratic Republic of Congo (DRC), reveal rich but often under-exploited biodiversity. While previous research has often focused on productivity as a function of various environmental factors, few studies have addressed the relationship between dry matter mass, water content, and species diversity in this specific context in an integrated manner (Ahouangan et al., 2010; Duru et al., 2010; Ngom et al., 2012).

Recent studies have highlighted the need to consider local ecological dynamics to optimize the management of these resources. Cobelli et al. (2023) show how farmers' agricultural practices can influence diversity and productivity in the groundnut basin. Similarly, the work of Coulibaly et al. (2020) highlights the importance of biodiversity for improving agronomic performance in the context of Burkina Faso.

The analysis of limiting factors in forage ecosystems was also explored by Hébert et al. (2011), whose research indicates that soil physicochemical conditions play a crucial role in the productivity of forage species. Similarly, Idrissa et al. (2020) observed that water availability is a determining factor for the growth of forage resources in Niger.

Studies by Guéguen (1959) address the mineral composition of forage species, indicating that the stage of development significantly impacts nutritional quality. Another study by Duru et al. (2010) emphasizes the importance of permanent grasslands in providing ecosystem services. The dynamics of plant communities in diverse environments have been analyzed by Bélair (2005), who highlights the interactions between species and their environment.

Furthermore, studies such as those by Tasset et al. (2019) emphasize the role of grasslands in providing ecosystem services, while Magniez (2010) examines the impact of climate fluctuations on ecosystem productivity. Sanon's (2014) research on vegetated stone bunds demonstrates how these structures can positively influence vegetation and soil quality.

This research therefore aims to evaluate the agronomic performance of different plant species by considering their dry matter mass, water content, and forage mass, while exploring the relationships between these variables. Based on robust statistical methods, including principal component analysis (PCA) and the Kruskal-Wallis and Wilcoxon tests, this study aims not only to reduce the dimensionality of the data but also to identify the most influential variables in the ecological dynamics of the ecosystem under consideration.

The tools used for this research include systematic sampling techniques along the M'fini River and physicochemical analyses of the water in order to better understand the conditions governing plant growth, as well as statistical analyses of the data using the Anaconda Python software. This methodological approach is essential to achieving our objectives and will provide answers to the identified issues concerning the productivity and efficiency of forage resources.

Thus, by integrating a multidisciplinary approach and relying on empirical data collected through field experiences, this research aims to fill the gaps identified in the state of the art while contributing to the development of management strategies adapted to the current challenges of conservation and sustainability in the region.

2. Material and methods

2.1. Presentation of the study environment

Figure 1 illustrates the M'fini watershed in the Mai-Ndombe province of the DRC, with botanical sampling points clearly marked by red dots on the map. These points represent the specific locations of the samples, essential for analyzing plant diversity. After numerous surveys, we delimited our study area to 15 observation plots. These plots were established along the M'fini River, extending from plot number 1 downstream to plot number 15 upstream, near the rural commune of Kutu, at the precise geographic coordinates of 018°08’42.2’’ East longitude, 02°43’44.5’’ South latitude, and 302 m altitude at the level of the territory's administrative building. The plots, numbered 1 to 11 on the left bank and 12 to 15 on the right bank, were chosen for their ecological and morphological interest. This configuration allowed for complete inventories of the forage grasses present in the study area.

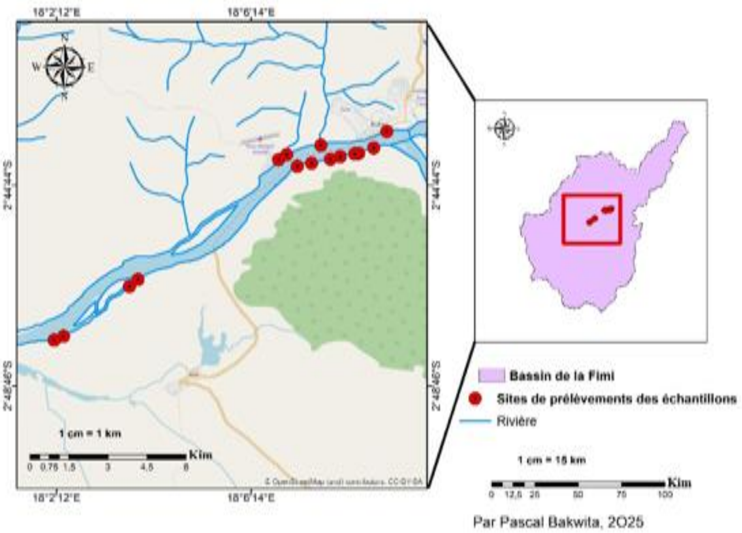

Figure 1: Botanical Sample Collection Sites

2.2 Data Collection

Data collection took place from May 30 to June 27, 2025, and involved collecting botanical samples from various sites to create herbarium and laboratory specimens. During this period, in situ analysis of the water's physicochemical parameters focused on key elements such as temperature, pH, total dissolved solids (TDS), and depth. Various appropriate equipment was used to carry out this collection. A Garmin 64 GPS was used to record the geographic coordinates of the selected sites. Each sample was carefully placed in plastic bags according to species for proper preservation. A TEMIUM precision balance was used to weigh the samples, and pruning shears were used for harvesting. Appropriately sized wooden presses were used to preserve and dry the samples. In addition, packing bags and newspaper were used to protect and dry the samples. Four wooden stakes were used to delineate the observation plots. A tarpaulin was also used for drying, and a machete facilitated access to the different sites (Ahouangan et al., 2010). For the analysis of physicochemical parameters, a pH meter and a TDS meter were essential to determine the water's acidity and dissolved solids concentration (Ouattara et al., 2016). A probe thermometer was used to measure the water temperature in the field. In the laboratory, instruments such as a HERAEUS oven and an OHAUS precision balance allowed us to rigorously dry and weigh the botanical samples. This methodology ensured accurate and reliable data for the study (Idrissa et al., 2020).

2.3. Data analysis

2.3.1 Data Analysis Using the Kruskal-Wallis and Wilcoxon Tests in Python within Anaconda

Data analysis was performed using Python in Anaconda, following a systematic approach. The necessary libraries, such as Pandas, NumPy, Matplotlib, and SciPy, were imported. A dictionary, named `data`, was created, containing the samples, species, dry matter mass, moisture content, and forage mass, and then converted into a Data Frame using `pd. Data Frame (data)` (Bélair, 2005). A preview of the DataFrame was checked with `print (df) ensuring ; data integrity (Duru et al., 2010). The Kruskal-Wallis test was used to compare forage mass and dry matter mass via `stats.kruskal (Bélair, 2005; Nzita et al., 2025), revealing significant differences between the groups (Coulibaly et al., 2020). The Wilcoxon signed-rank test was then performed, verifying the equality of sample lengths (Gaiffe, 2008). Visualizations, including variable histograms, were created using Matplotlib, facilitating the interpretation of the results (Idrissa et al., 2020). The graphs were saved with `plt.savefig (Mampuya et al., 2026; Mampuya nzita et al., 2025; Nzita et al., 2025)` and displayed with `plt.show (Mampuya et al., 2026; Mampuya Nzita et al., 2025; Nzita et al., 2025). This methodology allows for rigorous data analysis, essential for understanding ecological relationships (Tasset et al., 2019).

2.3.2 Principal Component Analysis (PCA) of Data Using Python in Anaconda

Data analysis using Python in Anaconda was performed methodically to conduct a principal component analysis (PCA) on species data. Key libraries, such as Pandas, NumPy, Matplotlib, Seaborn, and sklearn, were imported for the manipulation, visualization, and application of PCA (Ahouangan et al., 2010). A dictionary containing samples, species, dry matter mass, moisture content, and forage mass was created and then converted into a DataFrame (Bélair, 2005). The columns DM_Mass, Moisture_Content, and Forage_Mass were selected and normalized using StandardScaler to ensure an equitable contribution to the PCA (Coulibaly et al., 2020). Principal component analysis (PCA) was applied using the fit_transform method, reducing dimensionality while preserving information. A scatterplot using sns.scatterplot visualized the first two components (PC1 and PC2), with arrows indicating variable loads and species names (Gaiffe, 2008). PCA statistics, such as standard deviation and explained variance, were presented in a DataFrame and visualized using a line graph, helping to understand the significance of the components (Idrissa et al., 2020). This method allowed for a more in-depth interpretation of the relationships between variables (Kumari et al., 2003).

3. Results and Discussion

3.1 Results

3.1.1 Analysis of Plant Species Data: Mass, Water Content, and Visualization Figures

Table I illustrates the understanding and reference points for data analysis.

Table I. Dry Matter Mass, Water Content, and Forage Mass of the 21 Plant Species

N°	Species	Mass of Dry Matter dry weight in kg	Water content (kg) water content in kg	Fresh Forage Mass Fresh Weight in kg	Square number
1	*Commelina diffusa Burm.f.*	0,13	1,79	1,92	1
2	*Commelina benghalensis* L.	0,83	3,98	4,81	1
3	*Lasimorpha senegalense* (Schott) Engl.	0,34	2,72	3,06	1
4	*Alchornea cordifolia* (Schum.etThonn.) Muell.Arg.	3,28	6,46	9,54	1;3;4;5;7;8;11;12;15
5	*Heteranthoecia guineensis* (Franchet) Robyns	0,06	1,23	1,28	1;2;3;4;5;6;7;8;9;10;11;12;13; 14; 15
6	*Vossia cuspidata* Greff	4,42	1,1	5,52	1;2;3;4;5;6;7;8;9;10;11;12; 14; 15
7	*Cyperus esculentus* L.	4,47	1,14	5,63	1;2;3;4;5;6;7;8;9;10;11;12; 14; 15
8	*Echinochloa pyramidalis* (Lamarch) Hitchcoch et Chase	1,71	5,18	6,88	1;2;3;4;5;6;7;8;9;10;11;12;13; 14; 15
9	*Leersia hexandra Sw.*	1,14	4,49	5,64	1;2,3;4;5;6;7;9;10; 11;12;13;14; 15
10	*Polygonum lanigerum* R.Br var	3,35	0,55	3,9	2
11	*Pteridium aquilinum* (L.) Kuhn	3,7	0,69	4,39	2
12	*Nymphea latus* Lin.	0,07	1,33	1,41	3
13	*Ludwigia hyssopifolia*	23,63	1,99	25,62	4
14	*Dissotis erecta* (Guill.et Perr.) Dandy	2,05	5,49	7,54	5
15	*Cercestis congensis* Engl.	1,28	4,68	5,97	6
16	*Hypselodelphys poggeana* (K.Schum.)Milne-Redhead	1,47	4,92	6,38	7
17	*Costus phyllocephalus* K.Schum	0,19	2,12	2,32	15
18	*Aframomum alboviolaceum*(Ridl) R.Schum.	1,43	4,87	6,29	9
19	*Cyperus papyrus* L.	4,62	1,14	5,76	13
20	*Landolphia ovariensis* P. Beauv.	2,47	5,81	8,29	14
21	*Pteridium centrali africananum* (Hiern.)	1,07	4,38	5,44	12

Figure 2 illustrates the frequency of the different masses of forage measured in the samples in the histogram.

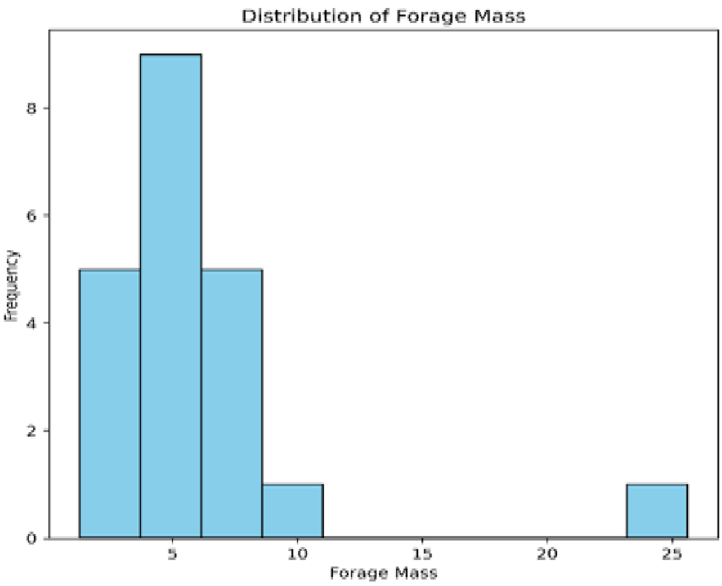

Figure 2 : Forage Mass Distribution

The distribution of forage samples shows a concentration around low values, primarily between 0 and 10 kg. The histogram reveals a peak at 5 kg, indicating that this weight is the most common among the samples. Conversely, frequencies decrease for masses above 10 kg, with very low occurrences around 15 kg and 25 kg. This distribution could reflect plant growth conditions and have implications for pasture management and animal feed, favoring the most readily available resources. Figure 3 illustrates the frequency of the different dry matter (DM) masses measured in the samples in the histogram.

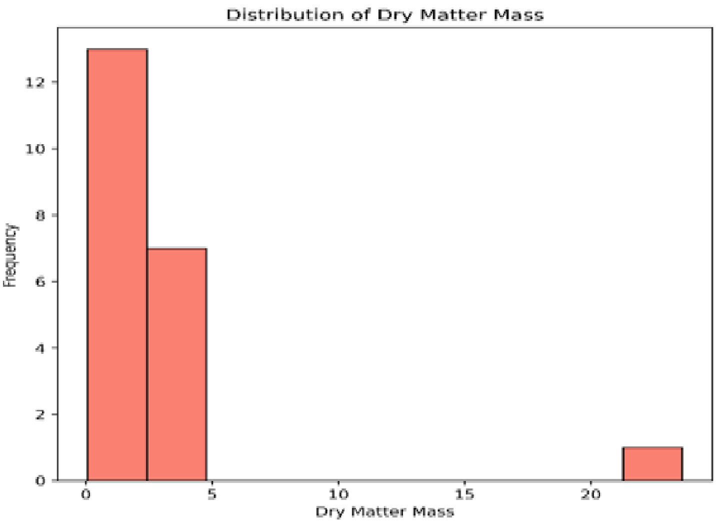

Figure 3: Dry Matter (DM) Mass Distribution

The histogram shows a high frequency of dry matter masses between 0 and 5 kg, indicating that many samples contain primarily small amounts of dry matter. On the left, for masses greater than 5 kg, the frequency drops significantly, with very few samples exceeding 10 kg and almost none at 20 kg. This distribution could reflect the growing conditions of the plant species or the dominant forage type in the ecosystem. The absence of high masses suggests low biomass accumulation, potentially influencing agricultural management practices and animal feed. Figure 4 illustrates the frequency of the different moisture contents measured in the samples in the histogram.

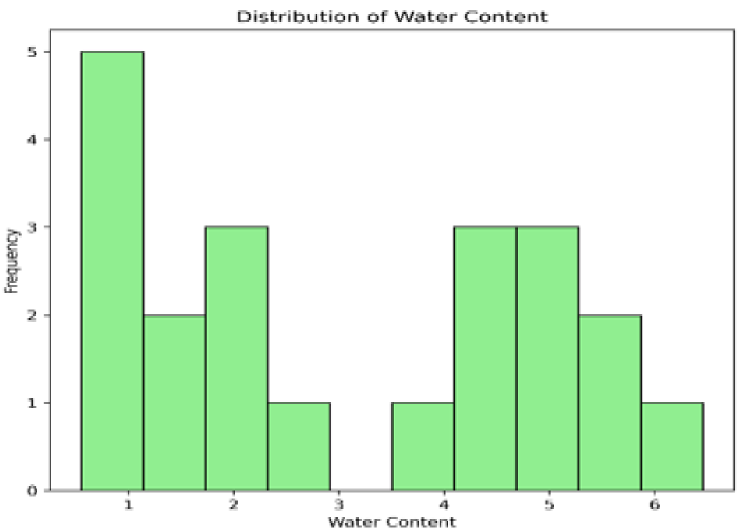

Figure 4: Water Content Distribution

The water content distribution reveals several peaks. Samples with a water content of approximately 1 kg are the most frequent, suggesting high plant moisture levels. A second notable group is around 4 kg, indicating diversity in water content. In contrast, values between 2 and 3 kg are less common, which could reflect specific environmental conditions. A few samples reach 5 and 6 kg, although these are less frequent. This variability in water content provides insights into the physiological characteristics of the species and can influence water resource management.

3.1.2 Kruskal-Wallis and Wilcoxon Statistical Analysis of the Relationships Between Forage Mass, Dry Matter Mass and Moisture Content

In this analysis, we used statistical tests to compare the relationships between different measurements: forage mass (Forage_Mass), dry matter mass (DM_Mass) and moisture content (Water_Content). The Kruskal-Wallis and Wilcoxon tests were applied to examine the differences between these variables. Regarding the Kruskal-Wallis test between Forage_Mass and DM_Mass, the statistic obtained was 14.43 with a p-value of 0.000145. This indicates that the difference between the two groups is statistically significant, as the p-value is well below 0.05. In other words, we have strong evidence that the distributions of Forage_Mass and Dry_Mass are not identical.

To further this analysis, the Wilcoxon test between the same variables yielded a statistic of 0.0 with a p-value of 9.54e-07. This information reinforces the idea that the two measurements, Forage_Mass and Dry_Mass, are very different. Thus, we can conclude that there is a significant difference between forage mass and dry matter mass. Regarding the Kruskal-Wallis test between Forage_Mass and Water_Content, the statistic is 9.04 and the p-value is 0.00265. As before, this p-value indicates a significant difference, so we can conclude that water content varies noticeably with respect to forage mass. Once again, the Wilcoxon test between forage_mass and water_content yields a statistic of 0.0 with a p-value of 9.54e-07, reinforcing the previous conclusion. It is clear that there is a significant variation between forage_mass and water_content, suggesting that a change in one of these measurements impacts the other. Finally, let's analyze the Kruskal-Wallis test performed between dry matter_mass and water_content. The statistic here is 3.33 and a p-value of 0.068. Although this p-value is greater than 0.05, indicating that the difference is not considered significant at the conventional level, it nevertheless suggests a potential trend that further investigation could clarify. Continuing with the Wilcoxon test between dry matter mass and water content, we obtain a statistic of 77.0 with a p-value of

0.1907, which confirms that, for these variables, there is no strong evidence of a significant difference. In other words, we cannot conclude that a change in dry matter content significantly alters the water content in our samples. The results of this analysis reveal clear and significant differences between forage mass and dry matter mass, as well as between forage mass and water content. So, essentially, this means that, based on our data, there is no convincing evidence showing that dry matter and water content are significantly related.

3.1.3 Analysis of Coefficients and Contributions of Variables in Principal Component Analysis (PCA)

Table II presents the coefficients of the variables (dry matter mass, moisture content, and forage mass) for the first three principal components (PC1, PC2), as well as the standard deviations, the proportions of variance explained, and the cumulative proportion of variances.

Table II. Principal component Analysis (PCA) of dry matter mass, moisture content, and forage mass for these 21 species

Variables	PC1	PC2
Dry matter mass	1.004	-0.206
Water content	0.013	1.025
Forage mass	1.006	0.192
Standard deviation	1.421	1.063
Proportion of variance	0.641	0.359
Cumulative proportion	0.641	0.999

The results of the principal component analysis (PCA) reveal significant information about the 21 species studied, based on an examination of the first three principal components (PC1, PC2, and PC3). First, the principal component PC1, which explains approximately 64% of the total variance in the data, is dominated by dry matter mass (DM_mass) and forage mass (Forage_mass). These two variables have positive coefficients, indicating that an increase in dry matter mass and forage mass is associated with a high score on this component. On the other hand, water content (Water_content) has a negligible contribution to this component, suggesting that, in the context of these species, characteristics related to dry matter and forage mass are more relevant for describing the observed variability. Second, the second principal component, PC2, explains approximately 36% of the remaining variance and is distinguished by a significant contribution from water content, which also has a positive coefficient. This suggests that species with high water content may be differentiated from those with lower water content, which could have implications for their habitat or environmental adaptation.

Dry matter mass (DM) and forage mass (FW) also show negative values in this component, indicating an opposition to water content in this analysis. Thus, the analysis shows that variations in dry matter mass and forage mass are key factors in the observed differences among these 21 species, while water content also offers interesting but perhaps less dominant insights in this context. This analysis has highlighted the relationships between species mass and water content and underscored the importance of these variables for understanding the adaptations and characteristics of the studied species.

Figure 5 illustrates the relationships between different species based on their scores on the principal components.

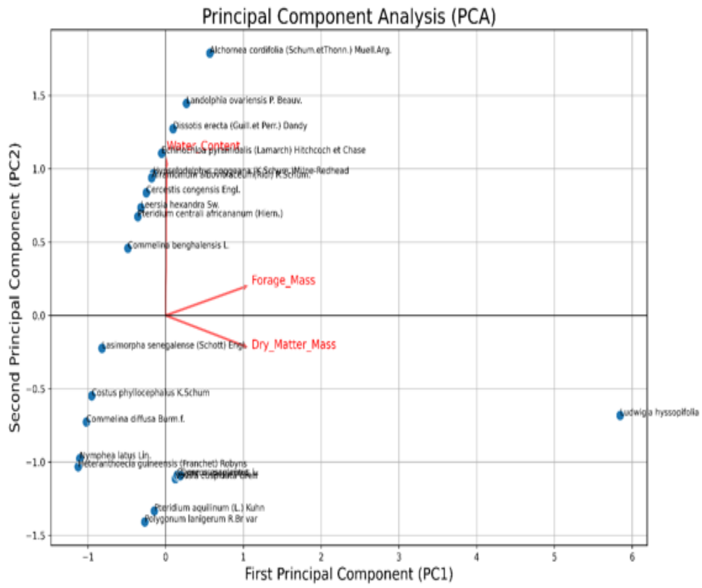

Figure 5: Principal Component Analysis (PCA) of the 21 plant species according to their contributions to dry matter mass

The Principal Component Analysis (PCA) performed on the 21 species revealed interesting relationships between the variables of dry matter mass, moisture content, and forage mass in figure 2. Species distinguished by their contribution to forage mass are ranked according to their positive scores in the PC1 and PC2 principal components. Initially, we focus on the species with positive scores in PC1. These species, such as Alchornea cordifolia, are particularly noteworthy for their high capacity to produce significant biomass in diverse environments. Known for its rapid growth, Alchornea cordifolia adapts readily to different soil types and environmental conditions, making it valuable for reforestation and conservation initiatives. Next, Landolphia ovariensis is another species worth highlighting. It is often used in practical applications, particularly for the production of cables and handicrafts.

Its workability and physical properties make it a valuable resource in its native habitat. Dissotis erecta also plays a significant role in the structure of plant communities. As ground cover, it helps stabilize the soil and prevent erosion, while also promoting surrounding biodiversity. Echinochloa pyramidalis, found in aquatic environments, is essential for regulating wetland ecosystems. Its ability to thrive in these areas allows it to play a key role in water filtration and supporting aquatic species. We also observe Hypselodelphys poggeana, which, thanks to its resilience and robust structure, contributes to boosting biodiversity. Its favorable growth in soil conditions makes it essential for the sustainability of ecosystems. Aframomum alboviolaceum is another beneficial species, used not only for its medicinal properties but also as an edible plant. This underscores the importance of this species in local food systems. As for Cercestis congensis, its high biomass makes it an important candidate for carbon sequestration, thus contributing to mitigating the effects of climate change. Leersia hexandra is a species often used as forage. It helps stabilize soils, playing a vital role in the sustainability of agricultural landscapes.

Pteridium centrali africanum, with its tendency to colonize rapidly, is particularly useful in rehabilitation projects. Its ability to spread quickly can also contribute to the creation of much-needed vegetation cover in disturbed areas. Finally, Commelina benghalensis is recognized for its medicinal properties while also sometimes serving as forage, further highlighting its value in the ecosystems where it is found. We must also address the species that stand out on PC2. These species influence forage mass while being strongly associated with water content. Ludwigia hyssopifolia, for example, is exceptional for its ability to retain soil moisture, giving it a strategic position in wetlands. *Cyperus esculentus*, meanwhile, plays an important role in providing a nutrient source for various animals while stabilizing shorelines, an asset in the preservation of aquatic systems. *Cyperus papyrus* is indispensable in aquatic ecosystems due to its historical use in papermaking. This function, combined with its role in water filtration, reinforces its ecological importance.

Finally, *Vossia cuspidata* is a key player in aquatic systems, contributing to water filtration and the creation of suitable habitats for aquatic fauna. In short, the analysis of these species demonstrates their diverse capacities to produce biomass and adapt to varied environments, particularly those with different moisture levels. Understanding these species is essential for biodiversity management, the development of sustainable agricultural practices, and the implementation of conservation initiatives. Identifying these species offer valuable insights for developing agricultural systems resilient to the challenges posed by climate change.

Species distinguished by their positive influence on soil moisture content, particularly through the main component PC1, play a fundamental role in the ecological dynamics of their habitats by conserving and optimizing soil moisture, an essential characteristic in environments subject to climatic variations. First, let's consider the species Alchornea cordifolia (Schum. & Thonn.) Muell.Arg., which stands out for its exceptional adaptability. This plant is capable of growing in a variety of water conditions, allowing it to establish itself in different environments, ranging from wet areas to drier soils. Its role in water conservation is crucial, especially for other species that thrive around it, as it helps regulate soil moisture and preserve water resources.

Another key player is Landolphia ovariensis P. Beauv., which also contributes significantly to soil moisture. Its presence enriches the surrounding ecosystem, promoting biodiversity by creating microhabitats suitable for other plants and animals. By providing favorable conditions for other species, it plays a fundamental role in maintaining ecological balance. The species *Dissotis erecta* (Guill. & Perr.) Dandy also deserves special attention. Often associated with wetlands, it is essential for stabilizing soils, minimizing the risk of erosion. This ability to provide ground cover helps strengthen ecosystem resilience while facilitating the regeneration of degraded soils. *Echinochloa pyramidalis* (Lamarch) Hitchcoch & Chase is a prevalent plant in wetlands, where it plays a dual role by increasing aquatic biodiversity and regulating soil moisture. Its presence is crucial, as it helps filter water and provides habitats for various aquatic species, thus contributing to the overall health of the ecosystem. Furthermore, Hypselodelphys poggeana (K. Schum.) Milne-Redhead promotes water retention in its habitats. In environments where humidity fluctuates, its ability to conserve water is essential for ecosystem sustainability, especially during periods of drought. Another species, Aframomum alboviolaceum (Ridl.) R. Schum., is valued for its adaptation to wet conditions, making it a sought-after plant for both its medicinal and edible qualities. Its potential to optimize soil moisture also has implications for the food security of local communities. The contribution of *Cercestis congensis Engl*. to soil moisture conservation is undeniable.

By facilitating ecosystem regeneration, this species helps maintain favorable conditions for other plants, thus strengthening the overall ecological structure. Leersia hexandra Sw. also plays a significant role by providing moisture-retaining ground cover. Its effectiveness in contributing to soil structure improves habitat quality, making land more suitable for sustainable agriculture and conservation. *Pteridium centrali africanum* (Hiern.) is often found in disturbed areas and can play a key role in soil restoration. Its ability to colonize degraded areas makes it an asset for land management. Alongside these numerous functions, *Commelina benghalensis* L. is well known for its medicinal properties, but its adaptation to water conservation makes it valuable in agricultural practices. By being able to survive in subterranean conditions, it contributes to soil hydration.

These diverse species, thanks to their ability to retain moisture and stabilize soils, are crucial in environments where water is a limited resource. They not only support biodiversity but also contribute to the resilience of ecosystems to climate change. By integrating this knowledge into the planning and management of natural resources, specialists can identify species that improve soil water content, thereby facilitating sustainable conservation approaches that will strengthen ecosystem health.

Contributions to dry matter mass are significant, particularly focusing on the main PC2 component. This analysis reveals marked differences between species that adapt to various soil types and those that, conversely, retain less dry matter. Let's begin by examining the species with positive PC2 scores. Ludwigia hyssopifolia stands out for its remarkable adaptability. This species thrives readily in wetlands and is known for its ability to develop a large biomass. This trait is essential, as high biomass can mean a greater capacity to support other organisms in the ecosystem, while also playing a key role in nutrient cycling. Similarly, Alchornea cordifolia (Schum. & Thonn.) Muell.Arg. also plays a crucial ecological role. Its ability to contribute biomass in diverse habitats makes it a resilient species, capable of adapting to fluctuating environmental conditions. It is therefore positioned as a stabilizing element within the ecosystems where it is present.

Next, we have Landolphia ovariensis P. Beauv., which is particularly valued not only for its biomass but also for its artisanal and medicinal applications. Its economic and ecological value illustrates the interaction between human needs and the conservation of natural resources. *Cyperus esculentus* L. also deserves mention due to its characteristics, as it is often used as a food crop. Its resistance to harsh environmental conditions makes it valuable for biodiversity and thus contributes to food security. Similarly, *Cyperus papyrus* L. is well known for its multiple applications, particularly in papermaking. This plant not only helps retain soil moisture but also provides essential habitat for various forms of aquatic life, strengthening the health of aquatic ecosystems. Another essential element is *Vossia cuspidata Greff*., which plays a key role in aquatic habitats. Its ability to regulate water quality makes it an essential species for wetland conservation. In terms of ecological importance, *Dissotis erecta* (Guill. & Perr.) Dandy makes a fundamental contribution to the structure of plant communities. By providing necessary ground cover, it helps stabilize the soil while promoting biodiversity.

Conversely, species that receive negative PC1 scores indicate a reduced capacity to produce dry matter. Lasimorpha senegalense (Schott) Engl. is an excellent example of this trend. It can exhibit limited growth under certain ecological conditions, suggesting a degree of sensitivity to environmental variations. Similarly, *Costus phyllocephalus* K.Schum shows a reduced impact on productivity, implying that it may not be ideally suited to competitive environments, which can affect its survival and spread. Interestingly, Ludwigia hyssopifolia, while showing positive scores on PC2, exhibits an ambiguous position on PC1. This duality warrants further exploration, as it suggests variations in its response to environmental conditions. Commelina diffusa Burm.f., although it has beneficial applications, may be limited by nutrient resources, impacting its dry matter productivity. As for *Nymphea latus Lin*., its specific water quality requirements may affect both its survival and dry matter measurement, limiting its effectiveness in environments with varying conditions. The species Heteranthoecia guineensis

(Franchet) Robyns, on the other hand, shows sensitivity to water conditions, which may also affect its productivity. The presence of *Cyperus esculentus* and *Cyperus papyrus* in both categories highlights their varied adaptive capacities.

This may indicate a flexibility that allows them to thrive in different environments depending on the conditions. Finally, *Pteridium aquilinum* (L.) Kuhn stands out by spreading easily, but its capacity to produce dry matter may not meet the needs of all habitats. Similarly, Polygonum lanigerum R.Br var., which is less productive in terms of dry matter, suggests adaptations specific to restricted habitats rather than a broad ecological range. These results highlight the significant dynamics between dry matter mass and environmental conditions. Species with positive contributions to this variable appear as promising candidates for resource and biodiversity management projects.

Conversely, those with negative scores may require special attention, perhaps through the implementation of conservation strategies or assessments of their adaptation to environmental changes. A thorough understanding of the interactions between these species and their environments can also help optimize agricultural practices and ecosystem management initiative.

3.2. Discussion

3.2.1 Analysis of plant species data: mass, water content and visualizations

Figure 2 shows the distribution of forage mass, indicating that the majority of samples are concentrated around low values, particularly between 0 and 10 kg. This may have implications for pasture management practices, suggesting that the most common species in this area produce less forage, which could affect animal nutrition. The histogram illustrating the distribution of dry matter mass (figure 3) shows a significant concentration of samples in the 0 to 5 kg range. This observation raises questions about growing conditions and biomass efficiency in the region. The scarcity of samples exceeding 10 kg could be an indication of environmental limitations, such as poor soils or inadequate management practices. Regarding water content, figure 4 reveals several peaks, suggesting diversity in water retention strategies among the studied species. The most common values are around 1 kg, which could mean that the majority of the analyzed samples are relatively moist. Conversely, the infrequent values between 2 and 3 kg could reflect moisture deficits or suboptimal conditions for certain plant types. The study by Ahouangan & colleagues (2010) on the productivity of forage species under different environmental conditions could corroborate the observation of variability in dry matter mass and water content. Similarly, the work of Guéguen (1959) on the mineral composition of forage plants supports the idea that the stage of development influences plant quality, which could be reflected in the observed variations. However, some results may diverge from the conclusions of these studies, particularly regarding biomass accumulation capacity. For example, the findings of Duru et al. (2010) on the forage services of grasslands could suggest that edaphic and climatic conditions differ from those of the livestock systems where the results of this study were obtained.

3.2.3 Analysis of Coefficients and Contributions of Variables in Principal Component Analysis (PCA)

Principal Component Analysis (PCA) simplified complex data while highlighting relationships between three main variables: dry matter mass (DM_mass), moisture content, and forage mass (forage_mass) for 21 different species. The first principal component (PC1) explains approximately 64% of the total variance. The coefficients for DM_mass and forage_mass are positive (1.003746 and 1.006449, respectively), indicating an increase in these variables. The fact that PC1 explains a large portion of the variance indicates that the chosen variables have a significant influence on the overall results of the study. This observation is reinforced by the positive coefficients, suggesting that increases in these masses are correlated. Subsequent studies, such as those by Duru et al. (2010), which assesses production services in permanent grasslands, could further explore this relationship by examining how these variables interact in similar contexts. Forage Mass vs. Dry Matter Mass: The Kruskal-Wallis test revealed a statistic of 14.43 with a p-value of 0.000145, indicating a significant difference between these two groups. The Wilcoxon test confirmed this with a statistic of 0.0 and a p-value of 9.54×10^{-7}, reinforcing the idea that the two measures are distinct. Forage Mass vs. Moisture Content: The Kruskal-Wallis test yielded a statistic of 9.04 and a p-value of 0.00265, also suggesting significant variation. The Wilcoxon test corroborated these results with a statistic of 0.0 and a p-value of 9.10×10^{-7}. Dry Matter Mass vs. Moisture Content: The Kruskal-Wallis test showed a statistic of 3.33 with a p-value of 0.068, indicating that this difference is not significant at the conventional level. The Wilcoxon test also showed a lack of significant evidence with a statistic of 77.0 and a p-value of 0.1907. The results of the Kruskal-Wallis and

Wilcoxon tests for forage mass and dry matter mass show a strong interaction, with considerable implications for grassland resource management. This is consistent with Ahouangan et al. (2010), who explored productivity in relation to various environmental conditions. The lack of a significant relationship observed between dry matter and moisture content suggests that these factors may interact differently in other studies, requiring further research to explore this apparent trend. These results highlight the importance of the variables studied in grassland resource management. Statistical tests confirm significant relationships between some variables while also indicating areas requiring further investigation. The cited references provide additional context and validation for the results obtained in this study.

3.2.3 Analysis of Coefficients and Contributions of Variables in Principal Component Analysis (PCA)

Principal Component Analysis (PCA) simplifies complex data while highlighting relationships between variables. In our analysis, we examined three principal variables: dry matter mass (DM_mass), moisture content (Wt_content), and forage mass (Forage_mass) for 21 different species. Table II provides the coefficients for the first three principal components (PC1, PC2). The first component (PC1) explains approximately 64% of the total variance. The coefficients for DM_mass and Forage_mass are positive (1.003746 and 1.006449, respectively), meaning that an increase in these two variables is associated with a high PC1 score. In contrast, moisture content has a negligible contribution, meaning it has less influence on PC1. This suggests that dry matter mass and forage mass are more relevant indicators for characterizing species in this context. The second principal component (PC2), explaining approximately 36% of the remaining variance, shows a significant contribution from water content (coefficient of 1.024613). This indicates that species with high water content are distinguished from those with lower water content. The negative coefficients for dry matter mass and forage mass in this component signal an opposition to water content, showing that these variables are not always associated. The results highlight the dominance of dry matter mass and forage mass in the first component. The importance of these variables indicates that they strongly influence the observed characteristics among the studied species. Ahouangan et al. (2010) emphasize that biomass is crucial for productivity in diverse environments, corroborating our findings on the importance of dry matter mass.

In PC2, water content plays a more proactive role, suggesting that it could be an important discriminating factor regarding habitat and species adaptation. According to Ngom et al. (2012), water content plays a key role in the pastoral quality of systems, validating our finding that this variable is a determining factor in species diversity. Some species, such as Alchornea cordifolia and Landolphia ovariensis, stand out for their high biomass production capacity, highlighting their potential for applications in conservation and sustainable agriculture. Bélair's research (2005) emphasizes aquatic species as regulators in wetlands, reinforcing the importance of water content observed in our analysis. Other species, such as Cyperus esculentus and Ludwigia hyssopifolia, show flexibility in their adaptation, which is essential for maintaining biodiversity and ecosystem health. Duru et al. (2010) indicate the importance of grasslands for forage production, consistent with our observations regarding species beneficial to biomass production. Species with negative PC1 scores, such as Lasimorpha senegalense and Costus phyllocephalus, may be particularly vulnerable to environmental changes, requiring special attention in conservation efforts.

The studies by Coulibaly et al. (2020) indicate the vulnerability of certain crops to climatic conditions, echoing our findings on less productive species. Variations in dry matter mass and water content are significantly correlated with the ecological characteristics and adaptive capacity of the plant species studied. This detailed study examines the relationship between dry matter mass, water content, and forage species diversity in the M'fini River basin. This type of integrated analysis is still relatively unexplored in the scientific literature for this specific region. The combined use of advanced statistical analyses such as Principal Component Analysis (PCA) and Kruskal-Wallis and Wilcoxon tests provides a robust methodological approach for studying the interactions between various ecological variables. This enhances our understanding of complex ecological relationships and provides a solid foundation for future research. The article highlights the importance of forage species diversity and its crucial role in ecosystem sustainability. This contribution is essential for conservation initiatives and the implementation of sustainable agricultural practices.

The research findings provide concrete recommendations for natural resource management, including the need to adopt agroecological strategies tailored to regional specificities. This can contribute to food security and the sustainability of local agricultural systems. The gaps identified in the study can serve as a starting point for future research, encouraging other researchers to further explore the ecological dynamics of forage species in similar contexts. By incorporating relevant and recent references in the field, the article contributes to the body of scientific knowledge on forage species productivity, thus enriching the existing literature.

This research therefore addresses pressing issues related to water and vegetation resource management and underscores the importance of a multidisciplinary approach to anticipate and mitigate the impacts of climate change in the region. In light of the results obtained, it is essential to promote sustainable forage resource management strategies in the M'fini basin. The study highlights the importance of prioritizing the conservation of plant biodiversity, particularly species with high biomass production capacity. These actions can help maintain ecosystem functionality while ensuring food security for local populations (Ahouangan et al., 2010). It is also recommended to intensify research efforts on agroecological practices adapted to the specific conditions of the region.

This research should include trials of diverse crops that take into account the genetic diversity of species in order to optimize forage production and reduce pressure on natural resources. Previous studies have shown that crop diversity can strengthen ecosystem resilience to climate change (Duru et al., 2010; Guéguen, 1959). Furthermore, developing awareness and training programs for farmers on sustainable management methods should be a priority. This includes the use of integrated pest management techniques and the promotion of practices such as crop rotation, which improve soil health and increase crop productivity (Coulibaly et al., 2020; Tasset et al., 2019). Public authorities and local decision-makers should also be involved in developing policies that promote the sustainable management of natural resources. This could involve providing economic incentives for farmers adopting sustainable practices, as well as protecting ecologically sensitive areas (Bélair, 2005; Magniez, 2010). Finally, establishing collaborative networks between scientists, producers, and natural resource managers is essential to fostering the exchange of knowledge and effective practices. Implementing such initiatives can strengthen local capacities and help integrate scientific knowledge into daily agricultural practices (Idrissa et al., 2020; Cobelli et al., 2023).

4. Conclusion

This study has highlighted the ecological dynamics of plant species in the M'fini River basin, revealing the importance of the relationships between dry matter mass, water content, and forage productivity. The results indicate that certain species, such as *Alchornea cordifolia* and *Ludwigia hyssopifolia*, exhibit a strong capacity for adaptation and biomass production, underscoring their potential for the sustainable management of aquatic ecosystems. Furthermore, statistical analyses, including principal component analysis and Kruskal-Wallis and Wilcoxon tests, have provided a better understanding of the environmental influences on species growth.

To strengthen the sustainability of agricultural practices in the region, it is recommended to adopt agroecological strategies that take plant diversity into account. This involves encouraging farmers to cultivate species adapted to local conditions, considering their capacity to retain moisture and stabilize soils. It is also crucial to invest in awareness programs to train farmers in sustainable management methods, including the use of practices such as crop rotation and integrated pest management. Furthermore, it is necessary to develop public policies that promote the conservation of ecologically sensitive areas and encourage the use of local forage species to improve food security.

Finally, future research should explore the diverse interactions between species and their environments in order to develop agricultural systems resilient to contemporary climate challenges. These efforts will contribute to the sustainability of ecosystems and the resilience of local communities.

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Conflict of Interest

The authors declare no conflict of interest in the publication process of the research article.

Ethical Considerations

This article was prepared in accordance with ethical research principles, ensuring compliance with current standards. It is important to note that no human or animal data were used in this study, ensuring full compliance with ethical requirements. The authors also declare that they have no conflicts of interest regarding this research, which reinforces the study's credibility. The data used for this analysis were obtained ethically and legally, complying with all relevant regulations. Finally, the study results were presented honestly and transparently, without any data manipulation, to ensure the scientific integrity of the entire work.

Authors contributions

Each author played a key role in the development and finalization of the research article.

P.B.N. was responsible for drafting and preparing the original version. He also focused on data collection and analysis and validated the final version.

A.M.N. was responsible for reviewing the survey, helped improve the quality of the original version, and performed the final revision, ensuring the article was ready for publication.

Finally, C.L.A. and C.N.L. oversaw the entire process, ensuring that all steps were followed correctly. All authors have read and approved the final version of the manuscript.

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