COMPARATIVE ANALYSIS OF POPULATION STRUCTURE, VEGETATION COMPOSITION AND SOIL PROPERTIES ACROSS SELECTED WILD LOQUAT (*Uapaca kirkiana*) POPULATIONS IN NORTHERN MALAWI

MASTER OF SCIENCE (FORESTRY AND ENVIRONMENTAL MANAGEMENT) THESIS

BRIAN ONALI NDUW

MZUZU UNIVERSITY

DECEMBER, 2025

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BRIAN ONALI NDUW

(MScFEM1123)

THESIS SUBMITTED TO THE FACULTY OF ENVIRONMENTAL SCIENCES IN FULFILMENT OF THE REQUIREMENTS FOR THE AWARD OF A MASTER OF SCIENCE (MSc) IN FORESTRY AND ENVIRONMENTAL MANAGEMENT

MZUZU UNIVERSITY

DECEMBER, 2025

DECLARATION

I hereby declare that this thesis, titled "**Comparative analysis of population structure, vegetation composition and soil properties across selected wild loquat (*Uapaca kirkiana*) populations in northern Malawi**" has been written by me and is a record of my research work. All citations, references, and borrowed ideas have been duly acknowledged. It is being submitted in fulfilment of the requirements for the award of the degree of Master of Science in Forestry and Environmental Management of Mzuzu University. None of the present work has been submitted previously for any degree or examination in any other University.

I acknowledge the use of ChatGPT [https://chatgpt.com] and Deepseek Chat [https://chat.deepseek.com] to generate an outline and edit, especially for the Literature Review. The following prompts were entered into both ChatGPT and DeepSeek [for comparison purposes since Artificial Intelligence can be incorrect] on 18-28th February 2025:

- 'Can you write an outline for a literature review with structure and potential themes on *Uapaca kirkiana* populatution structure, woody species association and soil properties'
- 'Can you edit for flow and not substance; do not change the content on this [selected paragraph/section]'

Grammarly [free package] was also used to edit and paraphrase the content. Editing for style, not substance.

Brian Onali Nduw

Signature — 4th December, 2025

Signature Date

CERTIFICATE OF APPROVAL

We, the undersigned, certify that this thesis is a result of the author's work, and that to the best of our knowledge, it has not been submitted for any other academic qualification within Mzuzu University or elsewhere. The thesis is acceptable in form and content, and the candidate demonstrated satisfactory knowledge of the field covered by the thesis through an oral examination held on 28th November 2025.

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DEDICATION

I dedicate this work to my parents, Mr. Simeon Nduw Otieno and Mrs. Rose Awuor, my siblings Venina Aluoch, Philip Mbar, Melka Yami and Hesbon Bicko. You have been pillars of support and strength; and to my late maternal grandparents, Mr. Jeremiah Ouma and Gaudencia Aoko, may their souls continue resting in peace.

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ABSTRACT

Uapaca kirkiana is an important indigenous fruit tree species whose population is declining in its natural habitat. Its fruits contribute to food security and serve as a source of income. Little is known about its ecological status in northern forests of Malawi. This research comparatively investigated the population structure, species associations, and soil preferences of *U. kirkiana* between Perekezi and Kaning'ina forest reserves. Fifty circular plots of 40 m diameter were established, and diameter at breast height (DBH) ≥5 cm were measured, while juveniles (<5) were counted to assess recruitment. Independent t-tests were used in comparison when assessing the population structure, species richness and soil properties. Diameter structures were further described through gamma distribution fitting. The data were analyzed using R v4.2.2 statistical software. Both sites showed an inverted J-shaped diameter distribution, although Kaning'ina contained more mature trees with a mean DBH of 20.58 cm, compared to Perekezi's 11.42 cm. Significant differences appeared in height, crown diameter and slenderness coefficient. Higher proportion of unhealthy *U. kirkiana* trees observed at Kaning'ina. *Brachystegia spiciformis* and *Faurea rochetiana* were among the species closely associated with *U. kirkiana* at both sites. Perekezi's soils were classified as loamy sand, showing a significantly higher sand content (79.80 ± 3.89%) and notably lower clay (5.90 ± 2.00%). Kaning'ina was characterized by sandy loam, with slightly less sand (76.60 ± 5.10%) and a higher clay content (8.47 ± 3.39%). Organic content was relatively similar in both reserves. It's concluded that Kaning'ina forest has *U. kirkiana* trees with larger DBH than Perekezi while sharing similar species in association with *U. kirkiana*. The two sites differ significantly in soil texture but organic matter content was not significantly different between them. The study recommends implementing long-term population monitoring, prioritising interventions that enhance regeneration and strengthening site-specific habitat management plans.

Key words: *Uapaca kirkiana*; Population structure; Species association; Soil properties

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ACRONYMS, ABBREVIATIONS AND SYMBOLS

ACENUB:	African Centre of Excellence in Neglected and Underutilized Biodiversity
Ca:	Calcium
Cd:	Crown diameter
CIFOR-ICRAF	Center for International Forestry Research (CIFOR) and World Agroforestry (ICRAF)
cm:	Centimetre
DBH:	Diameter at breast height
DFO:	District Forestry Office
FAO:	Food and Agriculture Organization
FRIM	Forestry Research Institute of Malawi
g:	Grams
GDP:	Gross Domestic Product
GoM:	Government of Malawi
GPS:	Global Positioning System
ha:	Hectares
K:	Potassium
m:	Metres
mm:	Millimetre
Mg:	Magnesium
N:	Nitrogen
NTFP:	Non-Timber Forest Product
P:	Phosphorus

pH:	Power of hydrogen
POWO	Plants of the World Online
SADC:	Southern African Development Community
SDG:	Sustainable Development Goals
SOC	Soil Organic Carbon
SOM	Soil Organic Matter
T/A:	Traditional Authority
TSC:	Tree slenderness coefficient
UNFCCC:	United Nations Framework Convention on Climate Change
USAID:	United States Agency for International Development
°C:	Degrees Celsius

CHAPTER 1: INTRODUCTION

The chapter presents the context and rationale for the research, and issues related to the ecology of *Uapaca kirkiana* in Malawi. It starts off with the background information of the study and then problem statement, research objectives, hypotheses and ends with a conceptual framework. The justification and the research contributions to knowledge are also described.

1.1 Background of the Study

Uapaca kirkiana Müell Arg. is an indigenous fruit tree that belongs to the family Phyllanthaceae. *Uapaca kirkiana* has the greatest diversity in the Zaire Basin and is prevalent in the Miombo region. Its distribution in the Miombo region of southern Africa includes Malawi, Tanzania, Zambia, Zimbabwe, Mozambique and Angola (Ngulube, Hall & Maghembe 1998; Assédé *et al.*, 2020; Chawafambira *et al.,* 2020a). *Uapaca kirkiana* has different vernacular names from its diverse distribution. It is commonly known as wild loquat in English and masuku by locals in Malawi.

Uapaca kirkiana is a multi-purpose deciduous fruit-bearing tree species (Chawafambira *et al.*, 2020a). It has great nutritional, therapeutic, cultural, social and economic benefits to the rural and peri-urban locals. It is highly valued for its sweet, nutrient-rich fruits and multipurpose wood. The edible fruit is the most marketed plant part and is commonly used for beverages, laxatives and purgatives (Akinnifesi *et al.,* 2004). The wood for timber and wood of *Uapaca kirkiana* trees make beehives with a high market value (Gillah, 2007; Msola, 2007). The socio-economic benefits of *U. kirkiana* makes it highly preferred by farmers, consumers and experts (Akinnifesi *et al.,* 2004). The multiple uses of this fruit tree justify research on this tree species (Akinnifesi *et al.,* 2004; Kadzere *et al.*, 2006; Chawafambira *et al.*, 2020a; Jinga *et al.*, 2020) to address conservation and domestication and overall food security (Chirwa & Akinnifesi, 2008), therefore contributing to ecosystem services which is important to the local livelihoods and forest dynamics.

The estimated diversity of miombo is 8,500 plant species (Ribeiro *et al.,* 2015), making it amongst five high biodiversity wilderness including Mopane and conservation is a priority (Mittermeier *et al.*, 2003; Shumba *et al.*, 2010). *Uapaca kirkiana* is a forest tree species and one of the key priorities of miombo fruit trees with potential for domestication (Chirwa & Akinnifesi, 2008). The miombo woodlands are comprised of diverse biodiversity, including the neglected and underutilized plant species. The neglected and underutilized species are important components of global biodiversity and require sustainable utilization, conservation and management. The benefits are ecological, economic and cultural. The miombo woodland has the highest rate of deforestation as a result of human population increase and economic dependence on natural resources (Campbell *et al.*, 2007).

The fruits of *Uapaca kirkiana* have the potential to improve socio-economic security and reduce household poverty and significantly contribute to food security when other foods are scarce (Akinnifesi *et al.,* 2004; Akinnifesi *et al.,* 2006; Mithofer, Waibel & Akinnifesi 2006). This is mostly in rural areas, particularly in Malawi. The fruits have a wide market and are most preferred by the communities in the southern African countries despite no known commercial cultivation of them. The fruits are eaten fresh and can also be processed to make wine, juice and jam.

The characteristics of a population, including genetic, demographic, and trait-based attributes, contribute to *Uapaca kirkiana's* variability (Luck *et al.*, 2004). Diversity within populations can be described through factors such as population richness, distribution, genetic diversity and size

(Ranketse *et al.,* 2022; Kokou *et al.*, 2024). Population richness refers to the count of populations within a specific area, while distribution describes how populations are spatially arranged, whether uniformly, in clusters, or randomly (Turchetto *et al.,* 2016; Ranketse *et al.,* 2022). The number of individuals present in a group determines population size. Higher levels of genetic diversity improve a population's ability to adapt to environmental changes (Jump, Marchant & Peñuelas 2009; Ranketse *et al.,* 2022).

Underutilized species have been referred to as neglected, underdeveloped, underused, traditional, alternative, forgotten, local, promising, orphaned species, underconserved and underexploited (Padulosi & Hoeschle-Zeledon, 2004; Armstead *et al.,* 2009; Mazibuko & Changadeya, 2024). Neglected or underutilized species, like *Uapaca kirkiana*, play an important role in biodiversity conservation and sustainable agriculture. Their marginalization highlights the need for a deeper understanding of their ecological roles and interactions with other species. Distribution, population abundance, and soil properties collectively influence the diversity and ecological dynamics of species like *Uapaca kirkiana* (Mwase *et al.,* 2007; Zimudzi & Chapano, 2016; Jinga & Palagi, 2020).

Forests play significant roles within the economic, social and ecological domains. Forests are characterised by a closed canopy and relatively continuous tree cover, while woodlands have more open spacing between trees and allow greater light penetration to the ground layer (McElhinny *et al.,* 2005; Thomas & Packham, 2007; Maginnis & Sayer, 2013). In Malawi, forests occupy about 23,677 km^2 (25% of the land area), with most of this area consisting of miombo woodlands, which cover 22,857 km^2 (Missanjo & Kadzuwa, 2021). Plantations account for the remaining 820 km^2

and are dominated by pine and eucalyptus, whereas miombo woodlands are largely composed of *Brachystegia* species (GoM, 2020; Stanturf & Mansourian, 2020; Missanjo & Kadzuwa, 2021).

Perekezi and Kaning'ina Forest Reserves are biodiversity hotspots in Malawi, having miombo woodlands at higher elevation gradients (Kokou *et al.,* 2024). These reserves are crucial for conserving indigenous species like *Uapaca kirkiana*. They also provide key ecosystem services, including carbon sequestration and water regulation. Understanding the ecological dynamics within these reserves is essential for effective forest management and biodiversity conservation (Mwase *et al.,* 2007; Ramachela, 2019). *Uapaca kirkiana* as a dominant or co-dominant tree of the miombo vegetation is useful in watershed management.

Climate change poses significant challenges to the distribution and survival of *Uapaca kirkiana*. Rising temperatures and changing precipitation patterns are expected to impact the species' habitats (Corlett & Westcott, 2013; Stocker, Spahni & Joos 2014). Studies predict a contraction in suitable habitats for *Uapaca kirkiana* by 2050 and 2070, primarily due to its semi-deciduous to evergreen nature, which requires higher precipitation (Jinga *et al.,* 2020; Folega *et al.,* 2023; Kokou *et al.,* 2025). This reduction in habitat suitability is consistent with findings for other tree species in the region (Bogawski *et al.,* 2019; Moat, Gole & Davis 2019). Both in-situ and ex-situ conservation strategies to mitigate effects of climate change must be developed. These strategies should integrate traditional practices and local knowledge to improve the resilience of *Uapaca kirkiana* populations (Bufford & Gaoue, 2015; Amahowe *et al.,* 2018).

Several studies have focused on traditional diets and socio-economic benefits (Chirwa & Akinnifesi, 2008; Chawafambira *et al.,* 2020a). There is dearth of information on ecological study of *Uapaca kirkiana*, especially at Perekezi and Kaning'ina Forest Reserves in the northern region of Malawi. The pressures of overexploitation, climate change impacts, and habitat loss reduce the forest ecosystem's capacity to protect and conserve biodiversity (Kokou *et al.,* 2023). Natural populations of the *Uapaca kirkiana* are declining as a result of these pressures and lack of conservation strategies (Chawafambira *et al.,* 2020b) despite its significant contribution to human livelihoods. Efforts to conserve *Uapaca kirkiana* from the risk of drastic decline include protection, domestication, and studies on regeneration techniques like propagule types and fruiting periods impacting seeds and seedlings (Mng'omba & Sileshi, 2015).

In Malawi, an inventory of alien and indigenous plants highlights *Uapaca kirkiana* as a highly valuable yet underutilized fruit-producing species (Omotayo & Aremu, 2020). The key knowledge gap on the ecology of *Uapaca kirkiana* hinders the development of informed conservation strategies. These strategies are necessary to address anthropogenic pressures and climate change. This study aims to provide information by exploring the relationship between biodiversity and soil properties and comparison between the forest reserves of Perekezi and Kaning'ina. More specifically, it aims to contribute to sustainable utilization, conservation and management to prompt efforts for domestication and conservation. This will subsequently guide future research on other specific forest ecosystems (Leakey *et al.*, 2022).

The analytical approach used in this study included comparing the structural attributes of *Uapaca kirkiana* between the two reserves, the study used independent t-tests to assess differences in DBH, height, crown diameter, slenderness coefficient, regeneration and health status, species richness and soil properties. Gamma distribution fitting was used to describe overall diameter structure.

Species diversity and associations were analysed using the relative abundance and Jaccard's similarity matrix assessed how similar or different tree communities in sampled plots are.

This study was guided by the assumptions that the measured structural attributes DBH, height, crown diameter and health status accurately reflect the general condition of the of *U. kirkiana* tree species within the sampled areas, regeneration counts obtained from juveniles within plots represent broader recruitment patterns across each forest reserve, all woody species identified during fieldwork were correctly classified based on field guides and herbarium verification and reflect actual woody species composition surrounding *U. kirkiana* and disturbance levels observed during data collection were consistent across unsampled areas areas of each reserve. The sampled plots were large enough to capture the structural variation and were representative of the broader forest conditions in both reserves.

The study faced several limitations, including time constraints that restricted sampling to a single season, potentially missing seasonal changes in seedling emergence or mortality. Accessibility issues in some areas of the reserves limited plot placement, which may have affected the spatial distribution of sampling sites. Regeneration was assessed through juvenile counts rather than long-term monitoring, possibly underestimating early seedling mortality. Additionally, human disturbances like firewood collection, logging, charcoal burning and informal activities could not be fully controlled or measured, and their impact likely varies across the landscape.

1.2 Problem Statement

Malawi is reported to have the highest rate of deforestation in the Southern African Development Community (SADC) region with at least 40,000 ha of forest being lost annually (Ngwira &

Watanabe, 2019). According to Decaëns *et al.* (2018), loss of forest cover leads to loss of biodiversity at an ecosystem level. *Uapaca kirkiana* is considered a neglected and underutilized edible fruit-producing tree species. Unfortunately, the focus on its status and conservation in the natural habitat is limited (Omotayo & Aremu, 2020; Kokou *et al.,* 2024; Kokou *et al.,* 2025). There is need of going deeper for better understanding of the ecology of the species despite a few studies focusing on the conservation process (Mazibuko & Changadeya, 2024).

Miombo woodlands harbor exceptional biodiversity that is increasingly threatened by climate change, land use, and other pressures. Overexploitation, climate change, habitat loss, and lack of conservation strategies are decreasing the natural populations of *U. kirkiana* species (Chawafambira *et al.,* 2020b; Jinga *et al.,* 2020). There is strong evidence of numerous studies on the protection, domestication, and valorization of the species, including the effects of propagule types, fruiting periods, seed germination, and growth (Mhango *et al.,* 2008; Mng'omba & Sileshi, 2015; Jenya *et al.,* 2016). The domestication of wild plants often focuses on their utilization rather than conservation, worsening existing threats to their biodiversity (Mazibuko & Changadeya, 2024). However, risks to ecosystems and the consistency of adaptation strategies remain understudied, making conservation and restoration efforts difficult (Kapuka & Hlásny, 2021). Despite many studies on *Uapaca kirkiana*, there is limited information on ecosystem population dynamics related to structural diversity, spatial distribution, associated tree communities, and soil physico-chemical properties, especially in Kaning'ina and Perekezi Forest Reserves in northern Malawi.

The population structure and distribution of *Uapaca kirkiana* across Perekezi and Kaning'ina forest reserves remain poorly understood. Lack of knowledge on population structure and distribution undermines the development of targeted conservation strategies and understanding how it influences the species' ecological dynamics (Kailash *et al.,* 2022; Jaiswal & Jayakumar, 2024; Martínez-Villa *et al.,* 2024; Negi *et al.,* 2024). Understanding species population structure and key ecological interactions helps guide ex-situ conservation by improving choices on sampling, genetic representation, and future reintroduction planning (Simkoko, Mwabumba & Gondwe 2021; Kailash *et al.,* 2022).

Further, the diversity of woody species associated with *Uapaca kirkiana* is critical for maintaining ecosystem health and resilience, yet it has not been adequately assessed (Gondwe *et al.,* 2021). Furthermore, soil physicochemical properties are significant for the growth and sustainability of *Uapaca kirkiana* populations. However, existing research (Kaumbu *et al.,* 2024; Ni & Vellend, 2024) lacks a detailed examination on how these soil properties impact the species interactions.

Therfore, this study is essential for realisation of the potential for conserving and sustainably utilizing this species, as well as for future domestication initiatives. Conservation is needed urgently for these underutilized and neglected species, including *Uapaca kirkiana*, which are lost through deforestation (Mazibuko & Changadeya, 2024).

1.3 Objectives of the Study

1.3.1 Main Objective

The main objective of the study was to make a comparative analysis of *Uapaca kirkiana* population structure, associated tree species, and soil physicochemical properties between Perekezi and Kaning'ina forest reserves

1.3.2 Specific Objectives

1. To analyse the population structure and distribution of *Uapaca kirkiana* at Perekezi and Kaning'ina forest reserves
2. To determine the woody species that grow in association with *Uapaca kirkiana* between Perekezi and Kaning'ina forest reserves
3. To assess the soil physicochemical properties associated with *Uapaca kirkiana* tree between Perekezi and Kaning'ina forest reserves

1.3.3 Hypotheses

1. There is no significant difference in the population structure and distribution of *Uapaca kirkiana* between Perekezi and Kaning'ina forest reserves
2. There is no significant difference in association of *Uapaca kirkiana* species and other species between Perekezi and Kaning'ina forest reserves
3. There is no significant difference in soil physicochemical properties between Perekezi and Kaning'ina forest reserves of *Uapaca kirkiana* stands

1.4 Justification of the study

Uapaca kirkiana is threatened by anthropogenic activities and climate change (Kokou *et al.,* 2024), and conservation and management efforts are possible within its natural habitat. Protecting and utilizing the fruit tree can help address food insecurity (Chawafimbira *et al.,* 2020a). This study is the first of its kind in the specific forest reserves of Perekezi and Kaning'ina. The generated knowledge will support the Department of Forestry with technical input from the Forestry Research Institute of Malawi and enforcement support from local leaders and community-based forest management structures in formulating and implementing policies and strategies for the conservation and sustainable management of *Uapaca kirkiana* in the respective districts.

The biodiversity of forests influences the functioning of ecosystems and that of humankind (Mazibuko & Changadeya, 2024). The study of the population structure, species associations, and soil physico-chemistry of *Uapaca kirkiana* in Perekezi and Kaning'ina forest reserves is important for guiding conservation strategies and policies. Such efforts will support both the in-situ and ex-situ conservation of this highly valuable yet underutilized tree species. Addressing these knowledge gaps on its ecology is crucial for sustainable management and utilization.

Understanding the population structure of *Uapaca kirkiana* revealed key trends in population dynamics, regeneration capacity, recruitment rates, and overall viability. This data formed the basis for creating evidence-based conservation and management strategies (Popma, Bongers & Castillo 1988; Gebeyehu *et al.*, 2019). As Voute (1970) highlights, analyzing population dynamics is essential for effective resource management.

Research findings will contribute directly to the Malawi National Forestry Policy goal on the conservation, establishment, protection and management of trees and forests for the sustainable development of the country. In addition, the findings will contribute directly to Malawi's transformative agenda (Vision 2063, Enabler 7 in particular), which seeks to achieve environmental sustainability. Globally, the findings will contribute significantly towards the attainment of Sustainable Development Goals, specifically SDG 2 (Zero Hunger), SDG 13 (Climate Action), and SDG 15 (Life on Land). This research is both timely and critical for advancing conservation and domestication efforts for *Uapaca kirkiana*.

1.5 Conceptual Framework

This study attempted to develop an understanding of the conservation and management of *Uapaca kirkiana* in its natural habitat. Subsequently, this would lead to its strategies of maximum conservation, management and sustainable utilization for improved household livelihoods. Eventually, such interventions will reduce pressure on biodiversity and the decline in the population of the species.

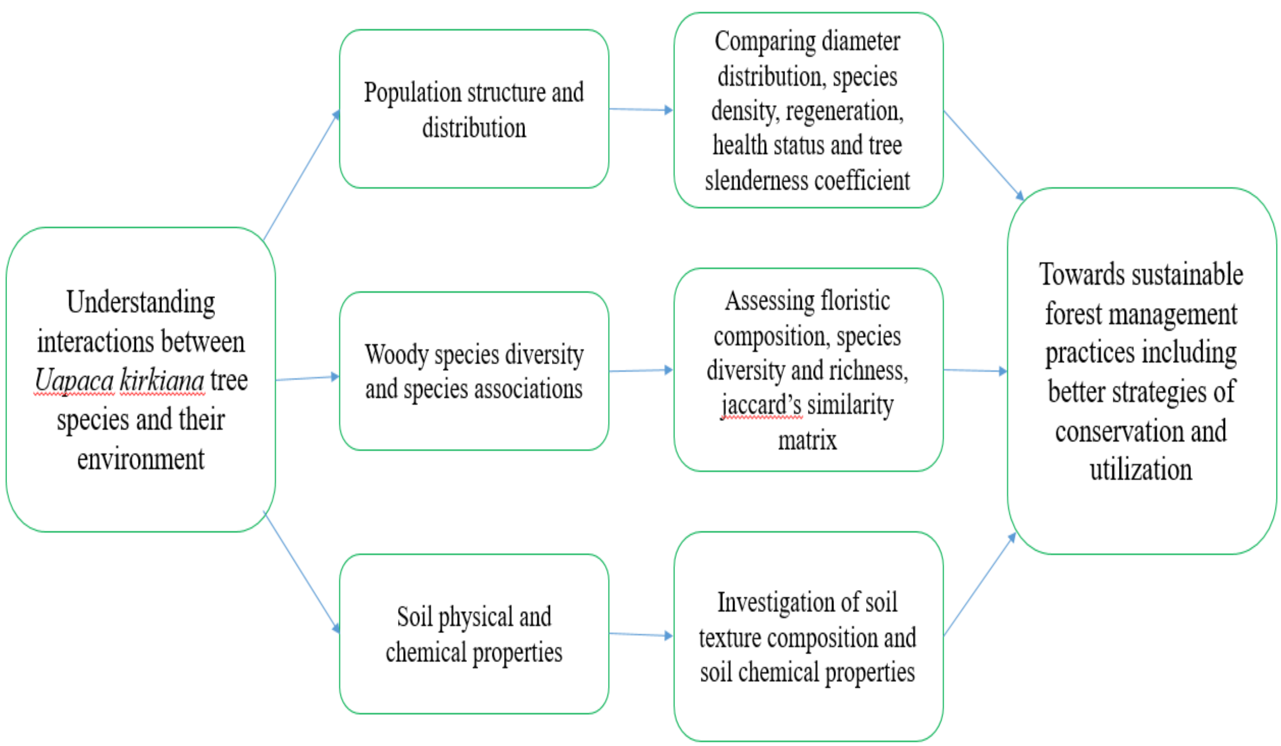

Figure 1: Conceptual framework *Uapaca kirkiana* population structure and distribution, associated tree species and soil physicochemical properties

CHAPTER 2: LITERATURE REVIEW

This chapter provides a review of published literatures on the ecology of the *Uapaca kirkiana* including taxonomy, morphology and geographical distribution in Africa and especially in Malawi. The socio-economic importance and conservation challenges have been reviewed. Further, it reviewed the *Uapaca kirkiana* population's threats, composition, ecosystem resilience, soil adaptations and conservation.

2.1 Botanical description of *Uapaca kirkiana*

According to Plants of the World Online (POWO, 2019), *Uapaca kirkiana* Müell. Arg. is a small to medium-sized tree, commonly evergreen to semi-deciduous, typically growing between 5 m and 12 m in height with a short, stout trunk of diameter approximately 5–25 cm (Orwa *et al.,* 2009). POWO (2019) further states that the crown is dense, rounded, and much branched. The Center for International Forestry Research (CIFOR) and World Agroforestry (ICRAF) (CIFOR-ICRAF) also reported that the bark is dark grey to grey-brown, thick, deeply fissured, and sometimes reticulate, branchlets are short and stout, often showing prominent leaf scars, and young shoots are covered in creamy-brown hairs.

Furthermore, CIFOR-ICRAF reported that the leaves are simple, alternately arranged, often clustered at the tips of branchlets. Their size range is wide, 7–36 cm long by 4–24 cm wide, according to the Flora Zambesiaca description. The lamina tends to be broadly obovate to sub-orbicular, thick and leathery (coriaceous), with a rounded or retuse apex and a cuneate to rounded base (Meerts & Farminhão, 2019; Jinga *et al.,* 2020). Moreover, POWO (2019) reports that the upper leaf surface is glabrous, while the lower surface is typically densely pubescent with curled or woolly hairs (crisped-puberulous), especially along the veins, and there are 12–24 pairs of lateral nerves, which are more prominent underneath. Besides, stipules are linear of about 5 mm long, pubescent, and soon fall off.

The reproductive structures include the flowers and fruits**.** The species is dioecious thus the male and female flowers on separate trees. Male flowers are borne in dense clusters on short peduncles and the inflorescence bracts are broadly elliptic and pale yellow to whitish according to POWO (2019). It further reported that male flowers have 4 stamens, and a small pubescent pistillode as the female flowers are solitary on short peduncles. The ovary is subglobose, 3–4 mm in diameter, densely tomentose, with styles that are multifid-flabelliform with many-forked. The fruit is a globose to subglobose drupe, typically 2.5–4.0 cm in diameter, with a relatively tough pericarp. When ripe, the fruit turns from green to yellow-brown or orange-yellow. Inside are 3–4, sometimes up to 5, pyrenes that is stone-like seed parts, each about 1.5 × 0.8 × 0.5 cm in size.

U. kirkiana is widespread in the Zambezian phytochorion and grows naturally in miombo woodlands, open or mixed *Brachystegia–Julbernardia* woodland, often on well-drained, acidic, gravelly or sandy soils (Chawafambira *et al.,* 2020b; Jinga & Palagi, 2020). It occurs at altitudes ranging from approximately 720 to 1,950 m above sea level (Kokou *et al.,* 2024). It tolerates a unimodal rainfall regime and annual precipitation typically between approximately 500–1,400 mm in its natural range according to the CIFOR-ICRAF findings. *U. kirkiana* is reported to demonstrate notable tolerance to climatic stressors, including prolonged aridity and mean annual temperatures of 18 to 29°C, and thrives in nutrient-poor soils with low organic matter and macronutrient content (Chawafambira *et al.,* 2020b; Jinga *et al.,* 2020; Ribeiro, de Silva & Timberlake 2020). This ecological adaptability supports its broad distribution across the miombo ecological zone.

The CIFOR-ICRAF stated that the species flowers during the rainy season, and fruit development can be prolonged up to 5–8 months. It further reports that pollination is believed to involve both insects such as bees and possibly wind, but out-crossing is required because of dioecy. In addition, the fruit's fleshy pulp, which can make up 40–60% of the fruit fresh weight, is attractive to animals especially mammals and birds, which likely contribute to seed dispersal. Also, seeds germinate readily from fresh seed, however, they have low storability.

According to botanical descriptions by the POWO (2019), the wood is somewhat pulpy and reddish. Additionally, CIFOR-ICRAF stated that *U. kirkiana* is valued for fruit, timber, firewood, charcoal, and medicinal uses (roots, bark, and leaves) by local communities. It further stated that the tree species is also frequently used in beekeeping due to its flowers. These traits, alongside its growth form as a small to medium-sized tree, facilitate its identification across its native range.

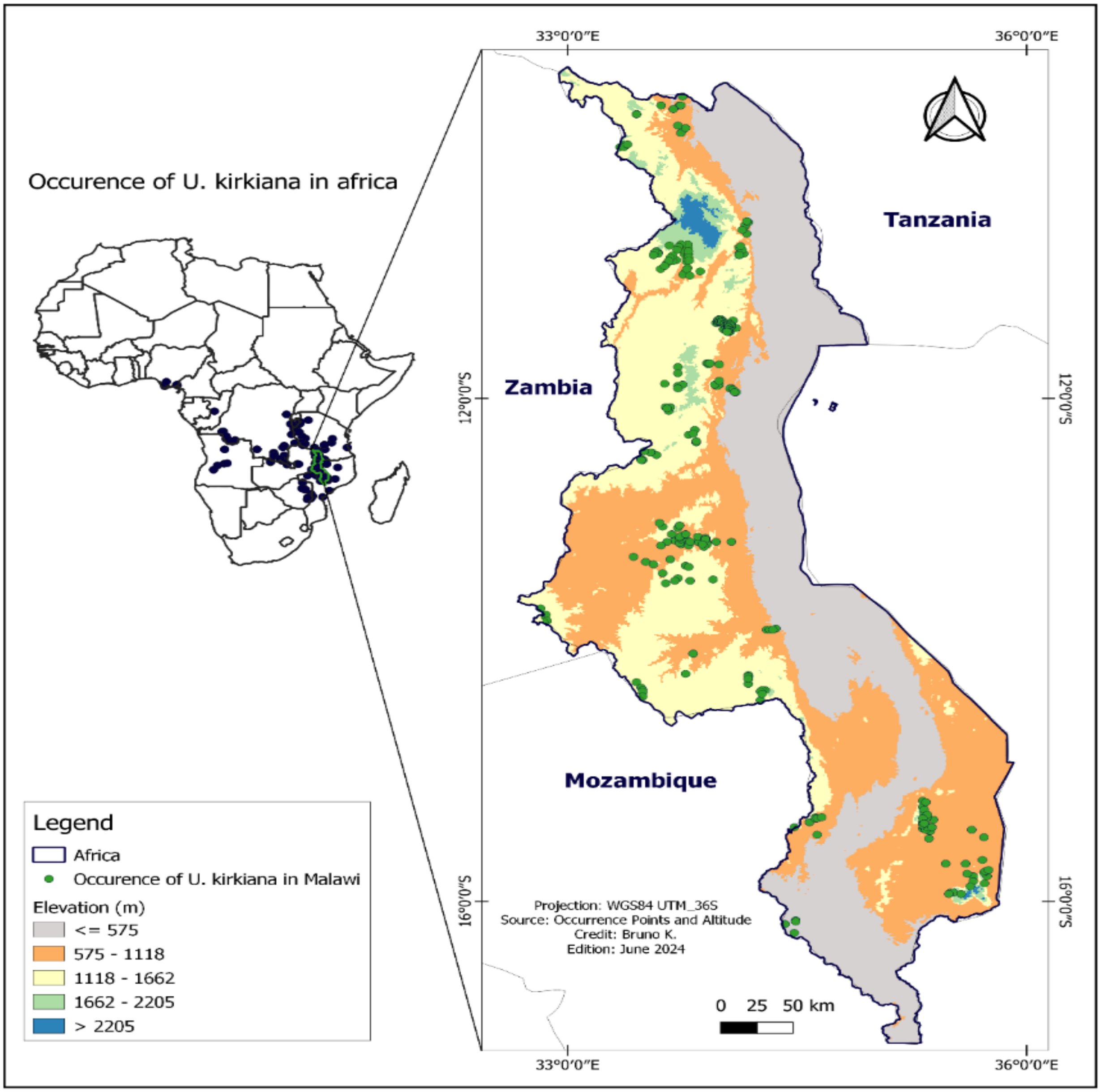

Figure 2: Geographical distribution of *Uapaca kirkiana* in Africa and Malawi (Source: Kokou *et al.*, 2024).

Uapaca kirkiana is a keystone species for both biodiversity and human livelihoods within sub-Saharan Africa's miombo woodlands (Chawafambira *et al.*, 2020a). Miombo woodland is regarded as a biodiverse and structurally complex tropical dry forest formation critical to ecosystem services provision in southern Africa (Godlee *et al.,* 2020; Ribeiro, de Silva & Timberlake 2020; Montfort *et al.,* 2021). These seasonally dry woodlands support the growth of the wild loquat. They also play an important role in soil stabilization, carbon sequestration, and hydrological cycle, therefore, supporting regional ecological resilience. The species' deep root system and adaptability to nutrient-poor soils further develop its capacity to mitigate land degradation in arid environments (Jinga *et al.,* 2020; Ribeiro, de Silva & Timberlake 2020).

2.2 Socio-economic significance and conservation challenges

Economically, *U. kirkiana* fruits hold significant value across rural and urban communities. The fruits provide a critical income source, particularly in climate-vulnerable regions where livelihoods depend on climate-sensitive sectors like agriculture and forestry (Hien *et al.,* 2021; Zuza *et al.,* 2021). Nutritional analyses reveal the fruits are rich in micronutrients (iron, copper, and zinc), vitamin C, phenolic compounds, and sugars, positioning them as a dietary supplement to fight malnutrition (Chawafambira *et al.,* 2020b; Tuyizere *et al.,* 2021). Their potential for processing into functional foods, such as probiotic jams, highlights opportunities for value-added products. However, reliance on seasonal availability limits year-round access, underscoring the need for sustainable harvesting and cultivation practices (Sibiya, Kayitesi & Moteetee, 2020).

The decline in *U. kirkiana's* population is associated with the systemic socio-economic challenges. Rural communities heavily depend on wild loquat for nutrition, income, and crisis mitigation during food shortages (Muok, 2019; Chawafambira *et al.,* 2020a; Hien *et al.,* 2021; Tuyizere *et al.,* 2021). Nevertheless, unsustainable harvesting results in environmental degradation, deepening cycles of food insecurity (Muok, 2019; Kazaba *et al.,* 2020; Nkosi *et al.,* 2020; Sibiya, Kayitesi & Moteetee, 2020). Conservation efforts should, therefore, balance ecological preservation with livelihood needs. It should also prioritize sustainable land management, community-based resource governance, and agroforestry integration. These shall safeguard both miombo biodiversity and human well-being.

2.3 Population structure of *Uapaca kirkiana*

2.3.1 Threats to the population of *Uapaca kirkiana* in its natural habitat

Uapaca kirkiana faces severe threats in its native range, regardless of its ecological and socio-economic significance. The threats include habitat loss and overexploitation leading to its population decline (Kapuka & Hlásny, 2021), particularly in Malawi (Kokou *et al.,* 2024). The agricultural expansion, timber extraction and charcoal production are forms of deforestation, reducing the cover of miombo woodlands. Food and Agriculture Organization (FAO) (2020) and Muluneh (2021) reported that sub-Saharan Africa experienced the highest annual net forest loss (3.9 million ha) globally from 2010 to 2020. Overharvesting of wild loquat fruits and wood, used locally for firewood, construction, and livestock housing, further strains populations, limiting natural regeneration (Hudson *et al.,* 2020; Jinga *et al.,* 2020; Djidohokpin *et al.,* 2024). Climate change worsens these pressures (Xiao *et al.,* 2024), altering temperature and rainfall patterns that threaten the survival of miombo tree species (Kapuka & Hlásny, 2021). Outside protected forest reserves, activities such as land-use intensification accelerate habitat degradation (Hudson *et al.,* 2020; Djidohokpin *et al.,* 2024; Nghonda *et al.,* 2024; Thomsen *et al.,* 2024). These anthropogenic pressures undermine biodiversity and ecosystem resilience.

Uapaca kirkiana's population structure, species associations, and edaphic relationships are critical to understanding ecosystem resilience (Godlee *et al.,* 2020; Fujita, 2021; Nghonda *et al.,* 2024). *U. kirkiana* is reported to be sensitive to climate shifts with phenological events like fruit maturation synchronized to summer rains (Jinga *et al.,* 2020; Kokou *et al.,* 2025). Nevertheless, inter-site variability in its distribution and soil preferences highlights the need to expand research into understudied regions (Araújo *et al.,* 2019; Schröder, Rodríguez & Günter 2021; Chitayat *et al.,* 2024) such as Malawi's Kaning'ina and Perekezi forest reserves. Identifying priority conservation zones, notably in Malawi's northern and central regions, where 21% and 13% of suitable habitats are located, is important to mitigating extinction risks and ensuring sustainable use (Kokou *et al.,* 2025). The ecological role of *U. kirkiana* in soil stabilization and carbon sequestration, coupled with its socio-economic value as an indigenous fruit species, necessitates urgent study of its population dynamics and habitat requirements (FAO, 2020; Sibiya *et al.,* 2020).

Uapaca kirkiana's population stability in miombo woodlands is shaped by age-class distributions, recruitment rates, and mortality, which are all influenced by biotic and abiotic factors (Kokou *et al.,* 2024). According to Jinga *et al.* (2020), summer precipitation, temperature regimes, and elevations of 500 – 2000 m strongly predict the distribution of *Uapaca kirkiana*. Kokou *et al.,* (2024) further stated that climate models project significant range contractions by 2050 – 2070 due to shifting temperature and precipitation patterns. This can exceed its physiological thresholds and disrupt regeneration cycles. Such shifts threaten to skew age-class distributions, favouring older cohorts as seedling recruitment declines. This pattern has been observed in other miombo keystone species under climatic stress from the studies of Atakpama *et al.* (2023) and Samarou *et al.* (2023) on *Adansonia digitata* and *Tamarindus indica* L., respectively.

Miombo woodlands are regarded as having high structural and compositional diversity. According to studies by Godlee *et al.* (2020) and Kokou *et al.* (2025), anthropogenic pressures have altered stand dynamics, fragmented habitats, and elevated adult mortality. These activities include land conversion, overgrazing, charcoal production, and selective logging. Chardon *et al.* (2020) found out that the disturbances reduce population resilience by limiting seed dispersal and creating microclimates unsuitable for sapling establishment. A study by Bonifácio-Anacleto *et al.* (2024) on wild tropical forages *Stylosanthes capitata* and *Stylosanthes macrocephala* reported that climate-driven biome shifts worsen habitat loss. The capacity of such species including *Uapaca kirkiana* to regenerate in degraded or transitional zones are extremely affected. A study by Montfort *et al.* (2021) on the regeneration capacities of woody species biodiversity and soil properties in miombo woodland after slash-and-burn agriculture in Mozambique reported that disturbances have a long-term effect on species composition and stand structure. The characterization of different forest stands has commonly utilized the gamma fit distribution function (Ige & Adedapo, 2021; Ige & Animashaun, 2023). This is because of its flexibility in modeling positively skewed, continuous data with a lower bound at zero.

According to a study by Yusup *et al.* (2022) and Chepkoech *et al.* (2024), understanding forest stand structures are key parameters in the sustainable management of forest ecosystems. The regulation of stand density provides a powerful tool for maximising in-growth, minimising mortality and improving tree growth and yield for a healthier miombo ecosystem (Njoghomi, Valkonen & Karlsson 2021). Mengich *et al.* (2020) on a study on semi-arid rangelands of Kenya suggested that the inverted J-shaped diameter distribution structure reflects a regenerating and stable population that is adapted to its site. Another study by Akweni *et al.* (2022) on savanna woodlands of South Africa, on edible fruit production reported that the diameter distribution of the trees had an inverted J-shaped structure. Njoghomi, Valkonen and Karlsson (2021) and Rudge *et al.* (2021) have also reported inverted J-shaped distribution structure on savanna trees of Australia and miombo woodlands of Tanzania respectively. Miombo woodland composition and structure remains understudied, particularly in northern Malawi's Perekezi and Kaning'ina forest reserves, where *U. kirkiana* populations face unique pressures (Godlee *et al.,* 2020; Schröder, Rodríguez & Günter 2021). These knowledge gaps hinder conservation prioritization, as *U. kirkiana's* survival is threatened by overharvesting, habitat fragmentation, and climate-driven range contractions (De Cauwer *et al.,* 2016; Hudson *et al.,* 2020; Kokou *et al.,* 2024).

Most studies described size-class distributions and regeneration patterns using simple histograms or descriptive accounts. While useful, these approaches often assume stable population processes. The methods each offer useful insight into forest structure, yet their limitations narrow how broadly their findings can be applied. Diameter class distribution provides a clear picture of size structure but can distort conditions where disturbance or sampling issues are present. Regeneration counts reveal recruitment but may inflate success by overlooking mortality and relying on small subplots. Stand density supports site-level comparisons but cannot indicate age patterns, restricting its value for long-term interpretation. Canopy cover links structure to light, though variation in measurement methods often reduces consistency across studies.

2.4 Woody species diversity and association mechanisms

2.4.1 Composition and ecosystem resilience of miombo woodlands

Decreasing precipitation and rising temperatures negatively impact forest undergrowth by disrupting its shady, humid conditions, favouring light-demanding and drought-tolerant species over those adapted to the understory (Bogawski *et al.,* 2021; Fujita, 2021). Studies by Godlee *et al.* (2020) and Montfort *et al.* (2021) further stated that this suppresses shade-intolerant herbaceous species while favouring a sparse grassy layer dominated by drought-adapted grasses. *U. kirkiana,* as a semi-deciduous crown tree, competes aggressively for light, water, and nutrients, particularly in undisturbed stands. Its dense foliage during the rainy season reduces light penetration to the understory and seasonal light gaps during the dry season. The pioneer species and shade-tolerant understory plants are thereafter enabled to establish. Studies by Jinga and Palagi (2020) and Montfort *et al.* (2021) demonstrated that the tree's leaf litter is beneficial in the improvement of soil moisture retention and organic matter, creating favourable microsites for seedlings of species like *Brachystegia* and *Julbernardia*. Disturbances like fire, overgrazing, and selective logging, reset competitive hierarchies and create regeneration opportunities (Gondwe *et al.,* 2021; Fujita, 2021; Montfort *et al.,* 2021). The anthropogenic pressures are increasingly disrupting these dynamics, skewing age-class distributions and threatening regeneration (Paul, Khan & Das 2019; van Tiel *et al.,* 2024).

2.4.2 Heterogeneity of miombo woodlands

Biodiversity in miombo woodlands, assessed through species richness, evenness, and the Shannon index (H'), reflects the ecosystem's structural complexity and resilience. Species richness is notably high in miombo due to habitat heterogeneity, where varied soil types, moisture gradients, and anthropogenic practices create diverse niches (Frost *et al.,* 1996; Timberlake & Chidumayo, 2011; Mensah, Salako & Seifert 2020). Evenness is about revealing ecosystem stability. Meneses *et al.* (2024) revealed that evenness values range from 0 to 1, where values closer to 1 indicate a more equal species distribution, and values near 0 indicate dominance by few species. A study by Gonçalves *et al.* (2017) on miombo woodlands in south-central Angola found evenness values around 0.53 in young fallows, with lower values in older fallows, indicating variation in species distribution during forest recovery after shifting cultivation. The fragmented stands show reduced functional diversity (Kalaba, Quinn & Dougill 2012; Bellamy *et al.,* 2018; Zambrano *et al.,* 2020), and are mostly driven by *U. kirkiana's* competitive dominance and limited regeneration (Kokou *et* *al.,* 2024). These metrics collectively highlight miombo's vulnerability to land-use changes. They also emphasize the need for explicit conservation strategies that preserve habitat heterogeneity.

Research on species associations often lists co-occurring species but does not analyse dominance or interaction strength. Many studies rely on presence–absence or species counts, which capture diversity. These species play different structural roles in the woodland, yet earlier studies often offered only broad descriptions of how they occur together. The canopy dominants *Brachystegia boehmii* and *Julbernardia globiflora* were noted mainly for overlapping crowns or frequent co-occurrence, with little quantitative assessment of their interactions. *Brachystegia floribunda*, occupying the mid-storey, was described in mixed patterns, though spatial variation was rarely considered. The understorey species have remained poorly explored despite patchy presence, while the fire-tolerant shrub *Combretum molle* was mentioned as scattered but rarely examined for its functional links with other species.

2.5 Soil adaptations and conservation

U. kirkiana thrives on soil conditions with low nutrient content and seasonal moisture availability (Chitayat *et al.,* 2024). *U. kirkiana's* can facilitate soil stabilization and seed bank preservation, safeguarding against erosion and nutrient leaching (Mhango *et al.,* 2008; Mazibuko & Changadeya, 2024). *U. kirkiana*, thrives in low-phosphorus conditions, a trait rare in fertile-soil ecosystems (Akinnifesi *et al.,* 2004; Chawafambira *et al.,* 2020a; Chawafambira *et al.,* 2020b). Its conservation requires tailored strategies, such as rotational harvesting and fire management. These balances human livelihoods with ecological resilience, a lesson less critical in *Acacia* systems where water scarcity drives management (Muluneh, 2021; Bonifácio-Anacleto *et al.,* 2024; Kokou *et al.,* 2024). Protecting miombo's heterogeneity is necessary to safeguard its unique flora and the ecosystem services it provides in an era of rapid climatic and anthropogenic change (van Tiel *et al.,* 2024).

According to Magalhães and Mamugy (2020), soil organic matter (SOM), soil organic carbon (SOC) and soil total nitrogen (N) stocks are affected by land use. A study by Ni and Vellend (2024), reported that soil conditions interact with climate to shape plant distributions, and unsuitable soils at higher elevations or latitudes and could limit future plant migration and biodiversity shifts. Assang *et al.* (2023) and Wu *et al.* (2024) further stated that soil, temperature seasonality, and annual precipitation are the most significant environmental factors affecting the distribution of the species. Therefore, understanding a species's current and future potential habitat is crucial to design its policy for management and cultivation practices that are more resilient in the face of climate change (Assang *et al.,* 2023; Lemi *et al.,* 2023).

2.5.1 Soil-plant interactions in miombo woodlands

The *Uapaca kirkiana* tree species thrives in sandy, acidic soils (pH 4.5–6.0) with low cation exchange capacity (Orwa *et al.,* 2009; Nyoka *et al.,* 2021). Its extensive root system develops nutrient cycling through exudates that mobilize phosphorus and micronutrients (Jinga *et al.,* 2020; Montfort *et al.,* 2021; Yan & Ghezzehei, 2022). Its semi-deciduous habit contributes seasonal leaf litter. The leaf litter is high in lignin and decomposes slowly, moderating soil organic carbon (SOC) accumulation and maintaining surface soil moisture in arid microsites (Ngulube, Hall & Maghembe 1998). Mature *U. kirkiana* stands correlate with elevated SOC stocks (12–18 Mg C ha^{-1}), compared to degraded or young regrowth areas (5–8 Mg C ha^{-1}) (Mhango *et al.,* 2008; Olsson *et al.,* 2019), reflecting its role in stabilizing carbon pools and improving fertility over time (Montfort *et al.,* 2021). The tree's litter chemistry also acidifies soils ($pH \leq 5.2$), potentially limiting nitrogen mineralization and favouring stress-tolerant understory species adapted to low-nutrient conditions (Chirwa & Akinnifesi, 2008; Pschenyckyj *et al.,* 2025).

Soil texture critically mediates these interactions. Sandy loams dominate miombo woodlands and facilitate deep rooting and water infiltration (Campbell, Cunliffe & Gambiza 1995; Shelukindo *et al.,* 2014; Nyirenda, 2022), buffering *U. kirkiana* against drought stress. Compacted or clay-rich soils inhibit root elongation, reducing growth rates by 30 % – 40% in waterlogged areas (Lipiec *et al.,* 2003; Ampoorter *et al.,* 2011). Sustainable management practices, such as retaining litterfall, minimizing tillage, can amplify *U. kirkiana's* positive feedback on soil health. This shall boost soil organic carbon and nutrient retention while mitigating acidity through organic amendments (Montfort *et al.,* 2021). These strategies are necessary for sustaining miombo productivity, as the species' resilience hinges on preserving the delicate balance between its soil-modifying traits and edaphic adaptations.

2.5.2 Edaphic adaptations of *Uapaca kirkiana*

U. kirkiana thrives under oligotrophic conditions marked by low exchangeable cations (Ca^{2+}, Mg^{2+}, K^{+}) and limited macronutrient availability (N, P, K) (Ngulube, Hall & Maghembe 1995; Kokou *et al.,* 2025). Its dominance in such soils positions it as a bioindicator of low soil fertility, reflecting adaptations to acidic substrates (pH 4.5–5.5) with minimal organic matter (≤1.5% OC) (Orwa *et al.,* 2009). *Uapaca kirkiana* adapts to phosphorus-deficient soils through deep, wide-ranging roots and mycorrhizal partnerships that boost nutrient absorption (Jinga *et al.,* 2020; Kokou *et al.,* 2025). Its competitive exclusion from more fertile soils, where faster-growing species dominate, highlights a trade-off between stress tolerance and resource acquisition (Bartlett, Scoffoni & Sack 2012; Poorter *et al.,* 2012). Conservation strategies targeting *U. kirkiana* must prioritize safeguarding its niche in nutrient-poor habitats. Its decline could signal broader ecosystem degradation and loss of adaptive traits critical to miombo resilience.

Uapaca kirkiana's ecological role in Miombo woodlands is shaped by dynamic interactions among its population structure, species diversity, and soil properties. Skewed age-class distributions, influence understory diversity. Mature trees suppress light-demanding species but creates microhabitats for shade-tolerant flora. The species thrives in nutrient-poor, acidic soils. Its slow-decomposing litter stabilizes organic carbon but limits nitrogen availability. Population structure drives microhabitat heterogeneity, moderating species diversity. Soil properties influence regeneration success. Anthropogenic pressures and climate change disrupt these cycles, risking ecosystem degradation.

Many studies relied on broad soil classifications rather than direct measurements, limiting the strength of ecological interpretations. Across miombo woodlands, soils are often sandy with low organic matter, and these conditions shape species performance, yet many studies have treated these factors rather loosely. Sandy textures and acidic pH favour the common canopy dominants, while shallow or variable soil depth influences rooting and stability, but much of the evidence depends on coarse maps, sparse sampling, or untested assumptions about uniformity. As a result, the influence of soil conditions on species distribution is acknowledged but not consistently supported by detailed measurements.

In conclusion, miombo woodlands, despite being important for biodiversity and livelihoods, remain understudied relative to tropical rainforests (Clarke *et al.,* 2017; Godlee *et al.,* 2020). This research bridges this gap by informing *U. kirkiana* conservation amid climate-induced range shifts, advocating strategies like domestication, protected areas, and marker-assisted breeding (Jinga *et al.,* 2020; Nkosi *et al.,* 2020; Omotayo & Aremu, 2020; Leakey *et al.,* 2022) to bolster resilience and livelihood security. Enriched stands boost ecosystem services such as carbon storage and watershed protection (Chang & Turner, 2019), therefore, supporting global climate goals.

Table 1: Synthesis of methodological strengths, weaknesses, and research gaps in miombo studies

Aspect	Strengths	Weaknesses	Research Gaps
Sampling design	- Many sites covered - Large regional datasets	- Variable plot sizes - Limited replication	- Need for standardised designs across landscapes
Structural measurements	- DBH and height widely used	- Crown metrics and health status rarely quantified	- Integrate full tree architecture analysis
Regeneration	- Seedling counts common	- Methods inconsistent - Seedling mortality ignored	- Long-term regeneration monitoring
Species associations	- Baseline data available	- No strong analytical testing	- Apply diversity and similarity indices
Soil factors	- General patterns known	- Few direct measurements	- Compare species patterns with measured soil variables
Statistical analysis	- Some use of importance value index and diversity metrics	- Mostly descriptive analyses	- T-tests and models needed

CHAPTER 3: MATERIALS AND METHODS

This chapter provides a description of the study sites, including the geographical location of the forest reserves of Perekezi and Kaning'ina. Further, it describes the research design and sampling framework and methods for the study. The chapter also presents the data collection and data analysis on the *Uapaca kirkiana* population structure and distribution, association with other woody species and the physical and chemical properties of soil across the two forest reserves.

3.1 Description of study sites

Malawi is a country located in the southeast of Africa, in Southern Africa. It is bordered by Tanzania to the North and North-East, Mozambique to the East, South and southwest and Zambia to the West and northwest. Malawi has three categorized seasons of hot-dry, warm-wet and cool-dry, therefore experiences a subtropical climate. From September-October, there is an occurrence of hot-dry season and an average temperature between 25°C and to maximum of 37°C. The warm-wet season starts from the month of November-April and has an average rainfall between 725 mm and 2500 mm annually. The 95% of the rainfall occurs annually, during the warm-wet season (Missanjo & Kadzuwa, 2021). The cool-dry season, in rotation, occurs between May and August at an average temperature between 4°C and 10°C. In the months of June and July, during the cool-dry season, isolated areas may experience frost (Steya, 2007; Missanjo & Kadzuwa, 2021).

The study was conducted in Perekezi and Kaning'ina forest reserves in northern Malawi (Figure 3). Perekezi forest reserve is found in Mzimba district and Kaning'ina forest reserve is found in Nkhata Bay district. These protected reserves are located approximately 55 km apart. This distance was sufficient to ensure independent site conditions for the purpose of comparison.

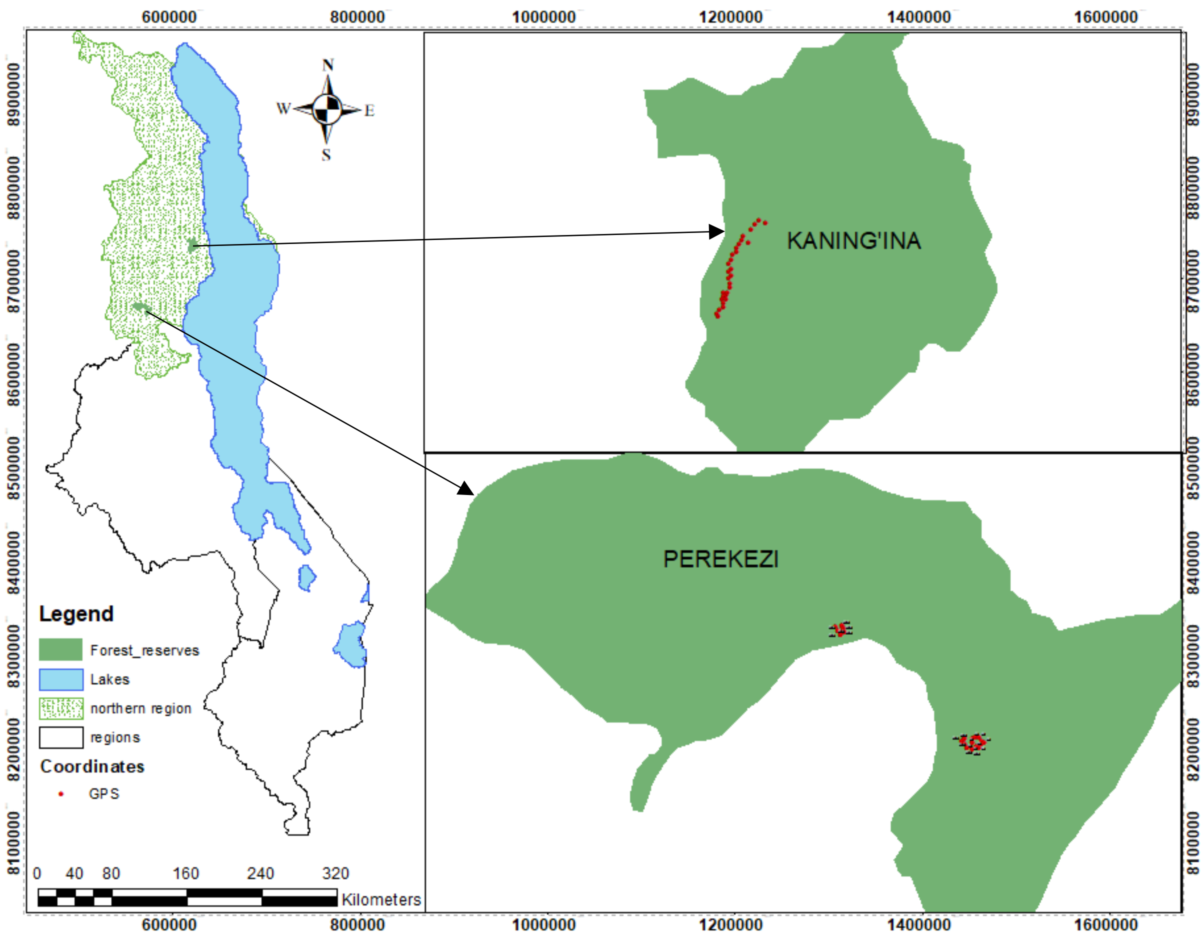

Figure 3: Location maps of the study sites

Kaning'ina forest reserve is located at coordinates 11°27′36″S, 34°07′73″E and receives annual rainfall ranging from 1200 mm to 2000 mm (Table 1). The area of the reserve is approximately 16,657 hectares, at an altitude of 1200 m – 1400 m that also includes patches of evergreen forest species (Banda, Schwartz & Caro 2006; Gondwe *et al.,* 2021). Perekezi forest reserve is located at coordinates of 12°29′32″S, 33°35′18″E. It receives rainfall in the range of 760 mm to 1270 mm annually. It is found at an altitude of 1500 m – 1700 m and covers an approximate area of 303,937 hectares under the management of the government and co-management with local communities in certain sections.

Table 2: Site characteristics and descriptions of the study sites

Characteristics	Forest reserve	
	Perekezi	**Kaning'ina**
Latitude	12°29′32″S	11°27′36″S
Longitude	33°35′18″E	34°07′73″E
Altitude	1500 m – 1700 m	1200 m – 1400 m
Temperature range	8.7°C to 27.3°C	10°C to 32°C
Rainfall range	760 mm – 1270 mm	1200 mm – 2000 mm

Perekezi and Kaning'ina forest reserves are state-owned, protected and managed by the District Forestry Offices of Mzimba and Nkhata Bay, respectively. Perekezi and Kaning'ina were gazetted as Forest Reserves in 1935 to conserve biodiversity, protect fragile woodland ecosystems, and safeguard water catchments (Gondwe *et al.*, 2021). *Uapaca kirkiana* populations are among the least studied natural forest assemblages despite their rich biodiversity and importance (Coutts *et al.,* 2019; Gondwe *et al.,* 2021). These forests are also under heavy pressure due to anthropogenic activities and climate change. Our study was conducted at the government management section of the forest reserves to compare population dynamics under these anthropogenic pressures.

3.1.2 Strategic values of Perekezi and Kaning'ina forest reserves

Conservation and protection of biodiversity, fragile woodland and water catchments were the main reasons for the gazettement of both of the forest reserves. Perekezi forest reserve is the source of rivers that supply water to the residents of Mzimba district and the city of Mzuzu. It is estimated that more than 96% of Malawi's population uses wood fuels (charcoal and firewood) for household cooking and heating (Missanjo & Kadzuwa, 2021). Apart from energy, forests provide timber and non-timber forest products as well.

In addition, forests including Perekezi and Kaning'ina contribute 6.9% to Malawi's GDP through domestic and export product sales, employment, and tourism (UNFCCC 2011, USAID, 2019; Stanturf & Mansourian, 2020; Missanjo & Kadzuwa, 2021; GoM, 2024). There are some agricultural activities around the forest reserves and issues of encroachment by the communities surrounding the reserve. In Kaning'ina forest reserve unlike Perekezi forest reserve, there are evidences of informal religious activities within the forest. This is evident with bare grounds under trees (Figure 4b) as charcoal burning instances were encountered during the data collection.

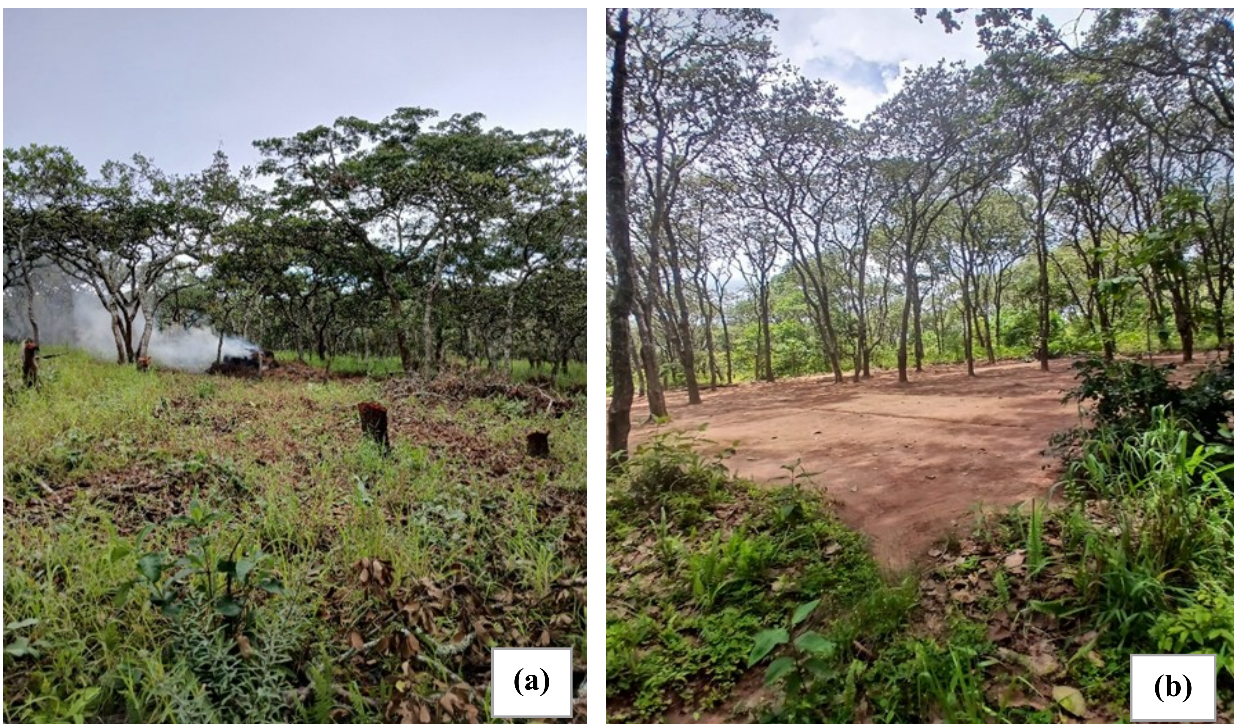

Figure 4: Effects of livelihood at (a) Perekezi forest reserve and informal religious activity at (b) Kaning'ina forest reserve

3.2 Sampling Design

The study used a two-stage sampling design. Initially, the study areas were stratified to delineate *Uapaca kirkiana* populations within the two forest reserves. Secondly, a systematic random sampling approach was used to locate sample plots to enable data collection of the population structure and distribution patterns, associated plant species, and soil physicochemical properties. This sampling design integrated forest inventory-based and soil sampling methods. This helped to provide an understanding on the ecological status and habitat associations of the plant species.

3.3 Sampling Framework and Methodology

Field data collection was conducted in February 2025. This was done after *U. kirkiana* fruiting and harvesting period, thereby avoiding disruption to the reproductive cycle of *U. kirkiana* and ensuring accuracy in population assessments. A total of 50 circular plots, each with a diameter of 40 m (area = 0.1257 ha), were systematically established. In Perekezi forest reserve, 20 sample plots were established while 30 sample plots were established in Kaning'ina forest reserve. Plot centres were identified using georeferenced coordinates obtained using handheld Garmin etrex GPS units (± 3 m accuracy), To minimize boundary effects and spatial autocorrelation, all plots were established at least 100 m from forest edges and spaced at a minimum interval of 100 m, consistent with recommended forestry sampling protocols (Ngulube, Hall & Maghembe 1995). The plot centres were marked using white chalk and boundaries delineated with measuring tapes and flagging tape to ensure spatial accuracy.

3.4 Data Collection

3.4.1 *Uapaca kirkiana* tree species inventory

Within each sample plot, a complete forest inventory was conducted for all individual *Uapaca kirkiana* trees with diameter at breast heights (DBH) of ≥ 5 cm. Diameter at breast height (DBH) was measured at 1.3 m from the ground using a diameter tape (± 0.1 cm precision). Sampled height trees were measured using a vertex with transponder with ± 0.1 m precision (Figure 5). The DBH values, grouped into ten size classes, and stem density were used to determine and compare population structure between the two forest reserves. Similarly, sampled crown diameter trees were determined orthogonally (in two perpendicular directions), projecting the perpendicular distance from the ground using a linear measuring tape (± 0.1 cm precision).

Juvenile individuals of *Uapaca kirkiana* of DBH < 5 cm and forking below 1.3 m were recorded separately to evaluate regeneration potential. Regeneration success and overall population health, including their stem density were assessed and calculated. A total of 627 and 539 trees of the *U. kirkiana* tree species were counted and recorded at Perekezi and Kaning'ina forest reserves, respectively.

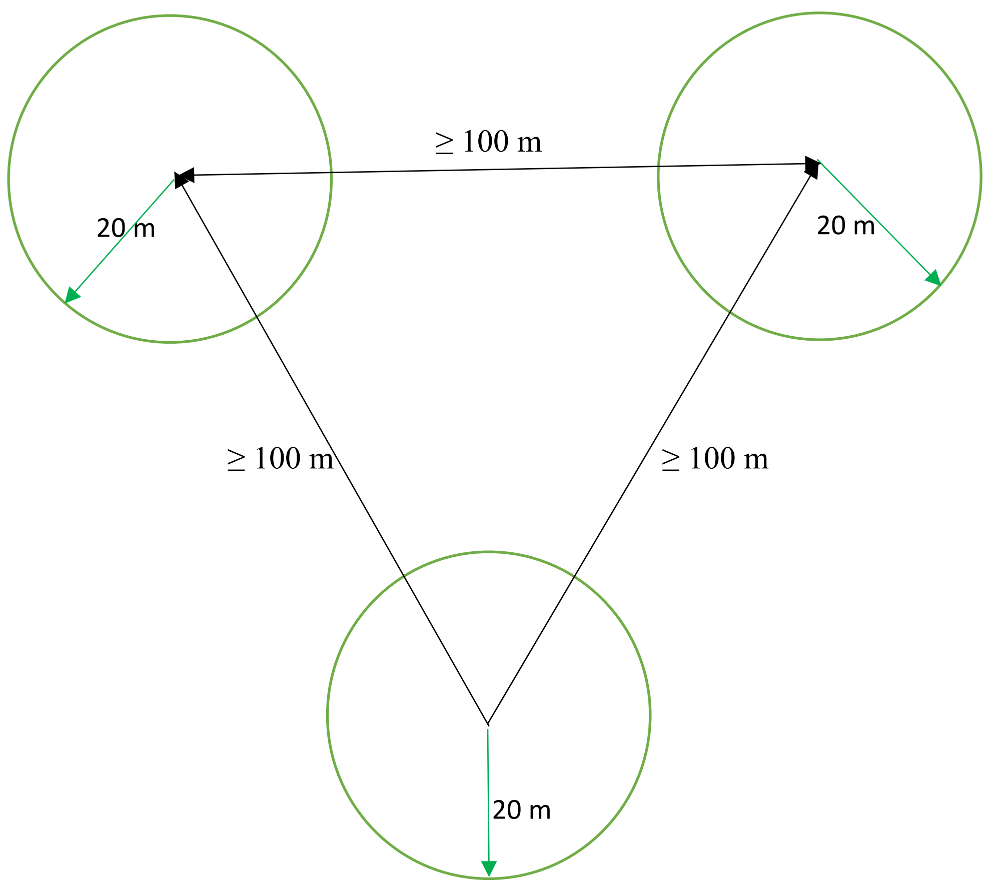

Figure 5: Shape and size of sampling plots at a distance of not less than 100 metres

Figure 6: Forest inventory crew with dendrology manual

Figure 7: Recordings and measurements being taken inside sample plot

3.4.2 Vegetation composition

A complete vegetation inventory was undertaken within each sample plot (Figure 7). All woody plants were identified to species level. Species identification was supported by an identification key and in consultation with a Botanist from the National Herbarium and Botanical Gardens of Malawi. The other woody species found within the sample plots of *Uapaca kirkiana* were recorded as present or absent. The assemblage of other vegetation species in a plot was considered as associates to *Uapaca kirkiana*.

Figure 8: Locating and recording the associated woody species in sample plot

3.4.3 Soil sample collection

Soil samples were collected within the 20 and 30 plots of Perekezi and Kaning'ina forest reserves, respectively. Soil samples were collected at a soil depth at 0 – 15 cm using soil auger in five directions (north, east, south, west and centre) within the plots. Sampled soils were then mixed to form a composite sample weighing 50 g (Figure 8). The composite soil sample was kept in air-tight ziploc plastic bags, well labelled, and transferred to the Lunyangwa Agricultural Research Station laboratory for analyses. This integrative approach facilitated assessment of both soil attributes and population characteristics of *Uapaca kirkiana*.

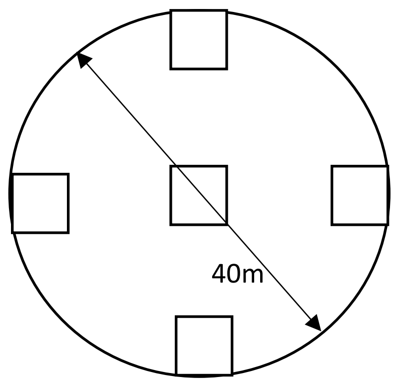

Figure 9: Quadrants for soil sampling in the plots

Figure 10: Soil sampling: (a) soil sample collection, (b) mixing and (c) packaging

Calibration, assumptions and limitations on the equipment

All field and laboratory instruments were calibrated before use to ensure accurate measurements. GPS units were checked for positional accuracy against known reference points at the start of each sampling day. Diameter tapes were inspected before measuring tree stem diameters, and vertex with transponder used for height estimation were verified using objects of known height to ensure measurement consistency. Measuring tape for crown diameter was also checked before measurement.

In the laboratory, all analytical instruments, including pH meters, spectrophotometers, atomic absorption spectrometers (AAS), and balance scales were calibrated prior to running soil samples. pH meters were calibrated using fresh buffer standards at pH 4.0 and 7.0, while spectrophotometer calibration was performed using reagent blanks and known standard solutions for phosphorus, nitrogen and organic carbon assays. The AAS was calibrated using multi-element standards for K, Ca and Mg and rechecked after every 10 samples to account for possible drift. Laboratory balances were checked with certified reference weights at the start of each batch.

The study assumed that all calibrated instruments performed consistently during field and laboratory work, that composite soil samples adequately represented average plot conditions, and that border effects were negligible due to the circular plot layout and systematic spacing. It was also assumed that devices such as GPS units and pH meters maintained accuracy within their stated tolerances after calibration.

Furthermore, despite precautions, border effects can arise where plots intersect ecotones, paths, or disturbed edges. Laboratory instruments like AAS and spectrophotometers may experience calibration drift during extended runs. Soil composites, while homogenised, may fail to capture fine-scale nutrient variability within plots.

Soil laboratory analysis

Prior to laboratory analyses, the soil samples were air-dried for 48 hours, sieved and properly preserved. Soil laboratory analysis included the analyses of texture (sand, silt and clay), pH, organic carbon (OC), available nutrients (nitrogen (N), potassium (P), phosphorus (K), calcium (Ca), and magnesium (Mg), and organic matter (OM) content calculated from organic carbon. There was no replication in the laboratory analysis to ensure the precision and accuracy of soil data, therefore, a limitation.

Carbon

The soil organic carbon was determined using the Walkley-Black wet oxidation method (De Vos *et al.,* 2007), utilizing potassium dichromate as the oxidizing agent, concentrated sulfuric acid for digestion, ferrous ammonium sulfate for titration, and diphenylamine as an indicator, with phosphoric acid stabilizing the reaction.

$$\text{The percentage } WBC = M \text{ x } \frac{V1 - V2}{W} \text{ x } 30 \text{ x } CF \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathit{Equation}\ 1$$

Where:

$WBC = \text{Walkley} - \text{Black carbon}$

$M = \text{Molarity of (FeSO4) solution from (Black titration)}$

$V1 = \text{volume (ml) of FeSO4 required in black titration}$

$V2 = \text{volume (ml) of FeSO4 required in actual titration}$

W = weight (g)of the oven dried sample

CF = correction factor (1.32)

Nitrogen

Total nitrogen was assessed via the Kjeldahl method (Goyal *et al.,* 2022). This involved digestion with sulfuric acid, distillation with sodium hydroxide, and titration using boric acid as a trapping agent. The methyl red and bromocresol green were mixed as indicators.

Phosphorus and Potassium

Phosphorus and potassium were extracted using the Mehlich III method (Wendt, 1995). This is where phosphorus detection relied on ammonium fluoride, nitric acid, ethylenediaminetetraacetic acid (EDTA), antimony potassium tartrate, and ammonium molybdate for colorimetric analysis. The potassium was quantified against a standard of potassium dihydrogen orthophosphate.

Calcium and Magnesium

Calcium and magnesium were also analyzed via Mehlich III extraction (Wendt, 1995). The acetic acid, ammonium nitrate, and ammonium fluoride were used to facilitate dissolution. The ethylenediaminetetraacetic acid (EDTA) ensured chelation for measurement.

Soil pH

Soil pH was electrometrically measured using a soil pH meter calibrated with standard buffer acqeous solutions at pH 4, 7 and 9 (Singh *et al.,* 2021). Deviations in reagent concentrations from stated values were noted but did not compromise the analytical validity.

Soil texture

The hydrometer method was used to analyse soil texture (Gee & Bauder, 1979). The method helped to determine particle size distribution (sand, silt, and clay) by measuring soil suspension density over time based on Stokes' Law. Sodium hexametaphosphate was used to act as a dispersing agent and amyl alcohol was used to prevent foam formation. The availability of P, Ca, Mg and K was quantified using colorimetric methods and flame photometry, respectively.

In addition to morphometric and edaphic data, observations on site conditions were also recorded, including regeneration status, visible signs of human disturbance, deadwood presence, terrain characteristics and general tree health. Mining activities, for example, at Perekezi forest reserve have impacted negatively the trees near the site (Figure 9).

Figure 11: Impact of mica mining in the Perekezi forest reserve

Figure 12: Health status of *U. kirkiana* tree species in Kaning'ina forest reserve

3.5 Data Organisation and Analysis

3.5.1 Data organisation

Data were diagnosed and organised in MS Excel 2016. For population structure and distribution data, a linear regression analysis was used to fit the model for estimation of height from sampled diameter-height pairs of *Uapaca kirkiana* trees. The natural logarithm of height was regressed against the reciprocal of DBH (Equation 2) prior to application of box-cox transformations on the dependent variable.

$$\ln(\mathrm{H}) = \mathrm{a} + \mathrm{b}\left(\frac{1}{\mathrm{DBH}}\right) \dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots\dots \text{Equation 2}$$

Where:

H = tree height (metres)

DBH = diameter at breast height (cm)

$\mathrm{a, b}$ = regression coefficients

To estimate crown diameter, a log-linear regression model was applied as shown in Equation 3.

$$\ln(\mathrm{Cd}) = \mathrm{a} + \mathrm{b}\left(\frac{1}{\mathrm{DBH}}\right) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{Equation 3}$$

Where:

Cd = Crown diameter (metres)

DBH = diameter at breast height (cm)

$\mathrm{a, b}$ = regression coefficients

Stem density (stems ha^{-1}) was calculated as a function of the number of trees and unit area using Equation 4 (Gavrikov, 2014)

$$\text{Stem density} = \frac{\mathrm{c}}{\mathrm{a}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots.. \text{Equation 4}$$

Where:

c = number of trees counted per plot

a = area of plot (ha)

Tree slenderness coefficient, defined as the ratio of total tree height to diameter at breast height was calculated using a t-test in the R version 4.4.2 software with pooled variance and degrees of freedom for equal variances considered as follows:

$$t = \frac{\bar{X}_1 - \bar{X}_2}{\sqrt{\frac{s^2{}_p}{n_1} + \frac{s^2{}_p}{n_2}}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. Equation\ 5$$

Where pooled variance ($s^2{}_p$) is:

$$s^2{}_p = \frac{(n_1 - 1)s^2{}_1 + (n_1 - 1)s^2{}_2}{n_1 + n_2 - 2} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots\ldots\ldots Equation\ 6$$

Degrees of freedom (df) for equal variances:

$$df = n_1 + n_2 - 2 \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..\ldots Equation\ 7$$

Where:

$t = a\ measure\ of\ how\ much\ the\ groups\ differ\ relative\ to\ variability[t - statistic]$

$\bar{X}_1 = sample\ mean\ of\ the\ first\ group$

$\bar{X}_2 = \ sample\ mean\ of\ the\ second\ group$

n_1 = number of observations in first group

$n_2 = number\ of\ observations\ in\ second\ group$

$s^2{}_1 = how\ spread\ out\ the\ data\ is\ in\ the\ first\ group$

$s^2{}_2 = how\ spread\ out\ the\ data\ is\ in\ the\ second\ group$

$s^2{}_p = combined\ variance\ of\ both\ groups, assuming\ equal\ variances$

A model of gamma distribution as applied in the study of Krishnamoorthy (2006) was used to determine the distribution of tree diameters of *Uapaca kirkiana* trees. It helped to capture the skewed nature of size class data in the uneven-aged forest reservess.

To quantify the association of *U. kirkiana* with other woody species, a species richness index was determined (Albatineh & Niewiadomska-Bugaj, 2011). The following formula (Equation 8) was used:

$$S = \sum species\ present \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots..Equation\ 8$$

Where:

S = Species richness

Σ = Sum of all species recorded as present in a plot

For presence-absence data, this translated to:

$$\mathrm{S} = \sum \mathrm{Xi} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots. \mathrm{Equation\ 9}$$

Where:

Xi = 1 if species is present, 0 if absent

Σ = Sum of all species recorded as present in a plot

This was limited because all present species are treated equally, present or absent, therefore, no abundance data. The index only reflected richness and not evenness.

The calculation of Jaccard similarity index was done by using Equation 10 as follows:

$$\mathrm{J} = \frac{\mathrm{a}}{\mathrm{a+b+c}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \mathrm{Equation\ 10}$$

Where:

$\mathrm{a} =$ number of species common to both sets (shared species)

$\mathrm{b} =$ number of species only in the first set

$\mathrm{c} =$ number of species only in the second set

3.5.2 Statistical data analysis

Data were statistically analysed using R Version 4.4.2. Prior to inferential testing, data were examined for normality and homogeneity. Normality test was assessed using the Shapiro-Wilk, and homogeneity of variances was done using Levene's test. Non-normally distributed variables were transformed guided by a Box-Cox test. Tables and figures were produced using Microsoft Excel 2016.

To compare the population structure of *U. kirkiana*, a t-test was used at $\alpha = 0.05$ between Perekezi and Kaning'ina forest reserves. The test parameters from these forest reserves were mean tree sizes, mean slenderness coeffients, mean heights, mean crown sizes, and mean regeneration and health statuses. The distribution of *U. kirkiana* trees was compared using the maximum likelihood estimates of the gamma fit distribution. The shape (α) and scale (β) parameters were assessed using the Akaike Information Criteria as well as the Bayesian Information Criteria for goodness of fit of the DBH distribution.

To assess woody species associations of *U. kirkiana* between the two forest reserves, the floristic composition and tree species relative abundance were determined as being present or absent. Tree species richness was compared using a t-test at $p = 0.05$. Further, a Jaccard's similarity coefficient was used to compare tree species compostion between the reserves. Dendrograms were used to represent cluster similarities. Species absent in both plots were not considered in the calculation. This is because they do not provide information on similarity under the formula (Albatineh & Niewiadomska-Bugaj, 2011).

To compare the means of physicochemical soil properties, a t-test was performed at $p = 0.05$. The mean proportions of sand, clay and silt soils under *Uapaca kirkiana* ecosystems formed the test parameters between Perekezi and Kaning'ina forest reserves. Further, the soil chemical properties comprising soil pH, organic Carbon (SOC), organic matter (SOM), Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca) and Magnesium (Mg) under *U. kirkiana* cover were also compared between the two forest reserves.

CHAPTER 4: RESULTS

This chapter presents the results of population structure and distribution, woody species diversity and association and soil physicochemical properties from the forest reserves of Perekezi and Kaning'ina. It also presents the findings on floristic composition, distribution of diameter, regeneration and slenderness coefficient, including crown diameter. It also contains results on cluster analysis, plots and visualizations.

4.1 Population structure and distribution

4.1.1 Stem density and diameter size relations

The results on diameter sizes in relation to stand density generally showed the existence of reverse J-shaped curves in both Perekezi and Kaning'ina forest reserves (Figure 11). As the diameter sizes increased, there was a correspondingly decrease in the number of stems per hectare. In Perekezi, a diameter at breast height (DBH) class of 5.0-9.9 cm recorded a peak density of 2,387 stem/ha with a drop at a class of 15.0-19.9 cm, recording a density of 700 stem/ha. The density remained below 100 stems/ha at DBH sizes from 30.0 cm to 54.9 cm. In Kaning'ina, the curve exhibited a binomial reverse J-shaped type of curve. A DBH class of 5.0-9.9 cm registered 811 stems/ha. A peak number of stems/ha was registered at a diameter class of 20.0-24.9 cm with a tail off starting from 40.0-44.9 cm.

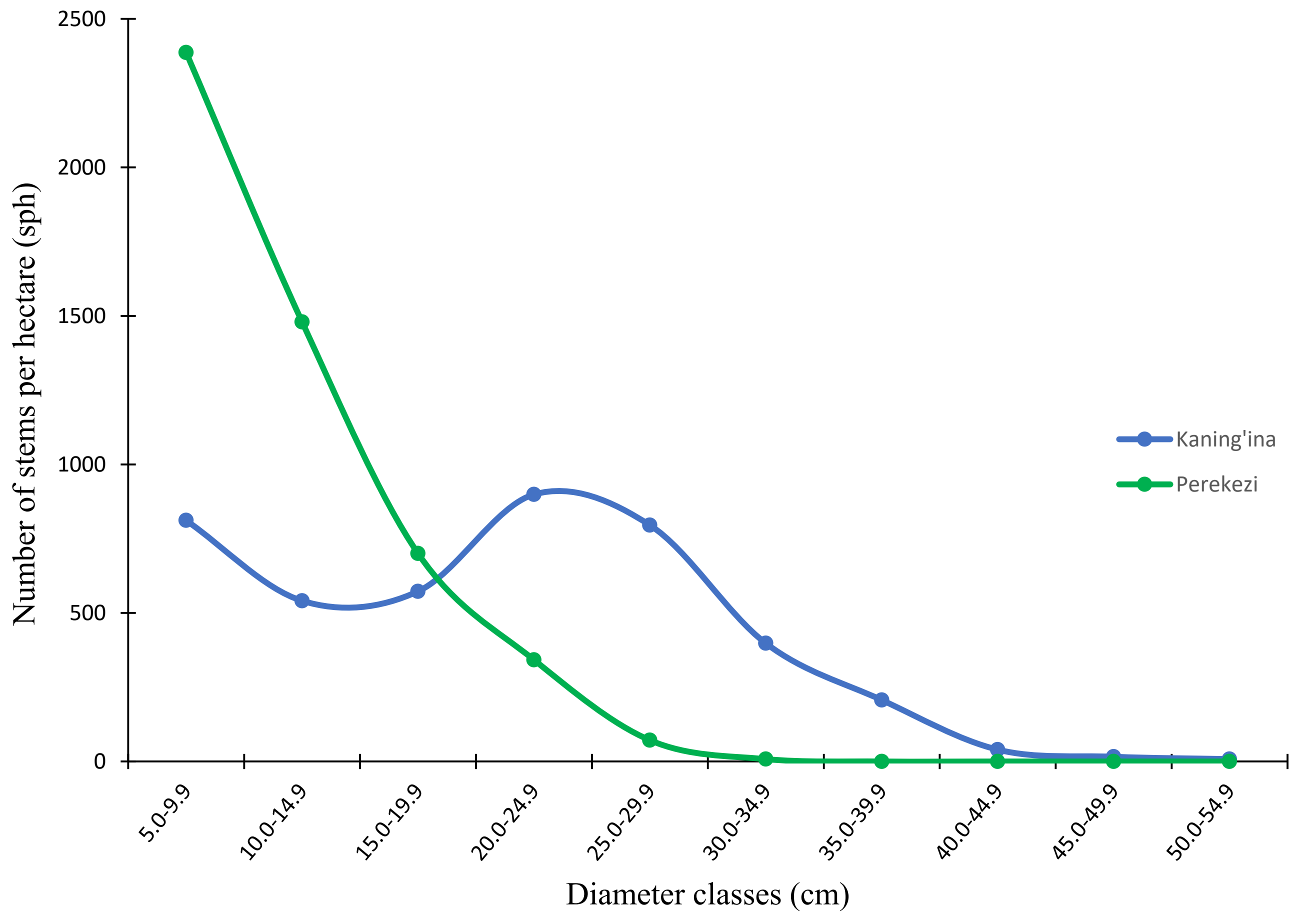

Figure 13: Stand density and diameter class relationship of *Uapaca kirkiana* in the forest reserves of Perekezi and Kaning'ina

4.1.2 Tree diameter structural diversity

In Table 2, the results showed a tree diameter structural diversity difference between Perekezi and Kaning'ina forest reserves. Kaning'ina showed a mean DBH of 20.58 ± 9.38 cm while Perekezi had a mean of 11.42 ± 5.08 cm. A mean comparison using test a t-test at $p = 0.05$ between the two forest reserves showed a very highly significant statistical differences ($p = 0.001$) between the two forest reserves.

Table 3: A t-test of tree diameter sizes between the forest reserves of Perekezi and Kaning'ina

Forest reserves	**Observations**	**Mean ± SD**
Perekezi	627	11.42 ± 5.08
Kaning'ina	539	20.58 ± 9.38
df	1164	
t	-19.18	
p-value	0.001	

4.1.3 Tree slenderness coefficient

The results of mean ± SD tree slenderness coefficient for Perekezi was 0.56 ± 0.01 (Table 3). The tree slenderness coeffient for Kaning'ina forest reserve was 0.55 ± 0.02. T-test results on mean tree slenderness coefficients between Perekezi and Kaning'ina forest reservess showed that there were statistical significant ($p < 0.05$) differences.

Table 4: Comparison of mean tree slenderness coefficient between the forest reserves of Perekezi and Kaning'ina

Forest reserves	**Observations**	**Mean ± SD**
Perekezi	627	0.56 ± 0.01
Kaning'ina	539	0.55 ± 0.02
df	1164	
t	2.35	
p-value	0.04	

4.1.4 Tree height at the study sites

Perekezi forest reserve recorded a tree mean height (m) of 5.84 ± 4.37 while Kaning'ina forest reserve recorded tree mean height (m) of 9.95 ± 3.85 as presented in Table 4. The Perekezi forest heights ranged from 2.60 m to 12.10 m while Kaning'ina forest reserve ranged from 2.50 m to 21.60 m. A t-test at $p = 0.05$ between the two forest reserves showed a very high statistical significant ($p = 0.001$).

Table 5: A t-test result on tree heights between the forest reserves of Perekezi and Kaning'ina

Forest reserves	Observations	Mean height (m) ± SD
Perekezi	627	5.84 ± 4.37
Kaning'ina	539	9.95 ± 3.85
df	1164	
t	16.91	
p-value	0.001	

4.1.5 Crown diameter in the study sites

Comparatively, Perekezi forest reserve recorded a mean crown diameter (m) of 4.27 ± 2.29 whilst Kaning'ina forest reserve recorded a mean crown diameter (m) of 6.32 ± 1.81 (Table 5). The Perekezi forest crown diameter ranged from 1.50 m to 9.40 m whereas Kaning'ina forest reserve ranged from 1.20 m to 16.10 m and results were very highly statistically significant ($p = 0.001$) between the two forest reserves. Taken together, these structural attributes indicate clear differences in stand form between the two reserves, which become more evident when examining how individuals are distributed across diameter size classes. The observed patterns in diameter classes are closely linked to recruitment processes, making it necessary to evaluate the regeneration status in each reserve.

Table 6: Comparison results on crown diameter between the forest reserves of Perekezi and Kaning'ina

Forest reserves	Observations	Mean diameter (m) ± SD
Perekezi	627	4.27 ± 2.29
Kaning'ina	539	6.32 ± 1.81
df	1164	
t	15.09	
p-value	0.001	

4.1.6 Regeneration and health status

Since regeneration alone does not fully explain population dynamics, the condition of standing individuals provides an additional perspective on stand stability and vigour. Perekezi Forest Reserve generally shows a very high proportion of healthy trees across most of its sampled plots (Table 6). There is a low number of unhealthy tree species of *U. kirkiana* is Perekezi forest reserve. Kaning'ina forest reserve shows the presence of unhealthy trees in the majority of its plots. The unhealthy trees included the damaged, diseased, broken tip, partly dry and completely dry tree species.

Table 7: T-test on the regeneration and health status of *U. kirkiana* in the forest reserves of Perekezi and Kaning'ina

Tree metrics	Forests reserves	Mean health ± SD	df	t-value	*p*-value
< 5 cm	**Perekezi**	20.00 ± 0.72	43	-1.91	0.068^{ns}
	Kaning'ina	10.80 ± 19.12			
≥ 5 cm	**Perekezi**	31.35 ± 3.96	48	-2.87	0.007**
	Kaning'ina	17.73 ± 23.28			
Healthy	**Perekezi**	31.20 ± 4.77	48	-3.06	0.005**
	Kaning'ina	16.93 ± 23.77			
Unhealthy	**Perekezi**	0.30 ± 1.31	18	2.55	0.014*
	Kaning'ina	1.03 ± 0.15			

Significant codes: '***' 0.001 very highly significant, '**' 0.01 highly significant, '*' 0.05 significant, $^{\text{'ns'}}$ not significant

The diameter size (< 5 cm) across the forest reserves of Perekezi and Kaning'ina revealed a no statistically significant difference $p = 0.068$. The diameter size (≥ 5 cm) revealed a highly statistically significant difference ($p = 0.007$) between the two forest reserves. There is also a highly statistically significant difference in health status between the two forest reserves ($p = 0.005$). The unhealthy status between the two forest reserves revealed a statistical significant difference ($p = 0.014$) at 0.05. Perekezi has a higher mean (31.20 ± 4.77) of healthy *U. kirkiana* tree species as Kaning'ina forest reserve has a higher mean (1.03 ± 0.15) of unhealthy *U. kirkiana* trees.

4.1.7 Gamma fit distribution for tree diameters in Kaning'ina and Perekezi forest reserves

The results showed that Perekezi has a diameter at breast height (DBH) distribution with less variability and less skewness. In contrast, Kaning'ina shows greater variability and skewness in DBH as presented in Figure 12.

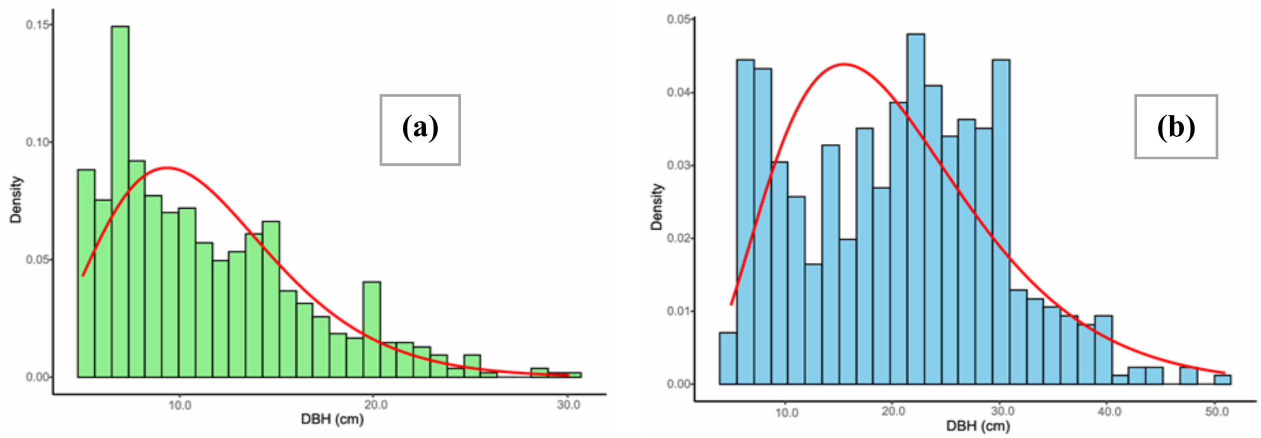

Figure 14: Gamma distribution fit to DBH measurements in the forest reserves of (a) Perekezi and (b) Kaning'ina

Perekezi has a more right-skewed but less variable DBH distribution (5.53) than Kaning'ina (4.08) as presented in Table 7. The smaller α indicates greater skewness and variability in tree sizes. Perekezi's higher β (0.48) reveals its DBH values are more concentrated around smaller sizes compared to Kaning'ina (0.20). Perekezi (-1840.85) has a model fit slightly better than Kaning'ina (-1969.35). Perekezi's AIC (3685.69) and BIC (3694.58) are lower than Kaning'ina's, supporting the slightly better fit. Lower values indicate better model fit considering model complexity.

Table 8: Maximum likelihood estimates (MLE) for the gamma distribution fitted to DBH

Forest reserves	Shape (α) ± SD	Rate (β) ± SD	Log-likelihood	AIC	BIC
Perekezi	5.53 ± 0.30	0.48 ± 0.03	-1840.85	3685.69	3694.58
Kaning'ina	4.08 ± 0.24	0.20 ± 0.01	-1969.35	3942.69	3951.27

AIC (Akaike Information Criterion); BIC (Bayesian Information Criterion)

Kaning'ina Forest Reserve has significantly larger trees (mean DBH = 20.58 cm) compared to Perekezi (11.42 cm) as presented in Table 8. There is also higher size variability with Kaning'ina (SD = 9.38) against Perekezi (SD = 5.08), leading to broader DBH distribution differences. Goodness-of-fit tests reveal moderate fits for both reserves. Beyond the condition of *U. kirkiana*, understanding the broader species composition helps clarify the ecological context in which the species occurs.

Table 9: Summary statistics of tree DBH (cm) in the forest reserves of Perekezi and Kaning'ina

Forest reserves	Minimum	Median	Mean ± SD	Maximum
Perekezi	5.00	10.10	11.42 ± 5.08	30.10
Kaning'ina	5.00	21.30	20.58 ± 9.38	51.00

4.2. Woody species diversity and species associates of *Uapaca kirkiana*

4.2.1 Floristic composition

Forty-nine (49) different tree species, apart from *Uapaca kirkiana,* and 23 families were recorded from the Perekezi forest reserve. A total of 28 families were also recorded from the 49 different tree species excluding *Uapaca kirkiana* in Kaning'ina forest reserve. In all the sample plots in the two forest reserves, there was variation in diameter at breast height and density (stems per hectare).

There was also variation in the frequency of species, with others appearing only in some plots and some occurring in most of the plots of the *Uapaca kirkiana* species. The dominant families of tree species included Fabaceae, Rubiaceae and Proteaceae in both of the forest reserves. The frequent tree species existing with *Uapaca kirkiana* were *Brachystegia spiciformis*, *Uapaca sansibarica* and *Faurea rochetiana*. While species lists indicate which taxa are present, diversity quantify how evenly these species contribute to the woodland structure.

Table 10: Presence-absence matrix of woody species in plots of *Uapaca kirkiana*

Species composition	Perekezi		Kaning'ina	
	Present/Absent	**Frequency**	**Present/Absent**	**Frequency**
Agauria salicifolia	+	2	+	6
Albizia adianthifolia	-	0	+	2
Albizia antunesiana	+	3	-	0
Anisophyllea boehmii	+	1	+	1
Annona senegalensis	-	0	+	2
Anthocleista grandiflora	-	0	+	2
Aphloia theiformis	-	0	+	5
Apodytes dimidiata	-	0	+	1
Brachystegia floribunda	+	14	-	0
Brachystegia longifolia	+	16	+	4
Brachystegia microphylla	+	1	-	0
Brachystegia spiciformis	+	9	+	21
Brachystegia taxifolia	+	3	-	0
Brachystegia utilis	+	5	+	3
Bridelia micrantha	+	3	+	18
Combretum molle	+	3	+	15
Craterispermum schweinfurthiana	-	0	+	9
Cussonia arborea	+	15	-	0
Cussonia spicata	-	0	+	1
Dalbergia nitidula	-	0	+	3
Dombeya rotundifolia	+	1	-	0
Ekebergia capensis	+	4	+	2
Embelia schimperi	+	3	-	0
Erica benguelensis	+	4	-	0
Erythrina abyssinica	+	2	-	0
Euclea crispa	+	1	-	0
Faurea rochetiana	+	8	+	24

Species composition	Perekezi		Kaning'ina	
	Present/Absent	Frequency	Present/Absent	Frequency
Faurea saligna	+	9	+	2
Ficus natalensis	+	1	+	1
Ficus sur	+	1	+	1
Flacourtia indica	+	1	-	0
Garcinia huillensis	-	0	+	1
Harungana madagascariensis	-	0	+	9
Isoberlinia angolensis	+	10	-	0
Julbernardia paniculata	+	13	-	0
Keetia gueinzii	-	0	+	12
Lannea discolor	+	11	-	0
Macaranga capensis	-	0	+	5
Maesa lanceolata	-	0	+	11
Magnistipula butayei	-	0	+	1
Maytenus heterophylla	+	1	-	0
Memecylon flavovirens	+	1	-	0
Memecylon sansibaricum	+	4	+	2
Monotes africanus	+	13	-	0
Multidentia crassa	+	2	+	2
Myrica salicifolia	-	0	+	2
Mystroxylon aethiopicum	+	1	-	0
Ochna schweinfurthiana	+	8	+	11
Ozoroa insignis	+	1	-	0
Parinari curatellifolia	+	15	+	17
Pericopsis angolensis	-	0	+	18
Pinus patula	-	0	+	1
Protea angolensis	+	9	+	12
Protea gaguedii	+	8	+	5
Protea saligna	+	1	-	0
Psorospermum febrifugum	+	4	+	5
Psychotria eminiana	-	0	+	1
Psychotria mahonii	+	1	+	3
Psychotria peduncularis	-	0	+	1
Rapanea melanophloeos	-	0	+	3
Rhus longipes	+	2	-	0
Rothmannia engleriana	+	1	-	0
Securidaca longepedunculata	+	1	-	0
Senna singueana	+	2	-	0
Synsepalum muelleri	-	0	+	1
Syzygium cordatum	+	1	+	1
Syzygium guineese	+	4	+	1
Syzygium owalensis	+	4	-	0

Species composition	Perekezi		Kaning’ina	
	Present/Absent	Frequency	Present/Absent	Frequency
Syzygium owariense	-	0	+	12
Tecomaria capensis	-	0	+	1
Tricalysia coleasea	+	1	+	1
Uapaca sansibarica	+	3	+	23
Vitex doniana	-	0	+	4
Ximenia caffra	-	0	+	2

(+) indicates present while (-) indicates absent

4.2.2 Species diversity

Although both forest reserves have several common species, some species are unique. Perekezi forest reserve had 25 species that were different from the 25 species from Kaning’ina forest reserve. The 7 families were found to be unique in Perekezi, including Anacardiaceae, Celastraceae, Dipterocarpaceae, Ebenaceae, Malvaceae, Polygalaceae and Salicaceae. Kaning’ina had a total of 11 families that included, Annonaceae, Aphloiaceae, Bignoniaceae, Clusiaceae, Euphorbiaceae, Gentianaceae, Lamiaceae, Metteniusaceae, Pinaceae, Sapotaceae and Ximeniaceae.

The shared (14) families include Anisophylleaceae, Combretaceae, Ericaceae, Fabaceae, Hypericaceae, Melastomataceae, Meliaceae, Moraceae, Myrtaceae, Ochnaceae, Phyllanthaceae, Primulaceae, Proteaceae and Rubiaceae. Between the two forest reserves, 24 species were common.

Table 10 shows Perekezi forest reserve has higher species richness (11.45 ± 4.24) compared to Kaning’ina forest reserve (9.67 ± 2.72) but no statistically significant (p = 0.129) different.

Table 11: Comparison of species richness between the forest reserves of Perekezi and Kaning'ina

Diversity index	Forests reserves	Mean ± SD	Df	t-value	*p*-value
Species Richness	**Perekezi**	11.45 ± 4.24	47	-1.57	0.129
	Kaning'ina	9.67 ± 2.72			

4.2.3 Comparative species richness

Although both sites share 24 species and 14 families, each reserve had 25 unique species (Figure 13). Perekezi exhibited higher representation of *Isoberlinia angolensis*, *Julbernardia paniculata*, and *Cussonia arborea*, while Kaning'ina was richer in *Pericopsis angolensis*, *Bridelia micrantha*, and *Faurea rochetiana*. The patterns of diversity and richness suggest potential interactions among species, which require further examination through species association analyses.

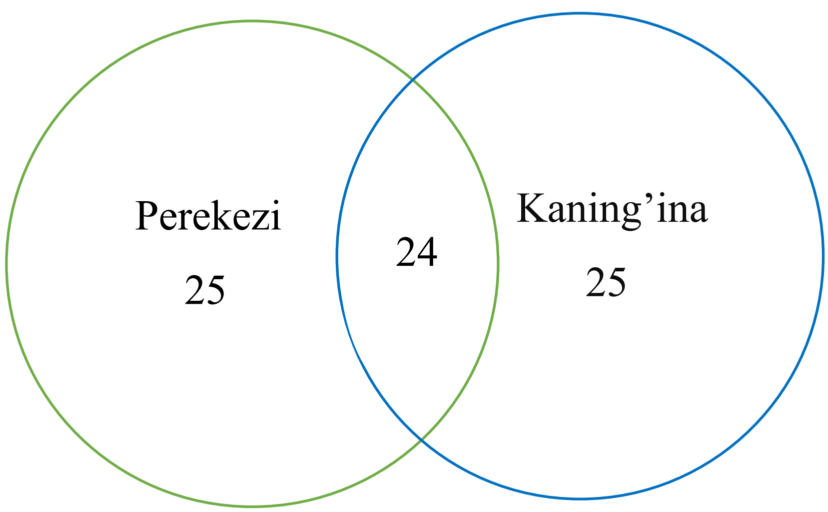

Figure 15: Venn diagram of woody species in forest reserves of Perekezi and Kaning'ina

4.2.4 Relative abundance

In Figure 14, the relative abundance values showed that *U. kirkiana* tree plots were highly dominated by *Brachystegia longifolia, Parinari curatellifolia, Cussonia arborea and Brachystegia* *floribunda* in Perekezi forest reserve whilst *Faurea rochetiana*, *Uapaca sansibarica* and *Brachystegia spiciformis* in Kaning'ina forest reserve.

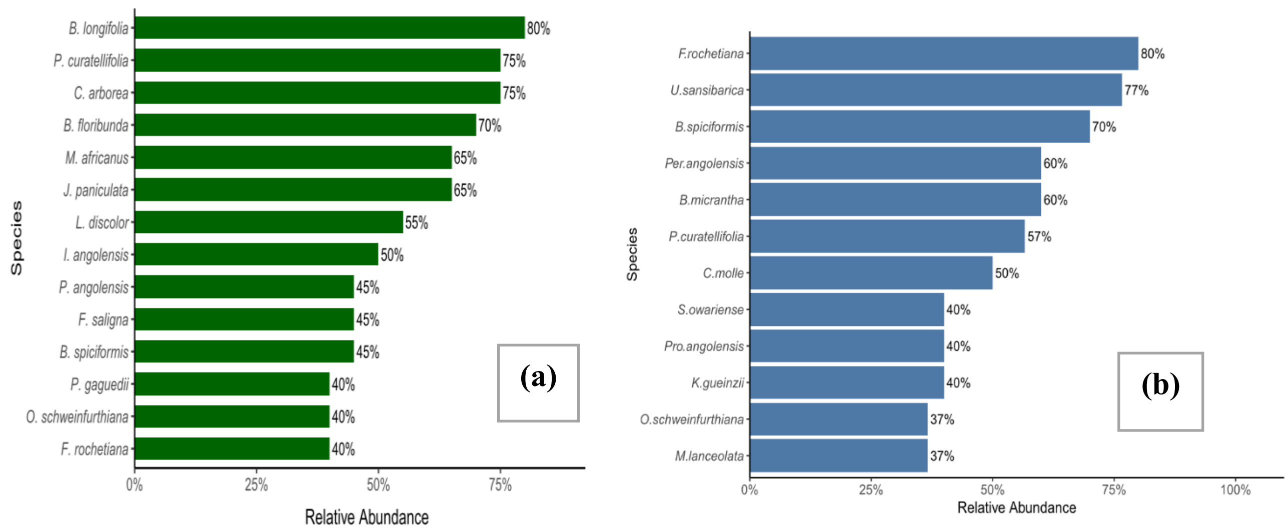

Figure 16: Relative abundance of tree species in forest reserves of (a) Perekezi and (b) Kaning'ina

4.2.5 Jaccard's similarity matrix

In Perekezi forest reserve, hierarchical clustering (Jaccard distance) revealed two distinct sample groups based on species presence-absence data (Figure 15). Similar sample plots are at lower heights and most dissimilar plots are joining at higher heights. At jaccard distance of 0.7, there are seven clusters. Plots 1 and 9 show the highest similarity, at approximately 0.3 height. Also plots 4 and 5 and 16 and 19. The majority of the plots show moderate associations. Merging below 0.7 shows no distant associations, the high Jaccard distance.

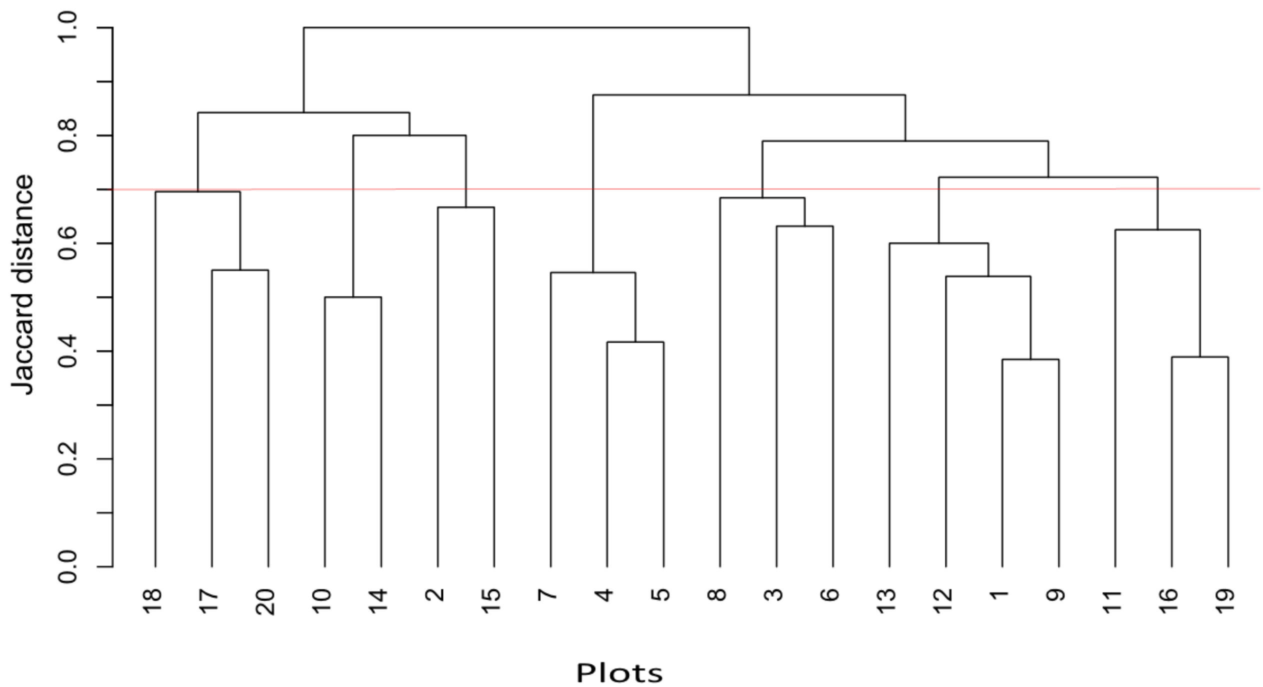

Figure 17: Cluster dendrogram of plots of Perekezi forest reserve

In Kaning'ina forest reserve, hierarchical clustering (Jaccard) revealed core species grouping (Figure 16). The plots are separated into two primary groups. The most similar plots join at lower heights and more different plots connect at higher levels. At jaccard distance of 0.7, there are twelve clusters. Plots 12 and 16, plots 10 and 26 and plots 5 and 27 shows stronger similarity, therefore very similar species composition. The majority of the plots have shown moderate associations. Because species associations may be influenced by resource gradients, assessing soil properties provides additional insight into the drivers of the observed patterns.

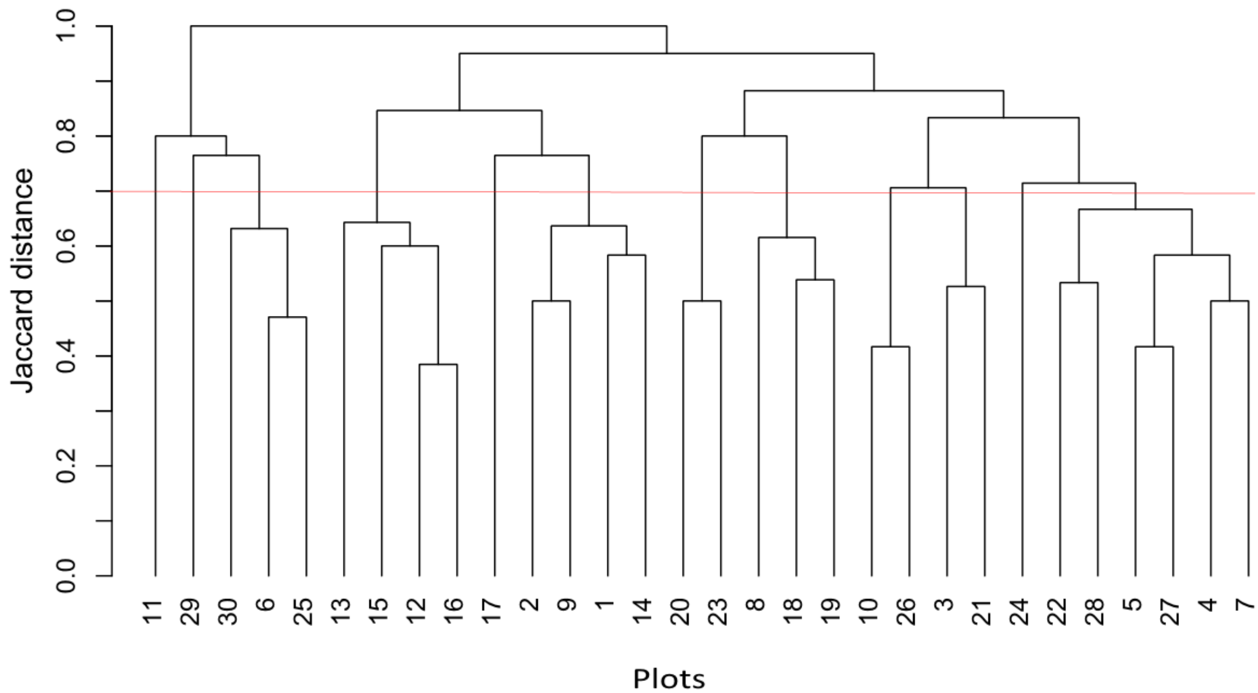

Figure 18: Cluster dendrogram of plots of Kaning'ina forest reserve

4.3 Assessment of soil physicochemical properties in *Uapaca kirkiana* ecosystems

4.3.1 Soil texture

The results, in Table 11, showed that the mean proportion of sand for Perekezi and Kaning'ina soils under *U. kirkiana* trees is 79.80 ± 3.89% and 76.60 ± 5.10%, respectively. Further, the clay content for Perekezi is 5.90 ± 2.00% while that for Kaning'ina is 8.47 ± 3.39%. T-test soil texture analysis results have shown that Perekezi and Kaning'ina forest reserves have different mean proportions of sand (p = 0.021) and clay (p = 0.004). In contrast, while the silt proportion for Perekezi was lower (14.30 ± 3.39%) than that of Kaning'ina, there were no statistical significant ($p > 0.05$) differences between the two reserves.

Table 12: T-test for soil texture of forest reserves of Perekezi and Kaning'ina

Parameter	Forest reserve	Mean ± SD	*p*-value
Sand (%)	Perekezi	79.80 ± 3.89	0.021*
	Kaning'ina	76.60 ± 5.10	
Silt (%)	Perekezi	14.30 ± 3.39	0.505^{ns}
	Kaning'ina	14.93 ± 3.18	
Clay (%)	Perekezi	5.90 ± 2.00	0.004**
	Kaning'ina	8.47 ± 3.39	

Significant codes: '***' 0.001 very highly significant, '**' 0.01 highly significant, '*' 0.05 significant, $^{\text{'ns'}}$ not significant

4.3.2 Soil chemical properties

Table 12 shows the results for soil pH, organic Carbon (SOC), organic matter (SOM), Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca) and Magnesium (Mg). Soil pH (H_2O) was very highly significantly ($p < 0.001$) different between Perekezi and Kaning'ina with the former registering a mean pH value of 5.88 ± 0.15 and the latter, 4.95 ± 0.19. Similarly, Ca and Mg were also very highly significantly different between the two forest reserves. On the other hand, no significant differences ($p > 0.05$) were observed in organic Carbon, organic matter, Nitrogen, Phosphorus and Potassium. Altogether, these results highlight multiple structural and compositional differences between Perekezi and Kaning'ina, underscoring the need to integrate these findings for a broader comparison.

Table 13: T-test and Mean ± SD for each chemical soil property between forest reserves of Perekezi and Kaning'ina

Parameter	Forest Reserve	Mean ± SD	*p*-value
Soil pH (H_2O)	Perekezi Kaning'ina	5.88 ± 0.15 4.95 ± 0.19	<0.001***
Soil Organic Carbon (%)	Perekezi Kaning'ina	1.30 ± 0.33 1.31 ± 0.29	0.863^{ns}
Soil Organic Matter (%)	Perekezi Kaning'ina	2.23 ± 0.57 2.26 ± 0.51	0.863^{ns}
Nitrogen (%)	Perekezi Kaning'ina	0.11 ±0.03 0.11 ±0.03	0.863^{ns}
Phosphorus (ppm)	Perekezi Kaning'ina	3.90 ± 2.27 3.00 ±1.60	0.090^{ns}
Potassium (Cmol/kg)	Perekezi Kaning'ina	0.04 ± 0.01 0.03 ± 0.03	0.633^{ns}
Calcium (Cmol/kg)	Perekezi Kaning'ina	0.43 ± 0.19 0.23 ± 0.05	<0.001***
Magnesium (Cmol/kg)	Perekezi Kaning'ina	0.25 ± 0.08 0.08 ± 0.02	<0.001***

Significant codes: '***' 0.001 very highly significant, '**' 0.01 highly significant, '*' 0.05 significant, '^{ns}' not significant

CHAPTER 5: DISCUSSION

This chapter discusses the results. The significant research is examined in more detail and connected to previous studies. These past studies support or challenge the current findings, adding to existing knowledge. The population structure and distribution, woody species associations, and physical and chemical soil properties are compared between the two forest reserves, even though both are Miombo woodlands in Malawi.

5.1 Population structure and distribution of *Uapaca kirkiana*

5.1.1 Diameter distribution and regeneration status

Perekezi and Kaning'ina forest reserves have shown a reverse J-shaped distribution. This diameter distribution indicates healthy population structure and active regeneration despite having differences. The natural forest ecosystems under intensified disturbances relies on its regenerating capacity (Ameja *et al.,* 2022). The results of diameter classes' composition and inverted J-shape diameter distribution were consistent with those reported in previous studies by Gotore *et al.* (2021) at Hurungwe in Zimbabwe and Njoghomi, Valkonen and Karlsson (2021) at miombo woodlands of Tanzania. Other similar results were reported in the studies by Botha, Witkowski and Shackleton (2004), Banda, Schwartz and Caro (2006), Syampungani *et al.* (2017), Paul, Khan and Das (2019), Mengich *et al.* (2020), Rudge *et al.* (2021), and Akweni *et al.* (2022). The findings further align with studies showing that forest age and disturbance regimes significantly influence diameter class distributions (Carreño-Rocabado *et al.,* 2012; Ding *et al.*, 2012; Ige & Adedapo, 2021; Ige & Animashaun, 2023; Nghonda *et al.,* 2024). There was evidence of an abundance of juvenile trees (<5 cm DBH) in most plots of Perekezi. The several plots of Kaning'ina had few juvenile trees (<5 cm DBH) and therefore, irregular regeneration. These patterns are associated to variations in seed availability, microsite conditions or browsing pressure (Ameja *et al.,* 2022; Nghonda *et al.,* 2024).

5.1.2 Health status and tree slenderness

The population of *U.kirkiana* tree species at Perekezi was healthier ($p = 0.002$). The higher proportion of unhealthy *U.kirkiana* trees at Kaning'ina could be due to aging cohorts and possible regeneration gaps since it had less regeneration and maintained mature individuals. Environmental stressors such as effects of climate change and pathogens can also be linked. A study by Krzyżaniak, Świerk and Antoszewski (2021) on the parks and urban forests, reported effects of urban pollution especially on air and soil. Kaning'ina forest reserve is regarded as an urban forest in Mzuzu City. The t-test confirmed this difference was highly statistically significant, highlighting the impact of site-specific factors on tree health. Long-term data on tree growth and productivity of miombo woodland resources are necessary for proper management (Chidumayo, 2019). According to Wang, Titus and LeMay (1998), the susceptibility of a stand to wind throw or damage is largely influenced by the tree slenderness coefficient or taper of the tree. This vulnerability to wind most times is based on a combination of some tree growth characteristics, stand conditions, site soil and site quality, topography and wind patterns (Ruel, 2000). These combinations generally substantiate the impact of both biological and physical factors on the individual tree or stand stability among exotic species.

The t-test revealed a statistically significant difference in Tree Slenderness Coefficient (TSC) between the reserves ($p = 0.014$). The higher TSC in Perekezi suggests trees are more slender (taller relative to their diameter), than Kaning'ina, which is consistent with the smaller diameter distribution observed in this reserve. This pattern typically reflects competitive growth responses in younger or denser stands where trees allocate more resources to height growth to compete for light, rather than radial growth for structural support. The lower TSC in Kaning'ina aligns with the presence of larger, more mature trees that have developed greater structural stability through increased diameter growth relative to height.

The differences observed in population structure between Perekezi and Kaning'ina forest reserves have direct implications for the sustainable management of *U. kirkiana* in Malawi. The relatively skewed size-class distributions and uneven regeneration suggest that natural recruitment is not keeping pace with extraction pressures and disturbance levels in some parts of the reserves. This pattern indicates a potential long-term decline in stand stability if current trends continue. Sustaining viable populations will therefore require management strategies that enhance seedling recruitment and protect juvenile cohorts from anthropogenic activities.

5.2 Species diversity and association with *Uapaca kirkiana*

5.2.1 Floristic composition

As shown in the results, a total of 1,166 tree species of *Uapaca kirkiana* were counted across the fifty (50) plots in the two forest reserves. The species richness (50) of woody species in both the forest reserves relates closely to a study done by Gonçalves *et al.* (2017) recording 51 species on miombo woodlands in south-central Angola. The results of another study by Likongwe *et al.* (2021) found a total of 51 species, with the Fabaceae family dominant in hills of Sadzi and Chiperoni in Malawi.

The dominant family in both forests was Fabaceae and this is evident in other studies on miombo woodlands (Gonçalves *et al.,* 2017; Ameja *et al.,* 2022; Nyirenda, 2022; Nghonda *et al.,* 2024).

The consistent presence of *Brachystegia spiciformis*, *Uapaca sansibarica*, and *Faurea rochetiana* indicates typical miombo woodland composition and association with *Uapaca kirkiana*. The findings of studies by Gotore *et al.* (2021) and Nghonda *et al.* (2024), reported that miombo woodlands are generally resilient to disturbances, maintaining similar species composition and structure at various levels of disturbance. The species of *Brachystegia longifolia*, *Parinari curatellifolia*, *Cussonia arborea* and *Brachystegia floribunda* have dominated the plots of *Uapaca kirkiana* in Perekezi forest reserve. The co-occurrence of *Uapaca kirkiana* with *Brachystegia spiciformis* and *Faurea rochetiana* supports shared habitat preferences in miombo ecosystems (Ribeiro *et al.,* 2015).

In Kaning'ina forest reserve, species of *Faurea rochetiana*, *Uapaca sansibarica, Brachystegia spiciformis* and *Bridelia micrantha* are highly prevalent in the plots of *Uapaca kirkiana*. Other related studies have associated the richest of Fabaceae, Phyllanthaceae and Rubiaceae and Combretaceae families with miombo woodlands, confirming Perekezi and Kaning'ina forest reserves as miombo woodlands (Mwakalukwa, Meilby & Treue 2014; Muvengwi *et al.,* 2020; Buramuge *et al.,* 2023). The dominance of Fabaceae species also aligns with typical miombo woodland composition (Backéus *et al.,* 2006; Dewees *et al.,* 2010).

The floristic similarity further suggests comparable habitat conditions despite structural differences in *U. kirkiana* populations. The presence of unique families such as Anacardiaceae and Annonaceae in Perekezi and Kaning'ina forest reserves, respectively, highlights the role of localized ecological conditions that shape the floristic diversity and groupings. The co-occurrence of *U. kirkiana* with *Brachystegia spiciformis* and *Faurea rochetiana* supports shared habitat preferences in miombo ecosystems (Ribeiro *et al.,* 2015).

The family of Fabaceae contains the species such as *Brachystegia*, *Isoberlinia angolensis*, *Julbernardia paniculata*, *Albizia antunesiana*, *Senna singueana* and *Erythrina abyssinica* are the most common in Perekezi forest reserve and the co-dominated by the Proteaceae and Rubiaceae. The family of *Uapaca kirkiana* is also a co-dominant with presence of *Bridelia micrantha* and *Uapaca sansibarica*. Miombo is considered homogenous despite differences in composition, diversity and structure of the species which is common at local scale (Giliba *et al.,* 2011). These differences are contributed to by geomorphic evolution (Cole, 1987), soil moisture and nutrients (Campbell *et al.,* 1988), land use changes, anthropogenic activities and climate change.

The species composition, assessed through cluster analysis and Jaccard's similarity coefficient, indicated moderate similarity between the reserves. The association of woody species with *U. kirkiana* in the forest reserves of Perekezi and Kaning'ina revealed notable ecological patterns. The lack of statistically significant differences in diversity indices between the forest reserves was reported. The forest reserves exhibited high species richness. The floristic composition was made up of 24 species across the forest reserves and 25 unique species each.

The species such as *Isoberlinia angolensis* and *Julbernardia paniculata*, characterized the Perekezi forest reserve, whereas species of *Pericopsis angolensis* and *Bridelia micrantha* were more prevalent in Kaning'ina. The differences in the species composition suggest habitat specialization and varying environmental conditions. Soil type, moisture availability and disturbance of human and nature contribute to the differences in species composition (Cole, 1987; Campbell *et al.,* 1988). The presence of unique families in each reserve further supports niche differentiation.

5.2.2 Species diversity and cluster

Analyses of Jaccard's similarity and cluster have shown diverse species groupings. The species such as *Parinari curatellifolia,* known as shade-tolerant, formed clusters distinct from the *Brachystegia longifolia,* which are considered light-demanding species. The species of *Pericopsis angolensis* which are considered late successional, co-occurred with the species considered as disturbance-associated taxa of *Bridelia micrantha*, in Kaning'ina forest reserve. This occurrence of these species indicated a mixture of successional stages. There was less anthropogenic pressure in Perekezi compared to the Kaning'ina. The lack of statistical significance could be due to the high variability within plots. Marginally higher diversity is usually a result of greater microhabitat preferences, ecological heterogeneity and succession stages (Cole, 1987; Campbell *et al.,* 1988).

The species such as *Brachystegia* and *Faurea* co-occurring with *Uapaca kirkiana* suggest shared habitat preference. The tree species of miombo woodlands depend on the hydraulic architecture affecting its habitat preference (Vinya *et al.,* 2013). The observed associations may reflect broader ecological trends rather than species-specific relationships. The results indicate that *Uapaca kirkiana* associates with a diverse but compositionally distinct set of woody species in each reserve, influenced by microhabitat conditions and successional dynamics. The species composition and community structure variations highlight that *Uapaca kirkiana* couples with different groupings depending on ecological context, challenging the notion of a uniform plant association. Principal Component Analysis is recommended as further statistical analysis.

The results have shown that *U. kirkiana* is embedded in a diverse miombo community, and its persistence depends partly on maintaining this broader ecological context. Species with strong associations, both canopy dominants and understorey companions, create microhabitats that support its regeneration. Therefore, conservation efforts must avoid selective removal of co-occurring species that contribute to shading, soil structure or nutrient cycling. Managing *U. kirkiana* in isolation would overlook these ecological interdependencies.

5.3 Physical and chemical soil properties

5.3.1 Soil physical properties

The analysis of soil physical properties revealed distinct characteristics between the two forest reserves. Perekezi Forest Reserve soils were classified as loamy sand, showing a significantly higher sand content (79.8 ± 0.6%) and notably lower clay (5.9 ± 4.1%). In contrast, Kaning'ina Forest Reserve was characterized by sandy loam, with slightly less sand (76.6 ± 5.8%) and a higher clay content (8.5 ± 1.0%) compared to Perekezi. A t-test confirmed a significant difference in sand content between the reserves (p = 0.021). The larger standard deviation in Kaning'ina's sand content suggests greater soil heterogeneity within this reserve.

The stability of soil texture is a critical physical characteristic, influencing a range of essential soil properties, including soil structure, water retention, and nutrient leaching (Baize, 1993; Msanya *et al.,* 2018). The differences in sand and clay percentages can have important implications for ecosystem functions. These findings align with previous research on miombo woodlands by Chidumayo (2019), who reported that soil texture is relatively consistent across both dry and wet miombo woodlands. Another study by Vågen and Winowieck (2013) reported that sand content influences the variability and storage capacity of nutrients. Based on the principle that soil texture is inherent to the parent material, the similar soil textures at the two forest reserves suggest they likely formed from the same or geologically similar parent materials.

5.3.2 Soil chemical properties

The analysis of soil chemical properties revealed significant differences in key nutrients and pH levels between the two forest reserves, highlighting variations in their fertility status. The pH measurements demonstrated a very highly significant difference ($p < 0.001$), with Perekezi soils being more acidic than those in Kaning'ina. This acidity in Perekezi is significant, as acidic soils are generally reported to be favourable for the growth of trees and plants in forest ecosystems (Baize, 1993; Landon, 2015). The chemical composition of soil and an appropriate supply of nutrients are fundamental for normal plant growth and development (Cekstere & Osvalde, 2013). *Uapaca kirkiana* is a non-nitrogen fixing crown species including *Brachystegia boehmii*, *B. spiciformis*, *B. utilis*, *B. microphylla, Combretum molle*, *Cussonia arborea*, *Julbernardia globiflora*, *J. paniculata* and *Isoberlinia angolensis* (Mtambanengwe & Kirchmann, 1995; Mayes *et al.,* 2019; van Langenhove *et al.,* 2020; Backéus *et al.,* 2022).The soils of miombo woodlands are acidic with low nitrogen, phosphorus and cation exchange capacities. Frost *et al.* (1996) reported that organic matter is usually low, with the exception of the densely wooded miombo vegetation, despite contributing to the cation exchange capacity in soils.

In contrast, organic carbon (% OC), organic matter (% OM), and nitrogen (% N) showed negligible differences between the reserves, with $p>0.05$. This suggests relatively similar organic content between Perekezi and Kaning'ina, despite variations in other chemical properties. Similarly, potassium (K) and phosphorus (P) levels did not differ significantly between the forest reserves ($p = 0.09$), indicating comparable nutrient availability for these elements across sites. These findings confirm previous research on the factors influencing soil properties in forest ecosystems. The research findings of Aticho (2013) in Ethiopia and Shelukindo *et al.* (2014) in Tanzania both emphasize that physical and chemical soil properties are significantly affected by topographic features. Our results resonate with these studies, particularly the observation by Aticho (2013) that organic carbon accumulation is influenced by bulk density and horizon thickness, and by Shelukindo *et al.* (2014) who attributed low soil fertility in the Kitonga Forest Reserve, a miombo woodland in Tanzania, to frequent fires, charcoal burning, and deforestation. The stability of soil texture and the balance of soil chemical properties are critical for supporting the biodiversity and long-term productivity of these miombo woodlands. As highlighted by Shelukindo *et al.* (2014), the sustainable management of miombo woodlands ecosystem soils necessitates reduced deforestation and mitigated land degradation. Understanding these site-specific soil characteristics is therefore paramount for developing effective conservation and management strategies to preserve the ecological integrity and services, such as water catchment, provided by these vital forest reserves.

In conclusion, the study supports the initial assumptions that variations regeneration patterns, disturbance levels and soil properties between Perekezi and Kaning'ina forest reserves significantly influence the population structure and ecological performance of *Uapaca kirkiana*, thereby confirming the central hypotheses of the research. Furthermore, miombo woodlands are shaped by recurrent fire, selective cutting and grazing, all of which interrupt successional pathways (Wieczorkowski *et al.,* 2024; Njoghomi & Valkonen, 2025). The dominance of *Brachystegia* and *Julbernardia*, and their consistent association with *U. kirkiana*, supports the idea that *U. kirkiana* is favoured in intermediate disturbance conditions where canopy gaps allow recruitment but disturbance is not severe enough to suppress seedlings. Successional theory further explains the distribution of size classes. Many miombo species follow a slow replacement trajectory, where older individuals persist for long periods and regeneration pulses occur mainly in years of favourable rainfall and reduced fire intensity (Ryan *et al.,* 2016; Gumbo *et al.,* 2018; Njoghomi, Valkonen & Mugasha, 2023). The skewed diameter distributions in parts of Kaning'ina resemble early-to-mid successional stands recovering from repeated fire or fuelwood extraction, while the more regular reverse-J pattern in Perekezi suggests a stand closer to a self-replacing equilibrium. These patterns indicate that *U. kirkiana* may be more sensitive to early-successional conditions than some associated species, requiring stable canopy conditions for juvenile survival.

The broader ecological literature increasingly recognises site heterogeneity as a key driver of miombo resilience. Differences in slope, soil depth and disturbance history influence both species associations and population structure. In this study, the contrasts between Perekezi and Kaning'ina fit within these models. Perekezi, with relatively lower anthropogenic pressure, shows structural patterns consistent with resilient miombo woodlands, where species coexistence and recruitment are maintained despite periodic disturbances. Kaning'ina, on the other hand, is shaped by its proximity to Mzuzu City and therefore experiences more frequent and diverse disturbances, fuelwood collection, informal trails and religious activities, livestock intrusion and edge effects. These pressures lead to spatially heterogeneous stands with irregular regeneration patterns. Urban-linked disturbances often create a mosaic of microhabitats that favour opportunistic or fire-tolerant species at the expense of slow-regenerating taxa like *U. kirkiana*. This aligns with broader models of woodland degradation in peri-urban landscapes, where chronic low-level disturbance reduces long-term resilience by limiting recruitment and altering competitive balances within the stand (Wu *et al.,* 2020; Sturtevant & Fortin 2021; Adewoyin *et al.,* 2024).

CHAPTER 6: CONCLUSION AND RECOMMENDATIONS

This chapter highlights the conclusions and recommendations of the study with a particular emphasis from the results and discussions from the previous chapters. The conclusions and recommendations are also based on the objectives of the study. The recommendations are based on suggestions concerned with conservation and utilization of *Uapaca kirkiana* in its natural habitat of the two forest reserves, Perekezi and Kaning'ina. The areas for further studies are also highlighted.

6.1 Conclusion

The study has revealed significant differences in the *U. kirkiana* population structure, health, and distribution between Perekezi and Kaning'ina Forest Reserves. Significant differences in tree health conditions between the reserves have been revealed as there is also evidence of different successional stages or disturbance histories. These differences indicate that the two forest reserves represent distinct population segments with varying conservation values and management requirements. The hypothesis that, there is no significant difference in the population structure and distribution of *Uapaca kirkiana* between Perekezi and Kaning'ina Forest Reserves is rejected.

The study has demonstrated that *Uapaca kirkiana* exists within heterogeneous plant communities in both Perekezi and Kaning'ina Forest Reserves. There is no significant difference in diversity levels but notable differences in species composition and community structure. The findings affirm that species associations are context-dependent, influenced by ecological factors and disturbance history. Nevertheless, the distinct clusters and unique species compositions emphasize the importance of habitat-specific conservation strategies.

This study revealed significant differences in the physical and chemical properties of soils between Perekezi and Kaning'ina Forest Reserves. Perekezi's loamy sand soils are more acidic, while Kaning'ina's sandy loam soils show higher clay content. These distinct soil characteristics, alongside the acknowledged assumptions of the Walkley-Black method for organic carbon, highlight their influence on water retention, nutrient availability, and overall ecosystem health, demanding tailored management approaches for the sustainable provision of important ecosystem services from each reserve.

6.2 Recommendations

The Department of Forestry with technical input from the Forestry Research Institute of Malawi (FRIM), and enforcement support from local leaders and community-based forest management structures is primarily tasked with implementing the following recommendations from the study:

1. Implement long-term population monitoring and strengthen forest health surveillance systems in order to provide reliable trend data to guide adaptive management and inform timely conservation actions.
2. Prioritising habitat-specific conservation interventions that enhance regeneration to maintain biodiversity and ecological functions therefore, protecting the distinct plant communities in each reserve.
3. Strengthen site-specific sustainable forest management plans for Perekezi and Kaning'ina Forest Reserves. This should address their unique soil characteristics while integrating robust measures to control anthropogenic activities.

6.3 Further recommended studies

Areas for further research studies include:

1. Investigate microhabitat variables such as disturbance regimes and climate that influence species associations with *Uapaca kirkiana*. This will result to better understanding drivers of community composition.
2. Quantify the long-term impact of varying soil physical and chemical properties on the productivity, biodiversity, and hydrological services of miombo woodlands in Perekezi and Kaning'ina Forest Reserves.

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APPENDICES

Appendix 1: List of woody species recorded in the study areas with corresponding local names

Family	Species	Local name	
		Chichewa	**Chitumbuka**
Anacardiaceae	*Lannea discolor*	Chiumbu	Kaumbu
	Ozoroa insignis	Mbewe	Mbewe
	Rhus longipes	Wuyawo	Kamwamadzi
Anisophylleaceae	*Anisophyllea boehmii*	Machilikiti	Mhotyo
Annonaceae	*Annona senegalensis*	Mpoza	Munthopa
Aphloiaceae	*Aphloia theiformis*	Musese	Mtanthanyerere
Araliaceae	*Cussonia arborea*	M'bwabwa	-
	Cussonia spicata	Chindimbo	-
Bignoniaceae	*Tecomaria capensis*	-	-
Celastraceae	*Mystroxylon aethiopicum*	Mbimbi	Mpakate
	Maytenus heterophylla	-	-
Chrysobalanaceae	*Parinari curatellifolia*	Maula	Muula
Clusiaceae	*Garcinia huillensis*	Mpimbi	Mtatani
Combretaceae	*Combretum molle*	Kadale	Mlama
Dipterocarpaceae	*Monotes africanus*	Mkakatuka	Mkalakate
Ebenaceae	*Euclea crispa*	Mpukuso	-
Ericaceae	*Agauria salicifolia*	-	Mzgozgo
	Erica benguelensis	-	-
Euphorbiaceae	*Macaranga capensis*	Bwabwa	Msimila
Fabaceae	*Albizia adianthifolia*	-	Mtangatanga
	Albizia antunesiana	Chisale	Mpepe
	Brachystegia floribunda	Tsamba	Mtuwa
	Brachystegia longifolia	Mombo	Chiyombo
	Brachystegia microphylla	Mombo	Mhana
	Brachystegia spiciformis	Tsamba	Mpapa
	Brachystegia taxifolia	Musani	Thung'unda
	Brachystegia utilis	Mombo	Kavwenje
	Dalbergia nitidula	Mlemgwe	Mtanthanyerere
	Erythrina abyssinica	Msewe	Muwale
	Isoberlinia angolensis	Msangaza	-
	Julbernardia paniculata	Matondo	Mtondo
	Pericopsis angolensis	Mwanga	Muwanga
	Senna singueana	Mtentanyelele	-
Gentianaceae	*Anthocleista grandiflora*	Mkungubwi	Mgolya

Family	**Species**	**Local name**	
		Chichewa	**Chitumbuka**
Hypericaceae	*Harungana madagascariensis*	Mbuluni	Musuwasuwa
	Psorospermum febrifugum	Phaka	Mdima
Lamiaceae	*Vitex doniana*	Mfulu	Mpindimbi
Malvaceae	*Dombeya rotundifolia*	Naduwa	Mchiu
Melastomataceae	*Memecylon flavovirens*	-	-
	Memecylon sansibaricum	-	-
Meliaceae	*Ekebergia capensis*	Msilima	-
Metteniusaceae	*Apodytes dimidiata*	Msusumba	Zuzuma
Moraceae	*Ficus natalensis*	Kachere	Kacheres
	Ficus sur	Mkuyu	Mkuyu
Myricaceae	*Myrica salicifolia*	Mufwenyesya	-
Myrtaceae	*Syzygium cordatum*	Nyowe	Katope
	Syzygium guineese	Mpani	Mchisu
	Syzygium owalensis	-	-
	Syzygium owariense	Katope	Katubwi
Ochnaceae	*Ochna schweinfurthiana*	Phatwe	Mgundangulube
Phyllanthaceae	*Bridelia micrantha*	Mpasa	Mlewezi
	Uapaca sansibarica	Mtoto	Kasokolowe
Pinaceae	*Pinus patula*	Mkunguza	-
Polygalaceae	*Securidaca longepedunculata*	Bwazi	Mbwazi
Primulaceae	*Embelia schimperi*	Nakonda	-
	Maesa lanceolata	Msanjipira	M’mkakama
	Rapanea melanophloeos	Katole	-
Proteaceae	*Faurea rochetiana*	Chisese	-
	Faurea saligna	Chisese	Chiyere
	Protea angolensis	Chinsense	-
	Protea gaguedii	Nkulukulu	-
	Protea saligna	-	-
Rhizophoraceae	*Anisophyllea boehmii*	-	-
Rubiaceae	*Craterispermum schweinfurthiana*	-	-
	Keetia gueinzii	-	-
Rubiaceae	*Multidentia crassa*	-	-
	Psychotria eminiana	-	-
	Psychotria mahonii	-	-
	Psychotria peduncularis	-	-
	Rothmannia engleriana	Mbyolilo/mfuko	-
	Tricalysia coleasea	-	-
Salicaceae	*Flacourtia indica*	Nthudza	Mttyokolo

Family	Species	Local name	
		Chichewa	**Chitumbuka**
Sapotaceae	*Synsepalum muelleri*	-	-
Ximeniaceae	*Ximenia caffra*	Mlebe	Mpinji

Appendix 2: Data tabulation sheet for the three objectives

DATA TABULATION SHEET						
Parameter						
Investigator						
Date						
Plot Name						
Plot Description						
Plot Area (m^2)						
Plot Radius						
GPS Latitude						
GPS Longitude						
Elevation						
Slope Condition						
No. of young trees						
Soil Sample						
TREE INVENTORY DATA						
Tree ID	Genus	Species	Family	DBH (cm)	Height (m)	Crown Diameter (m)
1.						
2.						
3.						
4.						
5.						
6.						
7.						
8.						
9.						
10.						
11.						
12.						
13.						
14.						
15.						
16.						
17.						
18.						
19.						
20.						

Appendix 3: Soil analysis

Elements analysed	**Method used**	**Chemicals used**
Total Carbon	Walkely-Black	Ferrous Ammonium Sulphate
		Concentrated Sulphuric acid
		Diphenylamine indicator
		Conc. phosphoric acid (85-90%)
		Potassium dichromate solution will offer .025N)
Total Nitrogen	Kjeldahl Method	Sodium hydroxide
		2% Boric acid will offer (4%) not 2%
		Cupric sulphate ($CuSO_4.5H_2O$)
		Selenium
		Conc. hydrochloric acid (37%)
		Sodium carbonate
		Methyl red
		Bromocresol green
		Hydrochloric acid (32%)
Phosphorous	Mehlich III	Ammonium Fluoride
Potassium		Potassium dihydrogen orthophosphate (KH_2PO_4)
Calcium		Acetic acid (0.2M) offer (0.1M)
Magnesium		Ammonium Nitrate (0.25 M) will offer powder
		Ammonium Fluoride (0.015 M)
		Nitric acid (0.013 M) will offer 2M
		Ethylene diamine tetra-acetic acid (EDTA)
		Antimony potassium
		Ammonium molybdate
Soil Texture	Hydrometer Method	Sodium hexametaphosphate
		Amyl Alcohol
pH	pH_meter	Buffer 4
		Buffer 7
		Buffer 9

Appendix 4: Physical soil properties of Perekezi forest reserve

Lab No.	Sample ID	Plot No.	Altitude (m)	Sand (%)	Silt (%)	Clay (%)	USDA Texture
338	PER	PLOT 1	1666	80	16	4	LOAMY SAND
339	PER	PLOT 2	1629	80	14	6	LOAMY SAND
340	PER	PLOT 3	1627	84	12	4	LOAMY SAND
341	PER	PLOT 4	1628	80	14	6	LOAMY SAND
342	PER	PLOT 5	1628	78	16	6	LOAMY SAND
343	PER	PLOT 6	1615	80	16	4	LOAMY SAND
344	PER	PLOT 7	1625	80	16	4	LOAMY SAND
345	PER	PLOT 8	1641	76	16	8	SANDY LOAM
346	PER	PLOT 9	1647	80	10	10	SANDY LOAM
347	PER	PLOT 10	1651	74	16	10	SANDY LOAM
348	PER	PLOT 11	1648	82	10	8	LOAMY SAND
349	PER	PLOT 12	1656	74	20	6	SANDY LOAM
350	PER	PLOT 13	1653	76	18	6	SANDY LOAM
351	PER	PLOT 14	1655	80	16	4	LOAMY SAND
352	PER	PLOT 15	1592	84	12	4	LOAMY SAND
353	PER	PLOT 16	1584	74	18	8	SANDY LOAM
354	PER	PLOT 17	1583	82	14	4	LOAMY SAND
355	PER	PLOT 18	1570	88	6	6	LOAMY SAND
356	PER	PLOT 19	1580	86	10	4	LOAMY SAND
357	PER	PLOT 20	1591	78	16	6	LOAMY SAND

Appendix 5: Physical soil properties of Kaning'ina forest reserve

Lab No.	Sample ID	Plot No.	Altitude (m)	Sand (%)	Silt (%)	Clay (%)	USDA Texture
358	KAN	PLOT 1	1332	70	20	10	SANDY LOAM
359	KAN	PLOT2	1321	68	16	16	SANDY LOAM
360	KAN	PLOT 3	1309	80	12	8	LOAMY SAND
361	KAN	PLOT 4	1302	76	14	10	SANDY LOAM
362	KAN	PLOT 5	1320	74	14	12	SANDY LOAM
363	KAN	PLOT 6	1315	76	12	12	SANDY LOAM
364	KAN	PLOT 7	1367	76	14	10	SANDY LOAM
365	KAN	PLOT 8	1339	74	14	12	SANDY LOAM
366	KAN	PLOT 9	1323	80	14	6	LOAMY SAND
367	KAN	PLOT 10	1316	80	16	4	LOAMY SAND
368	KAN	PLOT 11	1328	70	20	10	SANDY LOAM
369	KAN	PLOT 12	1292	84	10	6	LOAMY SAND
370	KAN	PLOT 13	1298	86	10	4	LOAMY SAND
371	KAN	PLOT 14	1298	84	12	4	LOAMY SAND
372	KAN	PLOT 15	1301	80	14	6	LOAMY SAND
373	KAN	PLOT 16	1310	80	16	4	LOAMY SAND
374	KAN	PLOT 17	1307	80	12	8	LOAMY SAND
375	KAN	PLOT 18	1331	80	14	6	LOAMY SAND
376	KAN	PLOT 19	1336	80	16	4	LOAMY SAND
377	KAN	PLOT 20	1332	78	16	6	LOAMY SAND
378	KAN	PLOT 21	1339	76	16	8	SANDY LOAM
379	KAN	PLOT 22	1335	70	20	10	SANDY LOAM
380	KAN	PLOT 23	1345	76	16	8	SANDY LOAM
381	KAN	PLOT 24	1344	70	22	8	SANDY LOAM
382	KAN	PLOT 25	1328	70	18	12	SANDY LOAM
383	KAN	PLOT 26	1344	76	12	12	SANDY LOAM
384	KAN	PLOT 27	1344	70	20	10	SANDY LOAM
385	KAN	PLOT 28	1358	70	14	16	SANDY LOAM
386	KAN	PLOT 29	1349	84	10	6	LOAMY SAND
387	KAN	PLOT 30	1296	80	14	6	LOAMY SAND

Appendix 6: Ethical clearance

MZUZU UNIVERSITY

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MZUZU UNIVERSITY RESEARCH ETHICS COMMITTEE (MZUNIREC)

Ref No: MZUNIREC/DOR/25/102 **17/11/2025**

Brian Onali Nduw ,
Mzuzu University,
P/Bag 201,
Luwinga,
Mzuzu .

Email: onalinduw25@gmail.com

Dear Brian,

RESEARCH ETHICS AND REGULATORY APPROVAL AND PERMIT FOR PROTOCOL REF NO. MZUNIREC/DOR/25/102: ACOMPARATIVE STUDY OF Uapaca kirkiana POPULATION DYNAMICS, VEGETATION COMPOSITION AND SOIL PHYSICOCHEMICAL PROPERTIES IN KANING'INA AND PEREKEZI FOREST RESERVES

Having satisfied all the relevant ethical and regulatory requirements, I am pleased to inform you that the above referred research protocol has officially been approved. You are now permitted to proceed with its implementation. Should there be any amendments to the approved protocol in the course of implementing it, you shall be required to seek approval of such amendments before implementation of the same.

This approval is valid for one year from the date of issuance of this approval. If the study goes beyond one year, an annual approval for continuation shall be required to be sought from the Mzuzu University Research Ethics Committee (MZUNIREC) in a format that is available at the Secretariat. Once the study is finalised, you are required to furnish the Committee with a final report of the study.

The Committee reserves the right to carry out compliance inspection of this approved protocol at any time as may be deemed by it. As such, you are expected to properly maintain all study documents including consent forms.

Wishing you a successful implementation of your study

Yours Sincerely,

Faith Mwangonde
Research Ethics Administrator.
FOR : MZUNIREC CHAIRPERSON

MZUZU UNIVERSITY
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