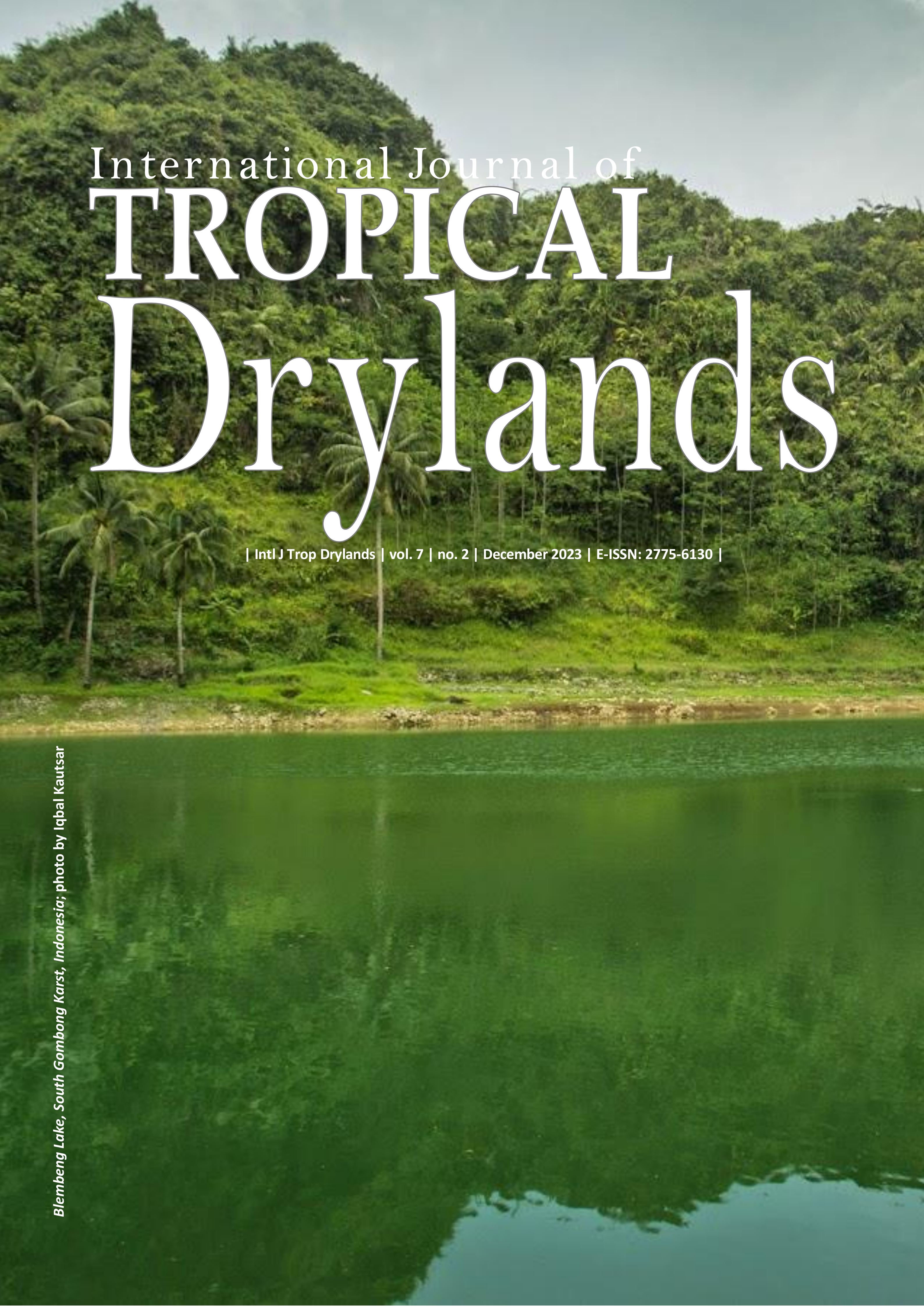

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Blembeng Lake, South Gombong Karst, Indonesia; photo by Iqbal Kautsar

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Abstract:

Assaeed AM. 2007. Seed production and dispersal of *Rhazya stricta*. 50th annual symposium of the International Association for Vegetation Science, Swansea, UK, 23-27 July 2007.

Proceeding:

Alikodra HS. 2000. Biodiversity for development of local autonomous government. In: Setyawan AD, Sutarno (eds.). Toward Mount Lawu National Park; Proceeding of National Seminary and Workshop on Biodiversity Conservation to Protect and Save Germplasm in Java Island. Universitas Sebelas Maret, Surakarta, 17-20 July 2000. [Indonesian]

Thesis, Dissertation:

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Balagadde FK, Song H, Ozaki J, Collins CH, Barnet M, Arnold FH, Quake SR, You L. 2008. A synthetic *Escherichia coli* predator-prey ecosystem. Mol Syst Biol 4: 187. DOI: 10.1038/msb.2008.24. www.molecularsystembiology.com.

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The potential utilization of non-timber vascular plants in the karst area of Ayah Village, Kebumen District, Central Java, Indonesia

SISCA INDRIYANI[1], DEVI MAYANG AURINA[1], MUHAMMAD FADHIL RAMADHAN[1], FAYZA RACHMALIA[1], MUTHI'AH DZAKIYYATUL FAUZIYYAH[1], AQRA DANIAL FATURRAHMAN[1], IRFAN ABU NAZAR[1], ANISA SEPTIASARI[2], DARLINA MD. NAIM[3], AHMAD DWI SETYAWAN[1,4,♥]

[1]Department of Biology, Faculty of Mathematics and Natural Sciences, Universitas Sebelas Maret. Jl. Ir. Sutami 36A, Surakarta 57126, Central Java, Indonesia. Tel./Fax.: +62-271-663375, ♥email: volatileoils@gmail.com

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Abstract. *Indriyani S, Aurina DM, Ramadhan MF, Rachmalia F, Fauziyyah MD, Faturrahman AD, Nazar IA, Septiasari A, Naim DMD, Setyawan AD. 2023. The potential utilization of non-timber vascular plants in the karst area of Ayah Village, Kebumen District, Central Java, Indonesia. Intl J Trop Drylands 7: 51-61.* Karst vegetation has unique characteristics in its shape and species composition. As a result, karst plant communities have a high ability to adapt to environmental stress. In addition to ecological functions, vegetation that grows in karst areas also has the potential as natural medicine, food ingredients, and materials for folk traditions. This study aims to determine the diversity and potential utilization of non-timber vascular plants in the karst area of Ayah Village, Kebumen, Central Java, Indonesia. This study used a survey method, namely direct observation, by exploring the Ayah Forest area to observe the studied object, namely vascular plants. The results showed 44 plant families of 111 species in the Ayah Forest area. Vascular plants in the Ayah Forest area are mostly from Fabaceae and Poaceae families. Therefore, five habitus types grow there, including trees, herbs, shrubs, epiphytes, and vines. The vascular plants found during the research have different potencies. In this study, eight prospects could be utilized from vascular plants in Ayah Forest: ornamental plants, medicinal plants, food ingredients, beverage ingredients, flavorings, natural coloring, animal feed, and woven crafts. The potential use of vascular plants in the Ayah Forest is most widely used as medicine.

Keywords: Ayah Forest, biodiversity, karst, non-timber, vascular plants

INTRODUCTION

Karst has unique hydrological conditions and landscapes caused by rock dissolution and secondary porosity development (Nugroho and Paripurno 2019). Karst landscapes are formed from the erosion of rock by surface waters. Most karst area comprises carbonate rocks, mainly limestone and dolomite (Sulastoro 2013). The landscape of the karst area usually has steep slopes, many basins, prominent and irregular limestone, and caves. Karst also has a continuous underground river system. Karst ecosystems are fragile landscapes; if this ecosystem is disturbed, it will take a very long time to recover (Widyaningsih 2017). One of the crucial factors in restoring damaged karst ecosystems and preserving karst landscapes is maintaining biodiversity in karst areas because biodiversity is the key to regional ecological succession (Li et al. 2013).

In addition, the high plant diversity in karst areas influences the hydrological system and soil formation. The variety of plants in the karst area plays a role in water absorption, so the function of karst underground river springs can be appropriately maintained. For the karst area to function optimally as a water reservoir, vegetation can shade the karst and absorb much water (Sugita et al. 2015). Karst vegetation has unique characteristics in its shape and species composition. Vegetation forms in karst areas usually have sparse crowns attached to cliffs (Marwiyati 2012), consisting of plants that grow naturally and are cultivated. As a result, Karst plant communities can adapt to environmental stress (Nasrudin and Parikesit 2020). In addition to ecological functions, vegetation that grows in karst areas has another potential: natural medicine, food ingredients, toy making, and materials for folk traditions (Lumpert and Kreft 2017).

Indonesia has the potential for karst landscape areas of around 20% of its land area (Widyastuti et al. 2019). One of the karst areas in Indonesia is the South Gombong karst area in the Kebumen District, such as the Ayah Karst of Ayah Subdistrict. The Ayah karst area presents the main typological characteristics of coastal karst hills, with their geology consisting of relatively thin layers of limestone. The Ayah karst area consists of Miocene limestone, which underwent uplift and karstification at the end of the Pliocene. The karst of Ayah and surrounding areas is characterized by harmonious karst formations and closed basins (Haryono et al. 2017). The karst forest area in South Gombong has a moderate to dense vegetation density with a percentage of 90% and a rare to very rare vegetation density with a ratio of 10%. The vegetation of the South

Gombong karst forest area also consists of cultivated plants. This is because the South Gombong karst forest area is close to residential areas (Suhendar et al. 2018).

According to Minister of Forestry Number 35 of 2007, non-timber forest products are vegetable and animal products, with their derivative products and cultivation, except for wood originating from forests. Non-timber forest products are by-products of plants, such as sap, leaves, skin, and fruit (Batubara and Affandi 2017). Local communities can utilize most non-timber plants as ornamental and food ingredients (Hadi et al. 2016). Moreover, non-timber forest plants are necessary to support increased community welfare and income without reducing forest ecological functions (Mansur et al. 2018). At the same time, each vascular plant type holds a unique potential. However, few studies have examined the possibility of vascular plant groups in the Ayah karst area. Therefore, this study aims to determine the diversity and potential utilization of non-timber vascular plants in the karst area of Ayah Village, Ayah Sub-district, Kebumen, Indonesia.

MATERIALS AND METHODS

Study area

The research was carried out in November 2022. Observations were made in the karst forest area, Ayah Village, Ayah Sub-district, Kebumen District, Central Java, Indonesia (Figure 1). Ayah Sub-district is one of the sub-districts in Kebumen District, with sea areas apart from their mountainous. Ayah Sub-district is included in the South Gombong karst area, at coordinates of -7.726532, 109.399676 (Central Bureau of Statistics for Kebumen District 2020). Ayah Sub-district in the inland and mountainous areas has a livelihood as a farmer, while those in the low-coastal areas have a livelihood as fishermen. Ayah Sub-district consists of 18 villages, especially Ayah Village. Ayah Village is located at the western end of Kebumen District and is directly adjacent to Cilacap District. Ayah Sub-district is known to the public for its several tourist objects (Faozi and Santoso 2020), which are famous for their natural potential, such as Logending Beach, Pasir Beach, Jatijajar Cave, and Petruk Cave. In Ayah Forest, Pasir Beach around Ayah Village has various plant potential.

Procedures

Observation

Data were collected using survey and observation methods, namely direct observation by exploring the study area to observe the object to be studied, namely vascular plants (Li et al. 2022). First, each plant found in the Ayah Forest area is recorded, starting with the plant type, its special characteristics, and its habitus. These plants' characteristics are then documented through photos to facilitate identification.

Plant identification

Plants are identified based on the type, characteristics, and habitus of each plant species obtained from observations. The identification information mostly used internet base identifiers, such as plantamor.com, theplantlist.org, identify.plantnet.org, gbif.org, and powo.science.kew.org. If the name of the plant species is known, then its potential is sought based on Table 1 for a list of literature.

Data analysis

The data obtained were analyzed descriptively using a qualitative approach, then explained more concisely and clearly in tabular form by attaching pictures of observations. As a result, the information or data written down was more valid and strengthened this research results.

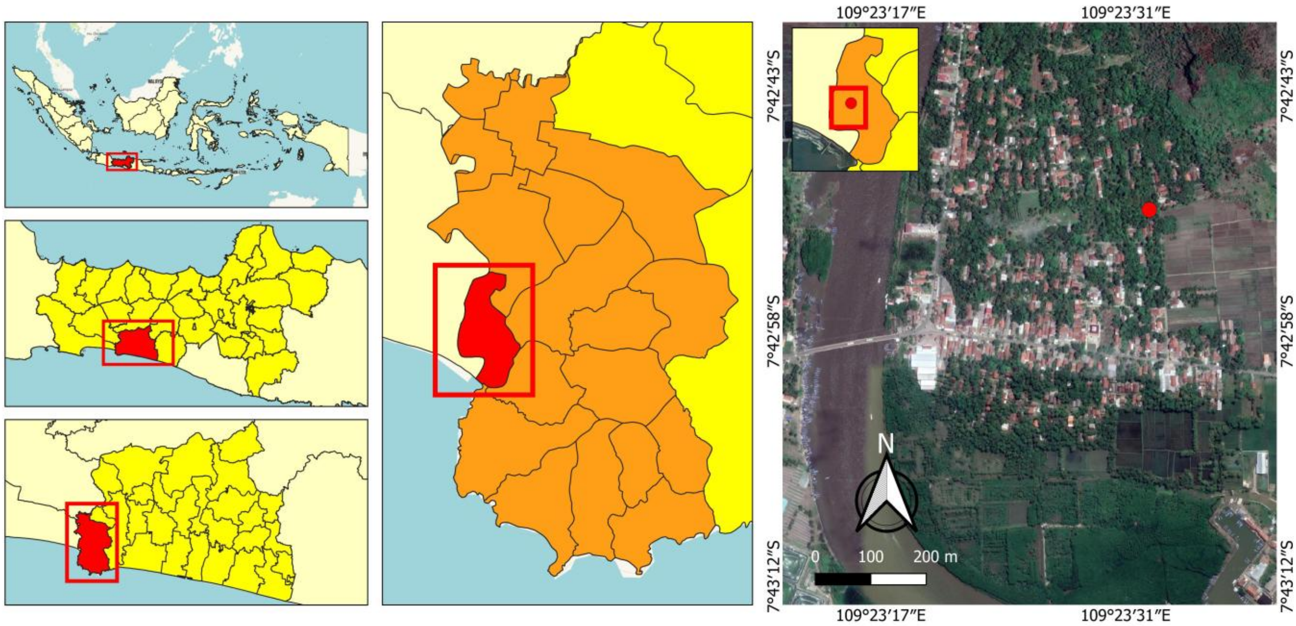

Figure 1. Location of Ayah Village Forest, Ayah Sub-district, Kebumen, Central Java, Indonesia

RESULTS AND DISCUSSION

Vascular plants in the karst area of Ayah Village

From research conducted in the karst area of Ayah Village, 111 species of vascular plants were found consisting of 44 families. The family most often found in Ayah Village Forest is the Fabaceae or the legume family (Figure 2). There are 12 species of plants of the family Fabaceae found in the Ayah karst area. Based on data found by Faida et al. (2018), four plant tribes are native karst, namely Euphorbiaceae, Moraceae, Fabaceae, and Palmae. The Fabaceae family is more prevalent because this group of plants is drought-tolerant and can live in tropical and subtropical climates (Dimmit 2014). Based on literature studies, the Fabaceae family was found to have many potential uses, such as medicinal plants, ornamental plants, animal feed, and foodstuffs (Table 1). Moreover, the Fabaceae family has potential as green plants, agricultural production plants, etc. (Adelita and Dharmono 2018). The Poaceae family is also found in the karst of Ayah Forest with ten species, widely known as a group of grasses, and the fourth largest family in the plant world (Sagar et al. 2018). Poaceae have an important role in resisting erosion at the cliff's foot. In addition, Poaceae are easy to grow and drought tolerant (Hirman et al. 2021).

Habitus is divided into five types: trees, herbs, shrubs, epiphytes, and vines. This study found herbs habitus were more dominant than others in Ayah Village Forest (Figure 3). The high percentage was herbs (49%), followed by shrubs (20%), trees (19%), epiphytes (9%), and the last is vines (3%).

Based on Figure 4, the highest potential utilization of non-timber vascular plants is medicinal plants 74 species, followed by ornamental plants 19 species; foodstuffs 17 species; animal feed 13 species; beverage ingredients four species; flavoring two species; natural coloring one species; and one species of woven craft.

Plant potential

The vegetation around Ayah Village Forest has possibilities that the surrounding environment can be utilized. The results showed nine potential plant uses: medicinal, ornamental plants, food ingredients, animal feed, natural dyes, flavorings, beverage ingredients, and woven crafts.

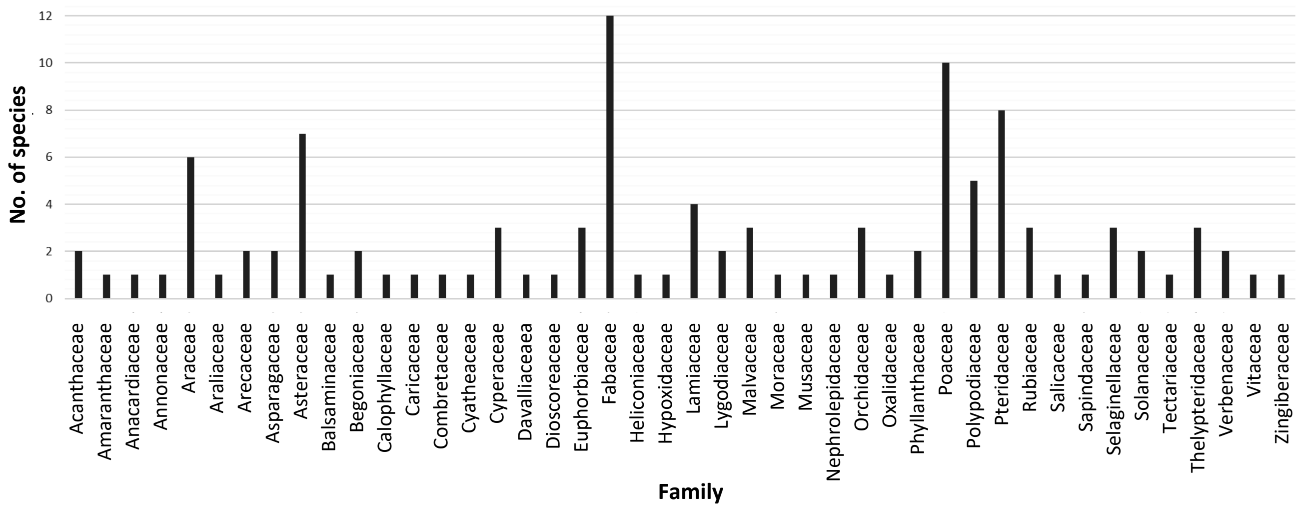

Figure 2. Bar chart of families found in Ayah Village Forest, Kebumen District, Central Java, Indonesia

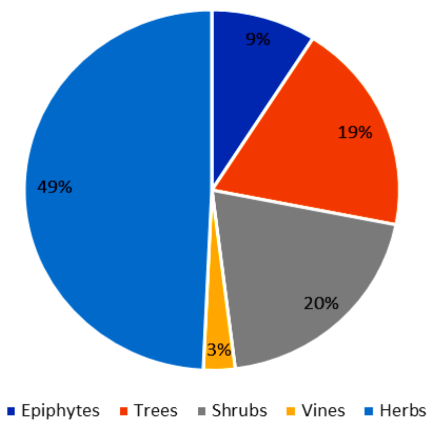

Figure 3. The habitus found in Ayah Village Forest, Kebumen District, Central Java, Indonesia

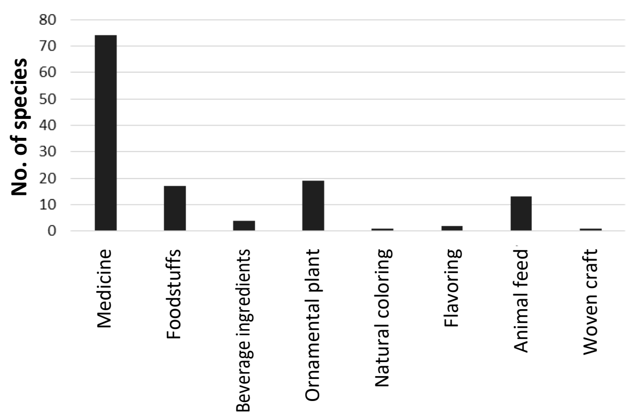

Figure 4. The potential non-timber utilization of vascular plants found in Ayah Village Forest, Kebumen District, Indonesia

Table 1. List of non-timber vascular plants recorded in Ayah Village, Ayah Sub-district, Kebumen District, Central Java, Indonesia

Family	Name	Local name	Habitus	Potency
Acanthaceae	*Asystasia gangetica* (L.) T. Anderson	Ara Sungsang	H	Medicine (45)
	Ruellia tuberosa L.	Pletekan	H	Medicine (1)
Amaranthaceae	*Alternanthera sessilis* (L.) DC.	Kremah	H	Medicine (74)
Anacardiaceae	*Mangifera indica* L.	Mangga	T	Foodstuffs, medicine (75), beverage ingredients
Annonaceae	*Annona muricata* L.	Sirsak	T	Foodstuffs, medicine (76), beverage ingredients
Araceae	*Alocasia inornata* Hallier f.	-	H	Ornamental plant
	Alocasia longiloba Miq.	-	H	Ornamental plant
	Amorphophallus sp.	-	H	-
	Colocasia esculenta (L.) Schott)	Talas (kecil)	H	Foodstuffs
	Philodendron grandipes K.Krause	-	H	Ornamental plant (54)
	Xanthosoma mexicanum Liebm.	-	H	Ornamental plant
Araliaceae	*Polyscias scutellaria* (Burm.f.) Fosberg	Mangkokan	S	Medicine (34)
Arecaceae	*Arenga pinnata* (Wurmb) Merr.	Aren	T	Foodstuffs
	Cocos nucifera L.	Kelapa	T	Foodstuffs, beverage ingredients
Asparagaceae	*Cordyline fruticosa* (L.) A.Chev.	Andong Merah	S	Medicine (38)
	Dracaena angustifolia (Medik.) Roxb	Suji	S	Medicine, natural coloring (41)
Asteraceae	*Ageratum conyzoides* L.	Babadotan	H	Medicine (46)
	Chromolaena odorata (L.) R.King & H.Rob.	Kirinyuh	S	Medicine (11)
	Cyanthillium cinereum (L.) H.Rob.	-	H	Medicine (16)
	Eleutheranthera ruderalis (Sw.) Sch.Bip.	Karenyuik	H	-
	Melampodium divaricatum (Rich.) DC.	Bunga Kertas	H	Medicine (39)
	Mikania cordifolia (L.f.) Willd.	-	V	Medicine (44)
	Porophyllum ruderale (Jacq.) Cass.	Ketumbar Bolivia	S	Flavoring (33)
Balsaminaceae	*Impatiens platypetala* Lindl.	Pacar Tere	H	Ornamental plant
Begoniaceae	*Begonia tenuifolia* Dryand.	Begonia	H	Ornamental plant
	Begonia urophylla Hook.	Begonia	H	Ornamental plant (37)
Calophyllaceae	*Calophyllum calaba* L.	-	T	Medicine (64)
Caricaceae	*Carica papaya* L.	Pepaya	H	Foodstuffs
Combretaceae	*Terminalia catappa* L.	Ketapang	T	Foodstuffs, medicine (42)
Cyatheaceae	*Sphaeropteris* sp.	-	T	-
Cyperaceae	*Cyperus iria* L.	-	H	Animal feed, medicine (48)
	Cyperus kyllingia Endl.	Rumput nnop	H	Animal feed
	Cyperus odoratus L.	Rumput Teki	H	Animal feed, medicine (20)
Davalliaceaea	*Davallia denticulata* (Burm.fil.) Mett. ex Kuhn	Paku Tertutup	E	Ornamental plant (22)
Dioscoreaceae	*Tacca palmata* Blume	Gadung Tikus	H	Medicine (53)
Euphorbiaceae	*Codiaeum variegatum* (L.) Rumph. ex A.Juss.	Puring	S	Medicine (12)
	Manihot carthaginensis (Jacq.) Mull.Arg.	Singkong	S	Foodstuffs, animal feed (84)
	Manihot esculenta Crantz	Singkong	S	Foodstuffs (77)
Fabaceae	*Acacia auriculiformis* A.Cunn. ex Benth.	Akasia	T	Medicine (61)
	Acacia mangium Willd.	-	T	Medicine (9)
	Albizia chinensis (Osbeck) Merr.	Sengon	T	Medicine (78)
	Cassia fistula L.	Tengguli	T	Medicine (43)
	Cassia siamea Lam.	Johar	T	Medicine (8)
	Clitoria ternatea L.	Telang	V	Medicine, ornamental plant (62)
	Desmodium gangeticum (L.)	Samak-Samak	S	Medicine (15)
	Flemingia strobilifera (L.) W. T. Aiton	Hahapaan	S	Medicine (19)
	Leucaena leucocephala (Lam.) de Wit	Lamtoro	T	Foodstuffs, animal feed, medicine (17)
	Mimosa pudica L.	Putri Malu	H	Medicine (2, 10)
	Sesbania grandiflora (L.) Poir.	Turi	T	Medicine, foodstuffs (27)
	Senna tora (L.) Roxb.	Senna Sabit	H	Medicine (52)
Heliconiaceae	*Heliconia psittacorum* L.f.	Sepit Udang	H	Ornamental plant (3)
Hypoxidaceae	*Molineria capitulata* (Lour.) Herb.	-	H	Medicine (57)
Lamiaceae	*Hyptis capitata* Jacq.	Rumput Knop	S	Medicine (24)
	Plectranthus scutellarioides L.	Miana	H	Ornamental plant, medicine (40)
	Tectona grandis L.f.	Jati	T	Medicine (60)
	Vitex altissima L.f.	-	T	Medicine (79)
Lygodiaceae	*Lygodium circinnatum* (Burm.fil.) Sw.	Ketak	E	Foodstuffs, medicine, woven crafts (4)
	Lygodium japonicum (Thunb.) Sw.	-	V	Medicine (6)
Malvaceae	*Hibiscus rosa-sinensis* L.	Bunga Sepatu	S	Ornamental plant
	Urena lobata L.	Pulutan	S	Medicine (21)
	Sida rhombifolia L.	Sidaguri	S	Medicine (47)

Moraceae	*Ficus septica* Burm.fil.	Awar-Awar	T	Medicine (10)
Musaceae	*Musa paradisiaca* L.	Pisang	H	Foodstuffs
Nephrolepidaceae	*Nephrolepis brownii* (Desv.) Hovenkamp & Miyam	-	H	-
Orchidaceae	*Acampe pachyglossa* Rchb.f.	Anggrek	E	Ornamental plant
	Dendrobium crumenatum Sw.	Anggrek Merpati	E	Ornamental plant, medicine (59)
	Rhynchostylis retusa (L.) Blume	Anggrek Ekor Rubah	E	Ornamental plant, medicine (58)
Oxalidaceae	*Oxalis barrelieri* L.	Belimbing Tanah	H	Medicine (23)
Phyllanthaceae	*Breynia vitis-idaea* (Burm.f.) C.E.C.Fisch.)	Buah Tinta	S	Medicine (51)
	Phyllanthus urinaria L.	Meniran	H	Medicine (2)
Poaceae	*Brachiaria mutica (Forskk.) T.Q.Nguyen*	Kolonjono	H	Animal feed
	Cymbopogon citratus (DC.) Stapf	Sereh	H	Flavoring, medicine (35)
	Gigantochloa apus (Schult.f.) Kurz	Bambu Apus	T	Medicine (63)
	Gigantochloa atter (Hassk.) Kurz	Bambu Legi	T	Foodstuffs (80)
	Melinis minutiflora P.Beauv.	Rumput Molasses	H	Animal feed (28)
	Oplismenus compositus (L.) P.Beauv.	-	H	Medicine, animal feed (81)
	Panicum repens L.	Lempuyang	H	Animal feed (18)
	Paspalum conjugatum P.J.Bergius	Papaitan	H	Animal feed, medicine (32)
	Sorghum bicolor L. Moench	Sorgum	H	Foodstuffs, animal feed (31)
	Themeda arguens (L.) Hack.	Rumput Merakan	H	Animal feed
Polypodiaceae	*Drynaria quercifolia* L.	Daun Kepala Tupai	E	Medicine (55)
	Drynaria sparsisora (Desc.) Moore	Simbar Layangan	E	-
	Microsorum scolopendria (Burm.fil.) Copel.	Pakis	H	Medicine (56)
	Phymatosorus scolopendria (Burm.fil.) Pic. Serm.	Pakis Kutil	E	Medicine (82)
	Pyrrosia nummularifolia (Sw.) Ching	Paku Duduitan	E	Medicine (83)
Pteridaceae	*Adiantum capillus-veneris* L.	Suplir	H	Medicine (65)
	Adiantum philippense L.	Kamuding	H	Medicine (68)
	Cheilanthes farinosa (Forssk.) Kaulf.	-	E	Medicine (69)
	Pityrogramma calomelanos (L.) Link	Paku Perak	H	Ornamental plant, medicine (67)
	Pteris biaurita L.	-	H	Medicine (36)
	Pteris ensiformis Burm.	Paku Pedang	H	Ornamental plant
	Pteris multifida Poir.	-	H	Medicine (66)
	Pteris vittata L.	Pakis Rem Cina	H	Medicine (26)
Rubiaceae	*Canthium horridum* Blume	Tembung Kanjut	S	Ornamental plant (73)
	Coffea canephora Pierre ex A.Froehner	Kopi Robusta	T	Beverage ingredients
	Spermacoce remota Lam	Gigiwangan	H	Medicine (7)
Salicaceae	*Flacourtia indica* (burm.fil.)Merr.	-	S	Medicine, ornamental plant (50)
Sapindaceae	*Schleichera oleosa* (Lour.) Oken	Kesambi	T	Animal feed, medicine (25)
Selaginellaceae	*Selaginella aristata* Spring	-	H	Medicine (49)
	Selaginella ornata (Hook & Grev.) Spring	-	H	Medicine (70)
	Selaginella plana (Desv. ex Poir.) Hieron.	Paku Rane	H	Medicine (70)
Solanaceae	*Capsicum frutescens* L.	Cabai	S	Foodstuffs
	Solanum melongena L.	Terong	S	Foodstuffs
Tectariaceae	*Tectaria angulata* (Willd.) Copel.	Paku bukit	H	Medicine (71)
Thelypteridaceae	*Christella subpubescens* (Blume) Holttum	Jajarat	H	Medicine (65)
	Cyclosorus interruptus (Willd.) H. Ito	-	H	Medicine (72)
	Cyclosorus sp.	-	H	-
Verbenaceae	*Stachytarpheta jamaicensis* (L.) Vahl	Pecut Kuda	S	Medicine (29)
	Stachytarpheta urticifolia Sims	-	S	Medicine (5)
Vitaceae	*Leea indica* (Burm.fil.) Merr.	Tanaman Girang	S	Medicine (14)
Zingiberaceae	*Amomum compactum* Roem. & Schult.	Kapulaga	H	Medicine (13)

Note: E: Epiphytes, T: Trees, S: Shrubs, V: Vines, and H: Herbs; 1. Xu et al. (2020), 2. Kartika (2017), 3. Silalahi (2019), 4. Rahayu et al. (2020), 5. Septiyadi et al. (2021), 6. Lee et al. (2006), 7. Meidalima (2013), 8. Rajegowda and Honnagirigowda (2022), 9. Pereira et al. (2022), 10. Huang et al. (2017), 11. Vaisakh and Pandey (2012), 12. Karyati and Adhi (2017), 13. Praditha et al. (2020), 14. Hossain et al. (2021),15. Vaghela et al. (2013), 16. Firison et al. (2018), 17. Zayed and Samling (2016), 18. Kumalasari et al. (2020), 19. Shital et al. (2021), 20. Dari et al. (2022), 21. Silalahi (2020), 22. Meliza et al. (2019), 23. Tagne et al. (2015), 24. To'bungan (2020), 25. Goswami and Singh (2017), 26. Paul et al. (2020), 27. Thissera at al. (2020), 28. Djufri (2016), 29. Liew and Yong (2016), 30. Dattaray (2022), 31. Khalid et al. (2022), 32. Garduque et al. (2019), 33. Winara and Suhaendah (2020), 34. Rosa et al. (2019), 35. Shah et al. (2011), 36. Dalli et al. (2007), 37. Surya and Astuti (2017), 38. Nurza (2019), 39. Rizki et al. (2019), 40. Hamidah et al. (2019), 41. Andila and Warseno (2019), 42. Santos et al. (2016), 43. Khairunnisa et al. (2019), 44. Mohammad et al. (2013), 45. Mugabo and raji (2013), 46. Harfiani et al. (2017), 47. Syafrullah (2015), 48. Malavika et al. (2021), 49. Silva et al. (1995), 50. Selim et al. (2021), 51. Nagar and Chauhan (2016), 52. Kang et al. (2020), 53. Trimanto and Hapsari (2016), 54. Rundel et al. (2020), 55. Gupta et al. (2021) , 56. Balada et al. (2022), 57. Umaru et al. (2020), 58. Rohani et al. (2018), 59. Tarmizi et al. (2020), 60. Nuralifah et al. (2021), 61. Aoetpah et al. (2019), 62. Marpaung (2020), 63. Sujarwo et al. (2010), 64. Laopian et al. (2019), 65. Pagea et al. (2022), 66. Yu et al. (2013), 67. Sutoyo et al. (2018), 68. Paul et al. (2017), 69. Yonathan et al. (2006), 70. Setyawan (2009), 71. Abdullah et al. (2021) , 72. Mitra et al. (2019), 73. Hidayat et al. (2010), 74. Walter et al. (2014), 75. Yap et al. (2021), 76. Yajid et al. (2018), 77. Abotbina et al. (2022), 78. Sharmin and Rashid (2022), 79. Bhavana et al. (2019), 80. Partasasmita et al. (2017), 81. Li and Xing (2016), 82. Mannan et al. (2008), 83. Wulandari et al. (2013), 84. Septiasari et al. (2021)

Medicinal

The research conducted in the forest area of Ayah Village shows that it has the potential for various medicinal plants. In identifying vascular plants, 74 species from 33 families were found in the forests of Ayah Village, which are useful in medicine. The ingredients contained in medicinal plants can accelerate the healing of disease (Lestari et al. 2021). Many people have used medicinal plants as herbal medicine. Therefore, the knowledge of these herbal medicine plants will be passed on to the next generation.

Many studies have been conducted to determine the content of plants. Usually, only certain parts of the plant can be used in medicine, even if all parts can be used in herbal medicine. According to Susanti et al. 2018, the plant parts mostly used for treatment are roots, stems, bark, flowers, fruit, and juice. Among the plant species found in Ayah Village Forest (Table 1), several plant parts can be used for treatment, starting from stems, leaves, sap, and roots. These plant species, as examples, *Urena lobata* (Figure 5A), *Ruellia tuberosa* (Figure 5B), *Polyscias scutellaria, Ageratum conyzoides*, *Chromolaena odorata, Melampodium divaricatum, Acacia auriculiformis, Albizia chinensis, Mimosa pudica*, *Plectranthus scutellarioides* and *Ficus septica* (Figure 5C). Medicinal plants have unique properties useful for curing diseases, such as wound medicine, inflammation medicine, fever reducer, and bladder stone.

Generally, the main factors that threaten the preservation of medicinal plants in the forest include habitat destruction, species scarcity, and excessive use of forest resources (Li et al. 2022). Nevertheless, some of these plants are active components in herbal medicine. For example, one of the medicinal plants that local people have used for a long time is *U. lobata,* which can be used as a fever reliever, rheumatism, wound and antiseptic, broken bones, and an anti-fertility agent (Silalahi 2020). In addition*, pulutan* leaf extract has antioxidant, antibacterial, and antifungal properties and can inhibit breast cancer cells (Fadillah et al. 2020).

The next plant that can be used as herbal medicine is *R. tuberosa (pletekan*). The presence of flavonoids, steroids, triterpenoids, and alkaloids in *pletekan* plants is well known. *Pletekan* leaves can be helpful to the bladder and coronary heart disease. Experimental studies have demonstrated these plants have ingredients as follows: antibacterial, anticancer, gastroprotective, antinociceptive, and anti-inflammatory properties of *R. tuberosa*. *Pletekan* also functions as a medicine in treating syphilis, bladder stones, bronchitis, cancer, heart disease, colds, fever, hypertension, and digestive problems (Nopiari et al. 2016). Next is *F. septica* or commonly known as *awar-awar*. People usually use *awar-awar* leaves as wound medicine. This plant also functions as a medicine for inflammation, and headaches, reducing fever, treating stomach aches, preventing diarrhea, as a medicine for fungal infections, and as a medicine in wound healing, namely steroids, flavonoids, and saponins (Tawi et al. 2019).

Ornamental plant

Therefore, 19 species of plants from 12 families have the potential as ornamental plants. Plant species that have the potential as ornamental plants are shrubs, epiphytes, and herbs. Ornamental plants have aesthetic value regarding leaves, flowers, and the whole plant (Majanah and Saputri 2019). The plants' types that have the potential to be ornamental plants found in the Ayah karst area include: *Alternanthera sessilis, Alocasia longiloba, Alocasia inornata, Philodendron grandipes, Xanthosoma mexicanum, Impatiens platypetala*, *Begonia urophylla, Begonia tenuifolia, Davallia denticulata, Heliconia psittacorum, Hibiscus rosa-sinensis, Acampe pachyglossa, Rhynchostylis retusa, Clitoria ternatea, Canthium horridum,* and *Pteris ensiformis.* The *D. denticulata* has beautiful leaves, so it is an ornamental plant that can be placed indoors and outdoors (Meliza et al. 2019). Apart from its potential as an ornamental plant, *H. psittacorum* has phytoremediation capabilities by reducing mercury metal contamination in the soil (Figure 5D) (Ulimma 2016). In addition to their potential as an ornamental plant, *H. rosa-sinensis* can analyze biomass and absorb carbon (Figure 5E) (Haruna 2020). The *R. retusa* is an orchid plant with exotic flowers and can be used as a commercial product (Nurfadilah 2013). The *A. longiloba* has arrow-shaped leaves with high aesthetic value, so it has the potential as an ornamental plant (Figure 5F) (Marega et al. 2016).

Foodstuffs

Ayah Forest area has abundant biodiversity. Among the species obtained in this study, several can be used as food by the local community. Regarding location, Ayah Forest is not far from settlements, so that local people can use the plants in the woods as food ingredients. Not only that, but the community can also plant fruit trees in the forest. Seventeen species in the Ayah Forest can be used as food. Among them are *Mangifera indica, Annona muricata, Colocasia esculenta, Arenga pinnata, Cocos nucifera, Carica papaya, Terminalia catappa, Manihot carthaginensis, Leucaena leucocephala, Sesbania grandiflora, Musa paradisiaca, Gigantochloa atter, Gigantochloa apus, Sorghum bicolor, Drynaria sparsisora, Capsicum frutescens,* and *Solanum melongena.* Usually, the species used as food ingredients are plants that produce fruit or vegetables to meet their daily needs. For example, bananas, soursop, tubers, chilies, and eggplants. Moreover, fruit has essential benefits for human health, especially for children growing up (Awuni and Isni 2022). Therefore, growing children would need balanced nutrition and nutrition by eating fruits and vegetables.

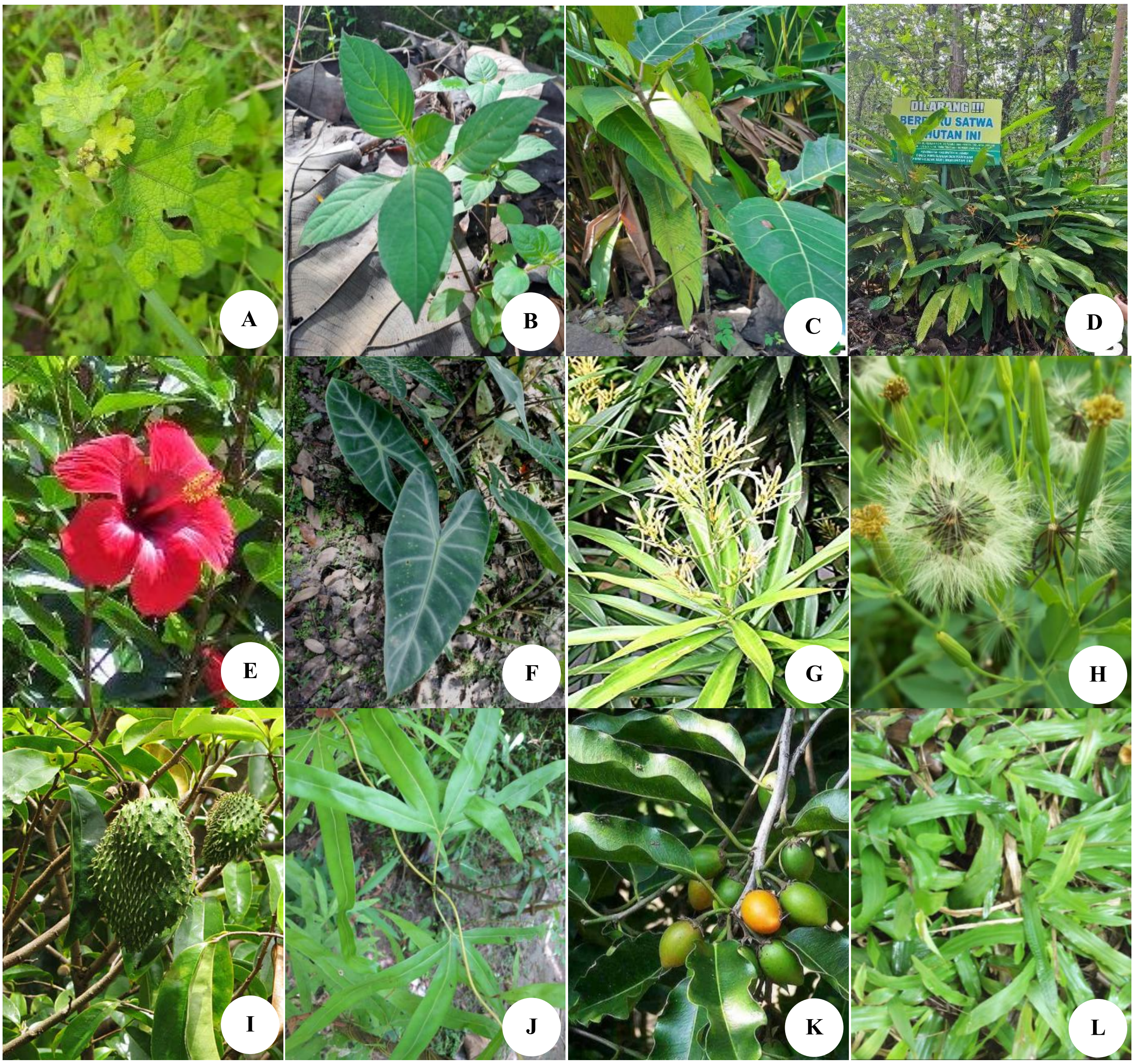

Figure 5. Some non-timber vascular plants found in Ayah Forest, Kebumen District, Central Java, Indonesia. A. *Urena lobata,* B. *Ruellia tuberosa,* C. *Ficus septica,* D. *Heliconia psittacorum,* E. *Hibiscus rosa-sinensis*, F. *Alternanthera sessilis*, G. *Dracaena angustifolia,* H. *Porophyllum ruderale,* I. *Annona muricata,* J. *Lygodium circinnatum,* K. *Schleichera oleosa,* L. *Brachiaria mutica*

Natural coloring

Based on the number of species obtained in the study, one species of plant found in the forests of Ayah Village could be used as a natural dye. The plant is *Dracaena angustifolia* (*suji*). A member of the *Dracaena* genus, *D. angustifolia*, also known as the suji leaf plant, is a widespread species and has long been used in Southeast Asia, including Indonesia. The *D. angustifolia* leaves are often used as a natural food coloring. That is because the chlorophyll pigment, which gives *suji* leaves their natural green color, is present. In the process, the *D. angustifolia* leaves are filtered after kneading with water. Next, *D. angustifolia* leaves are squeezed to release chlorophyll pigment (Andila and Warseno 2019). The juice from *D. angustifolia* leaves was then added to the cooking process to give color to the food. The high chlorophyll concentration in suji leaves simplifies chlorophyll extraction (Andistari et al. 2014).

Flavoring

There are two species from two families that have the potential to be used for food flavoring. The leaves of *Porophyllum ruderale* have an aromatic fragrance that can be used as a flavoring spice. The *P. ruderale* can be used as a condiment or spice in making traditional sauces known as "salsa" for mixed foods and soups in Mexico and South America (Putro 2021). Besides being known as kitchen lemongrass, *Cymbopogon citratus* is also known for its distinctive smell, like fresh lemon and orange taste. This aroma is obtained from citral compounds in lemongrass essential oil (Wany et al. 2013). Lemongrass and citronella essential oils have antifungal and antibacterial properties (Han and Tory 2017). Therefore, Lemongrass leaves have a fragrant aroma traditionally used to scent food. Besides being a food flavoring, lemongrass can be used as an herbal drink, essential oil, and aromatherapy. Therefore, to make flavoring from lemongrass is done by drying the leaves first then the dried leaves are made into powder. Once powdered, this flavoring can be used for soups, salads, and curries (Shah et al. 2011).

Beverage ingredients

Three types of plants have the potential to be used as a drink, namely *M. indica, A. muricata*, and *Coffea canephora*. Mango (*M. indica)* can be made into drinks such as juice and syrup. Drinks made from mangoes are efficacious as antioxidants to increase endurance (Handayani et al. 2020). Coffee *(C. canephora)* is believed to be a drink that can be used to relieve sleepiness, increase alertness, and elevate mood. That is because coffee contains caffeine (Latunra et al. 2021). Several variations of processed drinks can be made from coffee beans, one of which is brown coffee (Faturrahman et al. 2021). Soursop fruit *(A. muricata)* and leaves can be used to make drinks such as juice. Soursop leaves can be used as a tea to treat cancer (Adri and Hersoelistyorini 2013). Soursop leaves can also be used as the base for making ice cream because soursop leaves contain annonaceous acetogenin compounds, which are good for health (Aulia and Purwidiani 2017).

Woven craft

Indonesia's nature provides quite a lot of diversity of plants that can be used as raw materials for the handicraft industry, including weaving. Producing woven products from plant materials requires knowledge and experience in recognizing plants with long and robust fibers (Yoese et al. 2019). In the research that was conducted by tracing the forests of Ayah Village, there is one type of plant that has the potential to be used as woven handicrafts, namely *Lygodium circinnatum,* which is a plant that belongs to the Lygodiaceae family. The *L. circinnatum* (rhizome) is used as raw materials for the woven craft industry. Woven handicraft products include baskets, bags, trays, fruit containers, and other souvenirs. Crafts from *L. circinnatum* grass products sell well locally (Susila et al. 2019).

Animal feed

Based on the number of species obtained in this study, seven families in the Ayah Forest can be used as animal feed, including *Brachiaria mutica, Melinis minutiflora, Panicum repens, S. bicolor, Cyperus kyllingia, Themeda arguens,* and *Schleichera oleosa*. Of the seven types of plant species that can be used as animal feed, there is one dominant family, namely the Poaceae family, which consists of the grass family. At first, people thought weeds were useless and even a nuisance, so they sometimes threw them away and burned them, but these grasses can be used as animal feed, which has many benefits and properties that are good for animals. For example, grass has good nutrition and can launch the metabolic system of animals (Penu 2021).

In conclusion, tropical karst ecosystems support the life of various non-timber vascular plants, with various potential benefits. Based on research that has been conducted, 111 species from 44 families have been found growing in Ayah Forest, Ayah Village, Ayah Sub-district, Kebumen, Central Java, Indonesia. The vascular plants found during the research had different potentials, so in this study, eight prospects were found that could be utilized from vascular plants in Ayah Forest, including: ornamental plants (16 species), medicinal plants (68 species), foodstuffs (13 species), beverage ingredients (3 species), flavoring (2 species), natural dyes (1 species), animal feed (6 species) and woven crafts (1 species).

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Isolation and characterization of indigenous phosphate solubilizing bacteria from calcareous soil of dry land ecosystems in Timor Tengah Selatan, East Nusa Tenggara, Indonesia

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Abstract. *Nur MSM, Benggu YI, Tae ASJA, Ishaq LF, Soetedjo INP. 2023. Isolation and characterization of indigenous phosphate solubilizing bacteria from calcareous soil of dry land ecosystems in Timor Tengah Selatan, East Nusa Tenggara, Indonesia. Intl J Trop Drylands 7: 66-72.* Phosphate Solubilizing Bacteria (PSB) is a potential biofertilizer due to its ability to increase phosphorus (P) availability. That is important, especially in areas where P availability becomes a constraint for plant growth, such as calcareous soil in Timor Island, East Nusa Tenggara, Indonesia. The study was undertaken in three ecosystems, including *mamar*, farm, and coastal areas in Timor Tengah Selatan, with the objective was obtaining and characterizing PSBs from these ecosystems. Five soil samples from the rhizosphere of five plants were collected from each ecosystem for PSB occurrence and soil physicochemical properties. The results showed that PSB could be found in these three ecosystems observed, with the highest types of the isolate being in the coastal area ecosystem compared to *mamar* and farm ecosystems. PSBs were relatively low in the three ecosystems, possibly related to the soil properties. Despite the low population of PSBs obtained, 19 isolates of PSBs were found in this study. The study results provide initial information on the occurrence of PSBs in calcareous soil Timor. This study needs to be expanded to screen and identify the PSB isolates used as biofertilizers for calcareous soil in the region.

Keywords: Calcareous soil, phosphate solubilizing bacteria, phosphorus

INTRODUCTION

Phosphorus (P) is an essential macronutrient plants require for normal growth and development. P is required by plants in relatively large amounts after nitrogen and potassium, contributing around 0.2 to 0.8% of plant dry weight (Havlin et al. 1999). Despite the high amount of P needed by plants, the availability of P to plants for uptake and utilization is generally low, and it has become one of the most important factors limiting plant growth (Leytem and Mikkelsen 2005). The availability of P is strongly controlled by soil pH, with the maximum solubility and availability at pH 6.5. Iron and aluminum phosphate formation in acidic soil results in decreased P solubility. In alkaline and calcareous soil, calcium readily adsorbs P, forming low-soluble calcium phosphate (Brady and Weil 2002).

Low availability of P is a general problem occurring in semi-arid Timor Island in Indonesia, including Timor Tengah Selatan, where the soils are calcareous. In this soil type, the mineral calcium carbonate ($CaCO_3$) is present in the parent material, and lime is accumulated in the soil (Leytem and Mikkelsen 2005). Accordingly, decreased P availability in alkaline soil is driven by the reaction of P with calcium, and a high amount of lime, particularly in the calcareous soil, could exacerbate the P availability problem. Since a high amount of lime in calcareous soil could react with soil solution P, it could form a strong calcium phosphate bond at the surface of the lime, resulting in low available P (Hopkins and Ellsworth 2005).

Due to the low concentration and poor mobility of soil available P, inorganic phosphate fertilizer is the main solution to crop growth and yield in the Timor Tengah Selatan Region. However, phosphate fertilizer applied in calcareous soil is relatively inefficient as the majority of phosphorus applied would be rapidly converted into forms that are less soluble compounds (Oxmann and Schwendenmann 2015), leading to reduced solubility and availability to plants (Brady and Weil 2002). As a consequence, phosphate fertilizer should be applied in high amounts. On the other hand, a high amount of inorganic fertilizer could imbalance the availability of other essential nutrients, and it is not environmentally safe. Therefore, an alternative approach should be considered in managing P's low availability in the region's calcareous soil. Furthermore, using soil amendments, such as biochar-fortified compost, could decrease un-available phosphate and increase available P and the absorption of P calcareous soil in Timor, East Nusa Tenggara, Indonesia (Nur et al. 2014). Moreover, beneficial functional soil microorganisms such as mycorrhiza have also been reported to improve available P and plant growth and yield in Timor's calcareous soil (Ishaq et al. 2021).

Another potential beneficial soil microorganism that is also known could also improve the availability of soil P is phosphate Solubilizing Bacteria (PSB). PSBs are known to be abundant in the rhizosphere of various plants and can solubilize potential phosphorus from organic and inorganic sources. It not only could produce phosphatase enzymes but also could secrete various low molecular-weight organic acids such as citric acid, glutamate, succinic, tartrates, formic acetic propionic lactonic glyconic and fumaric acids (Pande et al. 2017; Yadav et al. 2017). These organic acids can form a chelate (stable complex) with P-binding cations such as Fe^{2+} and $Ca^{2+,}$ resulting in reduced reactivity of these cations, leading to increased solubility and availability of P (Pande et al. 2017). Many studies have reported the potential of PSB to improve plant growth and yield and reduce the use of inorganic fertilizer applications (Hussain et al. 2019; Fitriatin et al. 2021; Rawat et al. 2021). Due to its benefit in increasing phosphorus availability and plant growth, PSB has been suggested as an essential biofertilizer that could reduce chemical fertilizer applications (Dhuldhaj and Malik 2022).

Despite the benefits provided by PSB, up to now, very little is known about the presence of these bacteria in the calcareous soil of dry land ecosystems of Timor Island. Therefore, the study aimed to obtain and characterize indigenous PSBs from the rhizosphere of plants in *mamar*, farm, and coastal areas in Timor Island's dry land ecosystems, particularly in Timor Tengah Selatan.

MATERIALS AND METHODS

Soil samples collection

Soil samples were collected from some ecosystems in the Timor Tengah Selatan District, East Nusa Tenggara, Indonesia, including *mamar*, farm, and coastal areas. *Mamar* is local farming management typical to Timorese farmers, which is located in water catchment areas with various plants grown such as coconut, bananas, areca nut, coffee, and other natural tree species such as bamboo and *Leucaena leucocephala* (Lam.) de Wit. Farm in Timor Tengah Selatan is typical of a semi-arid agricultural farming system in Timor consisting of various crops and plants such as maize, nuts, cassava, *Moringa oleifera* Lam, and *L. leucocephala*. The coastal area site was located around 100 m from the beach with a few natural vegetation such as *Jatropha gossypiifolia* L.*,* *Borassus sundaicus* Becc.*,* *Albizia* sp., and *Ziziphus mauritiana* Lam*.* These three ecosystems were chosen due to their specific characteristics, including soil and microenvironment. Before soil sample collection, a survey was undertaken to select the area of these three ecosystems that could represent each. The selection of sampling sites in each ecosystem was based on the diversity of plants growing there.

Five soil samples were collected diagonally in each ecosystem at 0-20 cm depth. The soil, around 1 kg, was taken from the rhizosphere of the plants, put in a labeled plastic zip bag, and then kept in a cool container. The location of the sampling point and the vegetation in each were recorded. The soil samples collected from each ecosystem (five soil samples from each ecosystem) were divided into two portions: one portion was used to isolate PSBs, and the rest of the soil was bulk for soil analyses representing the soil properties of the ecosystem. The soil physicochemical properties analyzed consisted of organic-C, total N, C/N ratio, available P, pH, and water content.

Isolation of PSBs

PSB strains were isolated from each soil sample by serial dilution and spread plate method. One gram (1 g) of soil sample was dispersed in 9 mL sterile 0.85% NaCl solution and thoroughly shaken. Next, 1 mL of that solution was transferred to 9 mL of sterile 0.85% NaCl to form a 10^{-2} dilution. The same method was used to make 10^{-3}, 10^{-4}, and 10^{-5} dilutions. Then, 1 mL of each dilution was spread on Pikovskaya's agar medium (PVK) and incubated at 28°C for 7 days. The PVK medium contained (in g/L) 10 glucose, 0.5 yeast extract, 0.5 $(NH_4)_2SO_4$, 0.1 $MgSO_4.7H_2O$, 5 $Ca_3(PO_4)_2$, 0.2 KCl, 0.002 $MnSO_4.2H_2O$, 0.002 $FeSO_4.7H_2O$, and 15 agar (Sharon et al. 2016). Colonies showing halo zones were picked and purified by 5 times subculture method on Pikovskaya's (PVK) agar medium for observing colony morphology. The colony with a morphologically distinct appearance with halo zones were selected and purified by 3 times subculture method on PVK agar medium to identify their colony characteristics and microscopic observation (Santoso 2007).

The population of PSBs was expressed as Colony-Forming Units (CFU) and counted based on Somasegaran and Hoben (1994) using the following equation:

Population (cfu/g soil) = (number of colonies × dilution factor) / (Volume of the aliquot)

The halo zones formed by the PSBs were calculated based on Sharon et al. (2016) using the equation below:

Phosphate solubilizing index = (colony diameter + halo zones) / colony diameter

The halozone and colony diameter were measured on large, medium, and small colonies. The colony is categorized as Large (L) if the diameter of the colony is above 2,100 µm. While the colony is classified as medium (M) if the diameter of the colony is in the range of 1,000-2,100 µm, and it is categorized as small (S) if the diameter of the colony is less than 1,000 µm. Measurement of colony diameter and halo zone was undertaken using a Hirox microscope at 100x magnification.

RESULTS AND DISCUSSION

General conditions of the study site

The location of the study sites (*mamar*, farm, and coastal area) is described in Figure 1. The detailed condition of the ecosystems where the soil was taken for isolation and characterization of the PSB in Timor Tengah Selatan District is shown in Table 1. *Mamar* ecosystem is located on Kobelete II, Cendana Village, So'e City Sub-district, with an altitude of 744-753 meters above sea level (masl). The vegetation in this ecosystem mainly consists of betel nut, bamboo, coconut, and some *L. leucocephala*. The farm ecosystem is located in Besipae, Pubabu Village, South Amanuban Sub-district, with an altitude of 174-177 masl. The plants grown in the farm ecosystem are *Carica* *papaya* L., pigeon pea, cassava, maize, and *M. olivera*. The coastal area ecosystem is located in Tuafanu Village, Kualin Sub-district, the altitude is 0 masl, and the natural vegetation consists of *J. gossypiifolia, B. sundaicus*, *Albizia* sp., and *Z. mauritiana*.

Soil analysis

The soil C-organic content in the study sites varied from moderate to very high. The highest C-organic content was found in the *mamar* ecosystem, accounting for 5.6%, followed by farm at 4.8%, and coastal area at 2.2%. Total nitrogen in the soil is low in all ecosystems (0.12-0.17%). The C/N ratio varied from high to very high. The highest C/N ratio was found in the *mamar* ecosystem (32.74), followed by the farm ecosystem (28.25) and the coastal ecosystem (22.20). Available P is very low in all ecosystems, ranging from 1.38 mg/kg to 2.47 mg/kg. The soil pH of *mamar* and the farm is neutral, while in the coastal ecosystem, the soil pH is slightly alkaline (7.80) (Table 2).

Table 1. Detailed condition of *mamar*, farm, and coastal area ecosystems where the soil samples were taken

Soil Sample	Type of Ecosystem								
	***Mamar* (Kobelete II)**			**Farm (Besipae)**			**Coastal Area (Tuafanu)**		
	Rhizosphere	**Altitude (m asl.)**	**Position**	**Rhizosphere**	**Altitude (m asl.)**	**Position**	**Rhizosphere**	**Altitude (m asl.)**	**Position**
1	Betel nut	745	9°52'26.634"S, 124°15'54.954"E	*C. papaya*	174	10°1'47.16"S, 124°12'9.396"E	*J.gossypifilia*	0	10°10'2.058"S, 124°23'46.794"E
2	Bamboo	744	9°52'26.262"S, 124°15'53.79"E	Pigeon pea	177	10°1'47.364"S, 124°12'9.834"E	*B. sundaicus*	0	10°10'2.562"S, 124°23'47.436"E
3	Coconut	753	9°52'26.688"S, 124°15'53.334"E	Cassava	176	10°1'48.09"S, 124°12'9.57"E	*Albizia* sp.	0	10°10'0.684"S, 124°23'47.082"E
4	*L.leucocephala*	750	9°52'27.87"S, 124°15'54.006"E	maize	175	10°1'47.886"S, 124°12'10.332"E	*Z.mauritiana*	0	10°10'1.578"S, 124°23'48.474"E
5	Banana Tree	751	9°52'27.144"S, 124°15'55.152"E	*M. olivera*	174	10°1'47.658"S, 124°12'10.098"E	*Borassus*	0	10°10'1.692"S, 124°23'47.736"E

Table 2. Soil physico-chemical characteristic of *mamar*, farm, and coastal area ecosystems

Soil physico-chemical characteristics	*Mamar* (Kobelete II)	Farm (Besipae)	Coastal Area (Tuafanu)
Organic-C (%)	5.57 (Very High*)	4.8 (High)	2.66 (Moderate)
Total-N (%)	0.17 (Low)	0.17 (Low)	0.12 (Low)
C/N Ratio	32.74 (Very High)	28.25 (Very High)	22.20 (High)
Available-P (mg/kg)	2.47 (Very Low)	1.38 (Very Low)	1.86 (Very Low)
pH	7.25 (Neutral)	7.56 (Neutral)	7.80 (slightly alkaline)
Water Content (%)	22.88	10.63	19.07

Note: *The criteria based on Hardjowigeno (2005)

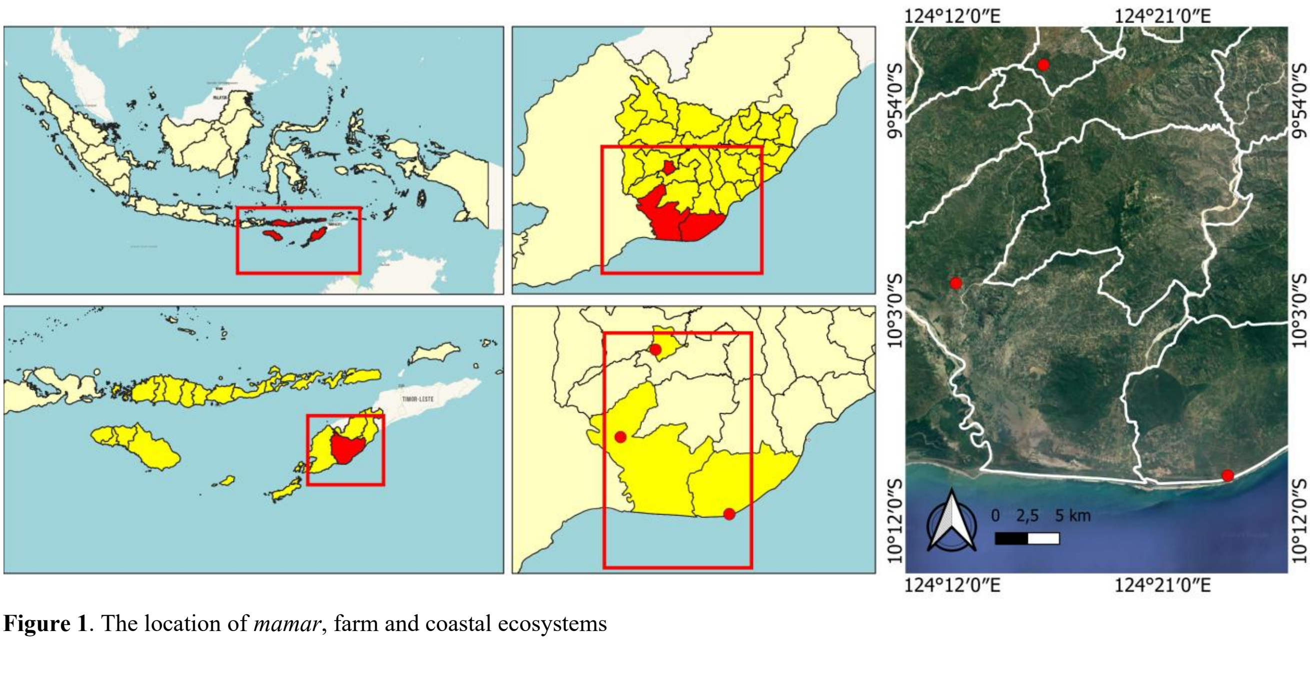

Figure 1. The location of *mamar*, farm and coastal ecosystems

Number of colonies, halo zones and colony diameter, and Phosphate Solubilizing Index (PSI) of PSBs in *mamar*, farm, and coastal area ecosystems

The population of PSBs observed in this study was relatively low as the colony was found in the first or second dilution. Most PSB was found in the coastal ecosystem, followed by the farm and *mamar* ecosystems. Particularly, in the *mamar* ecosystem, PSB was only found in the rhizosphere of bamboo and *L. leucephala*, while in the rhizosphere of betel nut, coconut, and banana samples, no PBS was observed. In the coastal area ecosystem, the highest population of PSBs was in the rhizosphere of *Z. mauritiana*, while in the farm ecosystem, the most populous PSBs were in the rhizosphere of pigeon peas (Table 3).

Although the halo zone diameter of the PSBs was quite variable between the three ecosystems, they were all small to medium categories. The diameter of the PSBs colonies ranges from 0.3 mm to 2.1 mm.

Macroscopic and microscopic morphological characteristics of PSB

The morphological appearances of PSB colonies are described in Table 4. The macroscopic characteristics of PSBs included in this study were shape, color, surface, margin, elevation, and size. The microscopic characteristics of PSB were the shape of the cell and gram staining. The shapes of colonies of PSB were circular and irregular. The color of the colony was observed as white, milky white, yellow, and green. The surface of the colony was shiny, smooth, and rough. The margin of the colony was entire, undulate, lobate, and serrate. The elevation of the colony was raised and flat. The size of the colony was pinpoint, small, and moderate. The cell shapes were monococcus, diplococcus, streptococcus, monobacil, diplobacil, streptobacil, and cocobacil, and the gram staining was positive and negative.

The types of colonies of PSB observed in the three ecosystems were different. There were 2 colony types found in the Mamar ecosystem, while in the farm and coastal area ecosystems, there were 8 and 9 colony types, respectively. The examples of the type of colony observed in three ecosystems are described in Figure 2.

Table 3. Number of colonies, the diameter of colony and halo zones, and Phosphate Solubilizing Index (PSI) of PSBs

Ecosystems	Rhizosphere origin colonies	Number of bacteria (CFU/g soil)	Phosphate solubilizing bacteria (PSB)		
			Mean of colony diameter(mm)	Mean of halo zones diameter (mm)	PSI
Mamar (Kobelete II)	Betel nut	0			
	Bamboo	33×10^{-1}	1.4	1.7	2.2
	Coconut	0			
	L. leucephala	46×10^{-1}	1.6	2.5	2.6
	Banana	0			
Farm (Besi pae)	*C. papaya*	68×10^{-2}	0.3	0.4	2.3
	Pigeon pea	93×10^{-1}	0.7	1.9	3.7
	Cassava	38×10^{-1}	2.1	2.7	2.3
	Maize	68×10^{-1}	0.7	1.1	2.6
	M. olivera	31×10^{-1}	1.2	2.0	2.7
Coastal area (Tuafa nu)	*J. gossypiifolia*	87×10^{-1}	0.8	1.4	2.7
	B. sundaicus	32×10^{-1}	1.6	2.7	2.7
	Albizia sp.	76×10^{-2}	0.5	0.6	2.2
	Z. mauritiana	114×10^{-1}	0.7	1.1	2.6
	B. sundaicus	55×10^{-1}	0.7	0.3	1.4

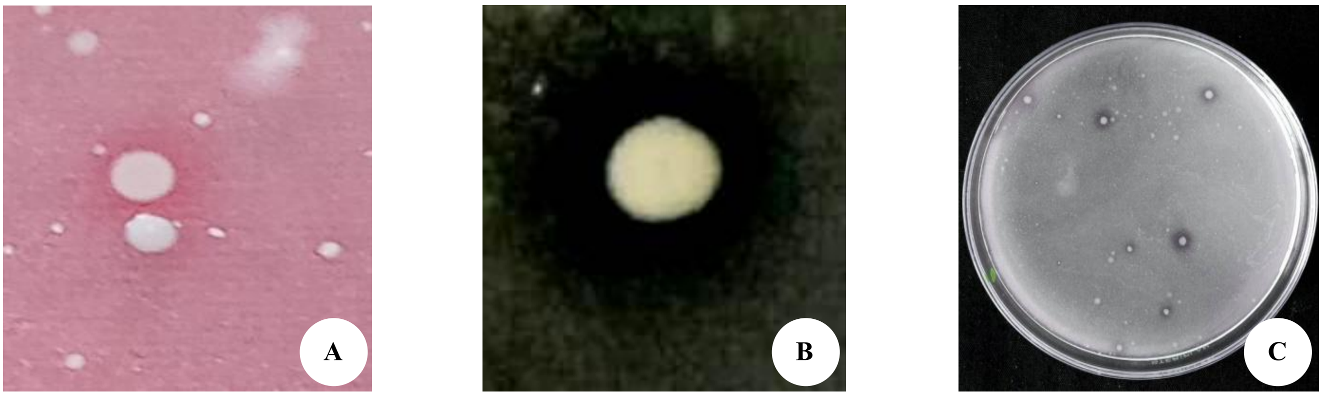

Figure 2. Examples of PSB colonies found in A. *mamar*, B. Farm, and C. Coastal areas ecosystems

Table 4. Macroscopic and microscopic characteristics of PSB isolated from *mamar*, farm, and coastal area ecosystems

Ecosystems	Isolate Origin	Macroscopic Characteristics of Colonies						Microscopic Characteristics of Colonies	
		Shape	Color	Surface	Margin	Elevation	Size	Shape of Cell	Gram Staining
Mamar (Kobelete II)	Betel nut tree	-	-	-	-	-	-	-	-
	Bamboo tree	Circular	Mw*	Ss	Entire	Raised	Small	Diplococcus	Negative
	Coconut tree	-	-	-	-	-	-	-	-
	L. leucephala	Circular	Mw	Ss	Entire	Raised	Small	Diplobacil	Negative
	Banana tree	-	-	-	-	-	-	-	-
Farm (Besipae)	*C. papaya*	Circular	White	Ss	Entire	Raised	Moderate	Cocobacil	Positive
	Pigeon pea	Circular	White	Ss	Entire	Raised	Small	Diplococcus	Positive
	Cassava	Circular	White	Ss	Entire	Raised	Moderate	Diplococcus	Positive
	Maize	Circular	White	Ss	Entire	Raised	Small	Streptobacil	Positive
	M. olivera	Circular	White	Ss	Entire	Raised	Small	Monobacil	Positive
	C. papaya	Irregular	White	Ss	Undulate	Flat	Small	Monococcus	Positive
	Pigeon pea	Circular	White	Ss	Entire	Flat	Moderate	Cocobacil	Positive
	Cassava	Circular	White	Ss	Entire	Flat	Small	Diplobacil	Positive
Coastal area (Tuafanu)	*J. gossypiifolia*	Circular	White	Ss	Entire	Raised	Small	Diplococcus	Negative
	B. sundaicus	Irregular	White	Ss	Lobate	Flat	Moderate	Diplococcus	Negative
	Albizia sp.	Circular	White	Rough	Entire	Raised	Small	Diplococcus	Negative
	Z. mauritiana	Circular	White	Ss	Entire	Raised	Pinpoint	Streptobacil	Negative
	B. sundaicus	Circular	Yellow	Ss	Entire	Raised	Small	Streptobacil	Negative
	J. gossypiifolia	Circular	Green	Rough	Serrate	Raised	Small	Diplobacil	Negative
	B. sundaicus	Circular	White	Ss	Entire	Raised	Small	Diplobacil	Negative
	Albizia sp.	Circular	Green	Rough	Entire	Raised	Small	streptococcus	Negative
	Z. mauritiana	Circular	White	Ss	Entire	Raised	Pinpoint	streptococcus	Negative

Note: *Mw: milky white, Ss: shiny smooth

Discussions

In this study, PSBs could be found in *mamar*, farm, and coastal area ecosystems. However, there is variability in the population and diversity of isolates obtained. The PSBs could be found in the five rhizospheres of plants in the farm and coastal area ecosystems, but in the *mamar* ecosystems, PSBs were only obtained in two rhizospheres of plants. Moreover, based on macroscopic and microscopic characterization, the number of isolates obtained was also low in the *mamar* ecosystems, with 2 isolates observed, compared with farm and coastal area ecosystems, with 8 and 9 isolates obtained, respectively. Many factors could affect the population and diversity of soil microorganisms. Plant species release various amounts and types of exudates, including carbohydrate, carboxylic acids, and amino acids, all of which can strongly affect the type of microorganisms colonizing the rhizosphere (Grayston et al. 1998).

In addition to host factors, soil properties such as organic carbon content, nitrogen, temperature, and aeration might influence the population and diversity of microorganisms, including PSBs (Mussarat and Khan 2014). In this study, the organic C content in the three ecosystems varies from moderate in the coastal area to high in the farm and very high in the *mamar* ecosystem. The lower organic C content in the coastal area ecosystem compared to the farm and *mamar* ecosystems is likely due to the lower population of vegetation in this area. Only a few vegetation in the coastal area ecosystem include *J. gossypiifolia, B. sundaicus, Albizia* sp., and *Z. mauritiana.* While in the farm and *mamar* ecosystems, the vegetation is more dense and variable, contributing more organic C resources. According to Chen et al. (2022), organic matter affects the properties of the soil, such as soil structure, moisture holding capacity, diversity and activity of soil organisms, and nutrient availability. However, this study found that the higher C organic content in the *mamar* ecosystem was unrelated to the population and diversity of PSBs. The higher population of PSBs was observed in the coastal area where the C organic content was lower than in *mamar* and farm ecosystems, which might be due to the C/N ratio of the soil. The organic matter with a lower C/N ratio is mineralized faster than those with a higher ratio (Havlin et al. 1999; Akratos et al. 2017), resulting in accelerated nutrient availability for supporting microorganisms and plant growth. In this study, the C/N ratio of the coastal area is lower than that in the *mamar* and farm ecosystems, indicating that the decomposition rate and nutrient supply in this area are faster than in the other two ecosystems.

Soil analysis showed that total-N in the three ecosystems is low. The low N soil content could explain the low population of PSB in the three ecosystems observed. Nitrogen is a crucial nutrient factor that could influence soil-inhabiting microbes' growth and functionality, including PSBs. If soil N content is low, it affects the growth and development of all microorganisms (Sandle 2016), including PSB (Mussarat and Khan 2014). In this study, all samples collected from each location were bulk to represent the soil-N content in that location. Therefore, it is hard to draw a correlation impact between soil total-N and its effects on the PSB population due to a low number of soil samples. In the future, more soil samples must be collected to evaluate the relationship between soil N and its effect on the PSB population.

In addition to N, the availability of P is also very low in the three ecosystems. The low availability of P in the ecosystems of Timor Island, including the Timor Tengah Selatan Region, is not surprising as the soil in the region is calcareous. Calcareous soils have high Ca content, which can adsorb P into insoluble Ca-P compounds (Brady and Weil 2002; Leytem and Mikkelsen 2005; Zhang et al. 2014). It is unknown whether the low availability of P in the soil could be related to the low population of PSBs in the study area; this needs to be further studied.

According to Mussarat and Khan (2014), aeration is one of the important factors that could influence PSB functionality in solubilizing phosphate. It has been reported that increasing the aeration rate to 0.4 L/kg DM min^{-1} was more conducive to enhancing P solubilization efficacy and available P accumulation than 0.2 L/kg DM min^{-1} (Ma et al. 2022). Related to the soil condition of the three ecosystems observed, it is likely that soil aeration in the *mamar* ecosystem could be less than in the farm and coastal ecosystems due to denser vegetation and higher organic matter content. This soil's physical conditions need to be investigated to evaluate this relationship.

The results showed that the phosphate solubilizing index was similar among the isolates obtained from *mamar*, farm, and coastal area ecosystems, with a value range of 2.2 to 2.7. The PSI of the isolates obtained in this study was slightly higher than the PSI of PSB isolates found in the mangrove rhizosphere in East Java, Indonesia (Fatima et al. 2023). That may indicate that the isolates found could be potential for biofertilizer purposes in the calcareous soil in the region. Therefore, further study was needed to screen and select the most potential isolate for biofertilizer use. In addition, since the characterization of the PSBs in this study was merely based on the macroscopic and microscopic characteristics of PSBs, there is a need to identify the potential isolated PSBs in the future using molecular analysis.

In conclusion, the results showed that the population of PSB isolates obtained in this study is variable between the ecosystems, and it is relatively low, possibly related to the soil's chemical characteristics. The population and types of PSB isolates are higher in the coastal area than in the *mamar* and farm ecosystems. There are 19 types in total of PSBs found in this study with different macroscopic and microscopic appearances.

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Phytochemical analysis and antimicrobial activity of *Tamarindus indica* extracts against *Fusarium oxysporum* and *Xanthomonas campestris*

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Abstract. *Gitari FM, Githae EW, Kuria EK. 2023. Phytochemical analysis and antimicrobial activity of* Tamarindus indica *extracts against* Fusarium oxysporum *and* Xanthomonas campestris. *Intl J Trop Drylands 7: 73-82.* Plant-pathogenic bacteria and fungi are a major threat to biodiversity and food security worldwide. The pathogens are difficult to control using cultural methods and have sometimes acquired resistance to conventional pesticides. This has necessitated the search for more efficient active compounds against them. One promising source of such compounds is tropical-medicinal plants such as *Tamarindus indica* L. This study first determined the phytochemical composition of *T. indica* extracts from different parts (leaves, bark, roots, and pods). Then it evaluated in-vitro the antimicrobial activity against plant pathogenic bacteria (*Xanthomonas campestris*) and fungi *(Fusarium oxysporum)*. Crude extracts were obtained using different solvents (dichloromethane, methanol, and acetone). The analysis revealed the presence of nine pharmaco-active phytochemicals; methanol extracts had the highest concentrations of these phytochemicals. All extracts demonstrated inhibitory effects against *F. oxysporum*. However, the extracts did not show any antimicrobial effect against *X. campestris*. There was a significant difference ($p<0.05$) in the percentage of inhibition of *F. oxysporum* growth by different extracts. Generally, high growth inhibition was observed in media containing different plant extracts at 250 and 500 ppm concentrations. For acetone extracts, the highest inhibition (71.042%) was induced by root extract at a 250 ppm concentration, whereas for dichloromethane extracts, the highest inhibition (68.811%) was induced by 500 ppm of leaf extract. Methanol extracts from stem recorded the highest inhibition of 86.953% at concentrations of 125 ppm. This was followed by root extracts (75.169% inhibition) at 500 ppm. The *T. indica*, therefore, has great potential as a source of bio-pesticide for use in integrated pest management of *F. oxysporum*.

Keywords: Antimicrobial, *Fusarium oxysporum*, phytochemicals, *Tamarindus indica, Xanthomonas campestris*

INTRODUCTION

Crops pathogens are of great economic importance and have warranted widespread and frequent use of pesticides (Mahmood et al. 2016). Bacterial and fungal pathogens negatively impact agriculture (Singh et al. 2015; Murithi et al. 2016). Such pathogens include the bacterium *Xanthomonas campestris* and the fungus *Fusarium oxysporum,* whose spread is helped by climate, soil, and human activities (Gitonga and Githae 2022). The *X. campestris* is a gram-negative bacterium that infects plants, causing diseases such as black rot in cruciferous vegetables and bacterial spot disease in tomatoes and pepper (Destefano et al. 2003; Mkandawire et al. 2004; Thieme et al. 2005; Mbaka et al. 2009). After infecting plants through wounds and openings such as stomata, the bacterium migrates to the xylem, where it accumulates and causes blockage, hence wilting of the host (Kidist 2003; Tripathi et al. 2009). The various disease control methods have failed (Nuñez et al. 2018). For instance, the bacterium has acquired resistance to some chemical pesticides (Shenge et al. 2014).

The *F. oxysporum* is an important group of fungi, with more than 150 strains that infect plants (Fourie et al. 2011). These strains cause *Fusarium* Wilt (FW) and *Fusarium* Crown Root Rot (FCRR) in different plants (Mustaffa and Thangavelu 2011; Bharat and Sharma 2014; Dita et al. 2018; Srinivas et al. 2019; Kalman et al. 2020; Awere et al. 2021). The *F. oxysporum* impairs plant water transport, leading to wilting and ultimate death (Ouyang et al. 2014). This fungus remains in the soil for a long time, even without a host, and only attacks plants when conditions are favorable (Velarde-Félix et al. 2018).

Cultural disease control methods effectively avoid infections (Agrios 2009). These methods include proper sanitation, crop rotation, and early or delayed planting (Bajwa and Kogan 2004). However, they become less effective once the plants have been attacked (Katan 2004). Therefore, it is paramount to integrate these cultural methods with other control strategies (Shenge et al. 2014). Such strategies include Chemical control which weakens or kills the pathogens (Vidaver and Lambrecht 2004; Agrios 2005). Managing *F. oxysporum* and *X. campestris* is mainly through chemical soil fumigation. However, this has adverse effects on the environment (Velásquez et al. 2018). For instance, killing non-target organisms upsets biodiversity (Ramaiah and Garampalli 2015). Additionally, Pesticide toxins remain in the produce after harvest, and their ingestion is suspected to cause human diseases (Dorri et al. 2018; Nuñez et al. 2018). Further, continuous use of these chemicals can cause resistance to pathogens (Pal and Gardener 2006). Therefore, replacing pesticides with environmentally safe methods will increase the quantity and quality of crop produce and reduce pollution (Pal and

Gardener 2006). For instance, plant-based pesticides provide an environmentally friendly option for combating plant pathogens (Yuan et al. 2012; Ramaiah and Garampalli 2015). Further, their modes of action are similar to those of chemical pesticides. Therefore, they can be applied in agriculture, medicine, and industry (Oyelana et al. 2011; Awere et al. 2021).

Tamarind *(Tamarindus indica* L.), a plant of the family Fabaceae, is a multipurpose leguminous tree that is drought-tolerant and thrives well in tropical climates (Rao et al. 2015; Kidaha et al. 2017). It is widely distributed in Kenya's arid and semi-arid areas and is common on farmlands (Muok et al. 2000; Maundu and Tengnas 2005). Tamarind has medicinal phytochemicals with antimicrobial, anti-inflammatory, antifungal, anti-nematode, antidiabetic, molluscicidal, and cytotoxic activities (El-Siddig et al. 2006; Escalona-Arranz et al. 2010; De Caluwé et al. 2010; Bhadoriya et al. 2011; Gumgumjee et al. 2012; Simon 2019). These compounds are contained in the leaves (Escalona-Arranz et al. 2010; Bhadoriya et al. 2011), the pods (Bhadoriya et al. 2011), the bark and fruit pulp (Nwodo et al. 2011). However, little information is documented about their activity against plant pathogens.

Plants have numerous phytochemicals of different solubilities in different solvents (Doughari 2006; Vaghasiya and Chanda 2009; Gumgumjee et al. 2012; Majekodunmi 2015). This study extracted different parts of tamarind using acetone, dichloromethane, and methanol. Their phytochemical composition and antimicrobial effect against *X. campestris* and *F. oxysporum* were evaluated, and promising prospects for controlling plant pathogens using tamarind were demonstrated.

MATERIALS AND METHODS

Study area

This study was carried out in Tharaka-Nithi County in Kenya. The county borders Embu County in the south, Meru County in the north, Kitui County in the east, and Mount Kenya in the west. This region lies between longitudes 38.0631460 east and 0.29650 south. The county is divided into six sub-counties: Tharaka North, Tharaka South, Chuka, Igambang'ombe, Muthambi, and Maara. Samples of *T. indica* were collected in the lower Igambang'ombe, classified as a semi-arid area (Tharaka-Nithi County Government 2016). It has an annual temperature range of 20-30°C and an altitude of around 800 m above sea level. The area receives an average annual rainfall of 125 mm/year (Tharaka-Nithi County Government 2016).

Collection of plant samples

Plant samples were collected according to Upadhayay (2016). Identification of *T. indica* was done with the assistance of a botanist from the National Museums of Kenya. Plant samples were collected randomly from 10 trees located within a radius of 50 m. Young and fresh leaves, green pods, bark, and roots were collected from each tree and bulked to form a composite sample. Each composite sample was placed in a separate bag, sealed, labeled, and placed in cooler boxes. The samples were taken to the Biochemistry Laboratory at the National Museums of Kenya for analysis.

Analysis of phytochemicals

According to Wadood et al. (2013) and Altemimi et al. (2017), crude extracts were prepared. Each plant sample was cleaned and rinsed in distilled water before drying for seven days at room temperature. One hundred grams of each sample were weighed and ground into a fine powder using a high-speed multi-function grinder (RRH-2000A). The crude extraction used different solvents (acetone, methanol, and dichloromethane). The mixture was put in a sealed container and left to stand for three days to ensure maximum extraction of soluble components. The samples were then filtered using Whatman filter paper number 1. The filtrate was concentrated using a rotary evaporator to get a crude extract. The residue was then re-soaked for 48 hours, and the extraction process was repeated to ensure it was exhaustive (Azwanida 2015). The filtrate was purified using fractional distillation to remove the solvent and leave only the pure crude extract. The extracts were then analyzed for the presence of phytochemicals, according to Gomathi et al. (2017). They were tested for the presence of alkaloids, steroids, saponins, flavonoids, terpenoids, phenols, tannins, glycosides, and resins. Dimethyl Sulfoxide (DMSO) was used to make the dilutions that were used for the antimicrobial assay at concentrations of 62.5 ppm, 125 ppm, 250 ppm, 500 ppm, and 1000 ppm (Do et al. 2014; Umaru and Umaru 2018).

Isolation of the plant pathogens

The *F. oxysporum* was isolated from the stems of tomato plants that showed symptoms of *Fusarium* wilt (Fourie et al. 2011). The stem was divided into one-millimeter portions using a sterile scalpel. After sterilizing the sections for one minute with a 1% sodium hypochlorite solution, the sections were washed in distilled water to eliminate any remaining disinfectant. The extra water was then blotted off using sterile blotting paper. The portions were then put on culture plates with Potato Dextrose Agar (PDA) media. The plates were then closed and incubated for three days at 25°C in an inverted position to allow growth. Further sub-culturing was done to obtain pure cultures using a single-spore isolation approach (Zhang et al. 2013). In preparation for the sensitivity test, the acquired pure culture was inoculated in fresh PDA media, allowed to grow at 25°C, then kept in the refrigerator at 5°C, awaiting the antifungal assay.

The *X. campestris* was isolated from the leaves of tomato plants that showed symptoms of *Xanthomonas* wilt (Wasukira et al. 2012). The leaves were cut using a sterile scalpel and packed in aluminum foil. The symptomatic leaves were surface-sterilized using 1% sodium hypochlorite for two minutes, then rinsed with distilled water and dried using sterilized blotting paper. Next, using a sterile blade, the contaminated area of the leaves was aseptically cut, then put into a sterilized mortar. Next, 1 mL of normal saline solution was added before the leaf pieces were crushed with a pestle. The sap from the crushed leaf was then injected into nutrient agar plates, where it was incubated for 24 hours at 28°C. The *X. campestris* colonies were morphologically identified and subcultured into Muller-Hinton Agar for 24 hours at 28°C to obtain pure cultures. Gram staining and oxidase tests were conducted to identify the pathogen. The pure cultures were then inoculated into freshly prepared media, grown overnight, and then stored at 4°C in the refrigerator, awaiting the antibacterial assay.

Antimicrobial assay

Antimicrobial tests were done according to Balouiri et al. (2016). One hundred and eighty plates for culture media were prepared for the antimicrobial assay of each pathogen. Next, 1 mL of the crude extracts, diluted at the different concentrations, was added to each plate and replicated thrice. Pure cultures of the pathogens were picked aseptically with a 3 mm diameter sterile cork borer and placed in their respective treated plates for the antimicrobial assay. The positive controls were Ridomil© for *F. oxysporum* and Liquicop© for *X. campestris*, while the negative control was pure distilled water. Mycelial growth diameter was measured using a vernier caliper on days 3, 6, and 9. Percentage inhibition was calculated using the formula:

$$inhibition = \frac{mycelial\ diameter\ of\ the\ negative\ control - mycelial\ diameter\ of\ treated}{mycelial\ diameter\ of\ the\ negative\ control}\ x\ 100$$

Statistical analysis

All variables were subjected to a two-way Analysis of Variance (ANOVA) in the Statistical Analysis System (SAS) version 9.4. Significant means were separated using the Least Significant Difference (LSD) at P = 0.05.

RESULTS AND DISCUSSION

Phytochemical analysis of *Tamarindus indica* extracts

A total of nine phytochemicals were identified from the stem, root, pods, and leaves of *T. indica*, with different concentrations. These were saponins, flavonoids, alkaloids, terpenoids, steroids, phenols, tannins, glycosides, and resins. In the acetone extract, seven phytochemicals were identified in all the *T. indica* extracts (Table 1). Phenols, steroids, and tannins were present in all the extracts. Alkaloids were highest in the stem, while steroids were highest in both leaves and pods. Glycosides were only present in the root extract, whereas terpenoids and resins were not detected in any of the extracts.

Only four phytochemicals were detected in all the dichloromethane extracts, some at very low concentrations (Table 2). A moderate concentration of flavonoids was found in the stem extract. Glycosides and tannins were only found in low concentrations, while steroids were found in high concentrations in the leaves and pods. No phytochemicals were detected in the root extract.

Furthermore, like the acetone extract, seven phytochemicals were identified in all the methanol extracts (Table 3). However, terpenoids and resins were not detected in all the extracts. On the contrary, Saponins were detected in all parts of the plant, with very low concentrations in some parts. Alkaloids were also detected in very low concentrations. Glycosides were only present in leaves, whereas phenols were only present in leaves and pods.

Table 1. Phytochemicals present in different parts of *T. indica* extracted using acetone

Phytochemical	Stem	Root	Leaves	Pods
Saponins	-	+	++	-
Flavonoids	+	+	+	-
Alkaloids	+++	++	+	-
Terpenoids	-	-	-	-
Steroids	+	+	+++	+++
Phenols	++	++	+	++
Tannins	+	++	+	++
Glycosides	-	+	-	-
Resins	-	-	-	-

Note: Key: Absent (-), Low Concentration (+), Moderate Concentration (++), High Concentration (+++)

Table 2. Phytochemicals are present in different parts of T. indica when the extract is obtained using dichloromethane

Phytochemical	Stem	Root	Leaves	Pods
Saponins	-	-	-	-
Flavonoids	++	-	-	+
Alkaloids	-	-	-	-
Terpenoids	-	-	-	-
Steroids	+	-	+++	+++
Phenols	-	-	-	-
Tannins	+	-	+	-
Glycosides	-	-	+	+
Resins	-	-	-	-

Note: Key: Absent (-), Low Concentration (+), Moderate Concentration (++), High Concentration (+++)

Table 3. Phytochemicals are present in different parts of *T. indica* when the extract is obtained using methanol

Phytochemical	Stem	Root	Leaves	Pods
Saponins	+	+++	+	+++
Flavonoids	+++	+++	-	+
Alkaloids	-	+++	+	-
Terpenoids	-	-	-	-
Steroids	-	-	+++	+++
Phenols	-	-	+	+
Tannins	+	+	+++	+
Glycosides	-	-	+	-
Resins	-	-	-	-

Note: Key: Absent (-), Low Concentration (+), Moderate Concentration (++), High Concentration (+++)

Antimicrobial assay of *Tamarindus indica* extracts against *Xanthomonas campestris*

In Mullier-Hinton agar, *X. campestris* appeared pale yellow (Figure 1). The antimicrobial tests of *T. indica* extracts obtained using different solvents against *X. campestris* were all negative and did not show any inhibition. However, the positive control showed a one-centimeter ring of growth inhibition from the point of inoculation of the pathogen after 48 hours of incubation. At this point, there was full growth in the negative control plate.

Antimicrobial assay of *Tamarindus indica* extracts against *Fusarium oxysporum*

Acetone plant extracts

The *F. oxysporum* produced white powdery mycelium in the PDA medium and microconidia that were single pink-red and hyaline (Figure 2). As observed under the microscope, the macroconidia were oval, thick-walled, hyaline, in short chains, and with hooked apices. The results showed a significant difference ($p < 0.05$) in the percent inhibition between acetone extracts at different concentrations. The maximum percentage inhibition (71.042%) was obtained in the stem extract at 250 ppm, followed by the root extract (57.556%) at the same concentration (Table 4). The lowest percentage of inhibition was in the leaf (13.551%), and pod (13.926%) extracts at a concentration of 1,000 ppm. The inhibition by the positive control (Ridomil) was significantly higher ($p < 0.05$) than all concentrations of the extracts except the stem extract at a concentration of 250 ppm, which was not significantly different. Generally, the highest inhibition mean was obtained at 250 ppm and the lowest at 1,000 ppm concentrations.

Inhibition of F. oxysporum *by dichloromethane plant extracts*

There was a significant difference ($p < 0.05$) in the percent of inhibition displayed by dichloromethane extracts against *F. oxysporum*. The highest inhibition (68.81%) was exhibited by leaf extract at 500 ppm, followed closely by stem extract (68.664%) at 125 ppm and leaf extract (65.004%) at a concentration of 62.5 ppm (Table 5). Extracts from pods exhibited the lowest inhibition compared to extracts from other parts. The lowest inhibition was exhibited at 62.5 ppm (23.224%) and 1,000 ppm (25.047%). There was a significant difference ($p < 0.05$) in the inhibition between all extracts and the positive control, except for the leaf extract at a concentration of 500 ppm. Like acetone extracts, the highest inhibition mean was obtained at 125 ppm, while the lowest was at 1,000 ppm concentrations. The positive control also exhibited a significantly higher inhibition percentage than the dichloromethane plant extracts.

Inhibition of F. oxysporum *by methanol plant extracts*

There was a significant difference ($p<0.05$) in the percent of inhibition exhibited by methanol extracts against *F. oxysporum* (Figure 3). The highest inhibition was recorded in the stem extract at 125 ppm (86.953%) and in the root extract at 500 ppm (75.169%) (Table 6). These were followed by stem extract at 250 ppm (74.742%) and leaf extract at a concentration of 500 ppm (74.041%). The lowest percent of inhibition was recorded in the stem extract at 62.5 ppm (34.705%) and in pod extracts at 1000 ppm (42.889%). There was no significant difference ($p<0.05$) in inhibition between the positive control and the stem extract (at 125 ppm and 250 ppm), the root extract (at 250 ppm and 500 ppm), and the leaf extract (at 500 ppm).

Table 4. Percentage inhibition of *Fusarium oxysporum* by acetone extracts from different parts of *Tamarindus indica* at different concentrations

Concentrations (ppm)	Treatment	Inhibition (%)	Means	LSD	CV
62.5	AC_LF	18.893 d	44.429	14.257	39.223
	AC_PD	25.055 cd			
	AC_RB	52.827 b			
	AC_SB	37.739 c			
	Ridomil	87.632 a			
125	AC_LF	19.400 d	52.358	21.456	11.953
	AC_PD	28.374 cd			
	AC_RB	48.569 b			
	AC_SB	32.762 c			
	Ridomil	87.686 a			
250	AC_LF	35.321 c	59.310	19.918	9.665
	AC_PD	53.208 b			
	AC_RB	57.556 b			
	AC_SB	71.042 a			
	Ridomil	79.423 a			
500	AC_LF	22.312 c	44.393	31.616	11.483
	AC_PD	28.379 c			
	AC_RB	50.452 b			
	AC_SB	40.176 b			
	Ridomil	80.645 a			
1000	AC_LF	13.551 b	36.600	29.201	9.700
	AC_PD	13.926 b			
	AC_RB	55.196 a			
	AC_SB	21.805 b			
	Ridomil	78.523 a			
Means		46.418			
LSD		4.873			
CV		29.212			

Note: AC_LF: Acetone leaf extract, AC_PD: Acetone pod extract, AC_RB: Acetone root extract, AC_SB: Acetone stem extract. The means denoted by the same letter show no significant difference in the percent inhibition.

Figure 1. Pure cultures of *Xanthomonas campestris* in Mullier Hinton Agar Media

Table 5. Percentage inhibition of *Fusarium oxysporum* by dichloromethane extracts from different parts of *Tamarindus indica* at different concentrations

Concentrations (ppm)	Treatment	Inhibition (%)	Means	LSD	CV
62.5	DC_LF	65.004 b	53.905	31.881	11.688
	DC_PD	33.224 d			
	DC_RB	51.004 c			
	DC_SB	41.164 c			
	Ridomil	87.632 a			
125	DC_LF	56.204 c	58.013	23.604	11.203
	DC_PD	29.082 d			
	DC_RB	48.430 c			
	DC_SB	68.664 b			
	Ridomil	87.686 a			
250	DC_LF	48.797 c	55.062	23.078	10.396
	DC_PD	37.324 d			
	DC_RB	49.434 c			
	DC_SB	60.333 b			
	Ridomil	79.423 a			
500	DC_LF	68.811 ab	55.672	37.909	17.267
	DC_PD	30.772 c			
	DC_RB	59.799 b			
	DC_SB	38.332 c			
	Ridomil	80.645 a			
1000	DC_LF	35.940 b	33.300	1.739	19.303
	DC_PD	25.047 b			
	DC_RB	35.940 b			
	DC_SB	39.758 b			
	Ridomil	78.523 a			
Means		32.499			
LSD		6.187			
CV		32.499			

Note: DC_LF: DCM leaf extract, DC_PD: DCM pod extract, DC_RB: DCM root bark extract, DC_SB: DCM stem bark extract. The means denoted by the same letter show no significant difference in inhibition

Table 6. Percentage inhibition of *Fusarium oxysporum* by methanol extracts different parts of *Tamarindus indica* at different concentrations

Concentrations (ppm)	Treatment	Inhibition (%)	Means	LSD	CV
62.5	ME_LF	50.663 bc	57.692	34.414	16.243
	ME_PD	54.249 b			
	ME_RB	61.210 b			
	ME_SB	34.705 c			
	Ridomil	87.632 a			
125	ME_LF	50.082 b	68.092	21.456	11.953
	ME_PD	60.594 b			
	ME_RB	55.143 b			
	ME_SB	86.953 a			
	Ridomil	87.686 a			
250	ME_LF	53.468 c	69.140	17.585	9.947
	ME_PD	68.262 b			
	ME_RB	69.807 ab			
	ME_SB	74.742 ab			
	Ridomil	79.423 a			
500	ME_LF	74.041 ab	70.014	17.043	9.762
	ME_PD	68.364 b			
	ME_RB	75.169 ab			
	ME_SB	51.851 c			
	Ridomil	80.645 a			
1000	ME_LF	56.601 b	57.608	35.355	16.664
	ME_PD	42.889 b			
	ME_RB	52.358 b			
	ME_SB	57.670 b			
	Ridomil	78.523 a			
Means		64.509			
LSD		5.823			
CV		25.117			

Note: ME_LF: Methanol leaf extract, ME_PD: Methanol pod extract, ME_RB: Methanol root bark extract, ME_SB: methanol stem bark extract. The means denoted by the same letter show no significant difference in inhibition

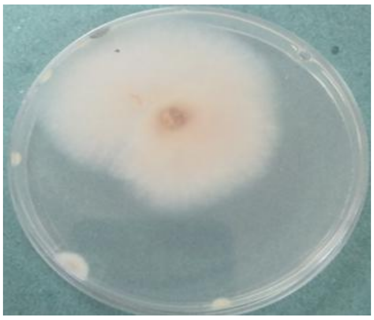

Figure 2. Pure culture of *Fusarium oxysporum* in Potato Dextrose Media (PDA)

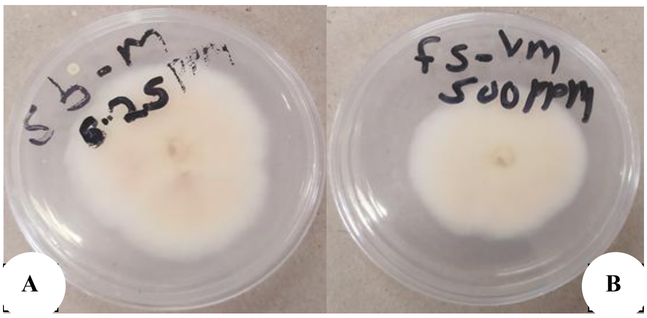

Figure 3. Inhibition of growth of *Fusarium oxysporum* by *T. indica* pods methanol extracts at a concentration of A. 62.5 ppm and B. 500 ppm

Discussion

Extraction of phytochemical compounds from plants

In this study, different extraction solvents resulted in differences in the phytochemicals extracted from different samples. Different solvents extract different phytochemical compounds based on the polarity of the solvent. Yadav and Agarwala (2011) researched seven medicinal plants using four solvents (water, methanol, ethanol, and acetone) and detected different phytochemical compounds. Extraction of the phytochemical compounds from plants depends on various factors, such as solvents, polarity, and temperature. These factors influence the types of metabolites in the crude extracts (Stéphane et al. 2021). Nwodo et al. (2011) found a significant variation in the phytochemicals present in a stem sample taken from *T. indica* when extracted using hot water, cold water, and methanol. Methanol and acetone extracts of *T. indica* provided higher phenol, flavonoids, and saponins yields than other solvent extracts (Moteriya et al. 2015; Estevinho et al. 2018). This demonstrates that crude aqueous and organic solvent extracts yield medicinally significant bioactive substances. When several extraction solvents (water, petroleum ether, and water) were used in the extraction process, the extracts obtained from *T. indica* displayed potential antibacterial action (Warda et al. 2007). Another study by Padalia et al. (2015) combined hexane and water to extract phenols, while

Abdallah and Muhammad (2018) combined water and methanol to detect different phytochemicals. However, the best extraction method should be realized quickly with minimal solvent consumption (Ameer et al. 2017; Rahimi et al. 2022).

In this study, methanol had a relatively high number of phytochemicals detected. The extracts obtained using methanol also showed the highest inhibition of growth of *F. oxysporum* as compared to extracts obtained using acetone and dichloromethane. These findings could be explained by the fact that various phytochemicals are more soluble in methanol than other solvents (Young 2004). In a study conducted by Abdallah and Muhammad (2018), methanol extracts of *T. indica* exhibited higher antimicrobial activity than aqueous extracts. According to Kalpana and Prakash (2016), methanol extracts exhibited greater antimicrobial sensitivity than extracts obtained using acetone. In a similar study, methanol extracts were more effective than other extracts in a comparable trial to test 12 medicinal plants for possible antibacterial activity against five medically important bacteria (Parekh et al. 2005). Similarly, Nauman and Arshad (2011) assessed the antibacterial activity of aqueous methanol extracts of 10 plants against two gram-negative and three gram-positive bacteria and found positive results. In addition, according to Biscaia and Ferreira (2009), the extraction yields of methanol extracts were higher than those of other solvent extracts, with a decrease in polarity.

Acetone also exhibited considerable extraction potential for seven phytochemicals, though at a lower concentration; this solvent has been used for extraction in many related studies because it is more affordable and reproducible to assess plant extracts' efficacy than to conduct animal experiments (Adamu et al. 2013). However, various studies use acetone only for precipitation and concentration of total proteins while simultaneously removing interfering substances (Niu et al. 2018). Dichloromethane was the least applicable solvent compared to acetone and methanol. Of the nine phytochemicals under study, only four were found at much lower concentrations. According to Mohammadi et al. (2016), *Urtica dioica* dichloro methanolic extract can efficiently induce apoptosis in PC3 cells; as a result, it may be employed as a novel therapeutic candidate for prostate tumor treatments. In a related investigation, the dichloromethane extract of the aerial portions of *Satureja khuzistanica* was used to characterize four substances with promising outcomes (Moghaddam et al. 2007). The differences observed in the phytochemicals present could be due to various solvent factors such as concentration, temperature, pressure, and polarity (Kar et al. 2019).

Phytochemical compounds of Tamarindus indica *extracts*

A total of nine phytochemicals were identified from the different parts of *T. indica*. This diversity of phytochemical compounds was reported in similar research (Nwodo et al. 2011; Gomathi et al. 2017). The presence of different enzymes in different plant parts, the different roles of the parts, and the level of exposure of each plant part could be caused this variation (Doughari et al. 2006; Saxena et al. 2014; Nemzer et al. 2020). In this study, steroids were the most abundant phytochemicals in *T. indica* leaves and pods, probably due to the high presence of cyclization enzymes that form steroids in various biological processes. Steroids are synthetic organic compounds crucial during hormone formation and activation (Wood and Gower 2010). They possess numerous intriguing medical, pharmacological, and agrochemical activities (Ericson-Neilsen and Kaye 2014). Numerous steroid compounds are produced by plants and are employed as hormones and allelochemicals (Dinan et al. 2001).

Tannins were present in every plant part of *T. indica*. Due to their antimicrobial and insecticidal effects, their presence probably protects the plant from pests and diseases. These important water-soluble plant phenolics fight pathogens integrally (Hussain et al. 2019) and have exhibited antimicrobial activity against some phytopathogenic fungi (Gade et al. 2020). Besides, Tannins and alkaloids also have a very high antimicrobial and insecticidal effect (Qiu et al. 2014; Hussain et al. 2019). Additionally, Terpenoids are non-polar phytochemicals that are insoluble in most polar solvents; hence, non-polar solvents are the best options for their extraction (Martins et al. 2017). Natural resins are known for their antiseptic and antibacterial benefits (Shuaib et al. 2013) and are also incredibly beneficial for helping plants repair their wounds (Timmermann et al. 2013). In this study, the resins were not found in any parts of the plant. These phytochemicals were most likely present in their precursor forms as diterpenoids and triterpenoids and would only be activated when the plant was injured. However, different locations and the plant part's general health and stress level may determine the phytochemical composition present (Gil et al. 2002; Özcan and Chalchat 2005; Timmermann et al. 2013; Papazian and Blande 2020).

Antifungal assay of Tamarindus indica *extracts against* Fusarium oxysporum

Extracts from *T. indica* showed significant antimicrobial activity against *F. oxysporum*. The inhibition was similar to that Rongai et al. (2012), and Awere et al. (2021) reported. Similarly, Dissanayake (2013) demonstrated radial mycelial growth inhibition when plant extracts were applied to their growth media. A different study studied the antifungal activity of *T. indica* (leaves, stem bark, and pulp) against *Aspergillus niger, A. flavus, and F. oxysporum* (Abubakar et al. 2010). Of the three plant parts, the stem bark inhibited the growth of *A. flavus* and *F. oxysporum*. In a similar study, the crude extracts of leaves, stems, fruit pulp, seeds, and bark of *T. indica* were toxic against *A. flavus* and *F. oxysporum* in vitro (Ramaiah and Garampalli 2015). In a phytochemical analysis done on *T. indica* by Hussain et al. (2019), the root and stem samples exhibited the highest yield of phytochemicals compared to all other parts analyzed. They showed high concentrations of tannins and flavonoids, which are very important in fighting plant pathogens. According to Barros et al. (2011), roots and leaves show great antifungal potential. Bautista-Baños et al. (2002) also found that the stem, fruit, and leaves of *T. indica* manifest significant inhibition of the growth of *Colletotrichum gloeosporioides.*

In this study, it was observed that an increase in the plant extract concentration reduced the percentage of inhibition. This can be attributed to an increase in the amount of bioactive compounds. This is similar to a study by Al-Hetar et al. (2011) and Ramaiah and Garampalli (2015). The reduced free reactive radicals can explain a gradual decrease in the percentage inhibition observed at 1,000 ppm. Thus the phytochemicals form a stable structure with tight bonds that are not easy to break, resulting in a reduction in kinetics (Ochoa-Gómez et al. 2009). The increase in concentration also meant that there was an increase in the viscosity of the extract. A study conducted by Meyer et al. (2014) showed an inverse relationship between viscosity and diffusion. That suggests as the viscosity increased, the distribution of the antimicrobial in the culture medium may have been reduced, lowering the overall inhibition of *F. oxysporum* growth. The positive control showed the highest percentage of inhibition compared to the plant extracts. The *T. indica* extracts inhibited growth in crude form, indicating that further purification and isolation of the bioactive compounds is possible.

Antibacterial assay of Tamarindus indica *extracts against* Xanthomonas campestris

All *T. indica* extracts showed no antibacterial activities against *X. campestris,* probably due to the pathogen's tolerance degree towards the bioactive compounds in the extracts. Compared to a study by Satish et al. (2009), where 30 plant extracts were assayed for their antibacterial effect against *X. campestris*, only eight showed significant inhibition against the *F. oxysporum* pathogen. Interestingly, the dryland plants showed less inhibition than the wetland plants. In a different study, the efficiency of *Bacillus subtilis* was evaluated against three strains of *X. campestris* pv. *campestris* in four *Brassica* crops (cabbage, cauliflower, rape, and broccoli) (Wulff et al. 2002). Biological control was effective in broccoli but not in cabbage. According to Bobis et al. (2015), gram-negative bacteria exhibit higher antibiotic tolerance than gram-positive bacteria. That was also reported by Paterson (2006), who demonstrated a wide range of resistance in gram-negative bacteria. The Gram-negative bacteria possess a periplasmic space between the outer lipid membrane and the inner peptidoglycan layer that contains enzymes that may lead to the breakdown of secondary compounds, thus offering great resistance (Costerton et al. 1974; Bondarczuk and Piotrowska-Seget 2013). The findings contradict those of Patel et al. (2013) and Kalpana and Prakash (2016), who described experiments in which plant extracts tested positive for pathogen sensitivity. While there are so many *X campestris* strains, maybe *T. indica* extracts may be effective in some but not others.

In conclusion, different phytochemicals can be found in different parts of *T. indica*; these phytochemicals are obtained with different solvents used for extraction. Compared to acetone and dichloromethane extracts, methanol-derived extracts have the highest percentage of *F. oxysporum* inhibition. The percentage of inhibition also varies among the various plant parts, with the roots and stem bark displaying the highest percentage of inhibition. *T. indica* extracts have a significant ability to combat *F. oxysporum* and can, therefore, play a crucial role in integrated pest and disease management. However, the extracts showed no inhibition against *X. campestris,* probably due to the pathogen's tolerance. More research is needed to determine the structures of the phytochemical compounds present in *T. indica* extracts.

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Review:
Rangeland management in Tanzania: Opportunities, challenges, and prospects for sustainability

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Abstract. *Muzzo BI, Maleko DD, Thacker E, Provenza FD. 2023. Review: Rangeland management in Tanzania: Opportunities, challenges, and prospects for sustainability. Intl J Trop Drylands 7: 83-102.* Rangelands in Tanzania play a crucial role in supporting local livelihoods and the country's economic development. However, their long-term sustainability is threatened. This review paper identifies challenges and explores opportunities to ensure their continued sustainability. Opportunities include implementing dedicated policies and regulations, using expertise in range science, leveraging technological advancements, investment land for opening private ranches, ample bushes and shrub resources for small ruminants, and high market demand for milk and meat from ruminants. Major challenges include insufficient technology and limited technical know-how, low and erratic rains leading to dry season pasture scarcity, infectious diseases, and the spread of invasive species. Other challenges include conflicting interests from other land users that have led to the massive conversion of communal rangelands to croplands, areas to protect wildlife, and human settlements. These challenges can be addressed by policy enforcement, strengthening pastoral organizations, fostering the growth of experts in climate-adapted forage breeding, and embracing advanced technology. Active involvement of local communities in decision-making processes and facilitating rangeland restoration can ensure the sustainable management of rangelands in Tanzania. Another promising avenue is the strategic use of locally adapted livestock species to control invasive plants, complemented by governmental enforcement of a grading system for meat and establishing a price-based quality meat market. Incorporating these prospects into rangeland management strategies can enhance the ecological sustainability and resilience of rangelands while supporting local livelihoods. Future research should focus on evaluating and implementing these strategies to promote sustainable rangeland management practices in Tanzania and elsewhere with similar environment.

Keywords: Invasive species, nomadism, rangeland improvement, shrubs and bushes, Tanzania

INTRODUCTION

Rangelands are extensive natural landscapes, covering approximately 40-50% of the Earth's terrestrial surface (Robinson et al. 2019). These landscapes include grasslands, shrublands, savannahs, woodlands, deserts, tundra, and riparian and wetland areas. The lands are unsuitable for cultivation activities but revegetated naturally or artificially and managed like native vegetation. The predominant vegetation in rangelands are grasses, forbs, shrubs, and fodder trees, proving suitable forage for wildlife and livestock species through grazing or browsing. Rangelands play a significant role in environmental, economic, and cultural functions supporting millions of people worldwide (Bremer et al. 2021). In Tanzania, rangelands which receive an annual rainfall of less than 700 mm, are mostly allocated in the country's Central and Northern regions (Figure 1). They provide several ecosystem services, including habitat for wild flora and fauna, carbon sequestration, and catchments for watersheds. They also provide forage for ruminant livestock production systems. Tanzania has 35.3 million cattle, 25.6 million goats, and 8.8 million sheep, mostly raised in rangelands (URT 2022). According to the NAFORMA (2015), grazing and wildlife areas cover 10.5% and 22% of the Tanzanian mainland, respectively. This provides an estimated 9,923,414 ha for grazing and 20,791,914 ha for wildlife, with nearly half of these areas managed as private or protected areas and ranches, while the remaining acreage is village or public land (Figure 2). Tanzanian livestock production is sustained by rangelands dominated by native pastures, contributing 7.4% of the national GDP (Nandonde et al. 2017). Most communal lands are dominated by miombo woodlands that receive less than 700 mm of precipitation per year (Ruvuga et al. 2021), followed by grassland (800-1200 mm), forest grassland, and gallery forest (1,200 to 2,000 mm) and thick bush lands (600 to 800 mm). The major Tanzanian rangeland products and services are potable water for human use, irrigation for forage crops for livestock, and various products such as meat, milk, wool, leather, and medicinal plants.

In 2022, the Tanzanian government formally incorporated communal rangelands into land regulations as a method for empowering the people to make proper use of existing resources. Kamwenda (2002) suggested that closely tracking resource utilization by village guards (*sungusungu*) and village assemblies (*dagashida*) in the north-western semi-arid regions of Tanzania could protect resources. However, these areas are degraded, and some cannot support grazing because of seasonal variations in the quantity and quality of forages (Selemani 2014). Rotational grazing systems are often used to promote recovery of diverse plant richness (Muzzo and Provenza 2018; Harmel et al. 2021). However, Tanzania's population is 61.7 million (NBS 2022), with an estimated annual average growth rate of 3.1% since 2012. This has led to the conversion of rangelands into settlements and croplands (Table 1) to increase food security. Although Participatory Rangeland Management (PRM) projects have been implemented in some regions of Tanzania, management practices remain less adaptable, and benefits from common properties are not equally distributed, and as Flintan (2012) noted, common property decisions are often made irrationally due to self-interest. Numerous practices can enhance Tanzanian rangeland management. In their studies, Rainsford et al. (2021) and Rego et al. (2021) emphasized the significant contribution of fire to ecosystem health, highlighting the importance of accurate timing in the application of prescribed burning to effectively manage undesirable rangeland plants that can hinder livestock productivity. Fire and herbivory are ecological processes that drive the heterogeneity of rangelands. Fires clear away dead vegetation, promote fast regrowth of fire-tolerant plant species (e.g., *Themeda triandra* grass and *Acacia nilotica* fodder tree), and create more open spaces (Lamont et al. 2019). The intensity and frequency of fires influence the type and structure of vegetation in a given area (Fernandez-Garcia et al. 2020), while excessive fires lead to massive death of plant communities. Grazing by herbivores affects the composition and structure of plant communities (Lindén et al. 2021). Different species of herbivores may selectively graze specific plant species, which can impact the overall vegetation composition (Pauler et al. 2020). When fire and herbivory occur in the same spatial and temporal scales, they create heterogeneity that can attract wildlife and livestock to recently burned patches (Fuhlendorf et al. 2009). Pyric herbivory or patch-burning strategic practice can not only enhance livestock production and benefit wildlife but also increase heterogeneity, which in turn increases biodiversity, enhancing ecosystem services (Allred et al. 2014; Scasta et al. 2016; Scasta et al. 2023). In a changing climate associated with extended drought and variable rainfall, improved pasture and irrigated farm pastureland are essential for maintaining annual livestock production (Ndesanjo and Theodory 2021). Feed conservation, crop residue, hay, and lopping practices offer alternative strategies to sustain livestock productivity during dry seasons (Muzzo and Provenza 2018).

In conclusion, proper range management practices will help sustain ecosystems and biodiversity, which can help reduce soil erosion, increase vegetation cover, and increase water infiltration, eventually increasing water flow into the soil, streams, and reservoirs. Conversely, a growing Tanzanian population is increasing demands for water, food, and other rangeland resources. Tanzanian rangelands support unique wildlife species important for tourism and recreation. The future of these multi-benefits from Tanzanian rangelands is uncertain due to global climate change and variability. Therefore, this review paper explores the challenges and opportunities within Tanzanian rangelands and fills some gaps in prospects for their sustainability.

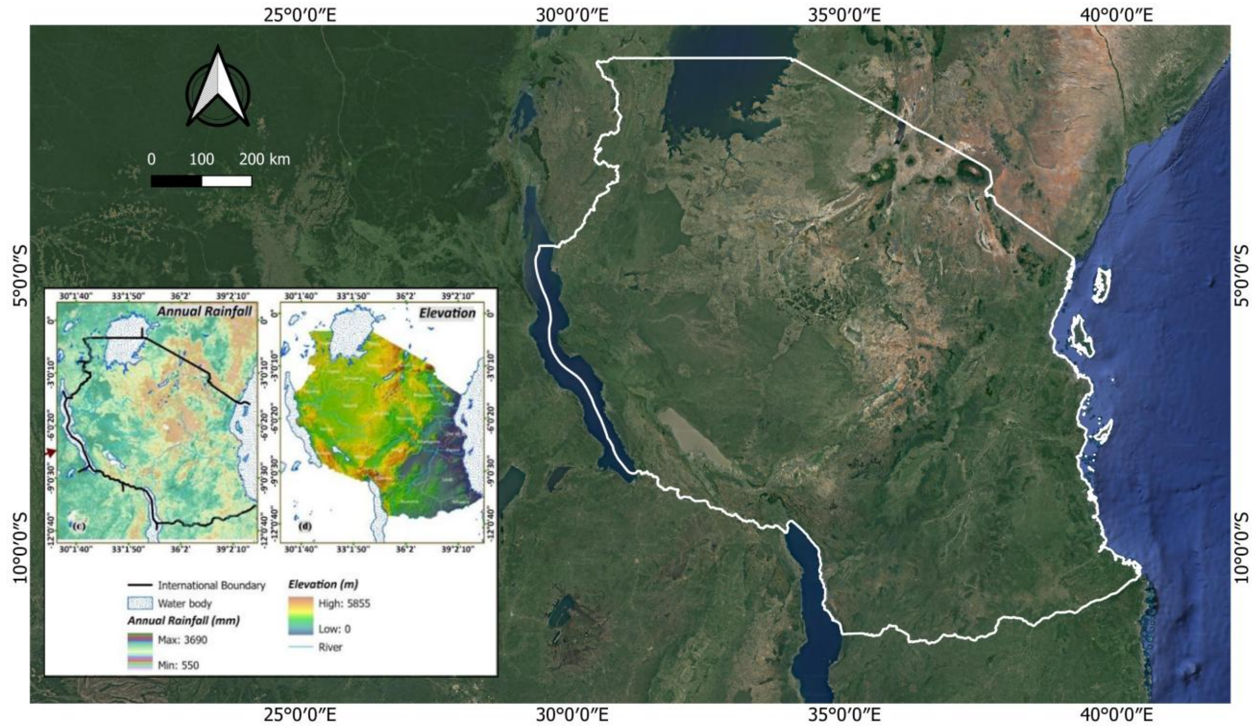

Figure 1. A map showing the location of Tanzania

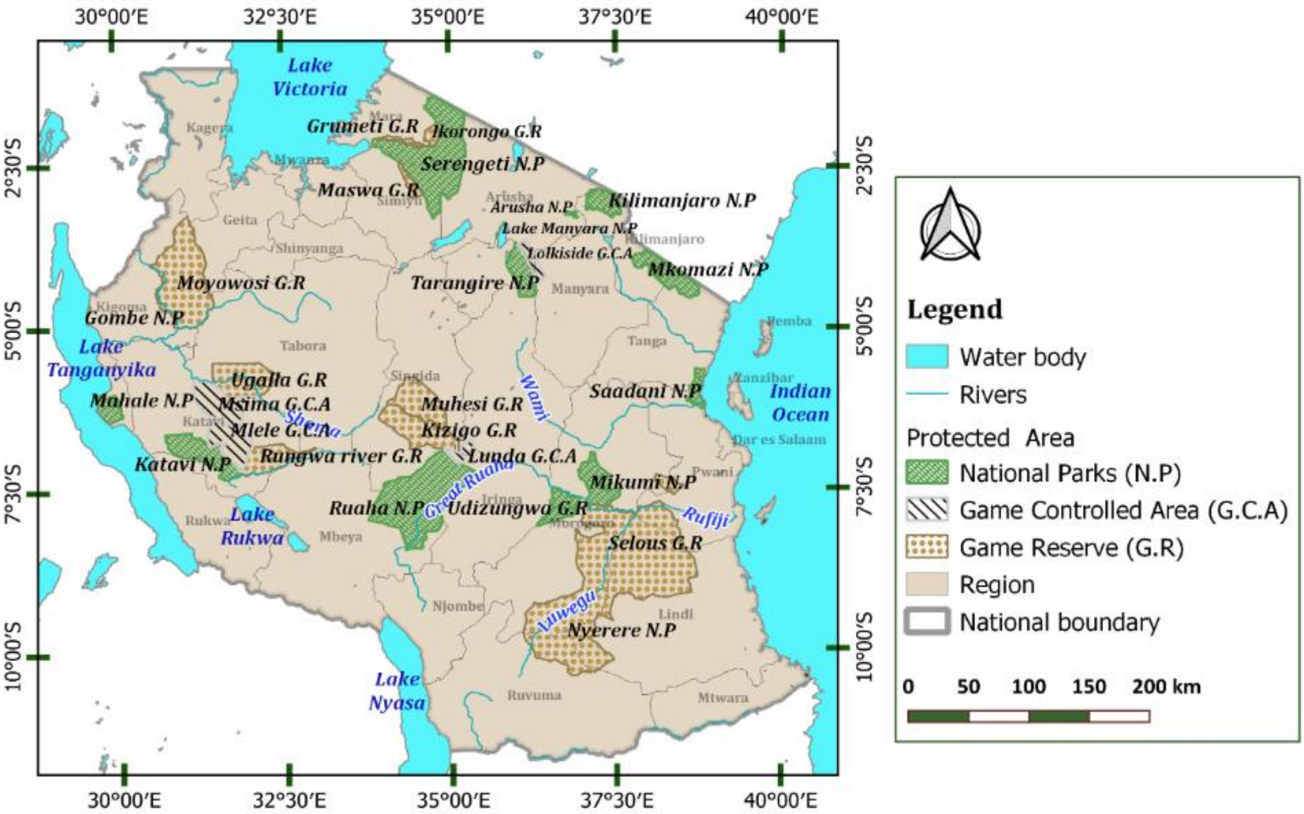

Figure 2. Map of Tanzania showing the distribution of different wildlife protected areas in the rangelands

Table 1. Land use area and rate of change in cover classification according to Nzunda and Midtgaard (2019)

Cover class and land use	Area (ha)[a]		Total changed area 2010–1995 (ha)	Changed area per year (ha/yr)	2010 Area as a percentage of 1995 area	% Annual rate of change [b]
	1995	2010				
Bushland	17,372,207	12,666,025	-4,706,182	-313,745	72.90	-2.10
Cultivation	9,764,073	31,967,393	22,203,320	1,480,221	327.40	7.90
Grassland	20,606,711	6,056,976	-14,549,735	-969,982	29.40	-8.20
Forest	38,097,662	33,296,651	-4,801,010	-320,067	87.40	-0.90
Cover and other land uses	1,715,590	3,569,198	1,853,608	123,574	208.00	4.90

Note: The 2010 land cover map did not include 514,594 ha of unclassified area, and rate annual changes was calculated according to Puyravaud (2003)

OPPORTUNITIES FOR PROPER MANAGEMENT

Availability of experts, institutions for rangeland management and research

Experts in range science, such as graduates from Sokoine University of Agriculture (SUA), the Tanzanian Presidents' Office, Ministry of Agriculture, Livestock, and Fisheries (MLF), Regional Administration, and Local Government Tanzania (PO-RALG), along with institutions like the Tanzania Livestock Research Institute (TALIRI) and Livestock Training Ageny (LITA), and the Rangeland Society of Tanzania (RST) an NGO, can make significant contributions to managing rangelands. Moreover, the Tanzania Wildlife Authority (TAWA) and Tanzania Wildlife Research Institute (TAWIRI) are another key stakeholders in addressing the various challenges of human, wildlife, and livestock interactions in the rangelands. The number of SUA graduates in range management averaged 60 students per academic year from 2011 to 2022. The first B.Sc. Range Management students enrolled in 2008; since 2011, students have continuously graduated, resulting in 664 graduates by 2022 (Figure 3). They possess the knowledge and skills required to sustainably manage rangelands. Regarding gender, between 2011 and 2022, SUA graduated 193 females and 471 males with a B.Sc. in Range Management (Figure 4). This underscores the institution's steadfast commitment to promoting gender diversity in this field, ensuring that Tanzania's livestock keepers benefit from a diverse and well-trained pool of graduates. However, there is a challenge in securing relevant employment for these graduates, as there are limited job opportunities in government rangeland management sections and private companies. This is due to lower government budget allocations, policies, and sectoral prioritization. Additionally, there may be a scarcity of companies specifically dealing with the graduates' specialty. Within MLF and PO-RALG, leading heads of the sector employ range/livestock officers to oversee and facilitate sustainable rangeland management practices. Their roles are instrumental for effectively implementing policies and practices essential for rangeland management. TALIRI operates seven research centers strategically located in seven agro-ecological zones of the Tanzania Mainland. These centers include Kongwa (Dodoma) and TALIRI Mpwapwa, TALIRI Naliendele (Mtwara), TALIRI Mabuki (Mwanza), TALIRI Tanga, TALIRI West Kilimanjaro (Kilimanjaro) and TALIRI Uyole (Mbeya), these centers conduct invaluable research on rangelands in diverse environments, significantly advancing our understanding of rangeland dynamics and serving as vital sources of guidance for sustainable use and conservation. TAWIRI comprises four Research Centers, including Kingupira Wildlife Research Centre (Selous Game Reserve), Njiro Wildlife Research Centre (Njiro in Arusha), Mahale-Gombe Wildlife Research Centre (Gombe National Park), and Serengeti Wildlife Research Centre (Serengeti National Park). These research centers provide invaluable insights into the intricate interplay between wildlife and rangelands. They offer essential research, extension services, and capacity-building initiatives that are fundamental for harmonizing rangeland conservation with wildlife habitat preservation. In addition to these government institutions and academic establishments, the Rangeland Society of Tanzania (RST) unites professionals and experts in range science. This collaborative platform fosters knowledge exchange and advocates adopting sustainable rangeland management practices. Moreover, the active engagement of non-governmental organizations (NGOs) is pivotal in this holistic approach. There are numerous NGOs, both national, such as Tanzania Natural Resources Forum (TNRF), and international, such as The Nature Conservancy (TNC), Wildlife Conservation Society, and International Livestock Research Institute (ILRI), working to promote sustainable rangeland Management in Tanzania. These organizations work in synergy with governmental bodies, academic institutions, and local communities to implement projects and initiatives aimed at rangeland conservation and supporting community livelihoods. Their involvement amplifies the collective impact on the sustainable management of Tanzania.

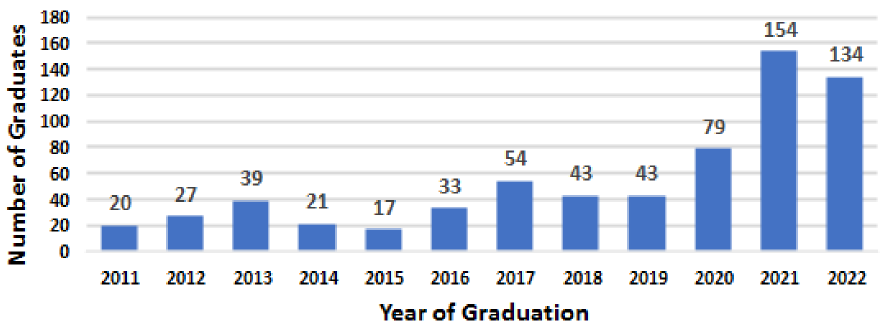

Figure 3. Number of individuals who graduated with B.Sc. Range Management at SUA between year 2011 and 2022 (Source: Sokoine University of Agriculture)

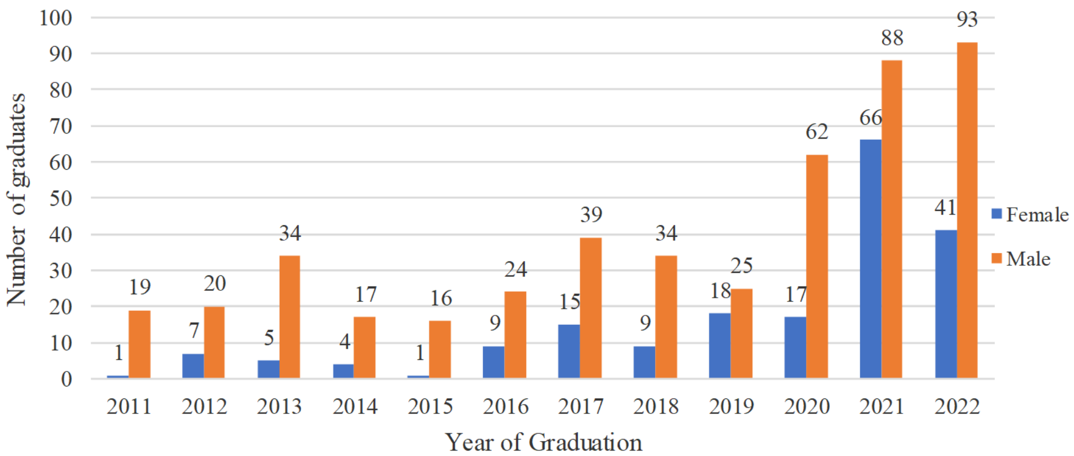

Figure 4. Number of individuals who graduated with B.Sc. Range Management at SUA between 2011 and 2022 by gender (Source: Sokoine University of Agriculture)

Availability of policy and regulations for rangeland management

The Grazing land and Animal Feed Resources Tanzania Act, 2010 (No. 13) provides legal frameworks for managing rangelands in Tanzania. The act promotes community participation in rangeland management, allowing for the involvement of local communities in decision-making processes. That promotes a sense of ownership and responsibility among the communities towards the sustainable management of rangelands. The act also regulates grazing activities, specifying the number of animals that can be grazed on a particular area of rangeland, the duration of grazing periods, and the use of rotational grazing systems. This helps to prevent overgrazing, soil erosion, and degradation of rangelands. In addition, the act promotes the conservation of rangelands and their biodiversity by providing guidelines for demarcating and safeguarding grazing lands. It recognizes the importance of rangelands in supporting wildlife, particularly in areas designated for conservation, while providing guidelines for managing rangelands in in ways that balance the needs of livestock and wildlife. Finally, the act penalizes illegal activities that damage rangelands, such as logging, charcoal production, and mining. This helps to deter illegal activities that can destroy rangelands and their ecosystems.

Technological advancement for range improvement

Tanzania has recently achieved major technological strides in range improvement with the goal of enhancing the management, sustainability, and production of rangelands. Remote sensing technology, such as satellite imagery, is used to monitor and map rangeland conditions, including vegetation cover, soil moisture, and land use changes (Jamali et al. 2023). According to a systematic review by Nzunda and Yusuph (2022), Geographic Information Systems (GIS) are used in rangeland management in Tanzania to analyze and visualize spatial data, assess land use changes, and monitor grazing patterns. GIS is also used to map the distribution of rangeland resources, identify areas of degradation and the potential distribution of invasive alien species (Sutomo et al. 2016). This technology has effectively identified potential areas for sustainable grazing and improved pasture management. Thus, GIS is a useful tool for rangeland managers in Tanzania to make informed decisions and develop effective management plans. Wiethase et al. (2023) found remote sensing and ecological modeling methods were used to investigate degradation of rangelands in Northern Tanzania. By integrating remote sensing and ecological modeling, researchers have identified pathways of degradation in rangelands, assessed the potential for recovery (Donovan and Monaghan 2021). They found degradation was driven by overgrazing, bush encroachment, and soil erosion and that these pathways led to a loss of vegetation cover and soil fertility. However, they also found with proper management practices, such as rotational grazing and bush thinning, rangelands can recover and regain their productivity and ecological functions. In addition, integrated ecological modeling has been employed to map the potential distribution of invasive species under current and future climatic conditions, providing valuable insights for managing *A. nilotica* invasive species in Central-Eastern Indonesia (Sutomo and Van Etten 2017). Mobile-based applications, such as the Tanzania Livestock Market Information System (TL-MIS), provide information on market prices, livestock diseases, and other relevant information to livestock farmers. This helps people make informed decisions on livestock production and marketing. Tanzania has developed and distributed improved pasture seeds, such as *Brachiaria* grass and *Napier* grass, that are more resistant to drought and pests and have higher nutritional value. According to a study by Tenga and Mramba (2015), adopting improved forage varieties has improved livestock production, reduced pressure on natural rangelands, and enhanced soil fertility. For example, the Tanzania shorthorn zebu cattle breed is known for its high disease resistance and adaptability to harsh environmental conditions. According to a study by Yonas (2020), crossbreeding of local and exotic breeds has improved breeds with higher productivity and resilience to the adverse effects of climate change. Water harvesting techniques such as constructing water ponds and dams, are used to store water for livestock and wildlife during the dry season. This helps to reduce pressure on natural water sources and supports the sustainable use of rangelands. Tanzania has also implemented community-based management systems, such as village land use planning and joint forest management, to promote community participation in rangeland management. Collectively, these practices help to ensure the sustainable use of rangelands and reduce conflicts over natural resources.

Investment land for opening private ranches

Achieving the sustainable use and management of rangeland resources in Tanzania requires a multifaceted approach considering ecological, social, and economic factors. The country's rangelands are critical to its economy, providing grazing areas for livestock, which is a key source of income for many rural communities. According to Yanda et al. (2021), private ranching provides an alternative land-use option for rangelands in Tanzania, especially in areas where communal grazing can lead to overgrazing, land degradation, and encroachment. Private ranching can provide incentives for proper land management, as the owners have a financial interest in maintaining the health and productivity of their land in ways that lead to better grazing management, reduced overgrazing, and improved rangeland health. The Mwiba Wildlife Reserve is one example of a successful private ranch in Tanzania. This 125,000-acre reserve was established in 2006 and is managed by the Friedkin Conservation Fund. The reserve provides more diverse habitats for wildlife, such as elephants, lions, and giraffes. It also generates revenue through ecotourism, with visitors paying to stay at the reserve's luxury lodges. Also, the Manyara Ranch Conservancy, spanning 45,000 acres and managed by the African Wildlife Foundation, offers another compelling illustration of private ranching's potential. This conservancy provides a sanctuary for wildlife such as elephants, zebras, and wildebeests and serves as an income source for the local Maasai community through ecotourism and grazing fees. Furthermore, the Makoa Farm, situated in the southern highlands of Tanzania, demonstrates the efficacy of private ranching practices that integrate this ranch supports livestock production and wildlife conservation over approximately 3,707 acres. The farm embraces holistic management principles, incorporating planned grazing, water resource management, and soil conservation to rejuvenate rangeland health. This approach has yielded tangible benefits, including increased livestock production, enhanced soil health, and restoration of previously degraded rangelands.

Availability of ample bush and shrub resources for small ruminants' production

Tanzanian rangelands have a high diversity of plant species, which include a variety of shrubs and woodlands over 33 million ha that provide valuable forage for small ruminants such as goats and sheep (Nzunda and Midtgaard 2019) (Figure 2). These shrubs and woodlands have high nutritional quality and palatability for small ruminants, making them a valuable source of protein, minerals, and vitamins. Browse species such as *Acacia*, *Commiphora*, and *Terminalia* spp contain high levels of crude protein and minerals in their leaves, making them highly preferred by goats and sheep (Kideghesho 2016). Furthermore, the fruit pulp and leaves of *Tamarindus indica* contain secondary compounds with potential medicinal properties, aiding in the treatment of digestive issues and acting as a natural anthelmintic. *Azadirachta indica*, commonly known as neem tree, represents another valuable resource for managing various livestock ailments, particularly external parasites (Landau et al. 2009). Certain *Acacia* shrub species, like *Acacia angustissima*, have condensed tannins that can reduce enteric methane emissions and environmental impacts (Naumann et al. 2018). Moreover, *Acacia* species are renowned as nitrogen-fixing legumes, offering valuable forage for animals and contributing to soil fertility.

The abundance of shrubs in Tanzania's rangelands presents a valuable opportunity for raising small ruminants, allowing them to benefit from a wide range of nutritious forages that benefit their health and human health. The selective grazing behavior of small ruminants, which enables them to target the most nutritious portions of vegetation, maximizes their nutritional intake and growth potential, enhancing the productivity and market value of small ruminants raised in rangelands (Claps et al. 2020). Shrubs within the grazing landscape offer small ruminants access to a more diverse diet, ensuring a balanced intake of nutrients and other health-promoting phytochemicals (Villalba et al. 2019). Goats raised in rangelands exhibit higher body weights and market values than those raised on farm-based diets (Dieters et al. 2021). In turn, the health of humans is promoted by eating meat and dairy products from livestock that consume diverse mixtures of phytochemically rich plants (Provenza et al. 2019; Van Vliet et al. 2021). Tanzanian pastoralists have historically relied on various shrubs as remedies for their animals nutritional and medicinal needs. Further research is needed to identify secondary compounds within the most common shrubs that may benefit animal health and production while reducing environmental impacts and greenhouse gas emissions. Muzzo and Provenza (2018) have proposed exploring ethno-veterinary pharmacopeia and plant usage as alternatives to costly veterinary medications. Thus, incorporating shrubs into the ecosystem can benefit soil health, promote plant growth, and enhance animal and human well-being.

High market demand for milk and meat from rangeland ruminants

The demand for a range of products is a significant driver for managing rangeland areas in Tanzania. According to the Tanzania Livestock Modernization Initiative, the country has an estimated 34 million cattle, which provide a valuable source of meat for the local and export markets (Nandonde et al. 2017). Over the last decade, milk production has increased significantly, but the need for improved breeds and specialized feed has resulted in poor milk yields (CSIRO 2022). In recent years, the milk demand has surged owing to population growth and the economy. This has widenec the gap between the demand and the local milk supply (Blackmore et al. 2022; Maleko 2022). According to MLF's report in 2017, the projected increase in beef meat production by 52% will not meet demands of the expected 71% growth in consumption by 2022, resulting in a 17% deficit (124,778 tons) in beef production and consumption (MLF 2017). Additionally, the Livestock Analysis (LSA) estimates a significant red meat (beef) supply gap of 1.7 million tons by 2031-32 under the business as usual (investment scenario. This suggests that by 2031, the anticipated domestic beef production will only meet 15% of domestic consumption (MLF 2017). The resulting deficit will likely increase meat prices, impacting consumers in Tanzania. This may increase pressures on rangelands and lead to overgrazing, soil erosion, and land degradation, which will decrease productivity, posing a threat to the industry's long-term sustainability. Therefore, managing rangelands sustainably presents an opportunity to improve the productivity and health of the land, thus increasing the supply and market value of range products. Sustainable management practices can improve the quality and quantity of pasture, leading to higher meat yields and better prices for farmers. Rotational grazing, where livestock are moved between pastures to allow for vegetation recovery, can increase the weight gain of livestock, resulting in higher meat yields (Msofe et al. 2019; Munson et al. 2020). Similarly, sustainable management of rangelands can enhance the availability and quality of pasture seeds and milk for sale, thus increasing the industry's profitability.

In addition to livestock, wildlife can become a valuable source of income. Wildlife can add value through utilitarian uses such as hunting or harvesting wild game meat for local use or as part of an ecotourism operation for international markets. However, unregulated hunting practices can lead to exploitation of wildlife, resulting in population declines and loss of biodiversity. When wildlife species have economic value, and their use is regulated, they help promote conservation and provide opportunities for conservation practices. However, caution should be used when creating or supporting wildlife markets; creating wildlife markets can lead to the exploitation of wildlife resources. While some argue that hunting operations have increase conservation efforts in places like Tanzania, others have questioned this approach's effectiveness, ethics, and social considerations (Lindsey et al. 2007). In North America, the elimination of wildlife markets that sold wild game meats is partially credited with reducing the illegal taking of game in the USA in the late 19th and early 20th century (Trefethen 1975). Regulating hunting and harvesting is essential to the long-term sustainability of game species (Trefethen 1975; Thacker et al. 2023). Sustainable hunting practices, such as regulated quotas and regulated hunting seasons, can provide a source of wild game meat for sale while ensuring the long-term conservation of wildlife (Ingram 2020; Ingram et al. 2021). Therefore, there is a need for a coordinated effort among stakeholders, including government agencies, farmers, and local communities, to implement sustainable management practices and meet the marketing demand for a range of products in Tanzania. Sustainable rangeland management practices can improve livestock and wildlife productivity and land health while reducing the industry's environmental impact.

RANGELANDS MANAGEMENT CHALLENGES IN TANZANIA

Limited knowledge of sustainable rangeland management

Limited knowledge and skills in rangeland management in Tanzania has led to degradation and desertification, with significant economic, social, and environmental consequences. Overgrazing, inadequate control of invasive species and unsustainable grazing practices are prevalent issues, resulting in soil fertility loss and declining vegetation cover (Beever et al. 2006; Middleton 2018; Wassie 2020). Increased investment in education and training programs is essential to address this challenge. Capacity-building initiatives should focus on soil and water conservation, range ecology, and livestock management (Cullen et al. 2014). Collaborative efforts involving research institutions, government agencies, and stakeholders can promote innovative approaches like precision livestock management techniques, using GPS tracking, and remote sensing to optimize grazing patterns and reduce overgrazing (Bailey et al. 2021). Other countries have improved rangeland management through technological advancements and research. Satellite technology in Australia aids in mapping rangeland vegetation, facilitating targeted management interventions (Ward et al. 2016). Incorporating indigenous knowledge and practices, such as rotational grazing and controlled burning, can also promote rangeland health and productivity (Finca et al. 2023). Similarly, shepherding practices, as adeptly employed by the Maasai, have been successfully harnessed for enhancing rangeland conditions and reducing predation pressures. By addressing knowledge gaps and applying successful strategies from other countries, Tanzania can improve rangeland management, mitigate degradation, and preserve these valuable resources.

Tanzania's rangelands are a critical resource for the country's economy, supporting livestock production and wildlife conservation and providing vital ecosystem services (URT 2022). Multisectoral competition among agriculture, forestry, mining, urbanization, and wildlife conservation is a significant challenge facing rangeland management in Tanzania (Kivelia 2007; Msoffe 2010; Nuhu 2019; Mahajan et al. 2021; Anthony et al. 2023). These sectors have different objectives and priorities, which can sometimes conflict, leading to unsustainable land use practices that degrade the rangeland ecosystem. For instance, the expansion of agriculture and settlement has resulted in the conversion of Maasailand rangelands to croplands and urban areas, which has led to habitat loss and fragmentation, reducing the carrying capacity of rangelands (Kivelia 2007; Msoffe 2010; Anthony et al. 2023). Similarly, mining activities in the Mara region have led to soil disturbance, land degradation, and water pollution, affecting the quality of rangelands (Matano et al. 2015). Establishing Wildlife Management Areas (WMAs) in Tanzania was intended to involve local communities in wildlife management on village lands and promote wildlife conservation. However, implementing WMAs have yielded the expected socioeconomic benefits due to top-down approaches that overlook the meaningful participation of local communities and led to conflicts and disengagement from local communities. WMAs have been converting community grazing land, leading to conflicts between local communities in the Maasai Steppe and the Eastern Arc Mountains and conservation authorities. Nelson et al. (2016) found that WMAs converted over 160,000 hectares of community grazing land between 2009 and 2014, negatively impacting local communities, particularly pastoralists. Similarly, Moyo et al. (2016) and Kicheleri et al. (2018) reported that establishing a WMA in the Burunge Wildlife Management Area resulted in conflicts between conservation authorities and local pastoralists due to the enclosure of communal grazing lands. Involving local communities in the WMA process and respecting their customary rights and practices is essential for successful conservation and sustainable livelihoods in Tanzania.

The government's budget allocation to rangeland management has been insufficient despite the importance of these lands to the national economy. Eilola et al. (2021) found that funding for rangeland management in Tanzania is limited and often fragmented across different government departments, leading to ineffective management and conservation of these lands. Additionally, a lack of coordination and collaboration among government departments, stakeholders, and communities involved in rangeland management can lead to conflicts over land use and cooperation in implementing conservation and management strategies. For instance, Mairomi and Kimengsi (2021) found limited coordination and communication among government agencies responsible for rangeland management, leading to conflicting policies and ineffective management strategies. The absence of a specific National Rangeland Policy also contributes to the challenges in managing Tanzania's rangelands. While the National Land Use Policy provides guidelines for the sustainable use and management of land, including rangelands, the absence of a dedicated policy makes it difficult to address these lands' unique needs and issues (Robinson et al. 2019). Tanzania's rangelands are not the only ones facing challenges in effective management. For example, despite having a national rangeland policy, Ethiopia has limited implementation of practices due to a lack of funding and weak enforcement mechanisms (Gelan 2014). Similarly, in Nigeria, the government's focus on other sectors, such as oil and gas, has resulted in the neglect of rangelands, leading to their degradation and loss of biodiversity, despite having a national policy on sustainable rangeland management (Leke and Leke 2019; Olayide 2021).

Communal grazing land is state-owned

State-owned communal lands are a key issue in Tanzanian rangeland management. Traditionally, rural communities managed lands communally under customary laws (Yanda and Mung'ong'o 2018). However, state ownership results in conflicts over land use and limited community involvement (Haller 2019; Robinson et al. 2019). This hampers effective strategies and conservation support (John and Kabote 2017). Neglecting customary practices caused conflicts and weakened community cohesion (Sulle and Nelson 2009). This challenge is also evident in other countries like Ethiopia and Kenya. In Ethiopia, converting communal lands into state-owned lands has sparked conflicts and undermined community involvement in land management (Atmadja et al. 2019; Sulle 2021). Similarly, Kenya's nationalization of communal lands has led to conflicts over land use and the neglect of customary land tenure systems (Little 2019). Recognizing and involving local communities in decision-making is essential (Atmadja et al. 2019; Little 2019). The National Land Policy acknowledges customary tenure, but implementation is limited (Biddulph and Hillbom 2020). Addressing state-owned communal lands necessitates a reverence for customary practices, community involvement in decision-making, and the establishment of robust legal and institutional frameworks. Strengthening community participation through capacity building empowers involvement, with transparent land tenure systems reinforcing equitable rights. Inclusive policies harmonizing land use with livelihoods and culturally sensitive conflict resolution mechanisms are vital for promoting effective rangeland management in Tanzania (John and Kabote 2017; Little 2019).

Poor cattle breeds

Effective rangeland management in Tanzania is challenged by the need to improve the performance of local animal breeds. According to Abdurehman (2019), most of Tanzania's livestock are local breeds generally well adapted to the harsh rangeland conditions. However, improving their performance is crucial to enhance rangeland productivity and sustainability. These breeds are often small, have low productivity, and are susceptible to diseases and parasites (Kangalawe et al. 2017). As a result, livestock production is low, and livestock keepers must graze their animals on larger areas of rangelands to meet their needs, leading to overgrazing and degradation of rangelands. Access to improved animal breeds has been challenging in Tanzania (Armson et al. 2020). The government's efforts to introduce improved breeds, such as the Mpwapwa breed, have been limited (Wilson 2021), and the private sector has not invested enough in breeding and distributing improved breeds to livestock keepers in rangeland areas. According to Baker et al. (2015), the lack of access to improved breeds has significantly constrained livestock production in Tanzania, particularly in rangeland areas. Other countries face similar challenges in improving animal breeds in rangeland areas. For instance, in Ethiopia, the low productivity of livestock breeds has been identified as a significant constraint to rangeland management (Ma'alin et al. 2021). Ethiopia has tried introducing improved breeds with higher production and performance than local breeds (Table 2). However, the adoption rates by livestock keepers have been low due to the high cost of purchasing and maintaining improved breeds (Gebreyohanes et al. 2021). Kenya has a long history of importing high-yielding animal breeds, such as Friesian, Ayrshire, Guernsey, and Jersey dairy cattle breeds from Europe and North America (Aliloo et al. 2020). These breeds were introduced to improve milk production and meet the growing demand for dairy products. However, these breeds have negative impacts on rangeland management, as they require more water and forage (Kelio 2022; Oloo et al. 2022) than local breeds, which are adapted to the arid and semi-arid conditions of these rangelands (Mudavadi et al. 2020).

Clearly, the trade-off between exotic and local breeds is a complex issue involving social, economic, and ecological factors. While exotic breeds may have advantages in terms of productivity and marketability, they may not be suitable for all environments because they require more inputs, such as feed and veterinary care. On the other hand, local breeds adapted to local conditions require fewer inputs, making them more sustainable and resilient in the face of environmental and economic shocks (Gerber et al. 2015; Ragkos et al. 2017; Tribaldos 2021). However, people's desire for higher performance and potentially better economic gain has triggered the adoption of exotic breeds (Opiyo et al. 2015; Snaibi and Mezrhab 2020), leading to the loss of local breeds and a decline in genetic diversity. This trend has also resulted in losing traditional knowledge and cultural practices associated with animal husbandry in pastoralist communities (Ayantunde et al. 2007; Njisane et al. 2020; Hailemariam et al. 2021). Crossbreeding with locally adapted and improved breeds can be a viable solution to enhance Tanzanian rangeland productivity and sustainability while preserving genetic diversity and traditional knowledge. Castaño-Sánchez et al. (2023)

conducted a study involving Hispanic heritage cattle (e.g., Criollo) and crossbreeds (Criollo × Angus), comparing them with traditional Angus cattle in the southwestern US. Crossbreed cattle exhibited lower water use, fuel consumption, nitrogen footprint, and production costs regardless of the finishing diet. Crossbreeding can produce offspring with desirable traits such as higher productivity, disease resistance, and adaptability to local conditions. However, crossbreeding has risks, such as unintended consequences on genetic diversity (Kitole and Sesabo 2022) and negative impacts on traditional knowledge and cultural practices. To improve the livelihoods of Tanzanian pastoral communities, local communities must be involved in the decision-making process while carefully evaluating the potential benefits and risks of crossbreeding.

Infectious diseases

Diseases in Tanzania's rangelands, such as East Coast Fever (ECF), Foot-and-Mouth Disease (FMD), Contagious Bovine Pleuropneumonia (CBPP), and Rift Valley Fever (RVF), significantly impacts on livestock productivity and human health. Annual outbreaks of FMD and CBPP across the country lead to losses (Swai et al. 2021), with CBPP outbreaks causing about 55% of cattle deaths in the southern highlands region (Msami et al. 2001). Rift Valley Fever (RVF), an important viral disease affecting ruminants in Tanzania, causes significant economic losses in the livestock industry (Sindato et al. 2011; Olovsson 2019; De Glanville et al. 2022;). Mosquitoes primarily transmit the RVF virus, and outbreaks in Tanzania have been reported since the 1930s, with the most recent outbreaks occurring in 2007 and 2018 resulting in significant human and livestock losses, highlighting the need for effective disease control strategies and interventions (Sindato et al. 2011, 2022). RVF is an emerging and re-emerging disease in Tanzania, with the potential to cause significant impacts. Poor animal husbandry practices, inadequate vaccination, and lack of quarantine measures contribute to disease transmission, and the movement of livestock between regions and countries exacerbates the issue and the spread of diseases in rangeland areas (Sindato et al. 2022). Limited access to veterinary services in remote rangeland areas also hampers effective disease control efforts (Kimaro et al. 2018). Mitigating the effects of these endemic diseases is crucial for ruminant health, farmer livelihoods, and the livestock industry. Disease control strategies should include surveillance, vaccination, and biosecurity measures to prevent disease spread (Sargison 2020). A comprehensive approach is needed to address the challenge of diseases in Tanzania's rangelands, focusing on improved animal husbandry, expanded vaccination and treatment programs, and strengthened veterinary services in remote areas. Community-based animal health programs can enhance disease control measures and access to veterinary services in rural regions (Auty et al. 2021; Enahoro et al. 2021). Additionally, improving surveillance and early warning systems can help detect and control disease outbreaks in rangeland areas. Species Distribution Models (SDMs) can be employed to predict the potential distribution of livestock disease vectors and assess the risk of outbreaks (Lippi et al. 2023), providing valuable insights for proactive disease management and control. Khwarahm (2023) showed how SDMs can also be applied to understand changing species' geographical distribution and abundance patterns, considering dynamic environmental conditions. These models have been used to create high-resolution maps of host distribution, reflecting the baseline risk of disease (Singleton et al. 2023). By using SDM such as MaxEnt (Maximum Entropy Modeling), one can accurately predict species distribution and identify the relevant environmental and bioclimatic determinants of disease risk (Gwaka et al. 2023; Rathore and Sharma 2023; Saputra et al. 2023; Singleton et al. 2023). Additionally, they can consider the temporal dimension, accounting for changes in species distributions over time (Karger et al. 2023). For instance, MaxEnt modeling has been used to estimate and predict zoonotic animal diseases under climate change in China (Cao et al. 2023) and to predict the spatial distribution of vector ticks of Crimean–Congo Haemorrhagic Fever in Iraq (Khwarahm 2023). Therefore, implementing SDMs, especially using MaxEnt in Tanzania rangelands, can contribute to a more effective and informed approach to addressing livestock diseases by predicting disease occurrence and identifying areas at high risk of outbreaks.

Acidic and infertile soils

Tanzania's rangelands face a significant challenge due to acidic and infertile soils. Mdegela et al. (2022) found a significant proportion of Tanzania's rangelands are in areas with soils that are acidic and low in essential nutrients, such as nitrogen and phosphorus. These soils are also susceptible to erosion. The acidic nature of the soil, ranging from pH 5.0-6.5 (Zarekia et al. 2012; Selemani 2015; Mdegela et al. 2022), affects the growth of vegetation, which is a critical resource for livestock production and wildlife conservation. The effect of acid pH on plant biomass production in rangeland was clearly observed in the study conducted by Werner et al. (2016) (Table 3). Poor rangeland management practices, such as overgrazing and deforestation, further compound the challenge, leading to soil erosion and degradation. The problem of acidic or alkaline and infertile soils is not unique to Tanzania's rangelands. For example, in Ethiopia, rangelands located in areas with acidic and low-fertility soils are less productive than those in areas with more fertile soils (Mesfin et al. 2018; Getabalew and Alemneh 2019; Hailu and Mehari 2021; Milisha 2021). In Kenya, soil acidity is a significant problem in rangelands, particularly in areas with high rainfall, which can leach essential nutrients from the soil (Jawuoro et al. 2017; Bolo et al. 2019). In South Africa, many rangelands suffer from highly acidic soils due to years of overgrazing, which affect plant growth and reduces biodiversity (Kotzé et al. 2013; Ntalo et al. 2022). Similarly, in Egypt, rangelands are also affected by highly saline and alkaline soils, which limit vegetation growth and reduces forage availability for livestock (El Shaer and Al Dakheel 2016; Deshesh 2021; Tahir et al. 2022). A multifaceted approach is necessary to address this issue.

Conservation measures like terracing, soil bunds, and agroforestry can reduce erosion and improve fertility. Promoting appropriate soil amendments and fertilizers can address acidity and nutrient deficiencies, improving soil structure and fertility (Horák et al. 2021). Lime and organic matter amendments help raise soil pH and increase nutrient availability (Bossolani et al. 2020). Sustainable land management practices, like rotational grazing, further enhance soil quality and reduce erosion. Therefore, a comprehensive approach that includes soil conservation practices, suitable soil amendments, and sustainable land management strategies is essential to improve Tanzania's rangeland health, productivity, and ecological sustainability.

Alien invasive species

Invasive plants pose a significant challenge to Tanzania's rangelands, impacting native species and reducing productivity. Studies by Ngondya and Munishi (2022) and Muzzo et al. (2023) reveal how invasive weeds decrease plant diversity and constrain ecosystem services. Improper rangeland management practices such as overgrazing and nomadism have also contributed to the spread of invasive plant species, further exacerbating the degradation of rangelands (Leroy et al. 2020). Invasive species, such as *Prosopis juliflora* (mesquite), *Parthenium hysterophorus* (carrot weed), *Astripomoea lachnosperma* (choisy), *Hygrophila auriculata* (marsh barbell), *Trichodesma zeylanicum* (cattle bush) and *Gutenbergia cordifolia* have taken over large areas of rangelands in Tanzania (Adkins et al. 2019). The *P. juliflora* and *Chromolaena odorata* are notable invasive species in Tanzania, negatively affecting rangelands near the Serengeti National Park and reducing forage quality and livestock productivity (Muzzo and Provenza 2018). Similarly, other countries like South Africa, Egypt, and the USA face invasive plant challenges. In South Africa, *Acacia* and *Eucalyptus* species cover over 10% of the land, including rangelands, adversely impacting water resources and biodiversity (O'Connor and van Wilgen 2020). In Egypt, *P. juliflora* reduces rangeland biodiversity and productivity (Dakhil et al. 2021). The USA grapples with invasive plants such as *Bromus tectorum* (cheatgrass), *Taeniatherum caput-medusae* (medusahead), and *Centaurea solstitialis* (yellow star thistle), altering ecosystem functions and hampering livestock production (USDA 2017). Managing invasive plants requires prevention, early detection, and integrated approaches (Van Beek et al. 2017). Ngondya and Munishi (2022) recommend Nature-based Solutions (NbS) like tree planting and promoting native species to control *G. cordifolia*. Integrated Weed Management (IWM) can also restore ecosystem composition and functioning. Effective management of invasive plants improves rangeland productivity and ecological health and provides economic benefits through increased livestock production. Innovative grazing management programs should also be implemented to increase the use of invasive species by livestock.

Climate change and variability

Climate change is a major challenge, increasing temperatures while decreasing the amount of rainfall on rangelands in Tanzania (Figures 5 and 6). Prolonged droughts have become more frequent and severe, resulting in the loss of vegetation cover and reduced productivity of rangelands (Wiethase et al. 2023). The effects of climate change are exacerbated by overgrazing and the continued expansion of human populations, which increase pressure on the limited grazing resources available in rangelands (Louhaichi et al. 2019). As a result, the loss of grazing land has become a major issue for many communities in Tanzania, as they struggle to maintain their livelihoods and feed their livestock (Sangeda and Maleko 2018). The situation is similar in South Africa, where prolonged droughts have led to the loss of grazing land and reduced productivity of rangelands (Vetter et al. 2020). In response, some communities have established community ranches, where grazing land is managed collectively and sustainably to ensure long-term productivity and livelihoods (Hall and Cousins 2013). These ranches are often managed through traditional governance structures that benefit local communities economically through increased livestock production and ecotourism activities (Taylor et al. 2016). Similarly, in Kenya, community ranches have been established to address the challenges of overgrazing, climate change, and the loss of grazing land (Maoncha 2021). These ranches are managed through participatory decision-making processes and often incorporate innovative practices, such as rotational grazing and the restoration of degraded rangelands (Niamir-Fuller 2005). As a result, these community ranches have successfully improved rangeland productivity and ecological health while providing economic benefits to local communities (Kimiti et al. 2018). However, climate change exacerbates other challenges beyond rangeland productivity. For example, it increases the frequency and intensity of wildfires, diseases, and invasive species (IPCC 2014; Gomez-Casanovas et al. 2021). Wildfires have increased in many parts of the world due to climate change, with the total number of large wildfires and the area burned increasing by 4.2% and 2.5% per year on average between 1984 and 2015, respectively (Mueller et al. 2020). Similarly, climate change has contributed to the spread of infectious diseases, such as Lyme disease and West Nile virus, into higher latitudes and altitudes since the 1980s (Semenza and Menne 2009). The rise in temperatures and changing precipitation patterns are creating more favorable conditions for invasive species to thrive, potentially exacerbating ecosystem degradation (IPCC 2014; Turbelin and Catford 2021).

Table 2. Livestock breeds in Tanzania and their performance parameters (Ministry of Livestock and Fisheries 2017)

Species	Breed	Total population	Parameters						
			Parturition rate	Prolificacy rates	Mortality rates	Weight adults	Dressing %	Milk yield	Loin Length
Cattle									
Local breeds	Tanzania Short-Horned Zebu (TSZ)	24,014,360	61%	1.00	2%-20%	260-380 kg	51-53%	270-1,200	250
	Sanga	1,062,440							
	Mpwapwa	800							
	Boran	103,200							
Exotic breeds	Ayrshire	61,920	67%	1.00	2%-10%	350-400kg		155-2,200	305
	Friesian	133,840							
	Jersey	9,536							
	Sahiwal	2,384							
	crossbreeds	411,500							
Total cattle		25,799,980							
Sheep									
Local	East African Blackheaded	1,979,952	1.50	1.20	2-7%	38-40kg	45-47%		
	Tanganyika Long-legged	5,182,627						NA	NA
	Red Maasai	1,522,182							
Exotics	Black Head Persian	15,239	1.60	1.10	2-6%	47-50kg	50%		
Total sheep		8,700,000							
Goats									
Local	Small East African	16,196,201	1.50	1.30	2-20%	38-65%	48%	NA	NA
	Malya	1,984		1.50			50%	90	180
Exotics	Anglo-Nubian	672		1.50	2-12%	49-70%	50%	500	187
	Boer	1,680					53%		
	Norwegian	1,903					50%		
	Saanen	1,680							
	Toggenburg	3,359							
	Crossbreeds	492,521							
Total goats		16,700,00							
Pigs									
local	Local Tanzanian	475,000	2	6.00	2-30%	55-60kg	60%	NA	NA
Exotics	Hampshire	19,000		8-10	2-15%	72-90kg	70%	NA	NA
	Landrace	95,000							
	Large white	133,000							
	Saddleback	38,000							
	Crossbreeds	1,140,000							
Total pigs		1,900,000							
Poultry									
Local	local	42,000,000	Not Established	Not Established	8-40%	1.2-1.5kg	80%	NA	NA
Exotics	Layers	12,000,000			2-5%	1.2-1.6kg	85.5%	NA	NA
	Broilers	22,500,000							
Total poultry		76,500,000							

Table 3. Soil pH and forage biomass in different range management systems

Treatment	Plant biomass		Total (kg ha -1)	Composition of grazing material		
	Grazing materials	Weeds		Grasses	Leguminous	pH
BR	465.50b	601.70a	1,067.20b	465.30b	0.20b	5.40a
NR	2,664.90a	330.50ab	2,995.30a	2,664.60a	0.30b	4.10b
IH	2,820.50a	204.90b	305.40a	2,690.90a	129.60b	4.00c
IC	1,640.00ab	198.80b	1,838.80ab	1,507.20ab	132.80a	5.00d
CV (%)	50.40	66.70	37.00	50.20	62.00	4.80

Note: NR: Natural rangeland; BR: Burned natural rangeland; IH: Natural rangeland improved with harrowing; IC: Natural rangeland improved with chisel plowing (Werner et al. 2016). Values followed by same letter(s) within a column did not differ significantly at 0.05 level

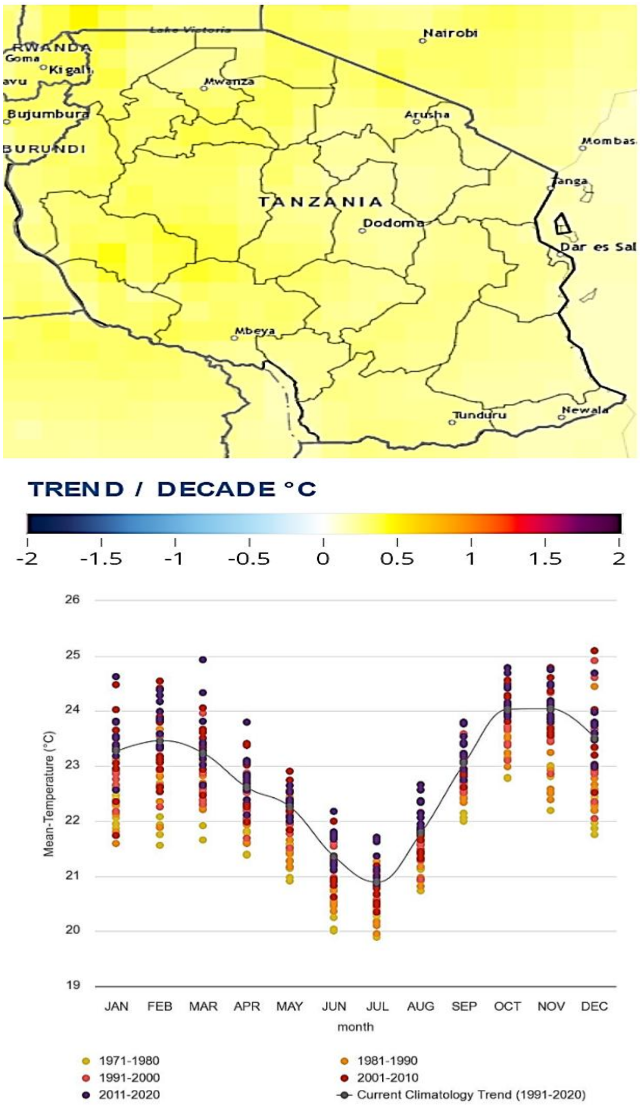

Figure 5. Tanzania mean temperature trend and variability across seasonal cycle per decade 1971-2020 (Source: World Bank group data).

PROSPECTS FOR SUSTAINABILITY OF RANGELANDS IN TANZANIA

Policy enforcement on rangeland resource use and management.

Tanzania has policies and laws governing rangeland resource use and management, such as the Grazing-land and Animal Feed Resources Act of 2010 and the Wildlife Conservation Act of 2009. These legal frameworks ensure the sustainable conservation of rangeland resources, including soils, water, plants, and animals. The Land Act of 1999 recognizes local communities' rights to use and manage land, including rangelands. However, enforcing these laws is challenging, especially at the local level, due to limited capacity and resources. Addressing these challenges and strengthening enforcement mechanisms is vital for sustainable rangeland management in Tanzania.

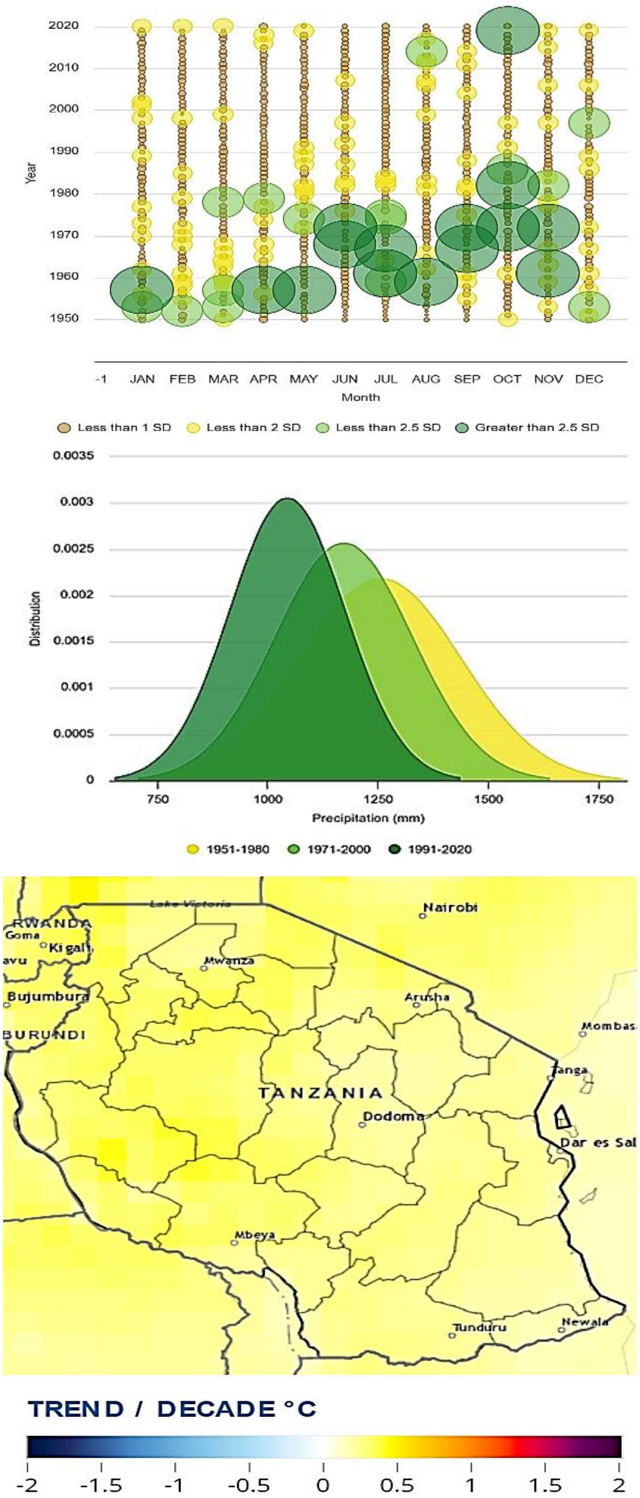

Figure 6. Tanzania's change in precipitation distribution and events intensity from 1971 – 2020 (World Bank group data)

Examples from other countries include Mongolia, where the National Rangeland Health Program, launched in 2003, addresses rangeland degradation through monitoring, training on sustainable grazing practices, and rehabilitation efforts. The Forest Service and Bureau of Land Management manage vast rangelands in the United States using policies like rotational grazing and habitat restoration. These examples highlight the significance of policies and laws in governing rangeland use and management. Effective enforcement, through monitoring and community involvement, is crucial to ensuring the sustainability of rangeland ecosystems.

Pastoral organizations

Forming pastoral organizations in Tanzania promotes sustainable land use practices and community involvement (Nganga et al. 2019). Village-level organizations endorse practices like rotational grazing, preserving rangeland productivity and ecological integrity. They bridge local communities and government agencies, facilitating communication and collaboration in rangeland management. Organizations coordinate rangeland management across villages and stakeholders at district and regional levels. The Tanzania Pastoralist Council (TPC) advocates for policies supporting pastoralists' livelihoods and sustainable land use. TPC collaborates with government agencies and NGOs for participatory rangeland management, ensuring community access to resources. The Forum for Pastoralists in Ethiopia (FPNE) promotes pastoralism and sustainable land use. FPNE influenced a national rangeland management policy supporting pastoralism (Gebeye 2016). The Maasai Mara Wildlife Conservancies Association (MMWCA) manages wildlife conservancies with holistic grazing and wildlife conservation, reducing conflicts and enhancing rangeland productivity (Weldemichel and Lein 2019). Pastoral organizations mobilize resources for research through the Pastoralist Knowledge Hub (PKH), led by the International Livestock Research Institute (ILRI), improving pastoral communities' well-being in East and West Africa (Nganga et al. 2019). Forming pastoral organizations is vital for rangeland management in Tanzania. They promote community-based practices, coordinate efforts, advocate for sustainable policies, mobilize research resources, and support local communities' livelihoods.

Advanced technology in rangeland restoration

Effective rangeland restoration in Tanzania relies on advanced technologies like re-seeding, bush control, remote sensing, mapping, and precision grazing management for sustainability. Strategic re-seeding involves planting resilient seeds in degraded areas to restore vegetation and biodiversity (Fertu et al. 2021). Mapping and remote sensing identify restoration areas and monitor progress through satellite imagery and drone sensors (Rhodes et al. 2022). Targeted re-seeding has been found to positively impact vegetation cover and diversity, improving rangeland health (Fertu et al. 2021). Invasive species control and promoting native vegetation involve various methods, including herbicidal applications, mechanical removal, and biological interventions. Tebuthiuron herbicide has effectively controlled invasive species while facilitating native vegetation regrowth in weed-invaded rangelands, with minimal disruption to ecological balance and cost-effectiveness (Chambers et al. 2021). Thus, making the herbicide a suitable choice for restoration initiatives in countries such as the USA, Canada, and Australia. Combining indigenous knowledge with modern tracking tools can safeguard vital rangeland environments and boost resilience in pastoralist livelihoods. Precision livestock management, exemplified by GPS tracking, prevents overgrazing, minimizing impacts on rangeland ecosystems (Bailey et al. 2021). Maasai shepherd practices, deeply rooted in cultural heritage, provide insights into localized grazing dynamics and animal behavior, merging indigenous wisdom with real-time data through GPS technology (Galvin et al. 2020). This integration enhances pastoralist livelihoods and preserves rangeland ecosystems (McKemey et al. 2020). Expanding climate-adapted forage breeding improves sustainability (Moorby and Fraser 2021). Recruiting more forage plant breeders mitigates climate impacts on livestock production, ensuring food supply and soil health (Gomez-Casanovas et al. 2021). Adopting climate-adapted forages enhances income and livelihoods and incorporates indigenous knowledge (Baker 2013). The fusion of tradition and technology promises a resilient and sustainable future.

Use of locally adapted livestock to utilize and control invasive species.

Strategic utilization of locally adapted livestock species and breeds offers an effective approach to addressing invasive species in Tanzanian rangelands. The Ankole cattle, Small East African goats, Red Maasai sheep, and Short Horn Zebu are notable examples of breeds with evolved capabilities to thrive in rangeland conditions (Sikiru et al. 2023). Ankole cattle have browsing behaviors that make them effective at consuming invasive plants. Small East African goats exhibit resilience and adaptability, allowing them to eat a variety of shrubs, as well as invasive species of grasses and forbs, efficiently. Red Maasai sheep possess grazing and browsing capabilities, selectively consuming invasive plants while preserving native vegetation. Short Horn Zebu cattle have evolved heat and drought tolerance, disease resistance, and efficient foraging abilities, making them adept at utilizing and controlling invasive species. Including these locally adapted livestock species in management strategies provides a scientifically supported approach to mitigate the spread and impact of invasive species in Tanzanian rangelands, leading to improved ecological sustainability and resilience. Further research and appropriate grazing management practices can optimize the effectiveness of this approach.

Enforcing grading system and quality meat market-based price

Implementing a meat grading system, standard prices, and meat inspectors holds potential in managing Tanzanian rangelands. However, the lack of necessary resources and law enforcement hinders the system's implementation outlined in the Meat Industry Act of 2006. Successful meat grading systems in South Africa and Egypt maximize quality meat production and resolve land use conflicts (Muzzo and Provenza 2018). Adapting such practices in

Tanzania could boost meat exports and address challenges beef producers face with high input costs and inadequate incentives for quality meat production. Enforcing meat grading systems and setting standard prices based on quality could transform Tanzania's beef industry. Consumers respond positively to quality meat even at higher prices. Short training courses and government certificates are necessary for successful implementation. This system improves beef production, encourages the meat processing industry, increases employment opportunities, and improves living standards. Reducing livestock numbers and optimizing use of pastures can mitigate farmer-pastoral conflicts (Benjaminsen et al. 2009; Neely et al. 2009). By embracing these measures, Tanzania can achieve sustainable rangeland management, economic growth, and improved community livelihoods, but collaboration among government agencies, local communities, researchers, and stakeholders is crucial for success.

Satellite, group, and family ranching initiatives in Tanzania

Tanzania, known for its vast rangelands and diverse landscapes, presents a lucrative investment opportunity in livestock and game farming. The concept of satellite ranches, smaller-scale livestock farming operations near central entities like NARCO, has gained attention in Tanzania. These satellite ranches are strategically designed to complement the objectives and activities of the central entities while addressing the specific needs and opportunities of local livestock keepers. However, the current state of satellite ranches often fails to fully utilize their potential, as they primarily serve as land for livestock keeping rather than integrated components of a comprehensive livestock production strategy. Therefore, to unlock the full potential of satellite ranches, it is crucial to reassess and align the goals of the government and the livestock industry towards profitability and sustainability. Well-established satellite ranches can facilitate structured and sustainable livestock management practices among local communities, optimizing the utilization of rangeland resources. This can be achieved by distributing grazing areas and reducing the risk of overgrazing and land degradation. Additionally, satellite ranches provide knowledge and skill transfer opportunities from central entities, fostering capacity building and enhancing local livestock management and land stewardship capabilities. These ranches also contribute to diversifying the income sources of local communities, potentially including ecotourism, which can enhance financial stability. The proliferation of satellite ranches collectively plays a pivotal role in supporting the growth of Tanzania's vital livestock sector and significantly contributes to its development and sustainability.

Group livestock ranching offers an alternative and accessible approach to sustainable rangeland management, particularly for individual pastoralists with limited resources (Boone et al. 2005; Kerven et al. 2021). By forming collaborative initiatives, pastoralists can pool their livestock herds and resources, share responsibilities, and collectively manage rangelands (Undargaa 2017). This approach reduces the workload for individual members and enables more efficient land management (Hannus and Sauer 2021). Group ranching often attracts support from governmental and non-governmental organizations, providing training, access to veterinary services, and funding for sustainable practices (Pas et al. 2023). Furthermore, collective action enhances the bargaining power of pastoralist groups in markets, leading to better prices for livestock and related products. Moreover, group ranches can implement sustainable practices to reduce environmental impacts, such as overgrazing and land degradation (Zhang et al. 2021). Beyond economic benefits, group ranching fosters community, mutual support, and collaboration among members, contributing to improved livelihoods and the conservation of rangeland ecosystems (Nishi et al. 2023).

Promoting family ranches, exemplified by multi-generational family ranches like the King Ranch in Texas, stands out as a key strategy for enhancing the sustainability of rangeland management (Henderson 2021). These family ranches provide numerous advantages, including multigenerational stewardship, localized expertise in understanding rangeland ecosystems, economic resilience, community integration, and a strong commitment to conservation practices (Grelet et al. 2021). This commitment includes responsible land management techniques like rotational grazing and the preservation of native plant species, contributing to the overall health of rangeland ecosystems. Tanzania supports the establishment of family ranches among pastoralists with substantial herds, often exceeding 200 head of livestock. Like the multi-generational family ranches in the United States that have often been in operation for decades, these family ranches significantly contribute to improved rangeland management, economic stability, and biodiversity preservation (Wilmer et al. 2020; Biggs 2022). The long-term planning views held by multigenerational ranchers in Utah contributed to the ranches implementing more innovative approaches. Their long-term plans included ensuring financial and economic sustainability for future generations (Didier and Brunson 2004). By supporting pastoralist families in transitioning to family ranches and ensuring that these initiatives align with sustainability goals, Tanzania can harness the potential of these ranches to benefit both its people and its vast rangeland ecosystem. Ranch income was a valuable predictor of ranching operations that were innovative (Didier and Brunson 2004). As pastoralists transition to ranching families, they must be able to rely on ranch income to support their families.

In conclusion, satellite, group, and family ranching initiatives offer promising prospects for enhancing the sustainability of Tanzania's renowned and ecologically diverse rangelands. By embracing these initiatives and aligning government policies with sustainability goals, Tanzania can unlock the full potential of its rangelands, ensuring their long-term viability and prosperity. However, the conversion from pastoralism to generational ranching will depend on future generations being able and willing to continue the family operation. In the United States, generational transitions include the transition of capital (often land ownership, equipment, and animals) and knowledge; this can result in a culture of socialization of the heirs to continue the "family tradition". First generation operations often face high barriers, such as the cost of equipment, animals, land, and knowledge. Therefore, creating family ranch operations will depend on policies and incentives that allow new ranchers to remove barriers to successfully establish satellite operations. This will likely require a combination of culturally relevant educational programs, financial assistance, and the needed capital to create economically sustainable ranching operations that can survive for multiple generations (Inwood 2013).

CONCLUSION AND RECOMMENDATIONS

Sustainable rangeland resource use and management in Tanzania can be achieved by employing a multifaceted approach that considers ecological, social, and economic factors. Strengthening policy enforcement, forming pastoral organizations, advancing technology for rangeland restoration, utilizing locally adapted livestock, and enforcing a grading system and price-based quality meat market are key possibilities to consider. Effective policy enforcement is essential to implement existing laws and regulations governing rangeland resource use and management. Forming pastoral organizations at various levels promotes community-based natural resource management practices and, facilitates stakeholder coordination, and embraces public-private partnerships. Advances in technology offer valuable tools for rangeland restoration, enabling targeted interventions, efficient monitoring, and informed decision-making, leading to enhanced vegetation cover, biodiversity, and overall rangeland health. Utilizing locally adapted livestock breeds is crucial in utilizing and controlling invasive species in Tanzanian rangelands, contributing to ecological sustainability and resilience, and enhancing livelihoods of people. Enforcing a grading system and price-based quality meat market can transform Tanzania's beef industry, incentivizing quality meat production, increasing profitability for beef producers, and improving living standards. By embracing these prospects and implementing them effectively, Tanzania can achieve the sustainable use and management of its rangeland resources, leading to ecological preservation, economic growth, and improved livelihoods for local communities. Collaborative efforts among government agencies, local communities, researchers, and other stakeholders are crucial to ensure the successful implementation of these strategies and secure a prosperous future for Tanzania's rangelands.

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Forage yields and quality of *Cenchrus ciliaris* and *Panicum maximum* ecotypes under varied harvest intervals in a semi-arid environment in Kenya

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Abstract. *Kisambo BK, Wasonga OV, Kipchirchir OK, Karuku GN, Kirwa EC. 2023. Forage yields and quality of* Cenchrus ciliaris *and* Panicum maximum *ecotypes under varied harvest intervals in a semi-arid environment in Kenya. Intl J Trop Drylands 7: 102-111.* Livestock production in Kenya typically relies on native pastures for nutrition and efforts are ongoing to develop varieties adapted to semi-arid conditions. A field experiment was conducted in a semi-arid environment to evaluate harvest intervals' influence on the yield and nutritional attributes of selected grass ecotypes of two native grasses used in reseeding and fodder production. The grasses included buffel grass *Cenchrus ciliaris* Kilifi (KLF), *C. ciliaris* Magadi (MGD), Guinea grass *Panicum maximum* Isinya (ISY) and *P. maximum* Taveta (TVT). They were planted in a randomized-complete block design in a split-plot arrangement and maintained under rain-fed conditions. Forage harvests were performed at 3 harvest intervals i.e., 14, 28 and 84 days, simulating different utilization regimes in semi-arid Kenya. Biomass yield, forage accumulation and quality of the grasses were determined. The highest yields were obtained at 28-day harvest intervals and were 74% higher than the 14-day interval, although almost similar to the 84-day interval harvests. Forage accumulation rates varied significantly (p <0.005) between ecotypes and harvesting intervals. Crude Protein (CP) declined significantly with maturity, from a mean of 11.67% for the 14-day harvesting interval to 5.22% at the end of the season and varied among treatments. In Vitro Dry Matter Digestibility (IVDMD) increased with increasing harvest interval. However, fiber components-Nutrient Detergent Fiber (NDF), Acid Detergent Fiber (ADF) and Acid Detergent Lignin (ADL) increased with plant age. Harvest intervals had a significant (p <0.05) influence on the yield and qualitative attributes of the grass ecotypes. *C. ciliaris* ecotype MGD and *P. maximum* ecotype TVT are viable options for further performance evaluation in semi-arid environments as efforts to develop new range fodder varieties are accelerated.

Keywords: Biomass, crude protein, digestibility, dry matter; grazing, livestock feed, reseeding

INTRODUCTION

Natural pastures are critical feed sources for livestock across the globe (Michalk et al. 2018) and constitute 48% of the total biomass used by livestock (Herrero et al. 2013). Indigenous perennial grasses in particular play a key role in livestock nutrition in dryland environments. With changing land use patterns, overgrazing, and climate change, most of these grasses are on the decline (Boone et al. 2018; Greiner et al. 2021), compromising the sustainability of livestock production. The lack of sufficient feed of good quality has been a major drawback in dryland production systems resulting in reduced livestock productivity (Koech 2014; Mganga et al. 2019; Balehegn et al. 2022).

In semi-arid Kenya, besides natural pastures, there is an unexploited potential for forage cultivation using indigenous grasses for hay production to bolster feed security and sustain livestock production. This is widely pronounced especially under increasing pasture scarcity, mainly occasioned by frequent droughts and diminishing grazing land. Many pastoralists and agro-pastoralists have ventured into fodder production not only for feed provision for feed provision and other co-benefits such as range grass seed production (Omollo 2017; Wasonga et al. 2017). Some of the key grasses used for reseeding and grown for fodder include African foxtail grass (*Cenchrus ciliaris*), Guinea grass (*Panicum maximum*), Masaai love grass (*Eragrostis superba*), Bush rye (*Enteropogon macrostachyus*), Horsetail grass (*Chloris roxburghiana*) among others (Koech 2014; Mganga et al. 2021) among others. The demand for better forage species that are more productive and able to cope with changing climatic conditions exists and will continue to increase (Wasonga et al. 2017).

Determining yields and nutritional attributes of livestock feeds is critical to the growth, well-being and productivity of livestock. Some of the factors affecting the productivity and nutritional profiles of grasses include: species, soil types growing environment, stage of utilization and management interventions. For instance, research has shown that as the harvesting interval increases, the feed quality attributes declines (Schnellmann et al. 2020; Gilo et al. 2022). For successful fodder production, management interventions must aim at optimizing production. One key management intervention involves harvesting or grazing grasses at appropriate intervals which has implications not only on the reproductive potential, persistence and quality of grasses (Capstaff and Miller 2018; Venter et al. 2021), but also on ruminant production.

Two grass species, *C. ciliaris* and *P. maximum* are key forage species in arid and semi-arid rangeland ecosystems in Kenya and elsewhere. In Kenya, these species are commonly preferred for various reasons including drought tolerance, high biomass production and the ability to thrive in varied environments (Mganga et al. 2015; Njarui et al. 2015). Currently, these grasses are commonly grazed or harvested as fodder. In semi-arid regions, the onset of rain normally results in rapid grass regrowth which grazers rapidly consume. At this point, the grasses are rich in nutrients such as Crude Protein (CP) but low in biomass yields. Fodder harvesting and utilization should coincide with the flowering stage when grasses are at their peak nutritional status. On the other hand, harvesting grass seeds for sale and reseeding, which has become common in Kenya's drylands is normally done after seed maturity (Omollo 2017). This has implications for the quality of grasses, mostly a decline (Koech 2014; Gilo et al. 2022).

Limited studies have considered within-species variability concerning biomass and nutritional aspects in semi-arid Kenya. Many local accessions or ecotypes of these grasses have been collected and preserved at the national genebank and in ex-situ field genebanks in Kenya. Kirwa (2019), investigated the performance of various accessions for reseeding in Kenya and found wide variability in yield attributes. No further studies have been done to evaluate the species based on responses to management interventions such as defoliation or harvesting intervals. Knowledge of grass responses and sensitivity to defoliation is crucial in designing grazing and harvesting regimes under semi-arid conditions and is critical for pasture-based systems' sustainability. With the development of fodder value chains and growth of the livestock sector, evaluating available forage germplasm and selecting high-yielding varieties is necessary. This is for breeding, multiplication and promotion of improved livestock productivity particularly under a changing climate.

This study was therefore conducted to evaluate the effects of harvesting intervals on cumulative forage yields and nutritional attributes of 4 selected grass ecotypes of two range grasses (*C. ciliaris* and *P. maximum*) commonly used in reseeding and fodder production in semi-arid Kenya. It complements efforts to identify new indigenous dryland varieties based on biomass yield and nutritional attributes which are key traits of forage crop (Capstaff and Miller 2018).

MATERIALS AND METHODS

Description of the study site

The study was conducted from October 2019 to September 2020 at the Kenya Agricultural and Livestock Research Organization (KALRO)-Kiboko Research Station in South-east Kenya (02°151S, 37°43E). The station lies at an altitude of 1024 m above sea level. The average annual rainfall is 534.3±66.2 mm, distributed in a bimodal pattern with the long rains received between March and May. The short rains are normally received between October and December and are more reliable for agricultural production within the study site. Temperatures vary from a minimum of 22°C to a maximum of 32°C (Ndathi 2012). The mean monthly rainfall and temperature data recorded during the study period are illustrated in Figure 1.

The vegetation at the station is mainly bushed grassland with a diverse mix of native tree and shrub species with an understory of various grasses. The common tree species include *Acacia, Commiphora,* and *Combretum* spp. The dominant grasses include Bush rye (*E. macrostachyus*), Foxtail grass (*C. ciliaris*) Horsetail grass (*C. roxburghiana*) and Maasai love grass (*E. superba*). The soils in the experimental site are classified as Acri-rhodic ferralsols (CIMMYT 2013) and the physiochemical composition at the beginning of the study is shown in Table 1.

Experimental grasses

The study used 4 r grass ecotypes: *P. maximum* Taveta (TVT), *P. maximum* Isinya (ISY), *C. ciliaris* Magadi (MGD) and *C. ciliaris* Kilifi (KLF). These were obtained from the KALRO Kiboko farm which serves as a field genebank for some accessions collected from different parts of semi-arid Kenya. The selection of the 4 ecotypes was based on previous work characterizing the ecotypes at the Centre (Kirwa 2019).

Land preparation, planting and experimental design

Land that had been left fallow for two seasons was plowed and prepared to a fine tilth in September 2019 in readiness to plant the grass ecotypes. A total area of 885 m^2 was divided into 3 blocks with each having 12 plots measuring 10.5 m^2. A 2-metre alley separated the blocks while a 1-metre alley separated the plots. The experiment was laid out as randomized blocks with three replicates as a split-plot design. The main plots were 4 grass ecotypes while the harvest intervals represented the sub-plots.

Table 1. Soil physiochemical properties of the experimental site at two depths (0-15 and 15-30 cm) at the beginning of the study

Soil Property	Value (0-15 cm)	Value (15-30 cm)
Texture grade	Sandy loam	Sandy loam
pH	7.66	7.17
Total nitrogen (%)	0.12	0.09
Total organic carbon (%)	1.11	0.76
Phosphorus (ppm)	23	13
Potassium (milliequivalents %)	0.68	0.66
Calcium (milliequivalents %)	2.2	2.2
Manganese (milliequivalents %)	0.33	0.33
Copper (ppm)	2.00	2.57
Zinc (ppm)	4.33	0.96

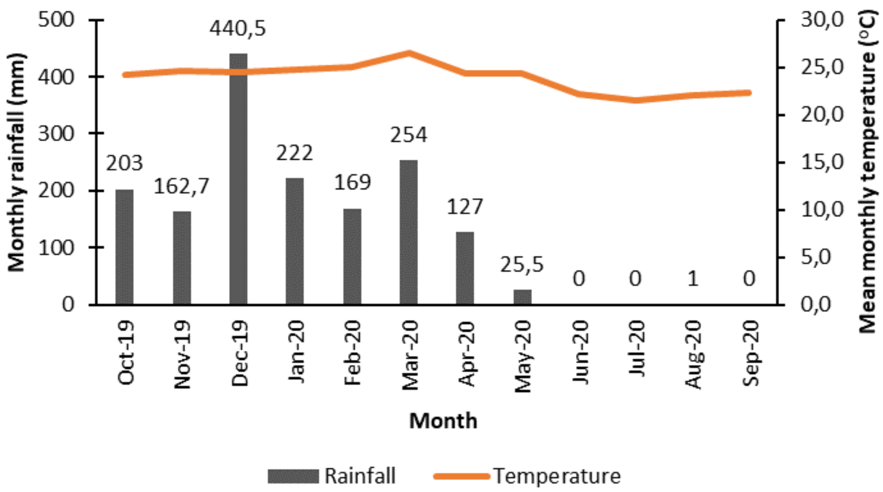

Figure 1. Monthly rainfall and temperature data of the study site during the experimental period

The 3 harvesting intervals included cutting once every 14 days; once every 28 days and a one-off harvesting at 84 days. The harvesting intervals represented a high-frequency regime; moderate/intermediate regime and low-frequency regime of utilization respectively. These utilization regimes are commonly practiced within arid and semi-arid areas by livestock keepers and farmers, with the latter being mainly adopted for hay production (Omollo 2017). The 4 grass ecotypes were uprooted from the field genebank and the vegetative root splits were transplanted immediately into prepared plots in holes measuring 10 cm in diameter. The spacing between rows and between plants was 50 cm. Plants were maintained under rain-fed conditions over the experimental period. A standardization cut was carried out at the end of the establishment phase of 30 days where the grasses were all clipped at 10 cm stubble height and top-dressed with Calcium Ammonium Nitrate (CAN) fertilizer at the rate of 50 $KgNha^{-1}$. This was done as per recommendations by Boonman (1993) for cultivated grasses to ensure optimal crop growth, even though few farmers fertilize their grasses with manure or fertilizer in semi-arid Kenya. The grasses were regularly weeded whenever weeds emerged, manually.

Data collection

Harvesting treatments commenced in February 2020 and data was collected through two regrowth cycles up to September 2020. Forage production was determined for each treatment by harvesting all plant tissues above ground within a 1 m^2 quadrat at the center of each plot, at a stubble height of 10 cm from the ground level. A hand sickle was used to clip the grasses. The harvested material was weighed in the field using a portable balance, for each treatment and a subsample was taken, weighed and taken to the laboratory for oven drying at 65°C for 48 hrs. This was then weighed and dry matter yields per hectare were determined by extrapolating to per hectare level. After harvesting, the whole plot was clipped to the same residual height, depending on the treatment. Total yields per treatment were calculated as the cumulative yields obtained from the plots by adding up individual yields at each harvest. Forage Accumulation Rate (FAR) was measured as the amount of accumulated forage mass (DM $Kgha^{-1}$) between harvesting intervals for every treatment divided by the number of days, i.e. 14, 28 and 84 days. Weather data, mainly rainfall and temperature were obtained from a nearby weather station at 500 m from the experimental site.

Laboratory feed quality determination

The oven-dried samples were ground using an electric mill and analyzed for Dry Matter (DM), Crude Protein (CP), ash, Nutrient Detergent Fiber (NDF), Acid Detergent Fiber (ADF), Acid Detergent Lignin (ADL) and In Vitro Dry Matter Digestibility (IVDMD) following procedures of AOAC (2010). Dry matter was determined through a forced air oven desiccator where a sample was oven-dried at 105°C overnight and the difference in mass was recorded. Crude protein was determined using the Kjeldahl method while ash content was determined using the dry combustion method where a sample was ignited in a furnace at 600°C for four hours to oxidize organic matter. Fiber components were analysed following the procedures of Van Soest et al. (1991) where samples were boiled for an hour in neutral detergent and a further hour in acid detergent to determine neutral detergent fiber (NDF) and Acid Detergent Fiber (ADF) respectively. In Vitro Dry Matter Digestibility (IVDMD) was determined following the two-stage procedure by Tilley and Terry (1963), where dried samples were incubated anaerobically at 38°C for 48 hrs with rumen fluid in a buffered solution. The samples were then digested in pepsin and hydrochloric acid at 38°C for 48 hrs.. Three samples were used for each analysis, which was done at the Animal Nutrition Laboratory at the University of Nairobi, Kenya.

Statistical analysis

Data was checked for normality under the Shapiro-Wilk test in Genstat software version 21 (VSN International). Analysis of variance was carried out using The General Linear Model (GLM) in Genstat software to determine the effects of harvesting intervals on cumulative forage yield, forage accumulation rate, and nutritive attributes of the grass ecotypes.

The model adopted was

$$Y = \mu + E_i + H_j + B_k + EH + \varepsilon_{ijk}$$

Where Y was the observed value (yield and nutritive parameter) of ecotype i in interval j and block k, next μ was the overall mean effect, E_i was the effect of ecotype, H_j was the effect of the harvest interval, B_k was the block effect- and EH the interaction between ecotype and harvest interval. Then ε_{ijk} was the random error effect. Means were compared using Tukey tests whenever significance was detected and differences were considered statistically significant at $p<0.05$. Additionally, the Pearson correlation was usedto determine the relationships between the nutritional; attributes of the grasses.

RESULTS AND DISCUSSION

Forage production

Generally, harvesting intervals significantly affected cumulative forage biomass yields ($p<0.05$). Each ecotype responded differently to clipping with higher yields obtained as the harvest interval increased from 14 days to 84 days especially during the wet season. However, during the dry season, yields were only greater during the 28-day clipping interval and reduced at the 84-day harvest interval. Harvesting the grasses at 14-day intervals resulted in the lowest cumulative yields during the dry season period. Overall, *C. ciliaris* MGD harvested at 28-day intervals produced the highest cumulative biomass (12,017.69 $KgDMha^{-1}$) while the lowest biomass was recorded at the 14-day harvest interval in *C. ciliaris* KLF (3,726.28 $KgDMha^{-1}$) as shown in Table 2. Mean yields produced at 28-day intervals were significantly higher at 7,829.66 $KgDMha^{-1}$ than the 14-day (4,479.64) and 84-day (7,167.30) $KgDMha^{-1}$ harvest intervals. Generally, a 32% yield decline was also reported during the dry season.

Forage Accumulation Rate (FAR)

The Forage Accumulation Rate (FAR) differed significantly ($p<0.05$) among the grass ecotypes across the harvest intervals. The highest mean FAR was realized in *C. ciliaris* MGD and *P. maximum* TVT at 90.66 and 86.86 82.61 $KgDMha^{-1}$ respectively. The highest accumulation rates were realized while harvesting the grass ecotypes at 28-day intervals followed by 84-day intervals and the lowest at 14-day intervals. The *C. ciliaris* MGD accumulated more biomass 241.51 $KgDMha^{-1}day^{-1}$ over 28-day intervals than all the other treatments. Among the grass ecotypes, forage accumulation rates declined during the subsequent dry season as illustrated in Table 3.

Forage quality

Dry matter, crude protein and ash content

The percentage of dry matter was above 96% for all the grass ecotypes and differed significantly ($p<0.05$) with *C. ciliaris* KLF having the highest DM. Overall, the mean crude protein among the grass ecotypes was between 8.25% and 9.01%. Ash content also significantly varied with values between 12.21% and 15.59% obtained. The *C. ciliaris* MGD had the highest ash content of 15.59%.

Harvesting interval had a highly significant ($p<0.01$) effect on CP and ash content, but not in DM. Ecotypes harvested at 14-day intervals had the highest CP with a mean of 11.67% followed by the 28-day interval at 8.78% while the 84-day interval had the lowest value of 5.22%. The highest CP value of 12.82% was found in *P. maximum* ISY, harvested at 14-day intervals while the lowest value of 4.49% was determined in the same species harvested after 12 weeks.

The ash content varied between 11.21%-16.93% with *C. ciliaris* MGD harvested at 14 day interval having the highest ash content (16.93%), followed by the same ecotype harvested at 28 day interval at 15.50%. The lowest ash content of 11.21% was determined in *P. maximum* TVT harvested at 28-day intervals (Table 4). Ecotypes clipped at 14-day intervals had the highest mean ash content (14.83) while those clipped at 84-day interval had the least (12.91%). Ash content generally decreased with increased harvest interval, with C. *ciliaris* grasses generally having a higher percentage than *P. maximum* ecotypes.

Fiber fractions (NDF and ADF) and Lignin content (ADL)

Table 5 indicates the Nutrient Detergent Fiber (NDF), Acid Detergent Fiber (ADF), Acid Detergent Lignin (ADL) and In Vitro Dry Matter Digestibility (IVDMD) of the grass ecotypes at different harvest intervals.

The NDF values obtained were between 71% and 74% and significantly differed (p = 0.011) among the grass ecotypes. Harvest interval also significantly ($p<0.001$) influenced NDF in the grass ecotypes, with grasses subjected to 14-day interval having a lower mean NDF (70.51) than the 28-day and 84-day harvest intervals which were 74.35% and 73.72% respectively. The highest NDF value was reported in *C. ciliaris* KLF (76.76%) harvested at the 84-day interval.

The highest ADF value of 43.26% was found in *P. maximum* TVT harvested after 84 days while the lowest was *C. ciliaris* KLF (29.79%) harvested after 14 days. The effects of harvest interval on ADF were highly significant ($p<0.001$) with lower values obtained at 14-day intervals increasing with harvest interval.

Variation in ADL values among the grass ecotypes was very minimal ($p = 0.08$) with mean values of 5.39%, 5.38%, 4.94% and 4.68%obtained for *C. ciliaris* MGD, *C. ciliaris* KLF, *P. maximum* TVT and *P. maximum* ISY respectively. The harvesting period significantly ($p<0.001$) influenced ADL with the highest ADL found among ecotypes harvested at the 84-day intervals. Finally, the IVDMD for the grass ecotypes ranged between 47% and 68% with the grasses harvested at 84-day intervals having significantly lower values than those harvested at shorter intervals.

Table 2. Effects harvesting interval on cumulative dry matter forage yields in $KgDMha^{-1}$ of 4 grass ecotypes in semi-arid Kenya over 2 growing seasons

Harvest Interval	***C. ciliaris* MGD**		***C. ciliaris* KLF**		***P. maximum* TVT**		***P. maximum* ISY**	
	Wet Season	**Dry Season**	**Wet Season**	**Dry Season**	**Wet Season**	**Dry Season**	**Wet Season**	**Dry Season**
14 days	5,294.00 ^{cHIJ}	4,627.18 ^{cHIJ}	3,726.28 ^{cJ}	4,311.19 ^{cHIJ}	5,352.08 ^{deHIJ}	3,934.42 ^{eIJ}	5,676.39 ^{cGHI}	4,295.98 ^{cHIJ}
28 days	12,017.69 ^{aA}	8,271.43 ^{bCD}	7,729.81 ^{aDEF}	6,174.77 ^{bEFGH}	9,811.90 ^{bBC}	7,776.62 ^{cDE}	7,282.06 ^{bDEFG}	5,427.54 ^{cGHIJ}
84 days	10,624.17 ^{aAB}	5,575.77 ^{cGHIJ}	8,544.38 ^{aCD}	5,556.16 ^{bGHIJ}	11,419.05 ^{aAB}	5,817.66 ^{dFGHI}	10,651.17 ^{aAB}	4,900.59 ^{cHIJ}
p-value	<0.001		<0.001		<0.001		<0.001	
LSD	658.4		652.8		970.8		1,048.5	
CV (%)	18.1		11.4		13.9		17.3	

Note: Different lower case letter after the number denotes significant difference at p <0.05 between harvest intervals and season. Different uppercase letter denotes significant differences between ecotypes at p <0.05

Table 3. Effects of harvest interval on forage accumulation rate (Kg DM ha^{-1} day^{-1}) of 4 grass ecotypes in tropical semi-arid Kenya during two growing seasons

Harvest Interval	***C. ciliaris* MGD**		***C. ciliaris* KLF**		***P. maximum* TVT**		***P. maximum* ISY**	
	Wet Season	**Dry Season**	**Wet Season**	**Dry Season**	**Wet Season**	**Dry Season**	**Wet Season**	**Dry Season**
14 days	75.63 ^{cEFGH}	58.08 ^{cHIJ}	53.22 ^{cIJ}	61.87 ^{cGHIJ}	56.20 ^{dHIJ}	76.03 ^{cEFGH}	81.09 ^{bcDEFG}	61.36 d ^{GHIJ}
28 days	143.06 ^{aA}	98.47 ^{bBCD}	92.01 ^{aCDE}	73.50 ^{bEFGHI}	116.80 ^{aB}	92.57 ^{bCDE}	86.70 ^{bDEF}	64.61 ^{cdGHIJ}
84 days	110.66 ^{bBC}	58.08 ^{cHIJ}	89.00 ^{aDE}	57.02 ^{cHIJ}	118.95 ^{aB}	60.59 ^{dGHIJ}	110.95 ^{aBC}	51.04 ^{dJ}
p-value	<0.001		<0.001		<0.001		<0.001	
LSD	15.17		7.29		10.61		11.51	
CV (%)	17.4		10.8		12.9		16.0	

Note: Different lower case letter after the number denotes significant difference at p <0.05 between harvest intervals and season. Different uppercase letter denotes significant differences between ecotypes at p <0.05

Table 4. Effects of harvesting interval on dry matter, crude protein and ash contents of 4 grass ecotypes in tropical semi-arid Kenya

Harvest Interval	***C. ciliaris* MGD**	***C. ciliaris* KLF**	***P. maximum* TVT**	***P. maximum* ISY**
Dry matter (%)				
14 days	96.15 ^{aBC}	97.50 ^{bABC}	98.95 ^{aAB}	96.87 ^{aABC}
28 days	95.77 ^{aC}	99.31 ^{aA}	97.44 ^{abABC}	95.44 ^{aC}
84 days	96.84 ^{aABC}	98.09 ^{abABC}	96.40 ^{bABC}	96.89 ^{aABC}
p-value	0.270	0.008	0.022	0.486
LSD	1.37	1.06	1.73	2.94
Crude protein (%)				
14 days	11.19 ^{aAB}	11.54 ^{aAB}	11.12 ^{aAB}	12.82 ^{aA}
28 days	10.13 ^{aABC}	8.08 ^{bCD}	7.25 ^{bCDE}	9.64 ^{bBC}
84 days	5.11 ^{bEF}	5.39 ^{cDEF}	5.90 ^{cDEF}	4.49 ^{cF}
p-value	<0.001	<0.001	<0.001	<0.001
LSD	2.76	1.78	0.97	1.16
Ash content (%)				
14 days	16.93 ^{aA}	15.34 ^{aABC}	13.52 ^{aCDEF}	13.52 ^{bcdeBCDEF}
28 days	15.50 ^{bAB}	15.03 ^{bABCD}	11.21 ^{bG}	12.50 ^{defBCDE}F
84 days	14.26 ^{cBCDE}	12.27 ^{cEFG}	11.91 ^{abFG}	13.19 ^{cdeDEFG}
p-value	<0.001	<0.001	0.054	0.216
LSD	1.1	0.98	1.89	1.194

Note: Different lower letters after the number denote significant differences between harvest intervals at p <0.05 while uppercase letters denote differences between ecotypes at p <0.05

Table 5. Effects harvest interval on fiber components and in vitro dry matter digestibility of 4 grass ecotypes in tropical semi-arid Kenya

Harvest Interval	***C. ciliaris* MGD**	***C. ciliaris* KLF**	***P. maximum* TVT**	***P. maximum* ISY**
Nutrient detergent fiber (%)				
14 days	70.47 ^{bBCD}	67.61 ^{dD}	71.58 ^{b}	72.32 ^{abBC}
28 days	73.78 ^{aAB}	73.79 ^{abAB}	76.43 ^{aABCD}	73.49 ^{aAB}C
84 days	74.03 ^{aAB}	76.74 ^{aA}	74.40 ^{abAB}	69.69 ^{bCD}
p-value	<0.001	<0.001	0.033	0.012
LSD	1.53	2.04	3.53	2.37
Acid detergent fiber (%)				
14 days	37.97 ^{bAB}	29.79 ^{bC}	35.88 ^{bB}	35.97 ^{aB}
28 days	42.96 ^{aA}	38.89 ^{aAB}	42.01 ^{aA}	35.99 ^{aB}
84 days	40.29 ^{abAB}	38.73 ^{aAB}	43.26 ^{aA}	38.98 ^{aAB}
p-value	0.016	<0.001	0.004	0.185
LSD	3.22	3.64	4.19	3.84
Acid detergent lignin (%)				
14 days	5.72 ^{aAB}	4.24 ^{aAB}	4.30 ^{abAB}	3.96 ^{bB}
28 days	5.18 ^{aAB}	5.83 ^{aAB}	4.57 ^{abAB}	4.52 ^{abAB}
84 days	5.28 ^{aAB}	6.06 ^{aA}	5.95 ^{aA}	5.57 ^{aAB}
p-value	0.467	0.075	0.002	0.031
LSD	0.93	1.71	0.85	1.17
In vitro dry matter digestibility (%)				
14 days	66.68 ^{aAB}	66.31 ^{aAB}	68.08 ^{aA}	67.42 ^{aAB}
28 days	63.16 ^{aABC}	60.93 ^{bBC}	63.10 ^{abcABC}	64.84 ^{abABC}
84 days	50.58 ^{bD}	47.23 ^{cD}	49.94 ^{dD}	58.08 ^{bC}
p-value	<0.001	<0.001	<0.001	0.024
LSD	4.53	1.73	3.31	6.43

Note: Lowercase letters after the number denote significant differences between harvest intervals at p <0.05 while uppercase letters denote differences between ecotypes at p <0.05

Discussion

Climatic conditions

The total precipitation recorded over the two seasons of the evaluation was 1604 mm of rain annually. This was 3 times heavier than the long-term mean of the study region. The highest rain amount was received during December (440.5 mm). The mean monthly temperature was also lower than long-term averages. Unlike previous seasons, no short dry season was experienced in February highlighting the high intra and inter-annual variability in climate experienced in semi-arid Kenya (Kisaka 2015). The heavy rainfall in November and December 2020 also highlighted potential precipitation anomalies in semi-arid East Africa, likely influencing forage productivity in these regions under future climate change scenarios (Wainwright et al. 2021).

Forage production

Biomass yield is a critical indicator of pasture productivity determining the amount of forage available to animals. All the studied grasses were morphologically different and a distinction can be noted in the yields of the ecotypes at the different harvesting intervals over the two seasons. For instance, *C. ciliaris* KLF is a short grass variety of less than 30 cm tall, unlike *C. ciliaris* MGD which is taller. The *C. ciliaris* MGD also has a higher tiller density than *C. ciliaris* KLF, contributing to the differences in biomass yields (Kirwa 2019). The *P. maximum* TVT had thicker stems and larger leaves than *P. maximum* ISY. These structural attributes and individual inherent genetic attributes contribute to the eventual differences in yields and dry matter production.

Cumulatively higher yields were recorded at 28-day and 84-day harvesting interval compared to the 14-day harvest interval. This was attributed to the sufficient resting period before the subsequent harvest, which allowed the grass ecotypes to accumulate as much biomass as possible. In *P. maximum* and *Urochloa* hybrids, Mwendia et al. (2022) also found a 28-day harvesting regime to promote cumulative biomass yields. These frequent harvests help ameliorate the frequent forage demands common in semi-arid regions. In this study, an even shorter grazing regime or harvest interval, 14 days, would be benefit small stock or calves that consume less forage. From this study, the 28-day harvesting intervals can enhance feed availability for livestock without compromising animal productivity in dryland environments. This finding is consistent with investigations in an enclosure system in Ethiopia with similar harvest frequencies to this study, where Gilo et al. (2022), reported low yields at higher harvest frequencies. The overall mean of 6,007.10Kg DM ha^{-1} obtained for *C. ciliaris* ecotypes in this study is superior but comparable to the mean value (5,358 KgDMha^{-1}) reported by Kirwa (2019), in semi-arid Kenya for the ecotypes and several accessions. Overall, the mean values obtained for the two *P. maximum* ecotypes are almost 50% higher than those reported for local *P. maximum* ecotypes in the same study region (Njarui et al. 2015). The probable influence of seasonal rainfall, which was higher during the study period, site and management practices could explain the differences in the study.

Overall, biomass yields in the dry season dropped by almost 32%. The notable decline of biomass production for individual ecotypes in the dry season was due to drier conditions experienced from May through September 2020. Such responses are common for grass plants in semi-arid environments as reduced precipitation and soil moisture may not have been sufficient for plant growth and development. These findings corroborate those reported for *P. maximum* grass ecotypes by Njarui et al. (2015) in a multi-location study in eastern Kenya. These seasonal variations in yields will continue to be experienced with increased climate variability in arid and semi-arid lands (Godde et al. 2020) since rainfall is a primary driver of forage productivity. This highlights the need for fodder bulking in the form of hay to deal with forage scarcity brought about by climatic uncertainties. This is already happening in East African rangelands where the preserved grasses of poor quality (Balehegn et al. 2022). Even though there was a decline in cumulative biomass in the dry season among the grass ecotypes, an exception was found in *C. ciliaris* KLF under a 14-day harvest regime, probably due to the variety's grazing and dry conditions tolerance. It is a rhizomatous ecotype and most of the nodal tillers are found below the defoliation level adopted for this study.Hence the frequent clipping yield effects on the ecotype were minimal. A farmer evaluation exercise of *C. ciliaris* ecotypes in this region found this variety preferred over other robust and taller ecotypes by pastoral and agropastoral communities (Kirwa 2019). This was attributable to its persistent nature and drought tolerance characteristics. Such ecotypes may require different management strategies and should be further evaluated for other attributes other than yields. These attributes may include the role of soil and moisture conservation, drought tolerance, persistence, and carbon sequestration. These aspects are key to grasslands and the resilience of agropastoral and pastoral ecosystems.

Forage accumulation rate

The likely prolific nature of *C. ciliaris* MGD resulted in more regrowth per harvest interval than the other ecotypes. Overall, higher biomass accumulation rates were realized at 28-day and 84-day intervals. This is because physiologically, the plants' growth rates were not interrupted as frequently as in the 14-day harvesting intervals, hence more energy was invested in plant growth. Frequent harvesting (14-day) intervals resulted in lower yields as most carbohydrate reserves were depleted faster by removing vegetative parts. This removal can impact the leaf area influencinglight capture and subsequent regrowth characteristics. This is consistent with results obtained in *Chloris gayana* grass species by Ruolo et al. (2019). Frequent defoliation regimes can also result in the death of some plant tissues, diminishing the regrowth potential of grasses and subsequent rangeland deterioration. During the dry season, FAR declined significantly due to inadequate precipitation. This demonstrates that soil water availability can significantly affect forage accumulation rate and subsequent availability. Similar results have been reported for elephant grass genotypes by de Almeida Souza et al. (2021). Remarkably during the dry season, FAR for *C. ciliaris* MGD and *P. maximum* TVT under the 28-day harvest intervals were higher than other ecotypes' FAR for the wet season. This demonstrates the capacity of the ecotypes to continue growing despite precipitation limitations and their potential adaptability to semi-arid conditions.

Species and ecotypes that accumulate more biomass quickly can generally be recommended for fodder production and rangeland restoration. This is because they maximize the use of soil nutrients and rainfall use at the onset of the rainy season, growing faster and yielding higher biomass. Considering the variability and unpredictable rainfall patterns in semi-arid areas, it is critical to take advantage of any precipitation events as early as possible and grow varieties that mature early and accumulate forage quickly.

Forage quality

The results presented in this study on quality attributes are consistent with general observations by Koech (2014), Njarui et al. (2015), Kirwa (2019) and Mganga et al. (2021) and for grass ecotypes and key African indigenous rangeland grasses found in Kenya. The findings also fall within the range of values as reviewed by Lee (2018) for forages grown in contrasting environments.

Crude Protein (CP)

The crude protein values obtained at the 28-day regime for *C. ciliaris* ecotypes (8.08 and 10.13%), though higher, closely relate to 6.6 and 9.6 for *C. ciliaris* KLF and *C. ciliaris* MGD ecotypes respectively as reported by Kirwa (2019) at a 42-day harvesting interval. The difference could be due to the harvest period since the grasses were harvested two weeks earlier for this study. With increasing harvest interval, the CP of the grasses is expected to decline. This is demonstrated in the highly significant drop in CP values of grasses harvested at 84-day intervals. Similar results have been reported for common rangeland grasses by Koech (2014) in semi-arid Kenya and Keba et al. (2013) in southern Ethiopia. However, no ecotypic or within-species variability was considered but the trends of reduced CP with a maturity of the grasses were confirmed. As the harvest interval increases, the number and amount of senescent leaves increasingly become prevalent particularly in the lower parts of the stem. Typically, these are low in protein as nitrogen is remobilized to other parts of the plant (Yang and Udvardi 2018). This contributed to lower CP in the grasses at 84-day cutting intervals. The higher proportion of young leaves and the decreased stem component within the 14-day harvest intervals contributed to higher CP values.

Crude protein is an essential nutrient for livestock and feeding animals on these grasses, especially at maturity (i.e. over 8 week-old pastures) may not meet livestock nutritional requirements (Erickson and Kalscheur 2020). This study obtained less than 8% CP values, considered poor quality for grasses (Leng 1990) at the 84-day harvest intervals. Feeding livestock on such material may only be beneficial for maintenance purposes and not to improve performance.

Ash content

The amount of ash generally represents the number or amount of minerals in a plant. For this study, the ash content varied significantly among the grass ecotypes, with *C. ciliaris* ecotypes having a higher ash content. Kirwa (2019), reported 11.2 and 15.2% ash with a mean of 13.7% in a study of 11 *C. ciliaris* grass ecotypes in semi-arid Kenya. The mean of 14.82 for *C. ciliaris* obtained in this study falls within this range. Similarly, Njarui et al. (2015) reported a mean of 12.2% for *P. maximum* ecotypes, which compares favourably with the value of 12.6% in this study. The slight differences are attributed to variables such as experimental sites and seasons. Shorter harvesting intervals (14 days) resulted in grasses with higher ash content than longer harvest intervals (28 and 84 days). As plants age, they continue to utilize minerals at vegetative stages for growth, resulting in less mineral content in the final harvests due to the translocation of minerals from the vegetative parts to the roots (Kitaba and Tamir 2007). Younger plants are therefore anticipated to have higher ash contents. These differences in ash content, attributable to harvesting interval have also been observed by Gilo et al. (2022) in the Borana rangelands of Ethiopia.

Fiber fractions (NDF, ADF and ADL)

As hypothesized, varietal and species differences explain the differences in NDF and ADF components. The harvesting stage significantly ($p < 0.05$) influenced the fiber components of the grass ecotypes and showed a corresponding linear response where an increase in harvest interval resulted in higher fiber components. Similarities have been observed in *C. ciliaris* and *P. maximum* grasses used in range restoration and fodder production in South Africa (Msiza et al. 2021). The slight discrepancies and variability in results could be attributable to site differences and weather parameters. The effects of harvesting interval on NDF are also demonstrated by Gilo et al. (2022) in natural pastures, where shorter cutting intervals led to lower NDF concentrations. Similarly, ADF within the grass ecotypes also increased as the cutting interval as Wassie et al. (2018) showed in a study involving *Brachiaria* ecotypes in Ethiopia. In addition, harvest interval also affected ADL in the grasses. The low NDF, ADF and ADL at shorter cutting intervals agree with values Lee (2018) reported from global studies on forage grasses. These trends of increasing NDF, ADF and ADL values as the harvest interval increased have been observed in the King Napier grass (*Pennisetum purpureum*) variety in Thailand (Lounglawan et al. 2014) and *P. maximum* in Argentina (Schnellmann et al. 2020). Harvesting these grass ecotypes late at maturity (after 84 days) resulted in highly lignified material which may lead to low intake by livestock and decreased productivity.

In Vitro Dry Matter Digestibility (IVDMD)

The differences in IVDMD between the grass ecotypes showed a pronounced decrease with increasing harvest interval. As plants mature, they require stronger support tissues producing lignification enzymes that promote lignin accumulation and deposition in cell walls. This tends to make the grasses less digestible (Getachew et al. 2018). Lower IVDMD values were observed at the 84-day harvest interval since the grasses had matured resulting in decreased digestibility. This contrasts with the 14-day and 28-day harvest intervals with higher digestibility values.

Table 6. Correlation matrix for nutritional characteristics of the grass ecotypes

	DM	CP	ASH	NDF	ADF	ADL	IVDMD
DM	-						
CP	-0.1412	-					
ASH	-0.0953	0.419***	-				
NDF	0.1288	-0.3754**	-0.4631***	-			
ADF	0.1254	-0.4167	-0.2637	0.5848***	-		
ADL	0.0413	-0.3629**	0.1453	0.1253	0.4641***	-	
IVDMD	-0.2311*	0.8169***	0.444***	-0.4713***	-0.4835***	-0.4037***	-

Note: ***: $p \leq 0.001$, **: $p \leq 0.01$, *: $p \leq 0.05$. DM: Dry matter, CP: Crude protein, NDF: Nutrient detergent fiber, ADF: Acid detergent fiber, ADL: Acid detergent lignin, IVDMD: In vitro dry matter digestibility

In most cases in semi-arid Kenya, grass cultivation for hay production and utilization is a common practice and strategy to mitigate feed shortages (Omollo 2017). However, the need to harvest grass seeds after grass maturity results in highly lignified pastures of poor digestibility. Grazing enclosures where grasses are left ungrazed for longer periods may also result in grasses with lower digestibility due to a decrease in leaf: stem ratio as shown by Gilo et al. (2022) in Ethiopian rangelands. IVDMD figures of the grass ecotypes harvested at 84-day intervals in this study ranged between 47% and 58%. In vitro dry matter digestibility values of less than 50% in forages are considered poor quality and of hardly any feeding value to livestock (Ball 2001).

Correlation of nutritive attributes among the grass ecotypes

Table 6 shows a correlation matrix for nutritive traits among the 4 grass ecotypes. Crude protein was positively and strongly correlated to ash content and IVDMD. However, CP negatively correlated with NDF, ADF and ADL components. Negative correlations were also observed between IVDMD and the fiber components

With the advancement in age, the CP of the grass ecotypes is expected to decline while fibercomponents' increase (Lee 2018). Younger plants,exhibit high CP and hence are of higher quality, as demonstrated by the strong correlation between CP and IVDMD. Such significant correlations have also been reported between IVDMD and fiber components in some tropical grasses of semi-arid north western Australia (Mahyuddin 2008). Similar relationships were observed in indigenous grass ecotypes by Kirwa (2019) in semi-arid Kenya.

This study reveals that the defoliation interval significantly effects cumulative yields, forage accumulation rates and the nutritional attributes of the selected grass ecotypes. The *C. ciliaris* MGD and *P. maximum* TVT yielded the highest cumulative biomass regardless of the harvest intervals. Shorter harvest intervals (14 days) resulted in the lowest biomass in all the grasses and should be discouraged as this may impact animal performance. Forage nutritional value was variable across the grass ecotypes at different harvest intervals. More frequently clipped grasses indeed have higher crude protein values, but this may not be an advantage in practice because concurrently, it lowered yields thus compromising animal productivity. Therefore, it is better to harvest these grasses at 28-day intervals, to obtain more biomass, with better forage quality. Among the 4 grass ecotypes evaluated, *C. ciliaris* MGD and *P. maximum* TVT can be options for further performance evaluation for fodder production and rangeland restoration.

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Modeling suitable habitats of Edible-nest Swiftlet (*Aerodramus fuciphagus*) to support ecotourism in karst ecosystem of Karang Bolong, Kebumen, Indonesia

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Abstract. *Wibowo AA, Ningrum FU. 2023. Modeling suitable habitats of Edible-nest Swiftlet (*Aerodramus fuciphagus*) to support ecotourism in karst ecosystem of Karang Bolong, Kebumen, Indonesia. Intl J Trop Drylands 7: 112-119.* The karst ecosystem plays a vital role as a habitat for the Edible-nest Swiftlet (*Aerodramus fuciphagus* (Thunberg, 1812)) (synonym: *Collocalia fuciphaga*) due to the availability of caves for roosting sites. Additionally, factors such as vegetation cover and drought influence the presence of *A. fuciphagus* in karst ecosystems. Karang Bolong in Kebumen, Indonesia is identified as a karst ecosystem inhabited by *A. fuciphagus*. However, there is limited information regarding potential suitable habitats for this species. This study aimed to model the potential habitat for *A. fuciphagus* using Species Distribution Modeling, considering vegetation cover variables represented by NDVI and drought represented by NDMI. The habitat suitability was assessed using the AUC metric, with values ranging from 0.875 to 0.968, indicating a good model fit for depicting potential habitats for the species. In Karang Bolong, the suitability of habitats was constrained by drought conditions. The model suggests suitable habitats are concentrated in caves along the Kebumen Coasts. This information is valuable for identifying areas suitable for ecotourism and providing an alternative to swiftlet nest cultivation/harvesting. Regarding ecotourism activities, birding and observing Edible-nest Swiftlets in their natural coastal habitats, featuring scenic coastal views, could be attractive options to support the tourism industry within the karst ecosystems of Karang Bolong and Kebumen.

Keywords: AUC, avian conservation, NDMI, NDVI, species distribution modeling, sustainability, TSS

Abbreviations: AUC: Area Under the Curve, NDMI: Normalized Difference Moisture Index, NDVI: Normalized Difference Vegetation Index, SDM: Species Distribution Modelling

INTRODUCTION

The *Aerodramus fuciphagus* (Thunberg, 1812) (synonym: *Collocalia fuciphaga*) belongs to the Apodidae, a family predominantly composed of cave-dwelling species. Apodids build their nests within caves using leaves and saliva. The species that use saliva in nest-building adds significant value, as these nests are edible and marketable. Consequently, the nests possess commercial importance and are harvested for sale. The majority of swiftlet species that are targeted for hunting and rearing, particularly for the production of swiftlet nests, are the *A. fuciphagus* (Suriya et al. 2004); *A. fuciphagus* (synonym: *C. fuciphaga*) has a wide distribution in South China and Southeast Asia, including Indonesia. Indonesia is among the world's leading producers of swallow nests, with swiftlet nest cultivation tradition dating back to the 18th century. The nests of the Edible-nest Swiftlet (*A. fuciphagus*) (Sankaran 2001) rank among the most expensive animal products in the world, leading to extensive exploitation of their nests across Asian regions, including India's Andaman and Nicobar Islands. In the Kebumen District, West Java, the caves along the coast serve as a habitat for *A. fuciphagus* (Daud and Hikmah 2021).

Three swallow species are renowned for their consumable nests: the white swiftlet (*A. fuciphagus*), the black swiftlet (*Collocalia maxima* Hume, 1878), and the linchi swiftlet (*Collocalia linchi* Horsfield & F.Moore, 1854) (Amin 2021). Edible-nest Swiflets construct nests entirely from saliva. Black swiftlets create nests in limestone caves on the coast. These nests consist of a mixture of saliva and black feathers, with the predominant presence of feathers giving the nest a black coloration. On the other hand, linchi swiftlets produce nests with mixed saliva and additional materials like pine leaves, twigs, or palm fiber. Hence, it is also known as grass-type nests. Swiftlets primarily feed on insects, with their diets predominantly composed of Hymenoptera, followed by Diptera, Hemiptera, and a small portion of Coleoptera and Isoptera. Among Diptera, *Megaselia scalaris* (Loew, 1866) was the most preferred diet for swiftlets. Carbohydrates serve as the primary energy source for swiftlets, while fats support growth, enzymes aid in nest construction, and tissues contribute to development (Ahmad et al. 2019).

Swiftlets select roosting sites, with caves being the preferred choice. A prior study noted that approximately 2% of the population did not return to the caves, while the majority did. Several variables influenced the preferred roosting sites within the caves, including predators, the breeding cycle, and even the lunar phase (Mane and Manchi 2017).

A crucial habitat for *A. fuciphagus* is the karst ecosystem, known for its numerous caves that swiftlets use for nest-building. In Southeast Asian regions, including Indonesia, karst ecosystems exhibit high species diversity and endemism levels (Clements et al. 2006). Karst formations serve as roosting sites for large aggregations and substantial numbers of swift species (Biancalana 2014). Swifts usually form breeding colonies in wet caves and areas near water sources. Asian karst ecosystems, with their caves, have been identified as one of four regional priorities for conservation research (Kingston 2008; Furey et al. 2010). Indonesia boasts a vast karst area, signifying a great repository for karst biodiversity (Sulistiyowati et al. 2021). Simultaneously, Kebumen is a region endowed with a vast karst ecosystem and holds biodiversity potential, especially for swift species (Muntofingah 2017).

In Central Java, the Ayah Sub-district and Menganti Coast in Kebumen District still have karst ecosystems with caves within their regions (Kholid 2020). Despite most karst ecosystems in Kebumen being located in the northern areas, the southern parts of Ayah Sub-district in the south west in Karang Duwur, and the south-east parts that bordered with Buayan Sub-district in areas known as Karang Bolong are still within karst ecosystems (Laksono 2019).

These caves served as habitats for *A. fuciphagus*, yet information regarding suitable habitats for *A. fuciphagus* within this karst ecosystem remains limited. This study aims to assess and model the suitable habitats of *A. fuciphagus* in this karst ecosystem. The findings of this study can be instrumental in supporting the conservation efforts for *A. fuciphagus* and promoting ecotourism in the Kebumen karst region. The key predictors employed in this study to model suitable habitats for *A. fuciphagus* include forest cover and soil moisture index, recognized as important variables for *A. fuciphagus* by providing natural habitats and a stable water supply.

MATERIALS AND METHODS

Study area

The study focussed on the karst ecosystem in Central Java, Indonesia, specifically the Ayah Sub-district and the Menganti Coast in the Kebumen District (Figure 1) (Afifah et al. 2023). Ayah Sub-district is geographically located at 7°39′36″-7°46′18″ S and 109°23′43″-109°27′27″ E. The topography of the Ayah Sub-district varies in altitude from 0-331 meters above sea level (masl), featuring an extensive coastline spanning 1,785.6 m. The area of Ayah Sub-district is characterized by hilly terrain, and numerous caves have developed within these areas. Notable caves include Karang Bolong Cave (7°45'33"S, 109°27'07"E) in the eastern part bordered with Buayan Sub-district and Siwowo (7°45'30"S 109°23'56"E) and Karang Duwur Caves (7°45'36"S 109°23'53"E) in the western region near Menganti Coast. Ayah Sub-district encompasses a total area of 76.37 km^2, of which 19.62 km^2 was an intact forest. Most of the region retains a stable water supply, including ground and surface water sources. However, a seasonal disparity in spring availability exists, attributed to changes in land use that alter its function. This transformation, coupled with large surface runoff and reduced rainfall, has led to soil water storages.

Procedures

Survey of A. fuciphagus

The survey for *A. fuciphagus* in the Ayah Sub-district, Kebumen, was conducted in August 2023. The survey employed visual encounters, repeated surveys, and random visits as designated procedures. Observations were conducted at various times throughout the day, with direct observations aided by binoculars or unassisted eyes. To align with *A. fuciphagus* activities, the survey spanned from 05.30-7.00 am and resumed from 04.00-06.15 pm.

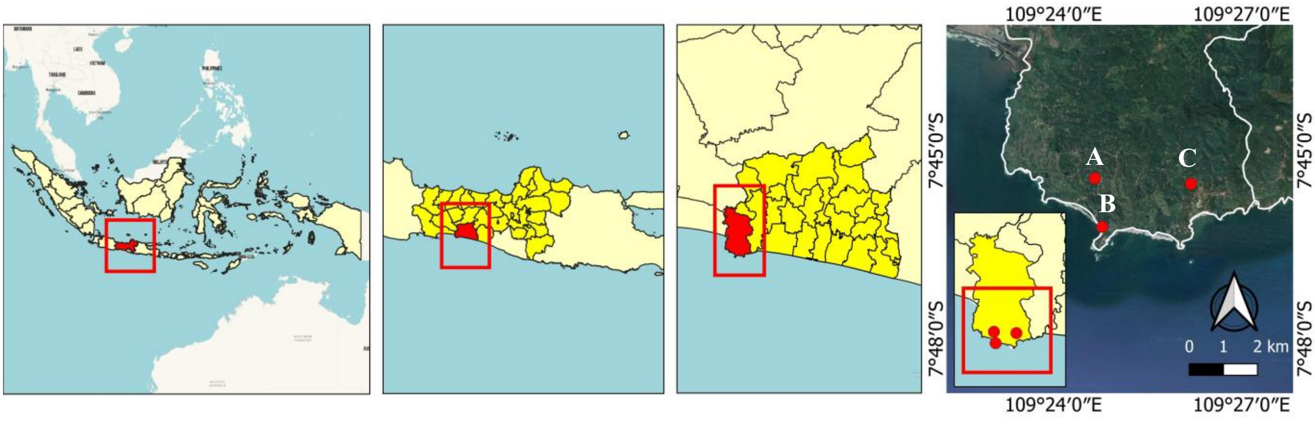


Figure 1. A map of the study area shows stations covering karst ecosystem and cave formation, including Karang Duwur (A) and Siwowo (B) Caves in the Western part of Ayah Sub-district within Menganti Beach, and Karang Bolong Caves (C) in the Eastern part of Ayah Sub-district bordered with Buayan Sub-district, Kebumen District, Central Java Province, Indonesia

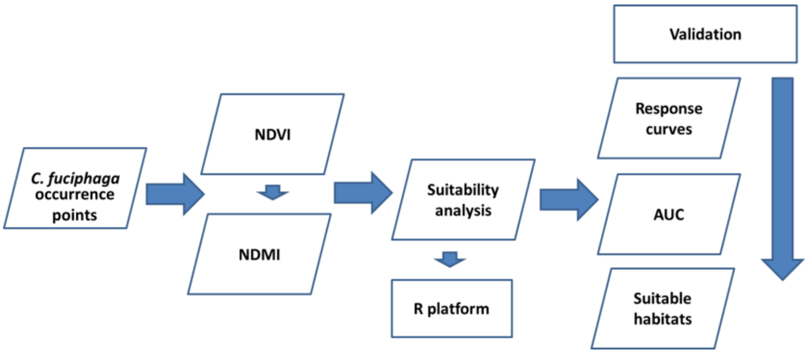


Figure 2. A chart of suitability analysis using the SDM method

The *A. fuciphagus* survey focused on three distinct study areas, each representing karst ecosystem and cave formation that served as roosting sites for *A. fuciphagus*. These locations included Karang Duwur and Siwowo Caves in the western part of the Ayah Sub-district within Menganti Beach and Karang Bolong Caves in the eastern part. Within each cave, three replicated stations were established, totaling nine stations. The swiftlet was identified using a dedicated bird identification book and field guide (MacKinnon and Phillipps 1993). Subsequently, the presence and occurrence point of *A. fuciphagus* were documented and tabulated for Geographical Information System (GIS) mapping purposes.

Suitability analysis

This study employed Species Distribution Modelling (SDM) analysis using R platform version 3.6.3 (Mao et al. 2022) (Figure 2) to generate predicted suitability maps of *A. fuciphagus* along Karang Duwur and Siwowo Caves within Menganti Beach and Karang Bolong Caves. The notable R packages used to generate the suitability maps comprise dismo, sp, maptools, rgdal, raster and so on. (Lemenkova 2020; Bivand 2022; Khan et al. 2022). The covariates for conducting SDM included rasters of forest cover, moisture, and drought variables. These variables were selected due to a linkage of swiftlet distribution with NDVI, forest cover (Ito et al. 2021), and drought (Burhanuddin and Hafidzi 2017). The main principle in SDM is to search for a probability distribution that is most spread out subject to the constraints imposed by the available information on species' occurrence and the associated environmental variables across the study area. SDM uses a deterministic sequential-update algorithm that iteratively picks and adjusts weights of predictors, which is guaranteed to converge to the most spread out probability distribution. SDM employs a probability distribution algorithm that belongs to the family of Gibbs distributions (exponential distributions), where these probability distributions are derived from a set of features $f_1 \ldots f_n$, parameterized by weights $\lambda_1 \ldots \lambda_n$ (Tesfamariam et al. 2022). SDM predicts occurrence rates as a function of the environmental variables at that location. These occurrence rates (P*(z(xi))) take the form as follows (Merow et al. 2013):

$$P^*(z(x_i)) = \exp(z(x_i)\mathbf{l}) / \Sigma_i \exp(z(x_i)\mathbf{l})$$

Where: z is a vector of *J* environmental variables at location x_i, and λ is a vector of regression coefficients, with $z(x_i)\,\lambda = z_1(x_i)^*\,\lambda_1 + z_2(x_i)^*\,\lambda_2 + \ldots + z_J(x_i)^*\,\lambda_J$. These occurrence rates sum to unity across the study area because the denominator is a sum of the occurrence rates over all grid cells in the study (called normalization). Normalization ensures that the occurrence rates are, relative.

NDVI and drought (NDMI) variables

The Normalized Difference Vegetation Index (NDVI) of the Ayah Sub-district was measured following the methodologies outlined by Philiani et al. (2016), Kawamuna et al. (2017), and Sukojo and Arindi (2019). NDVI serves as a straightforward graphical indicator utilized to interpret remote sensing data, often derived from space satellite platforms, to determine the presence of live green vegetation within the observed target. The calculation of NDVI involved assessing the wavelengths of a satellite image obtained from the Landsat 8 Operational Land Imager (OLI), specifically capturing images of vegetation such as forest covers. This measurement is feasible due to the cell structure of vegetative leaves, which substantially reflects near-infrared light wavelength ranging from 0.7 to 1.1 microns. The NDVI for each vegetation pixel was calculated as follows:

NDVI = near invisible red wavelength – red wavelength / near invisible red wavelength + red wavelength

The NDVI ranged from 0, indicating no vegetation, to 1, representing high vegetation density. Employing GIS technology, the NDVI values were overlaid and mapped onto the land cover layers of the Ayah Sub-district. After this analysis, the forest covers were systematically categorized and classified based on the NDVI as outlined below:

- if $0 < \text{NDVI} < 0.3$, the forest covers < 50%;
- if $0.31 < \text{NDVI} < 0.4$, the forest covers are 50-69%;
- if $0.41 < \text{NDVI} < 1.0$, the forest covers are 70-100%

Drought variables were assessed by measuring the moisture index, developed utilizing Landsat 8 satellite data, and denoted as Normalized Difference Moisture Index (NDMI). NDMI leverages near-invisible red and short-wavelength infrared bands to display moisture levels. The short-wavelength infrared band captures changes in the spongy mesophyll structure and the vegetation water content within vegetation canopies. Simultaneously, the near-invisible red reflectance is influenced by dry matter content and the internal structure of the leaf rather than by water content. The combination of the near-invisible red and the short wavelength infrared mitigates variations induced by the leaf's dry matter content and internal structure, thereby enhancing the accuracy of assessing the water content of vegetation. Water availability in the internal leaf structure significantly governs spectral reflectance in the short-wavelength infrared segment of the electromagnetic spectrum. Short-wave infrared reflectance demonstrates a negative correlation with leaf water content. Consequently, NDMI proposed by Gao (1996) is a valuable tool for monitoring changes in leaf water content. NDMI is computed using the near-infrared and the short-wave infrared reflectances as follows:

NDMI = near invisible red wavelength – short wavelength infrared/near invisible red wavelength + short wavelength infrared

Model validation

The evaluation of this SDM adheres to the methodologies outlined by Reddy et al. (2015) and Song et al. (2023). Specifically, the model's performance was assessed through Area Under the Curve analysis (AUC). The size of the AUC and the Receiver Operating Characteristic Curve (ROC) were used to assess the accuracy of the SDM model predictions. Higher AUC values correspond to greater accuracy in the model's prediction outcomes, and the selection of SDM model parameters aligns with the methodology proposed by Zhao et al. (2018). The AUC is an efficient and independent threshold index for assessing the model's capacity to differentiate between absences and presences. Performance categories are delineated based on AUC values, with values falling within the range of 0.9 to 1 classified as "great," 0.8 to 0.9 as "good," 0.7 to 0.8 as "reasonable," 0.6 to 0.7 as "poor," and values below 0.6 as "failing" or indicating rare occurrences in real-life scenarios (Shcheglovitova and Anderson 2013). A Jackknife analysis was run to systematically exclude each variable and evaluate the significance of NDVI and NDMI variables in determining the potential distribution of species. The relationship between the potential habitat for the species and the NDVI and NDMI variables factors was determined through the response curve generated by the model (Vilà et al. 2012). The relative contributions, expressed as a percentage, of each environmental variable to the SDM model were calculated and presented in Figure 2. in addition to the AUC values, model validation was conducted using TSS (True Skill Statistics) (De et al. 2020). TSS, as described by Allouche et al. (2006), is expressed as Sensitivity + Specificity – 1 and ranges from −1 to +1. A TSS value of +1 indicates a perfectly performing model with no error, 0 with a totally random error, and -1 with a total error (Marcot 2012; Ruete and Leynaud 2015).

RESULTS AND DISCUSSION

NDVI

Figure 3 depicts the NDVI variable in Ayah Sub-district. Dense forest cover extends from Karang Duwur Cave and Menganti Coast in the west to Karang Bolong Cave in the east, indicating the presence of forest cover within the karst ecosystems in the Ayah Sub-district. The NDVI values in this karst area were close to 1, signifying a high vegetation density. Conversely, in the Northern part of the region, the karst ecosystem exhibits declining NDVI values. The NDVI was lower in the North, with values less than 0.5 and approaching 0. This suggests that the forest cover in the northern karst ecosystem has been subject to logging. In these Northern areas, the forest has been converted into settlements indicating land use changes in the form of deforestation and urbanization.

NDMI

Figure 4 depicts the NDMI variable in Ayah Sub-district. Most areas are characterized by wet conditions, corresponding to the prevalent forest cover. However, certain regions were experiencing drought. Similar to NDVI patterns, the northern parts of Ayah Sub-district, characterized by lower NDVI values, also exhibit low NDMI values close to 0. Interestingly, the coastal areas extending from Karang Duwur Cave and Menganti Coast in the West to Karang Bolong Cave in the East display low NDMI values despite having high NDVI values and forest cover. This suggests that the karst ecosystems in the Ayah Sub-district have patchy areas with low NDMI values, indicative of lower moisture content, despite having high NDVI values and forest covers. The observed low NDMI values in the cave's proximity signify the presence of karst formations within the ecosystems.

Model validation

Table 1 depicts the results of SDM model validations, assessing the performance based on the AUC and TSS values. The SDM models were constructed using the NDVI and NDMI variables. In the case of NDVI, the model achieved an AUC of 0.968 and came under 'great' model category (Figure 5) and had no error with a TSS value of 0.749. Similarly, the AUC value for NDMI was 0.875 and 0.999 for TSS.

Table 1. AUC and TSS values for NDVI and NDMI variables

Variables	AUC	TSS
NDVI	0.968	0.749
NDMI	0.875	0.999

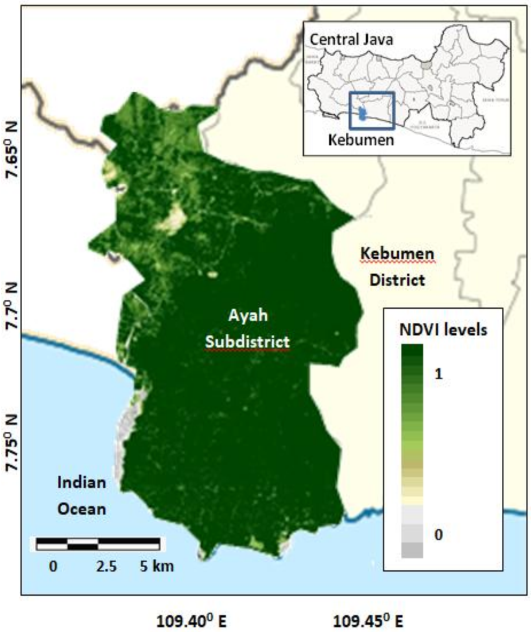


Figure 3. A map of NDVI variable of Ayah Sub-district, Kebumen District, Central Java Province, Indonesia

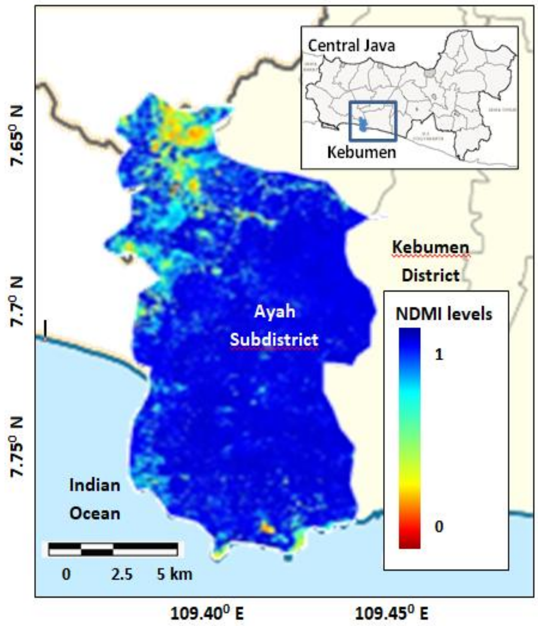


Figure 4. A map of NDMI variable of Ayah Sub-district, Kebumen District, Central Java Province, Indonesia

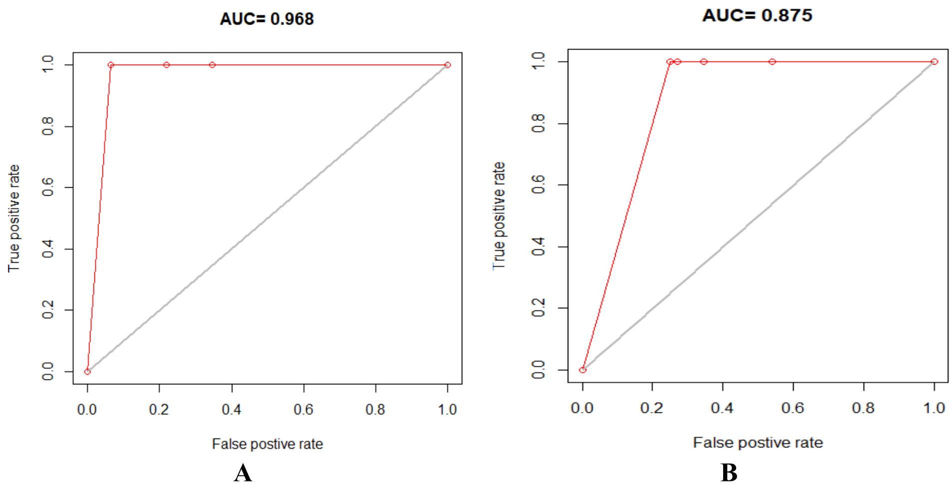


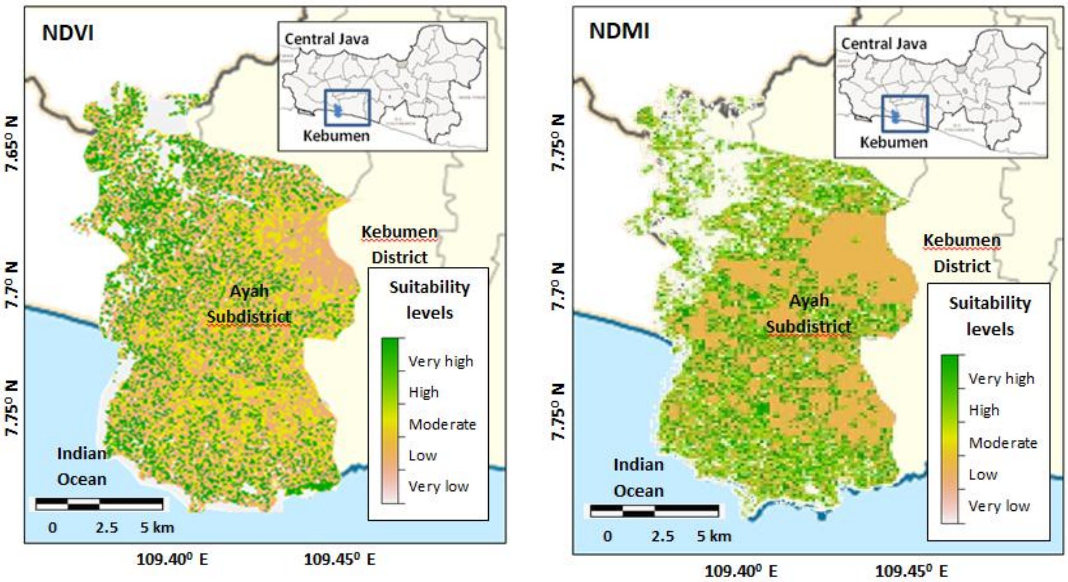
Figure 5. AUCROC values for A. NDVI (0.968) and B. NDMI (0.875) variables

Suitable habitat models

The SDM models for *A. fuciphagus* in Ayah Sub-district, Kebumen District, Central Java Province, Indonesia, are visually represented in Figure 6, highlighting projections based on NDVI and NDMI variables. When utilizing NDVI as a covariate, the model suggests that suitable habitats for *A. fuciphagus* are projected to be available across all areas of the Ayah Sub-district, including regions where the caves are uncommon. Conversely, the NDMI model indicates that suitable habitats for *A. fuciphagus* are more confined, with central parts of the Ayah Sub-district being deemed unsuitable. The middle region exhibits lower moisture levels, limiting the potential distribution of *A. fuciphagus*. In contrast, the models project that coastal areas are the most suitable habitats, with areas categorized as highly to very highly suitable predominantly concentrated in these coastal areas. These areas cover caves and beaches, contributing to their high suitability for *A. fuciphagus*.

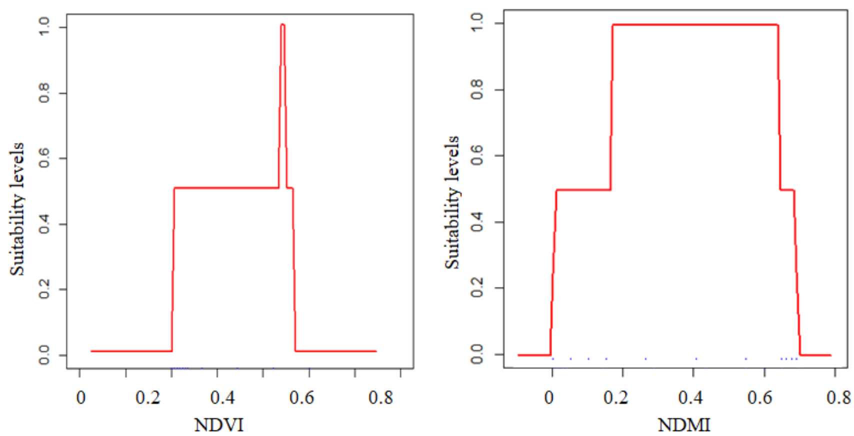
Response curves

The correlations of the NDVI and NDMI variables with suitability levels are depicted in the response curves (Figure 7). The threshold for suitability levels was set at 0.6, designating habitats as moderately suitable. For NDVI, habitats were deemed suitable at suitability levels 0.6 when NDVI values exceeded 0.5. In the case of NDMI, suitable habitats were identified by NDMI values surpassing 0.2.



A B

Figure 6. SDM models for suitable habitats *Aerodramus fuciphagus* in Ayah Sub-district, Kebumen District, Central Java Province, Indonesia for A. NDVI and B. NDMI variables



A B

Figure 7. Response curves for suitable habitats of *Aerodramus fuciphagus* for A. NDVI and B. NDMI variables in Ayah Sub-district, Kebumen District, Central Java Province, Indonesia. The suitability level means are 0.5 both for NDVI and NDMI

Discussion

This study presents the first assessment of suitability levels for *A. fuciphagus* within the karst ecosystem using NDVI and NDMI values. Previous spatial studies on swiftlets, such as those by Margareta and Abdullah (2010) and Ayuti (2016), were limited to urban scales and omitted the forest cover or drought-related variables like NDVI and NDMI, respectively. Notably, the high NDVI values across the study areas indicated that these regions were generally suitable for *A. fuciphagus*. Conversely, lower suitability was observed in areas with low NDMI, suggesting reduced moisture or potential drought conditions. The relationship between NDVI and *A. fuciphagus* presence is indirect, where high NDVI indicates ample vegetation cover that attracts insects, a primary diet for *A. fuciphagus* (Ambrosini et al. 2011; Mursidah et al. 2021). The lush vegetation in Karang Bolong's karst ecosystems draws aerial insects, making these expansive areas suitable for *A. fuciphagus* due to their high NDVI values.

NDMI values, indicative of moisture levels, are crucial in determining swiftlet occurrence. The *A. fuciphagus*, known for constructing nests primarily from saliva, prefers habitats with higher moisture indexes. The absence of *A. fuciphagus* in regions with lower NDMI suggests their affinity to moist habitats, as reflected in their nest-building behavior. Surrounding ecosystems significantly influence nest type and avifauna (Briggs and Deeming 2021). Moreover, moisture conditions indirectly impact swiftlets by affecting insect presence; drought conditions can reduce insect populations, thereby affecting swiftlet presence (Frank 2021). Karst ecosystems, including those in Kebumen, are prone to droughts due to their low water retention capacity due to exposed rocks and shallow soils that influence soil water distribution (Luo et al. 2022; Mo et al. 2023). Some coastal areas, despite exhibiting lower moisture, remained favorable for *A. fuciphagus* due to their high NDVI values and the presence of numerous caves, such as Karang Duwur and Siwowo Caves in the West and Karang Bolong in the East, which is inhabited by the swiftlets.

The SDM indicates extensive suitable habitats for swiftlets across the region, encompassing areas far inland from the coasts and distant from known roosting sites, consistent with the findings of Petkliang et al. (2017), which that the foraging distances of Germain's swiftlet are 25 km from its breeding sites. In India's Andaman Islands, India, the edible-nest swiftlet *A. fuciphagus inexpectatus* exhibits foraging behaviors up to 1-2 km from breeding sites, favoring forested areas over open land.

While keeping and rearing swiftlets for their nests persists (Benjakul and Chantakun 2022), this unsustainable activity contributes to population decline and poses an extinction threat. An alternative industry, such as ecotourism, capitalizing on the region's valuable geological features, including caves, has potential in Kebumen. Bird watching of swiftlets, an ecotourism attraction, could be developed by combining cave exploration with observing swiftlet roosting (Fullard et al. 2010).

In conclusion, the study identifies the karst ecosystem, particularly the vegetation-rich Karang Bolong, as conducive to *A. fuciphagus* breeding and ecotourism. The proposed alternative bird watching industry, intertwined with cave exploration and coastal scenery, holds promise for sustainable ecosystem activities supporting swiftlet conservation.

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