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Exploring the Role of Traditional Ecological Knowledge in Restoring and Managing Miombo Woodlands: A Case Study from the Lubumbashi Charcoal Production Basin, Haut-Katanga, DR Congo

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Abstract: The over-exploitation of forest resources in the Lubumbashi Charcoal Production Basin in south-eastern DRC is accelerating deforestation and *miombo* woodlands degradation, jeopardizing the livelihoods of local communities. In this situation, current forestry policies remain ineffective, not least due to the failure to integrate traditional ecological knowledge (TEK). This study explores this knowledge through focus groups and individual interviews in four villages (Maksem, Mwawa, Nsela and Texas), selected according to the availability of forest resources and the number of inhabitants. Interviews gathered data on sacred sites and trees, conservation practices, the transmission of traditional knowledge, the role of ceremonies and the socio-demographic determinants of their application. These data were analyzed using descriptive statistics (citation frequency), Fisher's exact test for associations between variables, and Jaccard's similarity index to compare villages. The results show that 75% of people surveyed in both types of villages were aware of sacred sites in their village, as opposed to cemeteries, where logging is forbidden. Thirty sacred wood species were identified, with stricter observance of related prohibitions in villages with a high availability of forest resources. Knowledge is transmitted orally, via family councils and traditional ceremonies. Conservation practices include small-scale farming, intercropping, the ban on cutting trees on sacred sites and the use of dead wood. However, only the first two are still widely practiced, especially in villages with limited resources (64%). These practices are mainly applied by women and the elderly, and those involved in charcoal production and the collection of non-timber forest products. Nevertheless, the application of these TEK is strongly affected by population growth and the consequent low availability of forest resources, amplifying the pressure on *miombo* woodlands. These results underline that the integration of this traditional ecological knowledge into DRC forestry policies would significantly strengthen forest restoration initiatives, through a fine-tuned understanding of local ecosystems, sustainable practices and key woody species, while fostering community involvement. Decision-makers must integrate these TEK into DRC forest policy to strengthen biodiversity conservation and *miombo* woodlands restoration efforts.

Keywords: Traditional knowledge; deforestation; *miombo* woodlands; conservation; biodiversity; ecological practices; sustainable management

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1. Introduction

The need to preserve tropical forests has become clear in recent decades. Not only are they exceptional reservoirs of biodiversity [1], but they also play a crucial role in sequestering atmospheric carbon [2]. In addition to their ecological function, these forests fulfill indispensable social and cultural roles for local and Indigenous communities. They enable the survival of over 1.6 billion people worldwide, both rural and urban, through the ecosystem services they provide [3,4]. These ecosystem services include the provision of timber, wood energy and various non-timber forest products (NTFPs) [5].

In sub-Saharan Africa, these forests are under increasing anthropogenic pressure, exacerbated by rapid population growth in the context of extreme poverty, as well as rapid and generally unplanned urbanization. These dynamics are leading to unprecedented deforestation and degradation of these forest ecosystems [6,7]. Consequently, statistics relating to this deforestation are alarming. Indeed, in 2010, forests accounted for more than 675 million hectares, or around 23% of the African continent's surface area [8]. But this figure has dropped to less than 636 million hectares (21%) in 2020 [9]. The situation is particularly critical in the Congo Basin, which lost almost 100 million hectares of forest between 2010 and 2020 [10,11]. In the Democratic Republic of Congo (DRC), the annual deforestation rate rose from 0.4% between 2000 and 2010 [12] to 0.61% between 2010 and 2020 [2]. With this rate of deforestation, the DRC's forest area had already fallen from 250 million hectares in 2010 to just 117 million hectares in 2020 [2,12]. If no corrective measures are taken, a forest loss of almost 22% is anticipated by 2050 [2].

The south-east of the DRC is particularly hard hit, especially in the area where *miombo* woodlands—a forest formation dominated by species of the genera Brachystegia, Julbernardia and Isoberlinia—is the most dominant vegetation unit [13]. Indeed, between 2000 and 2010, *miombo* woodlands covered 23,220,000 hectares, representing almost 11% of the Zambezi region, but this coverage has declined considerably, from over 70% of Katangan territory in 2000 to around 43% in 2010 [14]. This deforestation trend is particularly marked in the Bassin de Production du Charbon de Bois de Lubumbashi (BPCBL), where the deforestation rate is more than six times higher than the national average, reaching 1.51% [15]. This deforestation is exacerbated by difficult socio-economic conditions, which make rural and urban populations highly dependent on forest resources, notably through shifting agriculture and wood-energy production [16,17]. In addition, the growing demand for wood energy in urban areas, supported by galloping demographics and inadequate electricity supply in large conurbations, is contributing to the increased degradation of BPCBL forests [15]. This affects the *miombo* woodlands' rich biodiversity, characterized by a high rate of endemism, and threatens the livelihoods of the rural and urban populations that depend on it [18–20].

In response to deforestation and forest degradation, forest ecosystem restoration appears to be the main solution. Restoration refers to all practices aimed at re-establishing the ecological functionality of degraded habitats, thereby improving the living conditions of local populations. [21,22]. This restoration includes the production of seedlings of native or exotic forest species in nurseries, or the facilitation of natural regeneration in the habitats concerned [21,23], thus ensuring the continued provision of essential ecosystem services [24]. Nevertheless, to ensure the success of these initiatives, the integration of traditional ecological knowledge and practices (TEK) is necessary. TEK is defined as a set of culturally transmitted knowledge, practices, beliefs and taboos that evolve and play a central role in the sustainable management of ecosystems by local populations [25–29]. To this end, these TEK strengthen forest restoration through a fine-tuned understanding of local ecosystems, sustainable practices, and key species, while promoting community engagement in forest restoration processes and adaptation to environmental change [30]. The cultural and spiritual anchoring of these TEK guarantees responsible and sustainable management of restored forests [31]. As a result, since the 1992 United Nations Conference on Environment and Development, TEK has been recognized as a complement to modern scientific knowledge in approaches to ecosystem management and biodiversity conservation [32]. They now inspire forest policy through new

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management models, combining ecological conservation with the socio-economic needs of local populations [28].

Studies of these TEK in Africa show that they promote biodiversity conservation through orally transmitted taboos and beliefs. They protect ecosystems, regulate access to resources and maintain natural habitats [33–36], including in the *miombo* woodlands ecoregion [37–39]. Moreover, data on their effectiveness and an analysis of interactions with modern dynamics (urbanization, population growth) are often lacking. Yet these dynamics, like population growth, influence TEK implementation by increasing pressure on forest resources [40]. This would lead to the overexploitation of forest resources while limiting the observance of traditional practices, and weakening their transmission to younger generations [28]. Nevertheless, in the Lubumbashi region, research into TEK remains limited. The work of Refs. [41,42] addresses the importance of plant species in daily life and the farming system but does not explore the contribution of integrating these TEK in *miombo* woodlands management. This study fills these gaps by demonstrating the positive impact of these TEK in *miombo* woodlands conservation and management, particularly in reforested forest habitats. It documents these endangered practices and proposes their integration into environmental management policies, combining traditional knowledge and scientific expertise for sustainable forest management. The integration of traditional ecological knowledge and practices would promote sustainable management of residual *miombo* woodland patches and participatory restoration in the BPCBL.

This study aims to identify and describe traditional ecological knowledge and practices relating to biodiversity conservation and the sustainable management of *miombo* woodlands. It hypothesizes that (i) the endogenous knowledge of local indigenous communities in the Lubumbashi region abounds in TEK, such as sacred sites and trees, which would play a crucial role in forest restoration and sustainable management of *miombo* woodlands. These practices are transmitted orally within family councils, reinforcing respect for the prohibitions and beliefs associated with natural resource conservation. (ii) These practices are more likely to be applied in villages with small populations and limited forest resources, mainly by women, the elderly, and the less educated, due to their regular contact with the forest and the selective nature of their activities such as charcoal production, art carving and NTFP collection.

2. Materials and Methods

2.1. Study Area

The present study was conducted in the BPCBL in southeastern DRC (Figure 1), a region characterized by a Cw-type climate according to Köppen’s classification.

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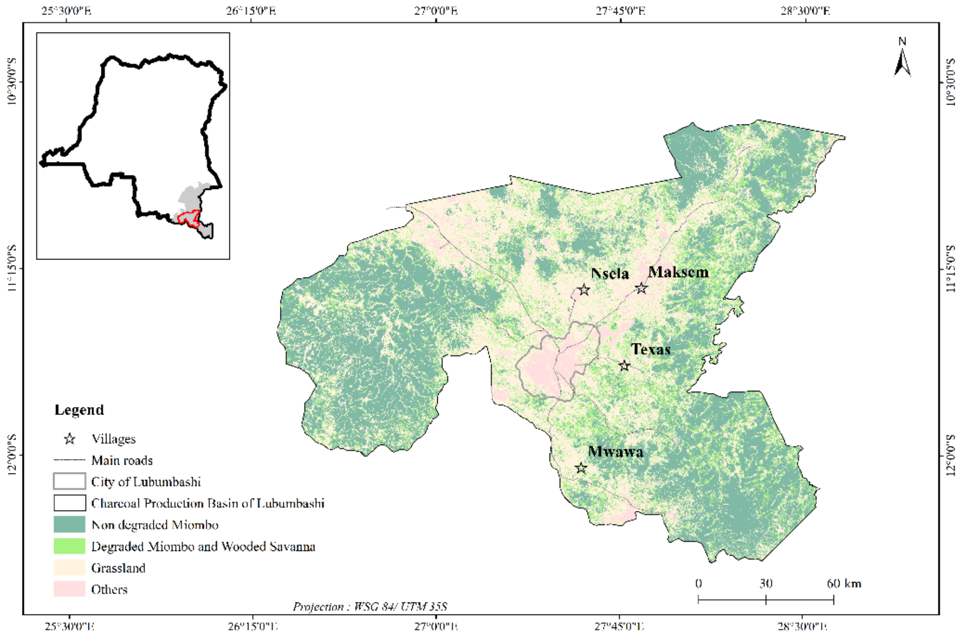

Figure 1. The geographical location of the BCPBL and the villages included in the study (represented by stars), within an 80 km radius of Lubumbashi, in the province of Haut-Katanga in south-eastern DRC.

This climate is marked by a dry season extending from May to September, a rainy season from November to March, and two transition periods in April and October [43,44]. The BPCBL, located at an altitude of between 1,200 and 1,300 m, receives annual rainfall of between 1,200 and 1,270 mm [13]. The mean annual temperature, which stood at around 20°C at the end of the XXth century [41], has risen significantly since the beginning of the XXI(st) century [45]. The predominant vegetation unit at the beginning of the 20th century in this region was *miombo* woodlands, generally established on ferralsols [46]. Today, however, this forest ecosystem is fragmented, a phenomenon attributable mainly to shifting agriculture, charcoal production, and increasing urbanization [15,16,47,48]. The local population, estimated at over 3 million [49], continues to rely heavily on natural resources. School enrolment remains low, with less than 50% of the population having access to formal education [17]. Main subsistence activities include shifting agriculture, firewood production (dendro-energy), illegal timber exploitation, small-scale informal trade, and artisanal mining [16,50].

2.2. Methods

2.2.1. Site Selection, Sampling, and Data Collection

The present study was carried out from November 20th, 2023, to January 20th, 2024, in the villages of Maksem, Mwawa, Nsela, and Texas, located in the rural area of Lubumbashi. These villages were selected because of their intense anthropogenic activities, mainly agriculture and charcoal production, their accessibility in all seasons, and their high connectivity to other satellite villages [17]. To verify the knowledge and application of TEK, these four villages were grouped according to the availability of forest resources (Figure 1), as well as the number of inhabitants (Table 1). This grouping assumes that villages with available forest resources and low population numbers will increasingly implement TEK due to the high availability of forest resources, enabling these inhabitants to remain selective in meeting daily needs. Forest resources are limited and the population is high in Maksem and Texas, compared with Mwawa and Nsela.

Table 1. This is a table. Tables should be placed in the main text near to the first time they are cited.

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Villages	Population size	Forests availability	Focus group participant	Number of people surveyed for validation	Gender (%)	
					F	M
Maksem	356	Limited	8	50	8	92
Texas	333		12	50	48	52
Mwawa	163	Available	11	50	24	76
Nsela	126		12	50	36	64

To gather information on traditional knowledge and practices relating to the conservation of forest resources, focus groups were organized in each village, following the methodology of [51]. These focus groups made up of 8 to 12 people, mainly the traditional chiefs and notables of each village (Table 1), collected data on the existence of sacred sites, sacred woody species, and associated beliefs and practices. Participation in these focus groups depended on local community members' mastery of TEK, particularly among the indigenous population. The aim was to determine the role of this traditional knowledge in biodiversity conservation and forest management.

Focus group data were validated by individual interviews with 200 local community members, i.e., 50 people per village. This number of respondents was chosen due to the lack of official statistics on the distribution of local communities, allowing a representative sampling of the different populations within these 4 villages. Nevertheless, this number of respondents is higher than that (40 respondents) recommended for social science studies [52]. The snowball method facilitated the identification of Indigenous local community members concerned by the present study, given the heterogeneity of origin (indigenous and non-indigenous) of the population of these four villages [53,54].

In addition, individual interviews were conducted using a semi-structured questionnaire [55], using the Kobotoolbox application version v2023.2.4. This approach made it possible to focus responses on specific themes defined in the questionnaire [56]. In addition to the information gathered during the focus groups, socio-demographic data such as age, gender, level of education, and professional activities of the respondents were collected to correlate them with the TEK responses. For age, participants were grouped into three categories: young (18-35 years), adult (36-60 years) and elderly (≥61 years) [57]. For educational level, participants were classified into four groups: uneducated, primary level, secondary level, and university level.

During these individual interviews, data on knowledge concerning sacred sites and woody species, traditional biodiversity conservation practices, and the modes and circumstances of TEK transmission were collected [37]. The identification of woody species, mentioned under their vernacular names by the respondents, was carried out using existing floras (Flora of Zambia, Flora of Zimbabwe, Worldflora), specialist literature, and various identification guides [41,58–60]. Field trips, in the presence of some of the respondents, enabled us to identify woody species cited in vernacular languages by the local communities, but not listed in existing books.

2.2.2. Data Analysis

To assess the importance of traditional knowledge and the influence of associated beliefs and prohibitions, the citation frequency (C_f) of sacred sites and trees was determined using the ethnobotanyR package in R software version 4.3.2. This analysis was also extended to biodiversity conservation practices, modes and circumstances of transmission of traditional knowledge, and the role of ceremonials in forest management. The frequency of citation assumes that elements considered sacred are those that appear most often during interviews [61]. This frequency is calculated according to the following relationship (equation 1):

$$C_f = \frac{S}{N} \times 100 \quad (1)$$

where: S is the number of people citing the site or species, and N is the total number of people interviewed. When Fc tends towards 0, the site/species is weakly known as sacred, and when Fc tends towards 100, the site/species is strongly known as sacred.

To examine the association between the qualitative variables relating to Traditional Ecological Knowledge and Practices and the two village groups, Fisher's exact test with a risk of error of less than 5% was used. This non-parametric test is an alternative to the Chi-square test of association, particularly suitable when a cell in the contingency table has theoretical values below 5, one of the limiting conditions for applying the Chi-square test [62,63]. In addition, Fisher's exact test was also used to analyze the association between these variables and elements of the socio-demographic profile of the people surveyed.

Finally, to highlight the similarities between the possession of knowledge and its practical application according to the two groups of villages mentioned above, the Jaccard index (J; equation 2; [64]) was calculated using Past version 4.05 software.

$$J = \frac{a}{a + b + c} \quad (2)$$

where a: represents the number of knowledge or practices common to both village categories, while b and c designate those specific to each category respectively.

3. Results

3.1. Traditional Knowledge, Transmission and the Role of Ceremonials in Biodiversity Conservation and Miombo Woodlands Management

3.1.1. Traditional Ecological Knowledge and Practices Related to Biodiversity Conservation and miombo Woodlands Management

Over ¾ of those surveyed indicated that cemeteries, associated with the resting place of ancestors, are the most widely recognized sacred sites in rural Lubumbashi, particularly in villages with limited forest resources and high population numbers. In addition, cemeteries and river springs appear to be common sacred sites in both categories of villages studied. A greater diversity of sacred sites is noted particularly in villages with more abundant forest resources and a low number of inhabitants present, compared to villages with limited forest resources and a high number of inhabitants. The taboos associated with these sacred sites mainly take the form of prohibitions on tree-cutting, access to sacred sites, and bushfires. However, observance of these beliefs and prohibitions is generally low, particularly in villages with limited forest resources and high population numbers, except for cemeteries (Table 2). These results underline the cultural importance of cemeteries in Lubumbashi's rural communities, particularly in villages with limited forest resources and high population numbers. They also indicate that, although beliefs and prohibitions relating to sacred sites are often neglected, cemeteries benefit from more rigorous protection. This suggests a need to strengthen the preservation of sacred sites in resource-limited areas to support local cultural practices.

Table 2. Sacred sites in the Lubumbashi rural area, according to citations (focus and individual interviews) by local community members. Sites are presented in alphabetical order, and quotation values are presented as percentages. The values in brackets show the percentage of respondents who continue to regard these sites as sacred and observe related beliefs and prohibitions in their daily lives. VRFMD & HE: villages with less available forest resources and a high number of inhabitants; VRFD & HF: villages with available forest resources and a low number of inhabitants; n: number of people surveyed; -: the sacred site was not cited in the village concerned; p: p-value of Fisher's exact test; *: statistically significant association between variables.

Types	Beliefs	Taboos	VRFMD & HE	VRFD & HF	p

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			Maksem n=50	Texas n=50	Mwawa n=50	Nsela n=50	
Cemeteries	Ancestors' rest	Tree cutting, Bush fires, Collects NTFPs, Access (authorization) Pregnant women, Children	92.00 (90.00)	78.00 (78.00)	74.00 (74.00)	62.00 (62.00)	0.007* (0.013*)
Mountain	Dwelling of spirits & divinities; place of prayer & exorcism	Access (except for insiders), Bush fires	-	-	8.00 (8.00)	-	0.121 (0.121)
Dense dry forests		Bush fires	-	-	6.00 (4.00)	2.00 (2.00)	0.121 (0.246)
River sources		Bush fires, Tree cutting, Access	8.00 (2.00)	22.00 (6.00)	10.00 (6.00)	28.00 (4.00)	0.573 (1.000)
Termite mounds			-	-	8.00 (6.00)	2.00 (2.00)	0.059 (0.121)

Ethnobotanical surveys carried out in both village categories identified a total of 30 sacred woody species (23 in villages with limited forest resources and high population density; 27 in villages with available forest resources and low density (VRFD & HF), divided into 29 genera (24 in VRFMD & HE; 27 in VRFD & HF) and 18 families (15 in VRFMD & HE; 15 in VRFD & HF), with a predominance of Fabaceae. Among these species, *Afzelia quanzensis*, *Entandrophragma delevoyi*, *Ficus* spp., *Parinari curatellifolia*, *Sterculia quinqueloba*, and *Strychnos cocculoides* are the most widely recognized by respondents, due to their associations with ancestor and spirit beliefs. In addition, species such as *Diplorhynchus condylocarpon* and *Bobgunnia madagascariensis* are considered sacred in both types of villages, with around 1/8 and over a quarter of species cited respectively in villages with limited forest resources and high numbers of inhabitants, and villages with abundant forest resources and low numbers of inhabitants. However, implementation of the beliefs and prohibitions associated with these species remains low in villages, particularly in those with limited forest resources and high population numbers. This is particularly noticeable for species such as *Afzelia quanzensis*, *Entandrophragma delevoyi*, *Ficus* spp. and *Sterculia quinqueloba*, which are otherwise rare in forest ecosystems (Table 3). The,se results show that, although many woody species are recognized as sacred, the implementation of associated prohibitions is often insufficient, especially in villages with limited forest resources and high population numbers. This highlights an urgent need to strengthen conservation practices to protect these culturally crucial species, particularly those that are rare.

Table 3. Ethnobotanical list of sacred wood species identified during focus groups and individual interviews held in various villages in the rural area of Lubumbashi. The woody species are presented in alphabetical order, and the quotation values are presented as percentages. The values in brackets show the percentages of respondents observing beliefs and prohibitions relating to sacred wood species. VRFMD & HF: villages with less available forest resources and a high number of inhabitants; VRFD & HE: villages with available forest resources and a low number of inhabitants; n: number of people surveyed; -: the sacred species was not cited in the village concerned; p: p-value of Fisher's exact test; *: statistically significant association between variables.

Scientific names	Families	Availability in	Beliefs about species	VRFMD & HE		VRFD & HF		p
				Makse	Texas	Mwawa	Nsela	

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		the forest		**m** n=50	n=50	**wa** n=50	n=50	
Afzelia quanzensis Welw.	Fabaceae	Rare	Ancestral habitat, medicinal species	4.00 (4.00)	-	36.00 (36.00)	22.00 (22.00)	0.000* (0.000*)
Anisophyllea boehmii Engl.	Anisophylleaceae	Available	Food, medicinal species, customary chief's establishment	10.00	32.00	10.00	12.00	0.081
Annona senegalensis Pers.	Annonaceae	Available	Sacred, medicinal species	2.00	-	2.00	-	1.000
Bobgunnia madagascariensis (Desv.) J.H. Kirkbr. & Wiersama	Fabaceae	Available	Sacred, medicinal species	-	-	4.00	10.00 (6.00)	0.498 (0.331)
Brachystegia boehmii Taub.	Fabaceae	Available	Helps make incantations underfoot to heal or get rid of evil spirits	-	-	10.00	-	0.059
Brachystegia spp. and *Julbernardia* spp.	Fabaceae	Available	Shelters ancestral spirits	8.00	6.00	22.00	20.00	0.007*
Cassia abbreviata Oliv.	Fabaceae	Rare	Sacred, medicinal species	-	6.00 (6.00)	12.00 (12.00)	6.00 (6.00)	0.134 (0.003*)
Combretum molle Engl. & Diels	Combretaceae	Available	Sacred, medicinal species	4.00	-	12.00	8.00	0.035*
Diplorhynchus condylocarpon (Müll. Arg.) Pichon	Apocynaceae	Available	Sacred, medicinal species	-	2.00	-	-	1.000
Entandrophragma delevoyi De Wild.	Meliaceae	Rare	Sacred species, medicinal, prediction of future events	44.00 (44.00)	20.00 (20.00)	40.00 (40.00)	40.00 (40.00)	0.302 (0.302)
Erythrina abyssinica Lam. ex DC.	Fabaceae	Available	Medicinal species, herald the good rainy season	4.00	-	12.00 (2.00)	12.00	0.010* (1.000)
Ficus spp	Moraceae	Available	Shelters ancestral spirits, medicinal	14.00 (6.00)	26.00 (12.00)	32.00 (18.00)	12.00 (10.00)	0.862 (0.376)
Isoberlinia spp	Fabaceae	Rare	Prayers of traditional chiefs, medicinal plants	8.00	-	6.00	10.00	0.373
Lannea discolor (Sond.) Angl.	Anacardiaceae	Available	Ancestral prayers, Enthronement of the chief	-	-	6.00	-	0.246
Marquesia macroura Gilg	Dipterocarpaceae	Available	Representation of ancestors, medicinal	-	-	12.00 (10.00)	8.00 (2.00)	0.002* (0.029*)

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Parinari curatellifolia Planch. ex Benth.	Chrysobalanaceae	Available	Food, medicinal, establishment of a traditional chief	14.00	26.00	32.00	12.00	0.862
Pericopsis angolensis (Boulanger) Meeuwen	Fabaceae	Available	Representation of ancestors, medicinal, dispels curse	-	8.00	6.00	10.00	0.373
Piliostigma thonningii (Schumach.) Milne-Redh.	Fabaceae	Available	Sacred, medicinal species	2.00	-	16.00	-	0.035*
Psorospermum febrifugum Spach	Hypericaceae	Available	Sacred, medicinal species	2.00	-	-	-	1.000
Pterocarpus angolensis DC.	Fabaceae	Available	Sacred medicinal species		-	2.00	4.00	0.246
Pterocarpus tinctorius Welw.	Fabaceae	Available	Sacred, medicinal species	6.00	-	14.00	8.00	0.049*
Rothmannia engleriana (K. Schum.) Keay	Rubiaceae	Available	Medicinal species, create disputes between partners	2.00	-	-	2.00	1.000
Securidaca longepedunculata Fresen.	Polygalaceae	Available	Medicinal species, home to the spirits	-	-	-	2.00 (2.00)	1.000 (1.000)
Sterculia quinqueloba (Garcke) K. Schum.	Malvaceae	Rare	Sacred species, medicinal, discover hidden events, luck tree, frighten away sorcerers, destroy the power of gris-gris, save poultry from epidemics	40.00 (40.00)	12.00 (12.00)	30.00 (30.00)	58.00 (58.00)	0.012* (0.012*)
Strychnos cocculoides Delile	Loganiaceae	Available	Food and medicinal species	18.00	12.00	30.00	14.00	0.275
Syzygium guineense DC. Subsp macrocarpum	Myrtaceae	Available	Food and medicinal species	-	4.00	-	-	0.498
Terminalia mollis M.A.Lawson	Combretaceae	Available	Sacred, medicinal species	2.00 (2.00)	-	-	6.00 (4.00)	0.621 (1.000)
Uapaca kirkiana Müll.Arg.	Phyllanthaceae	Available	Food species, ceremony before ploughing, medicinal	22.00	14.00	26.00	8.00	1.000
Zanha africana (Radlk.) Exell	Fabaceae	Rare	Sacred, medicinal species	-	-	2.00 (2.00)	-	1.000 (1.000)
Zanthoxylum chalybeum Engl.	Rutaceae	Rare	Sacred, medicinal species	2.00 (2.00)	-	14.00 (14.00)	10.00 (10.00)	0.003* (0.003*)

In addition, ecological practices for biodiversity conservation and forest management, traditionally known to local communities, include small-scale farming, intercropping (allowing 2 to 3 crops to be grown on the same plot), the prohibition of cutting trees in sacred places, long fallow/rotation periods, and the use of dead wood instead of charcoal. These practices were reported by ¾ of respondents in both village categories. It should be noted that knowledge of these ecological practices is almost equivalent to the two categories of villages located in the rural area of Lubumbashi. Regarding the actual application of these practices, it is observed that intercropping and the ban on cutting trees in sacred places are implemented by more than 65% of respondents in villages with limited forest resources and a high number of inhabitants, whereas these practices concern only around 26% of respondents in villages with abundant forest resources and a low number of inhabitants. Other practices, such as the gradual exploitation of forest areas (19%), long fallow/rotation periods (13%), and the use of dead wood instead of charcoal (12%), are most applied in villages with abundant forest resources and low population numbers (Table 4)

Table 4. Traditional ecological practices for biodiversity conservation and sustainable *miombo* woodlands management in rural Lubumbashi. Traditional practices are presented in alphabetical order, with citation values presented as percentages. The values in brackets show the percentage of respondents applying these cited practices. Practices with only implementation values are considered innovations. VRFMD & HE: villages with less available forest resources and a high number of inhabitants; VRFD & HF: villages with available forest resources and a low number of inhabitants; n: number of people surveyed; -: the practice was not cited in the village concerned; p: p-value of Fisher's exact test; *: statistically significant association between variables.

Traditional practices	VRFMD & HE		VRFD & HF		p
	Maksem n=50	Texas n=50	Mwawa n=50	Nsela n=50	
Leaving large trees and sacred trees standing	4.00	2.00	4.00	8.00	0.498
Rare and sacred medicinal trees left standing	(8.00)	(10.00)	(4.00)	(16.00)	(0.435)
Small-scale farming	16.00	32.00	14.00	16.00	0.153
Agriculture without stump grubbing	4.00		6.00	8.00	0.170
	(4.00)	-	(6.00)	(8.00)	(0.170)
Charcoal for domestic use	6.00	2.00	2.00	2.00	0.683
Intercropping	12.00	4.00	6.00	10.00	1.000
	(34.00)	(40.00)	(20.00)	(10.00)	(0.000*)
Selective cutting			2.00	2.00	0.170
	6.00	8.00	(2.00)	(2.00)	(0.498)
Progressive operation			4.00	4.00	1.000
	2.00	4.00	(16.00)	(22.00)	(0.498)
Tree-cutting banned in sacred places	20.00	26.00	14.00	14.00	0.145
	(36.00)	(20.00)	(8.00)	(14.00)	(0.004*)
Defending concessions	-	-	(12.00)	-	(0.029*)
Short fallow/rotation period (3-5 years)	(10.00)	(20.00)	(6.00)	(4.00)	(0.032*)
Long fallow/rotation period (15-20 years)	12.00	6.00	18.00	10.00	0.376
	(2.00)	(6.00)	(16.00)	(10.00)	(0.040*)
Optimum bushfire period	-	4.00	6.00	-	1.000
Use of dead wood	18.00	12.00	24.00	26.00	0.111
	(6.00)	(4.00)	(10.00)	(14.00)	(0.126)

In addition, certain long-standing practices such as the standing abandonment of large or sacred trees and long fallow/rotation periods, which were once essential for biodiversity conservation and forest management, have evolved. They have been transformed into standing abandonment of rare and sacred medicinal trees and shorter fallow/rotation periods. Implementation of these modified practices varies from 8% to 20% in villages with limited forest resources and high population numbers, compared with 4% to 16% in villages with abundant forest resources with low population numbers. Addition, concession fencing, a more recent innovation, is particularly observed in villages with abundant forest resources and low population numbers (Table 4). These results indicate that traditional ecological practices of forest conservation and management are more widely applied in villages with abundant forest resources and low population density. However, the evolution and reduction of certain long-standing practices, such as long fallow periods, point to a need to revise and strengthen sustainable management strategies, particularly in villages with limited forest resources and high population numbers.

3.1.2. Circumstances of Knowledge Transmission and the Role of Ceremonial in Biodiversity Conservation and Forest Management

The main means of transmitting traditional ecological knowledge and practices are songs (53%); fables, tales & stories (23%), and proverbs (12%) in both village categories. Specifically, riddles, riddles and skits were particularly cited in villages with abundant forest resources and few inhabitants. In addition, this knowledge and practice is particularly transmitted during family councils, bereavements and weddings (Table 5). These results underline the fact that this traditional knowledge is transmitted especially during family councils, mourning, and weddings, underscoring the importance of social contexts in the preservation of ecological practices.

Table 5. Modes and circumstances of transmission of traditional ecological knowledge and practices. Modes and circumstances of TEK transmission are presented in alphabetical order, and citation values are presented as percentages. VRFMD & HE: villages with less available forest resources and a high number of inhabitants; VRFD & HF: villages with available forest resources and a low number of inhabitants; n: number of people surveyed. - p: p-value of Fisher's exact test; *: statistically significant association between variables.

Elements	VRFMD & HE		VRFD & HF		p
	Maksem n=50	Texas n=50	Mwawa n=50	Nsela n=50	
Transmission modes (%)					
Songs	44.00	62.00	58.00	52.00	0.887
Riddles & puzzles	8.00	-	6.00	10.00	0.373
Fables, tales & stories	36.00	28.00	10.00	20.00	0.007*
Scenes	-	-	2.00	4.00	0.246
Proverbs	12.00	10.00	24.00	14.00	0.165
Circumstances of transmission (%)					
Family advice (around the fire)	28.00	40.00	46.00	50.00	0.254
Bereavement	32.00	22.00	20.00	24.00	0.511
Weddings	22.00	26.00	12.00	10.00	0.025*
Newborn births	6.00	8.00	12.00	8.00	0.613
Enthronement of a village chief	12.00	6.00	10.00	8.00	1.000

In the traditions of the tribes of rural Lubumbashi, certain ceremonials take place specifically under the forest canopy. These ceremonials mainly include the burial of a dead relative (79%), the enthronement of a new village chief (10%), and prayers to the gods (12%). Specifically, the burial of a dead relative and the enthronement of a new customary chief are particularly singled out in villages with limited forest resources and large numbers of inhabitants. On the other hand, ceremonials such as exorcism and prayers to the gods are most common in villages with abundant forest resources and numbers of inhabitants (Table 6). These results show a distinct distribution of these practices according to forest resources and village population. This underlines the importance of ecological and demographic contexts in the practice of certain ceremonials.

Table 6. Roles of ceremonials in forest conservation in rural Lubumbashi. Ceremonials are presented in alphabetical order and quotation values are presented as percentages. VRFMD & HE: villages with less available forest resources and a high number of inhabitants; VRFD & HF: villages with available forest resources and a low number of inhabitants; n: number of people surveyed; p: p-value of Fisher's exact test; *: statistically significant association between variables.

Ceremonials	VRFMD & HE		VRFD & HF		p
	Maksem n=50	Texas n=50	Mwawa n=50	Nsela n=50	
Funeral of a loved one	84.00	86.00	72.00	80.00	0.153
Exorcism	-	2.00	8.00	6.00	0.065
Induction of the new chief	16.00	12.00	6.00	4.00	0.051
Prayers to the gods (ancestors)	-	-	14.00	10.00	0.000*

3.2. Association Between TEK-Elements Variables of the Socio-Demographic Profile and Similarity of Biodiversity Conservation and Miombo Woodlands Management Practices

The application of biodiversity conservation and forest management practices in rural Lubumbashi is strongly influenced by socio-demographic factors such as gender, age, level of education and main occupation of the individuals surveyed. In particular, the application of intercropping and short rotation practices is strongly influenced by the gender and educational level of local community members. In addition, the implementation of most practices is age-dependent, except for stump-free farming practices, selective cutting, the ban on cutting trees in sacred places, and long fallow/rotation periods. However, the practices of leaving rare and sacred medicinal trees standing, intercropping, and prohibiting the cutting of trees in sacred places are particularly influenced by the types of main activities of the respondents. These observations underline the fact that the socio-demographic characteristics of members of the population play a decisive role in the application of biodiversity conservation and forest management practices (Table 7). More specifically, practices such as selective cutting, use of dead wood, leaving rare and sacred medicinal trees standing, long fallow/rotation periods, stump-free agriculture, progressive logging, and defending concessions are mainly adopted by women, the elderly, uneducated individuals or those with a primary level of education, whose main occupations include charcoal production, art carving and NTFP collection. Conversely, practices such as short fallow periods, intercropping, and the ban on cutting down trees in sacred places are more common among men, young people, and adults with secondary education, who are mainly involved in farming and logging for timber.

Table 7. Association between biodiversity conservation/forest management practices and elements of the socio-demographic profile of respondents. The figures presented in this table are p-values from Fisher's exact test. * : statistically significant association between variables.

Traditional practices	Type	Age ranges	Education level	Main occupation
Rare and sacred medicinal trees left standing	0.054	0.012*	0.095	0.000*
Agriculture without stump grubbing	0.297	0.297	0.053	0.504
Intercropping	0.006*	0.040*	0.004*	0.000*
Selective cutting	0.457	0.148	0.737	0.221
Progressive operation	0.596	0.022*	0.303	0.887
Tree-cutting banned in sacred places	0.334	0.714	0.983	0.002*
Defending concessions	1.000	0.027*	0.346	0.619
Short fallow/rotation period (3-5 years)	0.027*	0.000*	0.000*	0.915
Long fallow/rotation period (15-20 years)	0.694	0.637	0.700	0.211
Use of dead wood	0.051	0.006*	0.545	0.227

As regards the comparison between beliefs and prohibitions relating to sacred sites and their application, a total similarity of 100% was observed in both categories of villages. However, similarities in the application of taboos relating to sacred sites show a notable disparity, with a correspondence of only 40% between villages with limited forest resources and a high number of inhabitants and those with abundant forest resources and a low number of inhabitants.

Jaccard's index reveals a similarity of 21.74% between quotations of sacred woody species and the application of corresponding beliefs and prohibitions, in villages with limited forest resources and a high number of inhabitants. This compares with 42.31% in villages with abundant forest resources and few inhabitants. Furthermore, the application of taboos relating to sacred trees shows a similarity of 41.67% between the two categories of villages studied.

As far as biodiversity conservation and forest management practices are concerned, Jaccard's index shows a 50% similarity between citations of these practices and their implementation in villages with limited forest resources and a high number of inhabitants, compared with 61.54% in villages with abundant forest resources and a low number of inhabitants. Overall, the implementation of these practices was 70% similar between the two categories of villages. These results suggest that, although beliefs and prohibitions relating to sacred sites and trees are recognized in both types of villages, their implementation varies considerably according to the availability of forest resources and population in the village areas. Furthermore, the implementation of biodiversity conservation and forest management practices is more consistent in villages with abundant forest resources and small populations, indicating a better integration of these ecological practices in these contexts.

4. Discussion

4.1. Traditional Ecological Knowledge and Practices, Transmission and Role of Ceremonials in Biodiversity Conservation and miombo Woodlands Management

The depletion of forest resources in the Lubumbashi Charcoal Production Basin is having a direct impact on the livelihoods of local riverside communities, which are largely dependent on the productivity of *miombo* [65]. In response to this situation, various mechanisms for restoring forest cover and managing residual patches of *miombo* woodlands have been put in place in this region of southeastern DRC, notably through reforestation initiatives. However, these efforts are struggling to gain the support of local populations, largely due to the lack of integration of traditional ecological knowledge and practices into these mechanisms [17].

The results of the ethnoecological survey conducted as part of the present study reveal the existence of a range of traditional knowledge and practices for biodiversity conservation and *miombo* woodlands management. This knowledge has significant socio-cultural and spiritual values and plays a crucial role in maintaining forest ecosystems [66]. The beliefs and prohibitions associated with these TEK contribute to the preservation of forest resources and forest resilience [67,68]. These observations are consistent with the results of previous studies in Africa [28,69] and specifically in the *miombo* woodlands ecoregion [36,70]. The integration of TEK into the processes of vegetation cover restoration and *miombo* woodlands management could, to this end, represent a significant opportunity to encourage local communities to actively participate in these initiatives and take ownership of the processes [17].

On the other hand, the scarcity of forest resources, coupled with unfavorable economic conditions, increases anthropic pressure on these resources, thus compromising the forest restoration and management mechanisms put in place [17,22]. The data collected also shows that local communities in villages with abundant forest resources and a smaller population have a higher number of TEK than those in villages with limited resources and a large population (Tables 2, 3, and 4). This disparity can be explained by the fact that villages with abundant forest resources and low population numbers retain and apply traditions to a greater extent due to the high availability of resources, in contrast to villages faced with limited resources and high population numbers. Previous studies in Zambia have revealed that the scarcity of forest resources and population growth leads to a decrease in the importance attached to traditional knowledge, resulting in an erosion of this knowledge and practices [40,71]. The results of this study concur with the observations of Ref. [40] in Zambia, who showed that the scarcity of forest resources, coupled with rapid population growth, leads to a gradual erosion of TEK, as local populations turn away from traditional practices in the face of increased economic and ecological pressures.

However, the durability of TEK, such as sacred sites, also depends on several factors such as geography, hydrography, and the distribution of *miombo* woodlands variants in the study area. The transmission of TEK, mainly orally through songs and stories (Table 5), remains a common practice in Africa, not least because of the low rate of school enrolment and the virtual non-existence of written documentation on the subject [71–73]. This mode of transmission, although adapted to poorly educated populations [37] such as those in rural Lubumbashi, leads to a modification or even alteration of knowledge over time, leading to the loss or appearance of new knowledge and practices [36].

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The results of this study corroborate research conducted in Zambia, demonstrating that stories, songs, and proverbs are predominant modes of transmission of traditional ecological knowledge (TEK) [36,37,74]. Additionally, TEK is often transmitted during family councils, mourning ceremonies, and weddings (Table 5), as well as during ceremonies such as funerals exclusively held in the forest (Table 6). These events, frequent and gathering many community members, offer ideal opportunities for TEK transmission. The findings confirm the work of reference [37] in Zambia, which emphasizes the importance of these ceremonies for the transmission of traditional knowledge, as well as for biodiversity conservation and forest management.

In examining cultural diversity, the number and species of plants considered sacred can vary from village to village due to differences in cultural practices, historical contexts, and ecological conditions. These sacred species are generally linked to specific geographic regions and community beliefs, leading to variability among villages. In Angola, for example, the Moringa oleifera tree is highly revered among certain ethnic groups, especially in the southern regions, for its medicinal properties, nutritional value, and role in community rituals [75]. However, other communities in different parts of Angola might venerate different species, such as the Baobab (*Adansonia digitata*), which is considered a spiritual symbol and a source of food, water, and shelter [76]. Thus, the differences in sacred species reflect the diversity of cultural practices and the local environment.

Natural resource management also relies on a variety of traditional forest management practices. These practices, shaped by cultural beliefs, environmental conditions, and resource availability, vary across regions and villages. For example, in Malawi, traditional agricultural practices, such as short and long fallow periods, differ depending on soil fertility and climate. Villages in more fertile areas practice shorter fallows (3-5 years), while those in the northern regions with less fertile soils extend fallow periods to 15-20 years, allowing the land to fully regenerate before cultivation resumes [77,78].

The transmission of traditional local knowledge, including forest management practices, is crucial for maintaining these knowledges across generations. In Tanzania, for instance, songs are a central mode of transmitting knowledge about forest management. These songs, often sung during community activities such as planting or harvesting, emphasize the importance of tree preservation and sustainable land use [79]. Riddles and proverbs, such as “The forest is not a market, it’s a home for all,” are used to convey wisdom about resource conservation. In Zambia, fables and stories play a key role, particularly in rural communities, where elders pass down knowledge of sacred trees and sustainable farming practices [80]. Thus, family advice shared around the fire, during times of bereavement, weddings, or the enthronement of a village chief, offers a reflective space for elders to impart wisdom. These rituals ensure that forest management knowledge remains embedded in cultural traditions.

Finally, the timing of bushfires is a crucial element of forest management, especially when guided by traditional ecological knowledge. Indigenous communities have long understood the relationship between fire, vegetation, and seasonal cycles, using this knowledge to determine the most appropriate periods for controlled burning. In Zambia, traditional fire management practices involve burning during the early dry season (April to June), when vegetation is less dry and fires are less intense, reducing the accumulation of fuel loads and preventing destructive late-season wildfires [81]. Similarly, in Tanzania, Maasai communities use controlled burns in early dry seasons to stimulate fresh grass growth for livestock while preserving woody vegetation [82]. These practices are aligned with ecological cycles, ensuring minimal disruption to forest resources.

4.2. Association Between TEK and Similarity of Implementation of Biodiversity Conservation Practices and miombo Woodlands Management

Local communities in villages characterized by limited forest resources and a high number of inhabitants apply TEK less effectively than those in villages with available forest resources and a low number of inhabitants. This situation is attributable to the scarcity of forest resources and population growth, which encourage communities to modify or abandon TEK, thus compromising the sustainable management of forest resources [67,83]. Previous studies in Zambia have shown that the

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scarcity of forest resources, combined with growing economic needs, is leading to a decline in respect for traditional beliefs and prohibitions when exploiting forest resources to meet daily needs [40]. In addition, high population density significantly reduces the usable area for everyone, increasing anthropogenic pressure on already limited forest resources [84]. This increased pressure contributes to TEK deletion or partial adaptation to cope with resource scarcity, particularly in villages with high population numbers. These observations are in line with the findings of Ref. [28], who points out that TEK evolve over generations and are adapted to environmental changes.

On the other hand, in villages where forest resources are available and the population is small, biodiversity conservation and sustainable forest management practices are mainly implemented by women, who are elderly, poorly educated, and whose main activities include charcoal production, art carving, and the collection of non-timber forest products (Table 7). This predominance of women in the implementation of practices can be explained by their central role in Africa, and particularly in the study area, in the education and transmission of cultural knowledge, including TEK. By passing on this knowledge to the younger generations, they integrate it into everyday practices, thereby contributing to their sustainability. Research in Venezuela also shows that women are more respectful of traditional beliefs and prohibitions than men [85]. Furthermore, the application of TEK increases with age. Older people apply these forest conservation and management practices more assiduously because of their experience, their role as custodians of culture, and their lesser exposure to modernity, which reinforces their perception of the relevance of this knowledge [86,87]. It should also be noted that the transmission of these TEK begins at an early age in the Lubumbashi region.

In addition, people with low levels of education are also more likely to apply TEK. Indeed, activities related to the management of forest areas are often dominated by individuals with a low level of education, due to the lack of alternatives in the labor market and the absence of required skills [17]. Finally, charcoal producers, sculptors, and NTFP collectors are more likely to apply TEK than farmers. Agriculture, whether intensive or slash-and-burn, requires deforestation to avoid competition between natural trees and crops, which contrasts with other activities with selective exploitation of forest resources [6,88–90]. These findings corroborate those of Ref. [91] in the Yangambi Biosphere Reserve, who show that forest conservation and management practices are mainly linked to sacred tree prohibitions, agricultural practices, and respect for sacred sites.

However, the implementation of conservation and forest management practices is influenced by other factors, such as the amount of forest space available to an individual. TEK-integrated forest management requires not only recognition of this traditional knowledge but also adequate access to the resources needed for its application. The decrease in forest area available to an individual limits his or her ability to maintain and transmit TEK [84,92]. Furthermore, the application of these TEK in Africa is also influenced by cultural changes, such as formal education, modernization, and above all Western and Asian religions [36]. Indeed, formal education and modernization stemming from colonization have contributed to the marginalization of traditional knowledge in Africa, inculcating Western values that are largely incompatible with local cultures [36,93]. Furthermore, studies carried out in Nigeria, Ghana, and Botswana have shown that local communities adopting Western and Asian religions now reject the application of these TEK, considering them inferior, demonic, and fetishistic [94–96].

4.3. Involvement in Contributing to the Sustainable Management and Restoration of miombo Woodlands

TEK have considerable cultural and spiritual values, but their application is under constant threat from modernization and the shrinking of *miombo* woodland areas. This situation contributes not only to deforestation and forest degradation, but also to the erosion of the cultural and spiritual values of local communities. To remedy this problem, it is essential to promote the popularization of TEK within local communities. An effective approach for this popularization could include educational programs facilitating the empirical learning of TEK [97]. However, the low school enrolment rate in rural Lubumbashi is a significant obstacle to the application of this method. To overcome this obstacle, it is crucial to foster intergenerational exchanges of knowledge between grandparents, parents, and younger generations, as well as to organize various socio-cultural awareness-raising activities to facilitate the transfer of these TEK [36]. Furthermore, universities should collaborate with the Congolese government to systematically collect and document (including digitizing) the various forms of TEK, to prevent their erosion and preserve this knowledge for current and future generations [98,99]. This documentation is essential to prevent the loss of this traditional knowledge over time.

In addition, there is a need for conservation and sustainable management programs for *miombo* woodland remnants, as well as forest restoration initiatives through reforestation and assisted natural regeneration [21,100]. These programs should focus on sacred sites (such as cemeteries, river springs, and the habitats of ancestors and deities), using sacred woody species such as *Afzelia quanzensis*, *Entandrophragma delevoyi* and *Sterculia quinqueloba*, whose associated beliefs and prohibitions are respected by local communities [101]. This approach would not only help restore forest ecosystems but also revitalize the cultural and religious practices associated with these places [101,102]. In addition, taking these TEK into account in the forest restoration mechanism would encourage the involvement of local communities and ownership of these forest management and restoration mechanisms, which is crucial to ensuring their long-term success [17].

Finally, these results suggest that the integration of TEK into forest policy requires the creation of a local participatory framework, involving both local communities and decision-makers. This participatory framework could facilitate the identification of relevant TEK and their application at the local scale, their integration into forest management plans, and reforestation or assisted natural regeneration initiatives [103]. In addition, incorporating the sacred woody species identified in this study, such as *Afzelia quanzensis* and *Sterculia quinqueloba*, into reforestation initiatives could strengthen community commitment while respecting local beliefs. Furthermore, integrating fire management strategies, such as controlled burns and community firebreak systems, can enhance the sustainability of these efforts [104,105]. Tanzania's Participatory Forest Management (PFM) programs have successfully involved communities in fire prevention and controlled burning to reduce wildfire risks [106], while Zambia's Community-Based Natural Resource Management (CBNRM) initiatives have established firebreaks and promoted traditional fire control practices to protect forest ecosystems [107].

The present study focused on a limited number of villages and respondents, which may have constrained the breadth of insights into local ecological practices. Additionally, the study did not fully capture the cultural variability among the diverse tribes in the Lubumbashi region, which could influence traditional ecological knowledge and its application. While these factors may limit the generalizability of the findings, the research provides valuable foundational insights and highlights the need for further studies encompassing a broader cultural and geographical scope to build on this work.

5. Conclusions

This study aimed to identify and describe TEK relating to biodiversity conservation and *miombo* woodlands management, through interviews (group and individual) carried out in two categories of villages differentiated by the availability of forest resources and their population. The results show that most respondents are aware of sacred sites and woody species, including their beliefs and prohibitions. In addition, biodiversity conservation and *miombo* woodlands management practices include small-scale farming, intercropping, the prohibition of cutting trees in sacred sites, long rotation periods and the use of dead wood. Certain ceremonials, such as burials of the dead, take place only in the forests, encouraging people to leave certain forest patches untouched. TEK are more rigorously applied in villages with abundant forest resources and smaller populations, enabling daily needs to be met while respecting local beliefs and prohibitions. These TEK are particularly observed by women, the elderly and the less educated, involved in charcoal production, art carving and the collection of non-timber forest products.

The present study was carried out on a limited sample of villages and participants. Furthermore, the cultural diversity of the different tribes in the Lubumbashi region was not sufficiently considered, which limits the possibility of generalizing the results obtained. Nevertheless, this study demonstrates the existence of TEK in the Lubumbashi region and their potential to contribute to the sustainable management and restoration of *miombo* woodlands. The DRC's national forest policy must include concrete strategies for the integration of TEK. This could involve setting up local forest management committees, legally protecting sacred sites and species, and prioritizing TEK in reforestation initiatives. In addition, the documentation and digitization of this traditional knowledge by scientists is essential to ensure its transmission and preservation.

Supplementary Materials: The following supporting information can be downloaded at the website of this paper posted on Preprints.org

Author Contributions: Conceptualization, Jan Bogaert and Yannick Useni Sikuzani; Data curation, Héritier Khoji Muteya and Justin Kyale Koy; Formal analysis, Dieu-donné N'tambwe Nghonda, Héritier Khoji Muteya and Médard Mpanda Mukenza; Funding acquisition, Jan Bogaert and Yannick Useni Sikuzani; Investigation, Dieu-donné N'tambwe Nghonda; Methodology, Jan Bogaert and Yannick Useni Sikuzani; Project administration, Jan Bogaert and Yannick Useni Sikuzani; Resources, Médard Mpanda Mukenza, Sylvestre Cabala Kaleba and Justin Kyale Koy; Software, Dieu-donné N'tambwe Nghonda, Héritier Khoji Muteya and Médard Mpanda Mukenza; Supervision, Wilfried Masengo Kalenga, Jan Bogaert and Yannick Useni Sikuzani; Validation, François Malaisse, Justin Kyale Koy, Wilfried Masengo Kalenga, Jan Bogaert and Yannick Useni Sikuzani; Visualization, Jan Bogaert and Yannick Useni Sikuzani; Writing – original draft, Dieu-donné N'tambwe Nghonda and Médard Mpanda Mukenza; Writing – review & editing, Sylvestre Cabala Kaleba, François Malaisse, Justin Kyale Koy, Wilfried Masengo Kalenga, Jan Bogaert and Yannick Useni Sikuzani. All authors have read and agreed to the published version of the manuscript.

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