Ethnoweaving in Sumba Island, Indonesia: Ethnobotanical knowledge and use of natural dye plants

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Research

Abstract

Background: Traditional weaving on Sumba Island, Indonesia, represents an important cultural heritage closely linked with the use of natural dyes obtained from local plants. The limited ethnobotanical data of the natural dye plants, their uses, and their supply sustainability pose a high risk to both cultural preservation and forest-based livelihoods.

Methods: Semi-structured interviews, participant observations, and plant identification were used to gather ethnobotanical data. 122 informants from six Sumba weaving communities participated in the study. Relative Frequency of Citation (RFC), Informant Consensus Factor (ICF), and a simplified Functional Redundancy Index (FRI) were used to analyze the data regarding cultural importance, knowledge standardization, and substitution flexibility.

Results: 21 plant species from 14 families were identified and categorized into six functional dye categories. All informants mentioned *Indigofera tinctoria* L. (blue), *Morinda citrifolia* L. (red), and *Symplocos fasciculata* Zoll. (mordant) (RFC=1.00), according to RFC analysis. All three species were found to be fundamental. Informant consensus was consistently high across all categories (ICF>0.982), indicating standardized knowledge transmission. However, functional redundancy values were consistently low (FRI<0.023), indicating concentration of use on few key species and limited culturally recognized substitution.

Conclusions: Sumba's ethnoweaving is a plant-based cultural production system that suggests potential vulnerability due to the limited alternative species but stable due to the presence of key species. The vulnerability is further increased by overexploitation, land conversion, and pressure from synthetic dyes. By integrating a comprehensive ethnobotanical inventory and quantitative structural analysis, the study provides an analytical framework for the sustainability of weaving traditions on Sumba Island and in similar areas.

Keywords: Ethnobotany; Ethnoweaving, Natural dyes; *Indigofera tinctoria*; *Morinda citrifolia*; *Symplocos fasciculata*

Background

The use of natural dye plants has recently regained global attention. This trend is driven by growing environmental sustainability awareness of the risks posed by synthetic dyes, as well as by increasing interest in sustainable textiles. Natural dyes carry significant cultural value, as among the Karbi tribe in India, where their use plays an important role in social and religious life (Teron & Borthakur 2012). In Indonesia, traditional **batik** and weaving, closely associated with the use of natural dyes, indicate the community's deep ethnobotanical knowledge (Hapsari *et al.* 2025, Seran *et al.* 2024). Rich ethnobotanical knowledge reflects the community's deep relationship with nature (Sari *et al.* 2026).

One of the regions in Indonesia where weaving is associated with natural dye plants is Sumba Island, East Nusa Tenggara, Eastern Indonesia. The woven textile is locally known as **tinung** (Ningsih & Elfrida 2023). These fabrics not only used as clothing but also serves as traditional currency, wedding gifts, and as an indicator of social status between clans or **marga** (locally known as **kabisu**) (Pollock 2012, Murniasih & Soeriadiredja 2020, Babang & Rinata 2019). **Tinung** is made using natural dyes from plants, such as *Indigofera tinctoria* L. (locally known as **nila**) for blue and *Morinda citrifolia* L. (locally known as **kombu**) for red (Herawati & Adalina 2010, Murniati & Takandjandji 2015, Kaleka *et al.* 2024). Knowledge of plant identification, dye extraction, and the dye-making processes are a specialized skill and are often kept secret by weavers to maintain the exclusivity of their use of natural dyes (Ndamunamu 2024). In Sumba, weaving is not only a craft, but also a deep cultural knowledge. Specific plant species are associated with colors and rituals, while motifs are associated with specific meanings and spiritual messages (Nguju & Fatmawati 2023). According to Lolo (2018), each color has a meaning: white symbolizes inner purity and mental resilience, red symbolizes family ties and sacrifice, and black symbolizes the struggle for life.

This study uses the term "ethnoweaving" as a descriptive label to define a traditional production system in Sumba that integrates plant knowledge, technical skills, and cultural practices into a unified whole. Operationally, ethnoweaving is understood as a local production system characterized by three main pillars: ethnobotanical knowledge regarding the identification and processing of dye plants; technical skills in dye extraction, coloring, and weaving; and the placement of all these activities within the social, ritual, and symbolic frameworks of Sumbanese society, such as clan identity and **Marapu** cosmology. Unlike conventional ethnobotanical studies, which tend to focus on species inventories (Teron & Borthakur, 2012) or material culture studies that emphasize the social meanings of objects (Pollock, 2012), this term serves as a tool for simultaneously examining botanical, technical, and sociocultural dimensions. Thus, ethnoweaving does not emerge as a new theory replacing previous approaches, but rather as an effort to examine the close relationship between the preservation of natural resources and the sustainability of cultural heritage embodied in woven fabrics.

Although Sumba weaving has cultural and economic value, it faces threats such as the overexploitation of natural dye plants, competition with synthetic dyes, cultural changes, challenges to intergenerational knowledge transfer, and changes in land use (Teron & Borthakur 2012, Murniati & Takandjandji 2015, Murniati & Takandjandji 2016). Pressure on land for agriculture and livestock, intensive exploitation of raw materials without regeneration, the proliferation of cheaper, imported, synthetic-dyed fabrics, and the risk of losing oral knowledge of traditional techniques pose real threats to the existence of original Sumba weaving (Murniati & Takandjandji 2015, Murniati & Takandjandji 2016). Weavers learn by remembering oral stories from their elders, so knowledge of weaving and natural dyeing remains largely undocumented (Cunningham *et al.* 2011). They learn through observation, participation, and imitation (Cunningham *et al.* 2011).

Based on a bibliometric analysis using Biblioshiny of 216 global documents indexed by Scopus—78 of which focus on weaving in Indonesia—specific research trends were identified. Most research on Indonesian weaving, particularly in Sumba, focuses on topics of culture, identity, and symbolism. Meanwhile, research on the technical aspects of traditional dyeing is found in much smaller numbers (Detailed results are provided in the Supplementary Materials). Forest resources, non-timber forest products, and ethnobotany are examples of topics that have not received much attention. The literature on Sumba weaving still lacks information on topics such as ethnobotany, forest management, and quantitative methods to assess the importance of dye plants. Since existing ethnobotanical indices such as Use Value (UV; Phillips & Gentry 1993) and Cultural Importance Index (CI; Tardío & Pardo-de-Santayana 2008) mainly measure the general use and cultural significance of plant species, but do not fully capture more complex relationships, in this study we employ additional ethnobotanical indices to provide a more comprehensive analysis. Relative Frequency of Citation (RFC) (Tardío & Pardo-de-Santayana 2008) measures how widely a species is known; we chose it for its simplicity and comparability across studies. Informant Consensus Factor (ICF) (Trotter & Logan 1986) assesses agreement on species use per function; we chose it to evaluate knowledge standardization. Functional Redundancy Index (FRI) (adapted from Walker 1992, Elmqvist *et al.* 2003) quantifies substitution flexibility; we developed this simplified index specifically to assess potential vulnerability due to reliance on few species—a dimension not captured by RFC or ICF alone. This indicates a research gap in the relationship between plant diversity and local knowledge, which is the main basis for the Sumba weaving tradition, that has not been deeply explored.

While several previous studies have documented dye plants in East Nusa Tenggara—including Seran *et al.* (2024) in Belu Regency, Murniati & Takandjandji (2015) in East Sumba, and Pasaribu & Winarni (2020) on natural pigments originating from East Sumba—this study offers three distinct research contributions. First, unlike Seran *et al.* (2024) who focused on Belu (a region with different ecological conditions and higher rainfall), our study specifically covers six villages in East and West Sumba, including the less documented relatively wet zone of West Sumba. Second, while Murniati & Takandjandji (2015) and Pasaribu & Winarni (2020) identified 15 and 3 keystone species, respectively, we provide the first quantitative structural analysis of the dye plant knowledge system using three complementary ethnobotanical indices (RFC, ICF, and FRI) to assess not only cultural importance but also substitution flexibility and potential vulnerability. Third, unlike all previous studies that focused solely on the inventory of dye plant species, we introduce the concept of 'ethnoweaving' as an integrated analytical framework that connects botanical knowledge, dyeing & weaving technical skills, and socio-cultural dimensions. Furthermore, we explicitly acknowledge that there has been previous research on plants with potential as natural dyes in East Sumba (Ndamunamu 2024); however, that research did not document the entire dyeing process, did not use quantitative ethnobotanical indices, and did not address the challenges of sustainability or reproducibility of dye functions—gaps that this study fills. To address this research gap as well as to explore ethnoweaving in Sumba Island, this study aims to: (1) identify the plant species used as natural dyes in Sumba weaving and evaluate their cultural significance, informant agreement, and potential vulnerability; (2) document local knowledge and practices related to ethnoweaving; and (3) evaluate the challenges affecting the sustainability of traditional Sumba weaving.

Materials and Methods

Study area

Sumba Island (11,244 km², East Nusa Tenggara, Indonesia) is located in Wallacea (Fig. 1). Its limestone hilltops are mostly covered by savanna, which has a semi-arid tropical climate. Annual rainfall is less than 600 mm in the east, with 8 dry months, and up to 1,600 mm/year in the west. This diverse climate here supports a unique ecosystem for natural dye plants, such as *Indigofera tinctoria* L., *Morinda citrifolia* L., and *Symplocos fasciculata* Zoll. (Astuti *et al.* 2001, Cunningham *et al.* 2011).

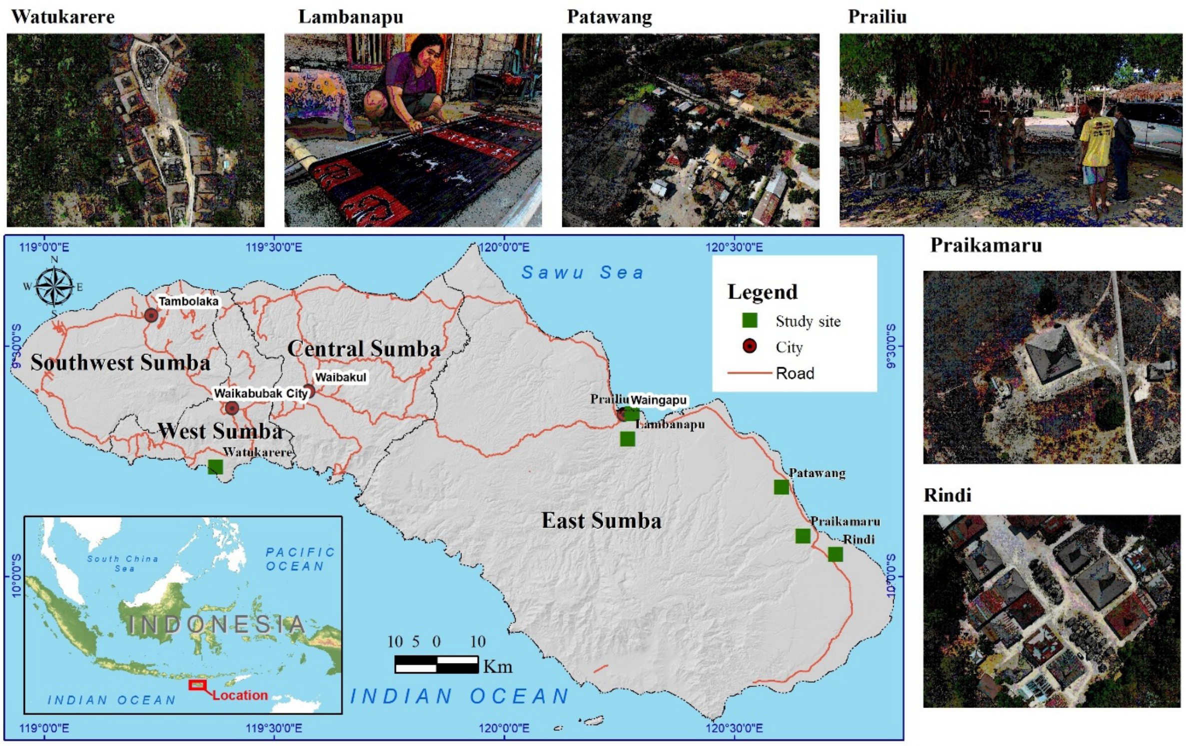

Figure 1. Map of Sumba Island, East Nusa Tenggara, Indonesia, showing the six study sites (green squares), with additional photographs of local landmarks and traditional weaving activities at each site. Source: Administration map of Sumba (2020) and Authors' documentation (2025). Informed consent was obtained from all weavers whose home, bodies, hands or faces appear in the photographs, following the International Society of Ethnobiology Code of Ethics (ISE 2006).

The local community follows the **Marapu** belief system, in which weaving expresses cosmology and social hierarchy. We selected six villages as study sites (Fig. 1): Rindi, Praikamaru, Patawang, Prailiu, and Lambanapu in East Sumba (dry zone), and Watukarere in West Sumba (wetter zone). We chose these sites because they represent different ecological conditions, retain substantial ethnobotanical knowledge of natural dyes, and face sustainability challenges from resource exploitation and synthetic dye competition (Hoskins 2009, Pollock 2012, Murniati & Takandjandji 2015, Hunga 2022, Joh *et al.* 2021). In addition, we selected six villages based on the following criteria: (1) active production of naturally dyed woven textiles, (2) presence of weavers with knowledge of traditional dye plants, and (3) accessibility during the fieldwork period. East Sumba has five villages (Rindi, Lambanapu, Prailiu, Praikamaru, Patawang) because this region has a higher density of active natural-dye weaving communities. West Sumba has one village (Watukarere) because natural dye use is less common there; additional villages in West Sumba either no longer use natural dyes or declined participation. The imbalance reflects the actual distribution of the practice, not a sampling bias.

Socio-cultural communities

This study involved a total of 122 weavers as informants spread across two main areas. A total of 100 informants came from five villages in East Sumba (Rindi, Praikamaru, Patawang, Prailiu, and Lambanapu) with a composition of 20 people each, while the other 22 informants came from Watukarere Village in West Sumba (Table 2). Based on gender distribution, the majority of informants were women (71%, n=87), which confirms their dominant role in the weaving process. However, male participation remained significant (29%, n=35), especially in the dye preparation and yarn winding stages. Overall, the age structure of informants shows that knowledge of natural dye weaving is currently concentrated in the middle-aged and elderly groups. The largest age group is 41-50 years (35%), followed by groups 51-60 years (20%) and 31-40 years (17%). In contrast, the involvement of the younger generation is very limited; Informants aged 21-30 years old represented only 12%, while those aged 20 years and under only reached 5%. Variations in age structure between villages showed different patterns. Praikamaru, Prailiu, and Watukarere villages had a more balanced age distribution, with the proportion of young informants (21-40 years old) reaching 50-59%. In contrast, Rindi, Patawang, and Lambanapu villages were dominated by older populations, with 70-75% of informants in the 41-60 age range. Specifically, in Watukarere Village (West Sumba), the highest proportion of informants over 60 years old (14%) was found, while the lowest proportion of men (5%). This indicates that in this region, knowledge of natural dyeing is largely controlled by elderly women. This demographic pattern overall indicates a risk to the long-term sustainability of traditional practices due to low participation and knowledge transfer to the younger generation.

Table 1. Description of the selected study villages.

Study site	Total of informants	Gender (%)		Group of age (%)					
		Male	Female	0-20 years	21-30 years	31-40 years	41-50 years	51-60 years	>61 yrs years
Rindi	20	35	65	5	5	10	55	20	5
Praikamaru	20	40	60	5	25	25	15	15	15
Patawang	20	35	65	5	5	10	55	20	5
Prailiu	20	40	60	5	25	25	15	15	15
Lambanapu	20	20	80	5	5	15	55	15	5
Watukarere	22	5	95	5	9	18	18	36	14
Total	122	29%	71%	5%	12%	17%	35%	20%	10%

Data Collection

Field research was conducted in three months (August - October 2025). A combination of observations, interviews, and plant identification was used to gather data. We interviewed 122 informants selected through a combination of purposive and snowball sampling. The **Marapu** customary leaders' recommendations were used to select the first informants. Recommendations from earlier informants were used to find the next informants. There were 122 weavers in total, 20 from each of five villages in East Sumba and 22 from West Sumba. Interviews included local plant names, parts used, harvesting methods, processing into natural dyes, weaving practices, and beliefs or taboos. Observations and documentation focused on the dyeing and weaving processes, from the preparation of plant materials to the final finishing of the fabric. Dye plant species were identified using a mixed-method approach. For 7 of 21 species (33%), we collected physical voucher specimens, which were deposited at the BRIN Herbarium (accession codes HR2025110386 to HR2025110403) and identified by BRIN taxonomists. For the remaining 14 species (67%), physical vouchers could not be collected due to field constraints (lack of drying facilities and export permits) and seasonal limitations, as several plant species were unavailable or not growing during the dry season. For these species, we used: (a) high-resolution photographs showing diagnostic morphological characters (leaves, flowers, fruits, bark, and habit) taken in situ; (b) consensus identification from local experts with knowledge of dye plants; and (c) comparison with published dye plant inventories from Sumba and eastern Indonesia (Herawati & Adalina 2010, Murniati & Takandjandji 2015, Kaleka *et al.* 2024).

Ethnobotanical Indices

To evaluate the cultural significance, informant consensus, and structural attributes of the ethnoweaving dyeing system, three ethnobotanical indices were used: RFC, ICF, and simplified FRI. Calculations were performed in Microsoft Excel using usage report data collected from 122 respondents.

Relative Frequency of Citation (RFC)

RFC is used to determine the importance or popularity of a species among informants, indicating how widely knowledge about the species is spread within the community, as described by Tardio & Pardo-de-Santayana (2008):

$$RFC = FC/N$$

Where, FC is the number of informants who cited a given species; N is the total number of informants (N = 122). RFC values range from 0 to 1. Values close to 1 indicate that nearly all informants know and use the species. RFC analysis was chosen because of its simplicity of calculation, independence from category size, and capacity for direct comparison between species (Tardio & Pardo-de-Santayana 2008).

Informant Consensus Factor (ICF)

ICF calculations were used to assess the level of agreement among informants regarding species use for a particular dye (Trotter & Logan 1986):

$$ICF=(Nur-Nt)/(Nur-1)$$

Where, Nur is the total number of use reports in a given category; Nt is the number of taxa used in that category. ICF values range from 0 to 1. Values close to 1 indicate strong consensus and uniform dissemination of knowledge, while low values indicate increased heterogeneity in species selection. Strong consensus suggests that knowledge about plants in a functional category is widely disseminated and culturally embedded (Trotter & Logan 1986).

Functional Redundancy Index (FRI)

A simplified FRI quantifies the degree to which multiple plant species can substitute for one another in fulfilling the same dyeing function (e.g., producing blue color). This index is important for examining the resilience of local knowledge and biological resources, which is conceptually grounded in the theory of ecological resilience (Walker 1992) and in biodiversity and ecological redundancy (Elmqvist *et al.* 2003).

$$FRI_c=Nt_c/Nur_c$$

Where, FRI_c is Functional Redundancy Index for functional category c (e.g., blue, red, mordant); Nt_c is the number of distinct plant species (taxa) used in category c; Nur_c is the total number of use reports (citations) in category c, summed across all informants. A low FRI value indicates concentration of use reports on few species, implying limited culturally recognized substitution (i.e., few alternative species are known or considered acceptable by informants). Higher values indicate more distributed use across species, suggesting greater substitution flexibility within the knowledge system. Importantly, FRI is a structural index of the knowledge-use system, not a direct measure of ecological abundance, population viability, regeneration rates, or long-term substitution behavior. Low FRI does not directly demonstrate ecological collapse or system failure; rather, it identifies a cultural-structural condition where reliance on few species is high. Whether this structural dependence translates into actual vulnerability depends on additional ecological factors (e.g., population status, harvest pressure, habitat trends) that were not measured in this study.

Data Analysis

Ethnobotanical indices were calculated using Microsoft Excel. Calculations included the RFC, ICF, and FRI for each functional dye category. Thematic analysis was conducted on qualitative data from interviews and observations to understand the social, cultural, and ecological aspects of the dye plants utilization.

Results

Natural Dye Plants Inventory and Ethnobotanical Quantitative Indices

Based on plant inventory and identification, we documented 21 plant species from 14 families used as sources of dyes and mordants in the weaving process in the six study sites (Table 2). From the dye plant inventory, Fabaceae (four species) and Anacardiaceae (three species) were families with the highest species richness. Informant classified these species into six functional categories: five color categories (blue, red, yellow, black, and brown) and one mordant category. In Sumbanese dyeing, *Symplocos fasciculata* Zoll. serves as the primary mordant. The mordant binds dye molecules to textile fibers to increase color intensity and durability (Bechtold & Mussak 2009). Quantitative data shows absolute consensus on three key species: *Indigofera tinctoria* L., *Morinda citrifolia* L., and *S. fasciculata*. These three have the highest RFC value (1.00), meaning they are mentioned by all informants (n=122) across villages and communities. This indicates a strong core of shared cultural knowledge across East and West Sumba. Regarding the plant parts used, bark and leaves are the most dominant ones utilized in the production process. The complexity of traditional chemical technology in Sumba is also evident in the use of additional materials in the color fixation process. All informants (n=122) reported the use of lime powder in the processing of *S. fasciculata* and *M. citrifolia*, while the use of specific mud was found in the processing of Swietenia (n=42) to produce black and brown pigments. Although there is uniformity in the main species, the use of companion species shows clustering based on local ecological availability and clan-specific traditions. For example, *Senna alata* (L.) Roxb. and *Euphorbia hirta* L. (blue category) were only reported by informants from Lambanapu (East Sumba), while *Lannea coromandelica* (Houtt.) Merr. (red/brown category) was only found in the records of informants in Praikamaru. These findings confirm that in addition to universal core knowledge in Sumba, there is variation in plant use influenced by the distribution of species in the surrounding environment and local traditions of each region.

Table 2. Ethnobotanical inventory of natural dye plants for Sumba weaving

Family	Species	Local Name	Voucher Code/ Identification Method	Part(s) used	Color/ Function	How to use	Study sites	RFC
Fabaceae	*Indigofera tinctoria* L.	**Nila, wora, indigofera, tarum, nilam**	HR2025110386	Stem, leaf,	Blue	Soak for two days with lime powder, then dye the yarn.	LAM, PRK, WTK, PRA, RIN, PAT	1.00
Rubiaceae	*Morinda citrifolia* L.	**Kombu, mengkudu, kudu**	HR2025110388	Root, bark, stem	Red, brown	Mash and soak with lime powder, then apply to yarn.	LAM, PRK, WTK, PRA, RIN, PAT	1.00
Symplocaceae	*Symplocos fasciculata* Zoll.	**Loba**	HR2025110402	Bark, leaf, seed	Mordant (for red)	Mash and soak with lime powder, then apply to yarn.	LAM, PRK, WTK, PRA, RIN, PAT	1.00
Menispermaceae	*Arcangelisia flava* (L.) Merr.	**Kayu kuning, akar kuning, iju**	Photo/ Expert confirmation/ literature	Bark, root	Yellow, black	Boil chopped bark or root and soak the yarn.	LAM, PRK, WTK, PAT	0.64
Anacardiaceae	*Mangifera indica* L.	**Mangga, pau**	Photo/ Expert confirmation/ literature	Bark	Yellow	Boil the bark until yellow, then soak the yarn.	LAM, PAT, WTK	0.51
Sapindaceae	*Schleichera oleosa* (Lour.) Oken	**Kesambi, kahembi**	Photo/ Expert confirmation/ literature	Bark (for ash)	Mordant (for blue)	Use the ash to soak the yarn for two days.	RIN, LAM, WTK	0.51

Family	Species	Local Name	Voucher Code/ Identification Method	Part(s) used	Color/ Function	How to use	Study sites	RFC
Euphorbiaceae	*Aleurites moluccanus* (L.) Willd.	**Kemiri, kawilu**	Photo/ Expert confirmation/ literature	Fruit	Mordant (for red)	Crush and boil the kernels, then soak the yarn.	LAM, WTK	0.34
Meliaceae	*Swietenia macrophylla* King	**Mahoni**	Photo/ Expert confirmation/ literature	Leaf, bark	Black, brown	Boil or soak, mix with lobo and mud, then soak the yarn.	PRK, WTK	0.34
Zingiberaceae	*Curcuma longa* L.	**Kunyit, kunta**	Photo/ Expert confirmation/ literature	Rhizome	Yellow	Boil the rhizome until yellow, then soak the yarn.	LAM, WTK	0.34
Combretaceae	*Terminalia catappa* L.	**Hapang**	Photo/ Expert confirmation/ literature	Leaf	Brown	Boil the leaves until yellow, then soak the yarn.	LAM, PAT	0.33
Myrtaceae	*Syzygium polyanthum* (Wight) Walp.	**Lobung, lobo, salam**	HR2025110392	Leaf, bark	Black, brown	Boil and mix with black mud, then soak the yarn.	PAT, PRK	0.33
Lythraceae	*Woodfordia fruticosa* (L.) Kurz	**Hayi, rungu**	HR2025110393	Root	Red, black	Boil with mud and other coloring agents, then soak the yarn.	PAT	0.16
Anacardiaceae	*Lannea coromandelica* (Houtt.) Merr.	**Kehi, kahi**	Photo/ Expert confirmation/ literature	Bark	Red, brownish	Boil the bark and soak the yarn repeatedly for deeper color.	PRK	0.16
Anacardiaceae	*Anacardium occidentale* L.	**Jambu mete**	Photo/ Expert confirmation/ literature	Bark	Yellow	Boil the bark until yellow, then soak the yarn.	PAT	0.16
Apocynaceae	*Calotropis gigantea* (L.) W.T.Aiton	**Biduri**	Photo/ Expert confirmation/ literature	Root	Mordant (for red)	Boil the roots with other red dye materials.	PAT	0.16
Arecaceae	*Areca catechu* L.	**Pinang**	Photo/ Expert confirmation/ literature	Seed	Mordant (yellow, brown, red)	Boil the crushed seeds and soak the yarn in the extract.	RIN	0.16
Euphorbiaceae	*Macaranga involucrata* (Roxb.) Baill. ex Müll.Arg.	**Kandinu**	HR2025110391	Fruit	Red	Boil the fruit and mix with black mud	PAT	0.16

Family	Species	Local Name	Voucher Code/ Identification Method	Part(s) used	Color/ Function	How to use	Study sites	RFC
						before soaking the yarn.		
Euphorbiaceae	*Euphorbia hirta* L.	**Rumba rara, wura wolu**	HR2025110400	Leaf, root	Blue	Boil the plant and soak the yarn in the extract.	LAM	0.16
Fabaceae	*Caesalpinia sappan* L.	**Secang, kandara**	Photo/ Expert confirmation/ literature	Bark	Yellow - Orange	Boil the bark until yellow, then soak the yarn.	PAT	0.16
Fabaceae	*Erythrina variegata* L.	**Dadap, walakiri**	Photo/ Expert confirmation/ literature	Bark	Mordant (for red)	Pound the bark with candlenut, then soak the yarn.	LAM	0.16
Fabaceae	*Senna alata* (L.) Roxb.	**Gandarusa, landukaka**	HR2025110401	Leaf	Blue	Pound the leaves with indigo, mix with water, then soak the yarn.	LAM	0.16

Notes:

- Species with voucher codes were validated with high confidence; species identified via photographs, expert confirmation, and literature were validated with medium-high confidence.
- Study sites and number of informant : RIN = Rindi (20), PRK = Praikamaru (20), PAT = Patawang (20), PRA = Prailiu (20), LAM = Lambanapu (20) and WTK = Watukarere (22)
- RFC : Relative Frequency of Citation

The ICF values ranged from 0.982 to 0.988 for all color categories (Table 3), indicating that the informants mostly agreed. This means that communities agree on which species should be used for which color functions, indicating that this traditional knowledge is still well-preserved. *Morinda citrifolia* dominated the red and brown color categories with a citation frequency (FC) of 122. *Indigofera tinctoria* dominated the blue color category with a citation frequency (FC) of 122. Meanwhile, *S. fasciculata* was the most important plant in the mordant category with an FC of 122.

Mordant category has the largest number of species, at 6 species, with 285 reported uses (Table 3). The Yellow category also has high redundancy with 5 species. If one species that provides yellow color or a mordant is lost, the community still has 4-5 other plant options to replace it. The Blue category has the lowest redundancy, at only 3 species (*S. alata*, *I. tinctoria*, and *E. hirta*). Dependence on I. tinctoria is very high (FC=122), while its companion species only has FC=20. The loss of *I. tinctoria* would have a significant impact on the blue color compared to the other categories.

The FRI values we obtained ranged from 0.019 (blue and brown) to 0.023 (yellow), all well below the proposed threshold of 0.05 for very low redundancy. This means that for every 100 use reports in a given color category, only 1 to 2 distinct species are represented on average. Specifically, if *I. tinctoria* (blue) were to become unavailable due to habitat loss or overharvesting, the community would have only two alternative species (*S. alata*, *E. hirta*), each of which was mentioned by only 20 of the 122 informants (16%). Based on interviews, these alternative blue species produce an “inferior” or “less stable” blue compared to *I. tinctoria*. Therefore, the practical disadvantage is not a simple 1:1 substitution; the cultural quality standard for “true blue” is tied to the dominant species. In contrast, the yellow category (FRI=0.023) has five species but similarly low redundancy because *Arcangelisia flava* (L.) Merr. (FC=78) and *Mangifera indica* L. (FC=62) dominate, while *Anacardium occidentale* L.*, Curcuma longa* L., and *Caesalpinia sappan* L. are rarely used (each FC=20). Thus, high species richness does not guarantee high functional redundancy. This finding is an important insight for conservation planning.

Table 3. Quantitative ethnobotanical indices by functional dye category

Functional Category	Number of Species (Nt)	Species & Frequency of citation (FC)	Number of Use Reports (Nur)	ICF	FRI
Blue	3	*Senna alata* (FC=20), *Indigofera tinctoria* (FC=122), *Euphorbia hirta* (FC=20)	162	0.988	0.019
Red	4	*Morinda citrifolia* (FC=122), *Lannea coromandelica* (FC=20), *Macaranga involucrata* (FC=20), *Woodfordia fruticosa* (FC=20)	182	0.983	0.022
Brown	5	*Swietenia macrophylla* (FC=41), *Morinda citrifolia* (FC=122), *Lannea coromandelica* (FC=20), *Syzygium polyanthum* (FC=40), *Terminalia catappa* (FC=40)	263	0.985	0.019
Black	4	*Swietenia macrophylla* (FC=41), *Arcangelisia flava* (FC=78), *Syzygium polyanthum* (FC=40), *Woodfordia fruticosa* (FC=20)	179	0.983	0.022
Yellow	5	*Anacardium occidentale* (FC=20), *Curcuma longa* (FC=41), *Caesalpinia sappan* (FC=20), *Arcangelisia flava* (FC=78), *Mangifera indica* (FC=62)	221	0.982	0.023
Mordant	6	*Symplocos fasciculata* (FC=122), *Schleichera oleosa* (FC=62), *Erythrina variegata* (FC=20), *Calotropis gigantea* (FC=20), *Areca catechu* (FC=20), *Aleurites moluccanus* (FC=41)	285	0.982	0.021

Notes:
- ICF : Informant Consensus Factor; FRI : Functional Redundancy Index

Local Knowledge of Dyeing and Weaving Practice

Based on our observations across the six study villages, we identified two main weaving techniques practiced by informants: **ikat** weaving (tying sections of thread before dyeing) and **pahikung** weaving (extra-weft technique producing raised motifs). All 122 informants confirmed that cotton (*Gossypium hirsutum* L.) spun manually (known locally as **pahudur**) is the traditional material, though approximately 50% of informants noted increasing use of factory-spun yarn due to declining cotton availability. Weaving is performed on traditional wooden and bamboo looms (**gedogan**), which we documented through direct observation and photography (Fig. 2).

Figure 2. Traditional weaving tools of Sumba. (a) **pahulur benang** (cotton processing), (b) **piepak** (yarn winding), (c) **wanggi kapala** (warp arranging), (d) **gedogan** (loom). Source: Authors' documentation (2025). All photographs were taken with informed consent from the individuals depicted.

During field observation, natural dyeing practices showed consistent patterns among informants. All informants described the extraction of blue dye from the leaves of Indigofera through fermentation in water mixed with ash or lime for 2-7 days. All informants also reported the use of **kesambi**, *Schleichera oleosa* (Lour.) Oken, as a mordant for fixing the blue dye. For red dye production, all informants described a process involving the roots of **kombu**, *M. citrifolia*, which are dug up, ground, boiled, and mixed with the bark of **loba**, *S. fasciculata*. Based on informant reports (n = 122), dyeing activities are seasonal. All informants stated that dye collection and motif tying are carried out during the rainy season, while all 122 informants reported that the dyeing process itself is conducted during the dry season due to the requirement for sunlight during drying.

Based on interview data, gender roles in the dyeing process are clearly differentiated within the weaving tradition. All 122 informants reported that women are primarily responsible for spinning, dyeing, pattern design, and weaving activities. Meanwhile, all informants also explained that men contribute by sourcing dye materials, mixing colors, dyeing yarn, tying patterns, and winding yarn. Regarding blue dyeing specifically, all informants stated that this activity is exclusively performed by women. In addition, almost all informants described several associated taboos, including the prohibition of men's presence during the blue dyeing process, as it is believed to disrupt fermentation, as well as restrictions for pregnant women, menstruating women, and dyeing activities conducted during the full moon. Furthermore, the term "**kawinni nggiling**" (women with blue-dyed hands) was reported by informants as a cultural symbol representing skilled and diligent weavers.

Based on field observation and interview data, producing natural dyes involves several steps. Blue dye is extracted from *I. tinctoria* leaves by fermenting them in water mixed with ash or lime for several days, and a mordant such as **kesambi** (*S. oleosa*) is added. Red dye is produced from **kombu** (*M. citrifolia*) roots, which are dug, ground, boiled, and mixed with mordant from **loba** (*S. fasciculata*) bark (Fig. 3). Furthermore, dyeing is adjusted to the season to ensure the quality of the resulting color. During the rainy season, weavers focus on motif creation and dye collection, as *I. tinctoria* (**nila**) is abundant during the rainy season. The dry season is used for the dyeing process to produce more striking colors, especially the red hues of young **kombu** roots. Sunlight is necessary for drying process, which can take weeks between dyeing sessions. This direct sunlight drying process not only ensures complete dye drying but is also believed to produce the desired color. These natural dyeing practices reflect ecological knowledge that adapts to raw material availability, climate patterns, and the quality of the weaving. Figure 4 shows a ball of naturally dyed yarn undergoing several dyeing processes to produce the desired color.

Based on fieldwork, some motifs from East Sumba focus more on sacred animals and symbols related to **Marapu** beliefs, such as shrimp (**kangaroo**), lion (**mahang**), flying lizard (**habaku**), crocodile (**wuya**), butterfly (**karihu**), turtle (**karawulangu**), dragon snake, big brother, deer (**ruha**), octopus (**wita**), and skull (**andung**). In contrast, West Sumba weaving displays visual characteristics that generally feature small, abstract, geometric, and symmetrical motifs with a predominance of dark or black colors (Fig. 5). Although the motifs are not as complex as those in East Sumba, West Sumba weaving has a distinctive feature called **kalindur** (layered edges) that enhances the fabric's value. Men's fabrics often feature lines, dots, and **mamuli** (female womb motif, Fig. 5) along the edges, while women's fabrics initially featured rhombuses (buffalo eyes) and triangles (horse tails).

Challenges to Sustainability

The identification of challenges to the sustainability of traditional weaving practices ($n = 122$) reveals critical barriers in intergenerational knowledge transmission. Commitment to formal education was found to limit the learning time of younger generations, resulting in the technical skills of natural dyeing now being concentrated among weavers over 50 years of age. The risk of losing this heritage is further exacerbated by a fully oral transmission method based on observation and imitation, without any written documentation. On the other hand, economic pressures and the technical complexity of natural dyeing are driving an increased use of synthetic dyes, which are perceived as more cost- and time-efficient. Culturally, this situation has led to the degradation of traditional motifs, such as the skull motif (**andung**), which is beginning to disappear due to low interest among the younger generation and market demand that increasingly favor simpler designs.

Regarding the availability of dye plants, informants reported several environmental challenges affecting the sustainability of traditional weaving materials. For **loba**, *Symplocos fasciculata*, informants explained that this species is found only in the highland areas of western and southern Sumba, mainly within state forest areas such as protected forests and national parks. Meanwhile, most informants also reported that populations of *Indigofera tinctoria* and *Morinda citrifolia* are increasingly threatened by land-use change, savanna degradation, and the expansion of livestock grazing areas, which reduce the availability of important natural dye resources for traditional weaving practices

Based on interview data, natural motifs and coloring of Sumba weaving have not been recognized as Geographical Indications (*Indikasi Geografis*)—a legal protection for product names that originate from certain areas and have distinctive characteristics due to their region. The absence of Geographical Indication (GI) makes Sumba woven textiles vulnerable to counterfeiting and unilateral claims by outside industries, which undermines market prices and the welfare of local weavers.

Without this legal protection, authentic products are difficult to distinguish from synthetic imitations, thereby reducing their bargaining position in international markets. The long-term consequences include the loss of product quality standards, the erosion of cultural identity, and the weakening of incentives to conserve traditional knowledge and the ecosystem of original dye plants.

Overall, the above issues demonstrate that the preservation of Sumba weaving is inseparable from efforts to protect local knowledge about dye plants and their habitats. Addressing this challenge requires collaboration between stakeholders that combines cultural preservation, biodiversity conservation, and economic development for the community. The goal is to maintain the weaving tradition as a socioecological practice that integrates nature and society, thereby enhancing the meaning of Sumba weaving.

Figure 3. Key dye plants and their processing methods as documented in Sumba. (a) *Indigofera* leaves and stems, (b) *Morinda* roots, (c) *Symplocos* bark, (d) fermented indigo leaves, (e) pounded **kombu** roots, (f) **loba** bark powder. Source: Authors' documentation (2025). Informed consent was obtained from all weavers whose hands or faces appear in the photographs.

Figure 4. Naturally dyed yarn balls (balls of cotton thread) showing a range of colors achieved through different dye plants and dyeing intensities. From left to right: indigo blue (*I. tinctoria*), red (*M. citrifolia*), yellow (*Curcuma longa* L.), and brown (*Swietenia macrophylla* King with mud). Source: Authors' documentation, 2025. No identifiable human subjects appear in this figure; however, all weavers who handled the yarn provided informed consent for documentation

Figure 5. Representative motifs of Sumba woven textiles. (a) Lion motif (**mahang**) from East Sumba, symbolizing bravery and social status; (b) Female womb motif (**mamuli**) from East Sumba, representing fertility and clan identity; (c) Symmetrical geometric motif from West Sumba, typical of the darker-colored textiles from this region. Source: Authors' documentation (2025). Informed consent for photographing these textiles and their weavers was obtained prior to data collection.

Discussion

Cultural context of Sumba Ethnoweaving

The weaving practices documented in this study reinforce the relevance of the Sumba weaving classifications described by previous researchers. Our findings confirm that the main categories of East Sumba weaving remain divided into **ikat** and **pahikung**, with the leading products being **hinggi** (men's cloth) and **lawu** (women's sarong) (McCullagh 2023, Murniasih & Soeriadiredja 2020, Sahertian *et al.* 2024). This consistency demonstrates the resilience of traditional production structures amidst changing times.

The symbolism of motifs plays a crucial role in Sumbanese cultural identity. The faunal motifs we observed—such as shrimp (**kangaroo**), lion (**mahang**), flying lizard (**habaku**), and skull (**andung**)—align with the symbolic systems mapped by Samadara *et al.* (2018) and Wicaksono (2022). Specifically, the presence of the **mamuli** (female womb) motif on the edge of the cloth serves as an indicator of social status and clan identity, consistent with Pollock's (2012) description. Interestingly, there are differences in visual characteristics between regions; East Sumba tends to feature bright colors with varied sacred animal motifs, while West Sumba is dominated by dark geometric motifs. This confirms Wicaksono's (2022) finding that these differences are influenced by the weavers' time allocation, with East Sumba weavers having more room for creative expression than West Sumba weavers, who must balance their time with agricultural activities.

The symbolism of color in Sumba also exhibits unique characteristics compared to other regions in Southeast Asia. In Sumba, red symbolizes family ties, white symbolizes purity, and black symbolizes the struggle for life (Lolo, 2018). While there are different meanings in the Philippines or Thailand—such as yellow as a symbol of royalty for the Maranao people (Ladrido, 2024)—the use of natural dyes is universally seen as an instrument for preserving cultural identity (Kaewsangsai *et al.* 2025). This underscores the importance of place-based documentation to avoid inaccurate assumptions of universal meaning.

Overall, this study confirms that the socio-cultural dimensions of Sumba weaving are still strictly governed by traditional values. Gender-based taboos, particularly in the blue dyeing process, are still actively observed, as reported by Nichols *et al.* (2017) and Hunga (2022). Weaving's function as a traditional communication medium (**lata panii**) and a crucial instrument in the life cycle—from dowry (**belis**) to birth and death ceremonies—strengthens weaving's position as more than just a commodity, but an integral element of the Sumbanese social system (Babang & Rinata 2019, McCullagh 2023).

Dye Plant Diversity and Ethnobotanical Indices

This study complements previous research conducted by Herawati & Aladina (2010), who identified 12 species of natural dye plants, and Murniati & Takandjandji (2015), who identified 15 species of dye plants in East Sumba Regency. The wider study area, namely West and East Sumba Regencies, and more than 100 informants allowed for additional information on the species of dyes to be obtained. Within East Nusa Tenggara province, a recent study in Belu Regency documented 38 dye plant species (Seran *et al.* 2024), nearly double the 21 species we recorded in Sumba. This difference may reflect: (1) Belu's inclusion of plants used for food coloring in addition to textile dyes, (2) different ecological conditions (Belu has higher rainfall and more forest cover), or (3) broader inclusion criteria for "dye plants" in the Belu study. Conversely, our study's use of quantitative indices provides a structural analysis absent from the Belu study, enabling assessment of knowledge distribution and substitution flexibility. In Pringgasela, West Nusa Tenggara, the use of less vital plant parts tends to be preferred, reducing pressure on keystone species (Rahayu *et al.* 2020). In contrast, the practice in Sumba, which primarily utilizes bark and roots—plant parts whose harvesting is potentially more damaging—suggests more critical sustainability implications. This comparison highlights that, despite regional similarities in plant family selection, specific harvesting techniques in Sumba require greater attention to ensure the long-term sustainability of these natural dye resources.

The documentation of 21 dye plant species in Sumba indicates a moderate level of diversity compared to similar studies in Southeast Asia. In comparison, much higher species richness was found in Thailand, such as in the northern region, where 104 species were recorded (Kaewsangsai *et al.* 2024), the northeastern region with 56 species (Junsongduang *et al.* 2017), and among the Karen community, where 52 species were identified (Kaewsangsai *et al.* 2025). Although the number of species in Sumba is lower, its taxonomic composition shows strong regional consistency.

Family-level analysis revealed that Fabaceae and Anacardiaceae are the most dominant groups in Sumba, a pattern also found widely across Southeast Asia. In Northeastern Thailand, Fabaceae (19%) and Anacardiaceae (9%) dominate the dye plant inventory (Junsongduang *et al.* 2017), while in Northern Thailand, Fabaceae remains the main family alongside Rubiaceae and Lamiaceae (Kaewsangsai *et al.* 2024). These cross-cultural preferences for particular families are likely driven by the content of specific secondary metabolites produced, such as anthraquinones in Rubiaceae or flavonoids in Fabaceae, which provide desirable color qualities.

This study found that there are three key species - **nila**, **kombu**, and **loba** (high RFC value) - which are the most commonly used plants, or in other words, categorized as the "Cultural Key Species" of the Sumba weaving community. These results are in line with previous studies that found these three species to be the most dominant (Herawati & Adalina 2010, Murniati & Takandjandji 2015, Kaleka *et al.* 2024). The results of this cross-time research indicate that these species are cultural key species, especially when associated with weaving. In other words, the persistence of these three species across time indicates their fundamental role in Sumba's ethnoweaving system. In Belu, East Nusa Tenggara, Seran *et al.* (2024) similarly reported *Indigofera tinctoria* and *Morinda citrifolia* as dominant species.

In a broader context, in Southeast Asia Region, particularly in northern Thailand, *Strobilanthes cusia* (Nees) Kuntze (indigo source) and *Morinda angustifolia* Roxb. (red source) were the most important species (Kaewsangsai *et al.* 2024). Among the Karen in Thailand, *S. cusia* had the highest color use value (0.93) (Kaewsangsai *et al.* 2025). For the Tai-Lao in northeastern Thailand, *I. tinctoria* and *Pterocarpus indicus* Willd. were the most important species (Junsongduang *et al.* 2017). Meanwhile in another Souteast Asia Region, the Philippines, indigo (*Indigofera* spp.) and morinda (*M. citrifolia*) are described as the "three sources of colorants" alongside turmeric (Ladrido 2024). This regional convergence suggests a shared "ethnobotanical core" of dye plant knowledge across mainland and island Southeast Asia, possibly reflecting historical diffusion, trade networks, or independent discovery of chemically similar plants. Notably, while the indigo source varies—*I. tinctoria* in Sumba and much of Indonesia versus *S. cusia* in northern Thailand—the functional role and cultural importance remain parallel.

The high ICF values (0.982-0.988) in Sumba are comparable to or exceed those reported elsewhere. This finding contrasts with studies from other Indonesian regions where different sub-ethnic groups show divergent plant use (e.g., Seran *et al.* 2024 in Belu, East Nusa Tenggara). The homogeneity observed here may be explained by the unifying role of the **Marapu** belief system and the long history of inter-clan marriage and trade in East Sumba. In northeastern Thailand, ICF for blue was 0.92 and for black 0.84 (Junsongduang *et al.* 2017). The slightly higher consensus in Sumba may reflect the more centralized role of weaving within **Marapu** cosmology and the restricted number of weavers per community, which may lead to more standardized knowledge transmission compared to the more diffuse dyeing practices among the Tai-Lao. The high ICF values across all color categories, despite the inclusion of two culturally distinct regions (East and West Sumba), demonstrate that knowledge of dye plants is uniformly shared across subethnic boundaries in Sumba. This finding is consistent with previous research by Teron & Borthakur (2012) in the Karbis Tribe of India, which also found high communal agreement in the use of natural dyes. This also indicates that even though such knowledge is oral and, in some cases, often secretive (Ndamunamu 2024), the transfer of knowledge related to natural textile dyeing remains uniform and strongly rooted from generation to generation.

The low FRI values we calculated (0.019-0.023) provide quantitative evidence for the structural concentration of dye plant use—a pattern previously described qualitatively by these authors. Our finding that use reports are concentrated on 1-2 dominant species per category, with few culturally recognized alternatives, highlights a structural condition that could increase the knowledge system's sensitivity to loss of key species. However, whether this structural condition translates into actual production vulnerability depends on ecological factors (species abundance, regeneration) and social factors (willingness to adopt alternatives) not measured here. This study thus identifies a potential vulnerability that merits further ecological and social investigation, rather than demonstrating an actual system failure.

Our study's use of FRI to assess substitution flexibility appears to be novel in ethnobotanical dye plant literature; we are unaware of comparable quantitative assessments of functional redundancy in other Southeast Asian studies. However, qualitative observations suggest similar patterns elsewhere. In northern Thailand, while 104 species were documented, the use values were concentrated on a few species (Kaewsangsai *et al.* 2024), indicating potential low functional redundancy as well. The presence of multiple indigo-yielding species across the region (e.g., *I. tinctoria* and *S. cusia*) suggests that some substitution is ecologically possible, but whether these are culturally recognized as equivalents—as in Sumba where *Senna alata* and *Euphorbia hirta* are known but rarely used—requires further investigation.

Sustainability Challenges

The sustainability challenges facing Sumba’s natural dye system are part of a broader phenomenon across Southeast Asia, where traditional knowledge is being eroded by modernization, urbanization, and changing lifestyles (Junsongduang *et al.* 2017). Ecologically, the survival of this tradition is threatened by ecosystem degradation and land-use change, which damage the habitats of dye plants (Murniati & Takandjandji 2015, 2016). This vulnerability is quantitatively evidenced by low FRI values (0.019-0.023) and the fact that production depends on very few key species—only 3-6 species per color category. This situation creates a structural risk: the loss of a single dominant species could cripple the entire dye production chain (Junsongduang *et al.* 2011).

In addition to environmental factors, the erosion of intergenerational knowledge is a serious threat due to the lack of written documentation and reliance on oral transmission (Cunningham *et al.* 2011, Ndamunamu 2024). Widespread formal education has also reduced the time young people have to learn, so even though they may recognize dye plants, they no longer master the detailed dyeing techniques (Istikomayanti & Mitasari 2021). This critical knowledge transition point is exacerbated by market pressures, which have driven informants to switch to synthetic dyes for greater time efficiency and motif simplification. This shift ultimately causes traditional motifs such as **andung** (skull) to disappear (Takandjandji & Tambotoh 2025).

The situation is further complicated by weak legal protection, as Sumba’s naturally dyed woven textiles have not yet received Geographical Indication (GI) certification (Muchtar *et al.* 2017, Hartanti *et al.* 2023). The absence of such legal protection makes authentic products vulnerable to imitation products using synthetic dyes. Therefore, a market-based conservation strategy through GI certification is needed to distinguish and protect the authentic value of Sumba’s textiles, similar to the successful use of global interest in sustainable products seen in the development of ecotourism in the Philippines (Ladrido 2024).

Implications

This study provides several implications, including theoretical, practical, and policy implications. Regarding theoretical implications, this study offers a research framework for describing ethnobotanical studies of dye plants not only qualitatively but also quantitatively by combining RFC, ICF, and FRI. With RFC values, we can identify dominant plant species—main cultural species and supporting species, ICF to assess strong consensus within the community or the distribution of knowledge about dyes, and FRI to determine dependence on dominant species and which species are most vulnerable or difficult to substitute.

Meanwhile, conservation implications include, first, the need for in situ and ex situ conservation of dye plant species, particularly three key species—**indigo**, **kombu**, and **loba**—which are threatened by overexploitation, land-use change, and climate change. Conservation efforts include community-based cultivation (such as home gardens for **nila** and **kombu**) and sustainable harvesting systems based on local Sumbanese wisdom and traditions, such as **pahomba** (sacred forests) (Joh *et al.* 2021). Low FRI values indicate that these key species are not easily replaced, making conservation efforts imperative. *Symplocos*, which grows exclusively in the highlands, faces threats from habitat fragmentation and land conversion, while *Indigofera tinctoria* and *Morinda citrifolia*, whose habitats are in savannas and remnant forests, are threatened by the expansion of free-range agriculture and livestock farming practiced by most Sumbanese. Another conservation implication is the urgency of documenting knowledge of companion species such as *Senna alata* or *Euphorbia hirta* for blue color (companion species of *I. tinctoria*), *Lannea coromandelica* and *Macaranga involucrata* for red color (companion species of *Morinda citrifolia*), as a form of anticipation of the worst-case scenario of key species extinction. One way to do this is through participatory research to improve the color quality of these companion species, aligning with the color quality or cultural standards of the key species.

Regarding the preservation of weaving culture, the younger generation's involvement remains low. This study aligns with the findings of Istikomayanti & Mitasari (2021), who found that the younger generation is generally familiar with dye plants, but has not yet mastered detailed dyeing techniques. The implication for cultural preservation is the need to incorporate this knowledge and skill of natural dyeing into local content in schools in Sumba. Furthermore, cultural preservation can also be achieved through training or workshops that facilitate the transfer of knowledge from senior weavers to the next generation.

Implications for the preservation of other cultures require strengthening the protection of Sumba weaving Geographical Indications, as a strategic response to the challenges of commercialization and market influence that encourage the use of synthetic dyes and motif simplification (Takandjandji & Tambotoh 2025). For example, some weaving companies outside Sumba produce Jepara cloth (**troso**) by imitating Sumba motifs that have dominated the online market. These fabrics have also entered Sumba and are sold in tourist spots. Inexperienced buyers may be deceived. The Geographical Indication document—as a form of formal recognition—will provide added economic value that can counter the appeal of synthetic dyes. Additionally, this document also serves as support for marketing strategies that emphasize the unique cultural value of weaving, while also creating a premium market segment that appreciates the authenticity of Sumba weaving.

In addition to protecting Geographical Indications, local governments have also undertaken various efforts to sustain Sumba weaving. Some of them include: weaving development strategies being included in the East Sumba Regency Regional Development Plan (Ndamunamu 2024), the provision of capital assistance, spinning tools, thread, and dye plant seedlings (**kombu** and **nila**) to weaving groups (Njara 2022), the addition of weaving collections (for example, giant Kaliuda motif weaving measuring 100 meters and 3 meters wide) in the regency museum, weaving training assistance, business credit assistance from banks, and capital assistance for the development of weaving houses (Samadara *et al.* 2018), policies for civil servant attributes by mandating the use of weaving on Wednesdays and Thursdays, as well as appeals from the East Nusa Tenggara governor regarding the use of weaving as gifts for guests from outside East Nusa Tenggara (Babang & Rinata 2019).

The results of this study emphasize that preserving Sumbanese woven fabrics requires an integrated approach that combines conservation policies, cultural preservation, and economic development. Existing policies tend to be sectoral and operate independently. Therefore, they need to be integrated within the Ecological and Cultural Conservation framework. Relevant stakeholders, such as the Department of Environment, the Department of Education and Culture, and the Department of

Industry and Trade, need to collaborate to formulate an integrated program to protect dye plant habitats, document traditional knowledge, and promote naturally dyed woven products.

Limitations and Future Research

Although capable of providing qualitative and quantitative insights related to the ethnobotany of Sumba weaving, this study has several main limitations. First, its geographical coverage is limited to six villages in East and West Sumba, so traditional weaving practices from Central and Southwest Sumba, including possible unique dye species from certain community groups, are not represented. Second, plant identification relied on a combination of local names, photographs, fresh samples and literature, rather than on physical herbarium voucher. Voucher specimens could not be completely prepared due to field constraint (limited access and export permits for specimen). Third, this study focuses more on botanical aspects, so the economic dimension (the reasons for the shift to synthetic dyes) and ecological data (the abundance of plant populations in nature) have not been explored in depth.

Further studies are recommended to: expand coverage to Central and Southwest Sumba to document inter-regional knowledge; conduct detailed ecological research on key species to support their conservation efforts; examine the dynamics of the transmission of dyeing and weaving knowledge to younger generations; analyze the economic value chains of natural and synthetic dye weaving; and encourage multidisciplinary collaboration (e.g., weavers, chemists, botanists, and policymakers) to optimize the use of dyes from less frequently used companion species.

The term "ethnoweaving" was introduced in this study as a descriptive label for the integrated system of plant-based dyeing and weaving in Sumba. We wish to be transparent about its limitations and intended scope. First, the term is not proposed as a formal analytical category equivalent to well-established concepts like "traditional ecological knowledge" (TEK) or "ethnobotany". Unlike TEK, which has a substantial theoretical literature (Berkes 2012), ethnoweaving is a heuristic device specific to this study. Its utility lies in drawing attention to the interconnection of botanical, technical, and social dimensions that are often treated separately. We encourage other researchers to adopt, modify, or reject the term based on the needs of their own contexts. Second, the configuration described for Sumba may not apply elsewhere. In other weaving communities, the relationship between plant knowledge, technique, and social meaning may differ. For example, in some contexts, synthetic dyes may be used without eroding social meanings; in others, plant knowledge may be retained but technical skills are lost. The term "ethnoweaving" should not be assumed to describe a universal type. Third, we do not claim that Sumba's ethnoweaving system is unique in having integrated plant knowledge, technique, and symbolism. Many traditional textile-producing communities worldwide exhibit similar integration (e.g., the Karbi in India, Teron & Borthakur 2012; Mayan weavers in Guatemala, Modesto & Niessen 2005). Our use of the term is a matter of emphasis and convenience, not a claim of exceptionalism. With these caveats, we offer "ethnoweaving" as a modest framing device that has helped us organize a complex set of observations. We hope it may serve as a useful descriptor for other researchers studying similar integrated systems, but we do not advocate its reification as a rigid theoretical construct.

Conclusion

Ethnoweaving in Sumba represents more than a weaving production technique; it is a complex socio-ecological system integrating social and cultural values, ecological knowledge, and the management of natural dye plant resources. The sociocultural dimension of ethnoweaving is reflected in gender-based division of labor, cultural taboos (**pamali**) in the dyeing process, and the function of woven cloth as a medium of traditional communication, a status symbol, and a ritual life instrument—from birth, marriage, to death. The different ecological conditions between East and West Sumba result in distinctive visual characteristics of the weaving: sacred animal motifs with bright colors in the dry eastern region, versus geometric motifs with dark colors in the wetter western region.

Regarding natural dye plants resources, the ethnobotanical survey recorded 21 species of dye plants from 14 families used in six categories of dye functions, with *Indigofera tinctoria* (blue), *Morinda citrifolia* (red), and *Symplocos fasciculata* (mordant) as cultural key species mentioned by all informants (RFC=1.00) and having a high level of knowledge consensus among weaver communities in all color categories (ICF value 0.982-0.988). Although species diversity was recorded, the low FRI value (0.019-0.023) indicates that the distribution of plant use as a source of color remains concentrated among few culturally dominant species. From a knowledge-system perspective, the Sumbanese ethnoweaving system shows structural dependence on a small number of culturally key species. This structural dependence suggests a potential vulnerability: if a key species were to become unavailable due to environmental change or overharvesting, the community has limited culturally recognized alternatives. However, we caution that FRI does not directly measure ecological decline or system failure. Whether such structural dependence translates into actual production loss requires additional ecological data on population trends, regeneration rates, and the technical feasibility of substitute species. The challenges identified—ecological pressure on dye plant habitats, erosion of intergenerational knowledge transfer, and market influence toward synthetic dyes—are real pressures, but their interaction with the structural dependence identified by FRI remains a subject for further research. The strategy that can be undertaken to overcome the sustainability challenges of Sumba weaving is through an integrated approach, including: conservation of key species and their habitats, revitalization of traditional learning through formal education and apprenticeships, strengthening economic value through geographical indication certification and premium marketing, as well as cross-sector policies that connect the environmental sector - for the sustainability of dye plants, Education - for socio-cultural sustainability, and industry - for economic sustainability.

Overall, this study demonstrates a framework that not only qualitatively narrates local knowledge but also quantitatively evaluates the resilience of traditional knowledge systems — an approach that can be applied to similar cultural heritage in Indonesia and other tropical regions. Further studies with a broader geographic scope, population-ecology approaches, participatory research to develop alternative species, and in-depth economic analysis will further strengthen the scientific foundation for efforts to preserve Sumba's ethnoweaving as an invaluable cultural heritage and biodiversity.

Declarations

List of abbreviations: GI - Geographical Indication; NTFP - Non-Timber Forest Product; RFC - Relative Frequency of Citation; ICF - Informant Consensus Factor; FRI - Functional Redundancy Index.

Ethics approval and consent to participate: This study received ethical approval from BRIN. Prior informed consent was obtained verbally and in writing from all participating community members and key informants before interviews and observations were conducted, in accordance with the International Society of Ethnobiology Code of Ethics. Additionally, specific informed consent was obtained for photography and publication of images that could potentially identify individuals (including weavers' hands, faces, or distinctive body features). All participants were informed that photographs would be published in an open-access scientific journal and could be viewed internationally. Participants retained the right to withdraw consent before manuscript submission, and none exercised this right.

Consent for publication: All people shown in images agreed to have their image published.

Availability of data and materials: The datasets (plant inventory, interview transcripts) generated and analyzed during the current study are available from the corresponding author on reasonable request.

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