Natural Dyes from the BTR of Assam: Ethnobotanical insights and standardized evaluation of dye stability

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Research

Abstract

Background: The BTR region of Assam lies in the trans-border area adjoining Bhutan and forms part of the foothills of the Eastern Himalayas. It is inhabited by several ethnic tribes who have traditionally woven their ethnic garments and used plants as sources of natural dyes since time immemorial. Despite their cultural and ethnobotanical significance, systematic documentation and scientific evaluation of dye-yielding plants from this region remain scarce. This study addresses this gap by documenting traditional knowledge and characterizing dyes extracted from regional plant species in terms of their color yield and thermal stability.

Methods: The study was conducted between December 2024 and March 2025 across 15 locations situated within the three districts of BTR, Kokrajhar, Chirang and Baksa, of Assam, India. Primary information was gathered via semi-structured interviews and informal discussions with 30 purposively selected informants who were local weavers, industrial dyers, or resourceful custodian of traditional knowledge system. Collected plants were processed for dye extraction and tested for color yield, heat stability, and dye performance. Each species was assigned a dye score based on color strength, solubility, and stability, while conservation status was assessed using IUCN Red List categories.

Results: A total of 42 plant species from 31 families were documented. Malvaceae and Fabaceae were the most prevalent families. The study identified 21 distinct dye colors, with yellow (18.75%), cream (15.63%), and red (14.58%) being the most common. Approximately 63.64% of the dyes exhibited heat stability, with yellow and brown dyes demonstrating the greatest stability. Plant parts utilized for dye extraction included leaves, flowers, roots, bark, and fruit. Dye scores ranged from 24 to 84, reflecting a spectrum of dye performance. Notably, *Hibiscus x rosa-sinensis* L. and *Hibiscus sabdariffa* L. achieved the highest dye scores of 84 and 78, respectively.

Conclusions: The study highlights the rich diversity and ethnobotanical importance of dye-yielding plants in the BTR. Several native and cultivated species demonstrated promising dye potential for sustainable, eco-friendly textile applications.

Keywords: Natural dye; Dye-yielding plants; Ethnobotany; Indigenous practices of dye; Dye score

Background

The use of natural dyes has a long history, dating back thousands of years. For example, a cloth fragment dyed with madder (*Rubia cordifolia*) was discovered, which is believed to be over 5,000 years old (Ozturk *et al*. 2013). Building on this historical context, the traditional knowledge of using natural dyes remains deeply ingrained in the cultural sphere of Northeast India. In support of this, a study by Sharma et al. (2005) documented the ethnobotanical knowledge of the Meitei community, identifying 34 plant species used as natural dyes and 19 as mordant.

In Assam, which is an integral part of NE India, indigenous communities have long practiced dyeing of materials such as silk and cotton using locally available plants (Teron & Borthakur 2012; Akimpou *et al*., 2005; Phukan *et al*. 2018). The region consists of rich in plant diversity, including plants that produce unique dyes. These bright and distinctive colors reflect the cultural identity of the local tribes (Kar & Borthakur 2008). Local artisans from communities like Bodo, Rabha, Mising etc. continue to rely on plant-derived dyes for dying traditional textiles like muga and eri silk, which are renowned for their unique luster and cultural significance (Banerjee *et al*. 2019; Singh, 2017, Sutradhar *et al*. 2015).

Natural dyes are safe for environment because they are generally biodegradable, non-toxic. They also often possess medicinal or health-promoting properties. For example, turmeric, a common dye plant, has antiseptic and skin-soothing effects. Indigo is loved for its deep color and also has healing properties (Patil *et al*. 2019, Verenkar & Sellappan 2017). Recently, there has been a global resurgence of interest in natural dyes as eco-friendly and a sustainable alternative to synthetic dyes (Andriamanantena *et al*. 2023). On the contrary, the production of synthetic dyes involves harmful chemicals that pollute water bodies and pose health hazards to workers and consumers (Türkmen *et al.* 2004; Patel et al. 2019).

The Bodoland Territorial Region (BTR) of Assam is rich in biodiversity, with a significant forest cover area of 35.23 %of the reagion's geographical area, and is home to multiple ethnic groups such as the Bodo, Rabha, Garo, Santhal, Rajbongshi, Koch, Assamese, and others. BTR is rich in biodiversity and cultural diversity and has a strong traditional heritage (Paul, 2022). The ethnic communities are rooted in their traditional knowledge system. However, despite such a rich traditional knowledge, limited research has been conducted on dye-yielding plants from this region. Research in the BTR is sparse compared to other regions of Assam Most of the traditional knowledge in the area is orally transmitted, resulting in a gap in formal ethnobotanical documentation. Furthermore, scientific evaluations of extraction methods, dye stability, and performance of natural dyes are still lacking. Therefore, this study aims to fill this research gap by documenting the traditional knowledge and practices related to dye-yielding plants used by the Bodo community in selected localities of BTR. The study also attempts to characterize the extracted dyes through laboratory-based analyses to assess their potential and stability as natural dyes.

Materials and Methods

Study area

The study was conducted between December 2024 and March 2025 across 15 locations within the three districts of the Bodoland Territorial Region (BTR)—Kokrajhar, Chirang, and Baksa—in Assam, India. The geographical coordinates of each survey site were recorded using a handheld GPS device (Table 1). Most fieldwork was carried out in Kokrajhar district (13 sites), with one site each in Baksa and Chirang.

Survey method

Informants were purposively selected based on their expertise in traditional dyeing practices. The majority of them were local weavers and industrial dyers belonging to the Bodo community. In total, 30 informants (12 males and 18 females) participated in the study, representing three age groups: young (6), middle-aged (18), and elderly (6). Primary data were collected through semi-structured interviews and informal discussions using a pretested questionnaire. Prior informed consent was obtained from all participants, and permission for photographic documentation was sought in each case. Interviews focused on documenting local knowledge of dye-yielding plants, including vernacular names, plant parts used, methods of collection and extraction, colors obtained, seasonal availability, and cultural or commercial significance. The overall approach followed standard ethnobotanical protocols employing semi-structured interviews and key informant techniques as outlined in previous studies (Song *et al*. 2014).

Traditional method of extraction and dying process

Dye-yielding plant materials were collected and thoroughly washed to remove dirt and impurities. Depending on the species, the materials were cut, crushed, or used in powdered form (if available in markets). As informed by the informants, a standard dyeing ratio of 1:20 (one part plant material to twenty parts water) was used. For the extraction process, the water was boiled in a dye pot. The plant material was then added, and this was allowed to simmer until the desired color was extracted. Finally, the plant residue was removed, leaving a colored extract in liquid form. For the dyeing process, the temperature was lowered, and the yarn was soaked in the dye pot. The yarn was stirred gently with sticks in an upward circular motion for 1-3 hours. After dyeing, the yarns are dried for a day (longer during rainy weather). The dried yarns were stored in a cool, dry place away from direct sunlight.

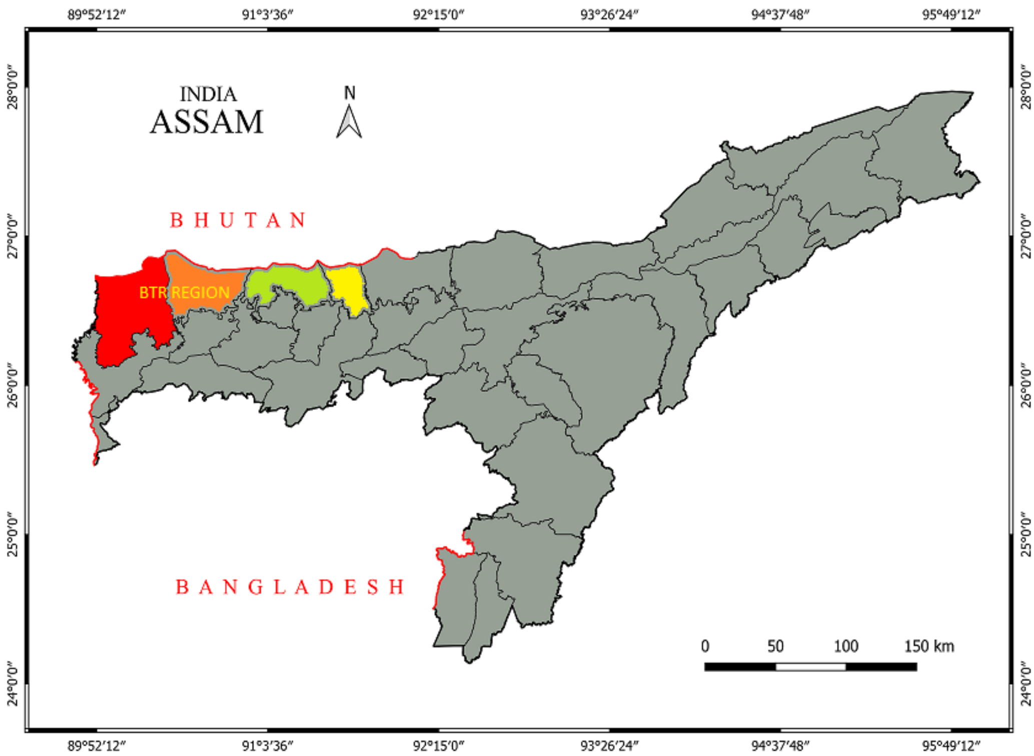

Figure 1. Map of BTR region and Assam, India, showing the study area

Table 1. Locations of field survey area

SL NO.	LOCATION	VILLAGE	DISTRICT
1	Lat 26.418126 Long 90.269484	Boro Bhatarmari	Kokrajhar
2	Lat26.417607 Long 90.27277	Boro Bhatarmari	Kokrajhar
3	Lat26.543628 Long 90.364784	Shyamsing Killa	Chirang
4	Lat26.418753 Long 90.27263	Boro Bhatarmari	Kokrajhar
5	Lat26.411373 Long 90.277413	Tengapara	Kokrajhar
6	Lat26.425443 Long 90.275906	Mainao Puri	Kokrajhar
7	Lat26.434862 Long90.234361	Chandrapara	Kokrajhar
8	Lat26.435145 Long 90.276607	Dimalgaon	Kokrajhar
9	Lat26.397502 Long 90.305763	Adabari	Kokrajhar
10	Lat26.442864 Long 90.28654	Titaguri	Kokrajhar
11	Lat26.442806 Long 90.286616	Titaguri	Kokrajhar
12	Lat26.441924 Long 90.280903	Titaguri	Kokrajhar
13	Lat26.45068 Long 90.293282	Shyamgaon	Kokrajhar
14	Lat26.4378 Long 90.248656	Chandrapara	Kokrajhar
15	Lat26.663011 Long 91.34306	Mushalpur	Baksa

Standardized method of extraction and dying

A standardized laboratory method was developed for dye extraction. Plant materials were prepared either by grinding or cutting, depending on the plant parts used. For some pigments, commercially available powdered materials were used. The volume of water was adjusted between 200 and 500 mL, depending on the plant material. The mixture of water and plant material was boiled until the desired color intensity was achieved. The dye solution was then cooled and filtered to remove any residues. Small pieces of cotton fabric **(**9-12 cm × 8-10 cm**)** were immersed in the extracted dye for 15 minutes to 2 hours, depending on the pigment's ability to adhere to the fabric. For dyes with weak pigment-binding capacity, the fabric was soaked overnight.

Heat stability test

To evaluate the thermal stability of the extracted pigments, a four-step heat resistance test was conducted. In the first step, the dyed fabric samples were immersed in cold water for 3 hours. If no visible color change was observed, the samples were subjected to a second test involving incubation at 30°C for 1 hour. Samples that remained stable were then exposed to water heated to 70°C for 2 hours. Finally, the samples were immersed in boiling water at 100°C for 1 minute to assess the maximum heat tolerance of the dye. The test was done in triplicate.

Evaluation framework for dye plant potential (Andriamanantena *et al*. 2023)

Preparation of Criteria

To identify the most promising natural dye plants, an evaluation system was developed based on eight specific criteria. This approach was based on the study by Andriamanantena *et al*. (2023) but was modified to suit the objectives of the present study. The first six criteria (C1-C6) were derived from local ethnobotanical knowledge, field observations, and existing literature. The final two criteria (C7 and C8) were formulated based on laboratory experiments, focusing on the extractability and thermal stability of plant pigments. Each criterion was scored on a scale from 1 to 10. Lower scores (closer to 1) indicated that the plant required further attention due to rarity, limited data, or poor dye quality, while higher scores (closer to 10) signified greater abundance, better dye potential, and suitability for industrial use. This scoring system was specifically designed for this study.

Criterion 1(C1): Endemic status

This criterion assessed the geographical distribution of the plant. The information on native and non-native plant species was collected from the online Plants of the World Online (POWO 2021) website of the Royal Botanic Garden, Kew. Species found exclusively in Assam received a score of 1, indicating priority for conservation. Plants native to India but also found outside Assam were given a score of 3, suggesting regional importance. Species with unknown origin were scored 7. Non-native or introduced species received the highest score of 10 as they are considered of least concern for conservation priorities.

Criterion 2 (C2): Scientific knowledge

This evaluated the existing scientific knowledge. Species with minimal or no research were assigned a score of 1, showing a need for further research. Those with limited documentation received a 3. Plants with basic biological information, but lacking pigment data, scored 7. Fully documented species with detailed chemical and botanical data were given a score of 10.

Criterion 3 (C3): Accessibility and availability

This criterion assessed the accessibility and availability of the plant species. Therefore, the conservation status was collected from the IUCN Red List data (IUCN, 2021). Species that are critically endangered, rare, or legally protected were given a score of 1 due to restricted access. Those requiring permits or found only in protected forests received a 3. Plants that are naturally abundant and easy to locate in the wild scored 7. Cultivated and widely available species were scored at 10.

Criterion 4 (C4): Cultivability

This criterion considered how feasible it is to grow the plant in Assam. Plants that are nearly impossible to cultivate because of challenging growth conditions or specific ecological requirements are scored 1. Species that could be cultivated but require specialized care or grow very slowly are assigned a 3. Plants that are known to grow under controlled conditions or locally with some efforts are rated a 7. Those that are already successfully grown and managed in Assam are given a top score of 10.

Criterion 5 (C5) Sustainability of harvest

This evaluated the environmental impact of harvesting the part of the plant used for dye extraction. Using the entire plant or trunk, which caused the most environmental damage, received a score of 1. Harvesting adventitious roots, which can still affect plant survival, scored 3. Use of renewable parts like bark, fruit, or flowers earned a score of 7. Plants, whose leaves are used, considered the least harmful to the plant survival and environmentally sustainable, received the highest score of 10.

Criterion 6 (C6) Industrial interest and known uses
This assessed the plant's usefulness beyond dye production. Species with no known additional uses were given a score of 1. Plants with one or two minor uses (e.g., in folk medicine or handicrafts) scored 3. Species with three or four uses, such as food, cosmetics, or fuel, received a 7. Plants with five or more significant uses, including food, medicine, or construction, were scored at 10, indicating high economic and cultural value.

Criterion 7 (C7) Color rarity and visual appeal
This criterion evaluated the visual appeal and uniqueness of the pigment. Plants that produced no visible color were scored 1. Common and less vibrant shades, such as cream, light brown, or reddish-brown, scored 3. Brighter but commonly found colors like yellow and orange were rated 7. Rare and visually striking colors (pink, violet, blue, mauve, and purple) received a score of 10 due to their desirability and market potential.

Criterion 8 (C8) Heat stability of the extracted pigment
This assessed the stability of pigments in water at varying temperatures. Plants whose pigments degraded even at room temperature were scored 1, indicating a need for stabilization research. Species with moderate stability at room temperature but fading at 30°C were given a score of 3. Those stable up to 70°C were rated 7. Species with pigments that remained vibrant even at 100°C received the highest score of 10, reflecting excellent thermal and water stability.

Calculation of Dye Score (Andriamanantena et al., 2023)
Four indexes were calculated based on the eight criteria:
(1) Endemicity Index (Iend.): (C1) x (C2)
(2) Cultivability Index (Icult.): (C3) x (C4)
(3) Industrial Extrapolation Index (Iind.) (C5) x (C6)
(4) Coloring Strength Index (Icol.) (C7) x (C8)
Each index was classified according to the dye score ranking system developed in this study. Because of the importance of hue, pigment yield, and extraction difficulty in industrial use, the "Coloring Strength Index" was weighted twice as much as the other indexes in determining the final dye score.
The dye score was calculated using the formula:

$$\text{Dye score} = (\text{Iend.} + \text{Icult.} + \text{Iind.}) + (\text{Icol.} \times 2)/5$$

Use of mordant and analysis of the effects of mordant in color binding
A mordant is a substance that helps dye to adhere to fabrics by forming a bond between the dye and fiber. In this study we have used natural mordant *Terminalia chebula Retz.*, a plant rich in tannin to see color binding effects of different dyes extracted from plants. *T. chebula consist of* high tannin content that makes it particularly effective for binding natural polyphenols to fibers (Sarma *et al*., 2025). A natural mordant was prepared from *T. chebula* by boiling 1 part of dried fruit in 10 parts of water for 2-3 hours. Yarn was soaked overnight in the cooled solution and air-dried before dying. To evaluate the effect of mordanting, five dye-yielding plants were tested with and without the mordant. Visual assessments of color intensity, uniformity, and fastness were conducted and the result was recorded.

Statistical analysis: The calculation of dye score and statistical analysis was done in excel
Ethnobotanical data were organized using Microsoft Excel spreadsheets. The results of heat stability tests, and all the 8 criterions were organized, and descriptive statistical analysis was used using Microsoft excel.

Results

Plant Diversity and Ethnobotanical Relevance of dye yielding plants
The survey yielded a total of 42 plant species belonging to a total of 31 plant families, with Malvaceae and Fabaceae being the most represented families (Table 2). Several species occurred in both wild and cultivated area. Many of the recorded species are traditionally used as food, medicinal plants, as timber, cosmetic purposes, ritualistic and other cultural significance indicating a close relationship between ethnobotanical knowledge and dye practices. The multifaceted use of these plant species emphasizes the depth of indigenous ethnobotanical knowledge and strengthens the role of local flora in sustainable natural resource management. The plant parts used for dyeing are leaves, flowers, roots, bark, and fruit. Fruits are the most commonly used part (21.95%), followed closely by flowers (17.07%) and leaves (15%) (Fig 2). For 12.19% of the dye-yielding plants, all parts of the plants are used for dye extraction (Fig 2). Woody parts and roots are moderately used are less used parts include rachia, skin, tubers, and dry scales**.** The frequent use of reproductive parts (fruit, flower) suggests

strong pigment presence in these organs. The diverse color spectrum extracted from them demonstrates the phytochemical potential of the local flora as a foundation for natural dye production.

Conservation status of dye-yielding plants

The conservation status of the surveyed species, as per IUCN Red List categories, revealed a mixed profile. Most species were classified as Least Concern (LC)**,** indicating no immediate threat. However, *Tectona grandis* L.f. was classified as "Endangered (EN)" highlighting the urgency of implementing conservation actions in response to habitat loss and overharvesting. *Aegle marmelos* (L.) Correa, were categorized as "Near Threatened (NT)" indicating a potential risk of population decline if unmanaged. Species like *Curcuma longa* L. and *Camellia sinensis* (L.) Kuntze were listed as "Data Deficient (DD)" underscoring the need for further ecological studies to accurately determine their conservation status. Notably, *Rosa chinensis* is a hybrid species, and thus its precise family classification is not scientifically established.

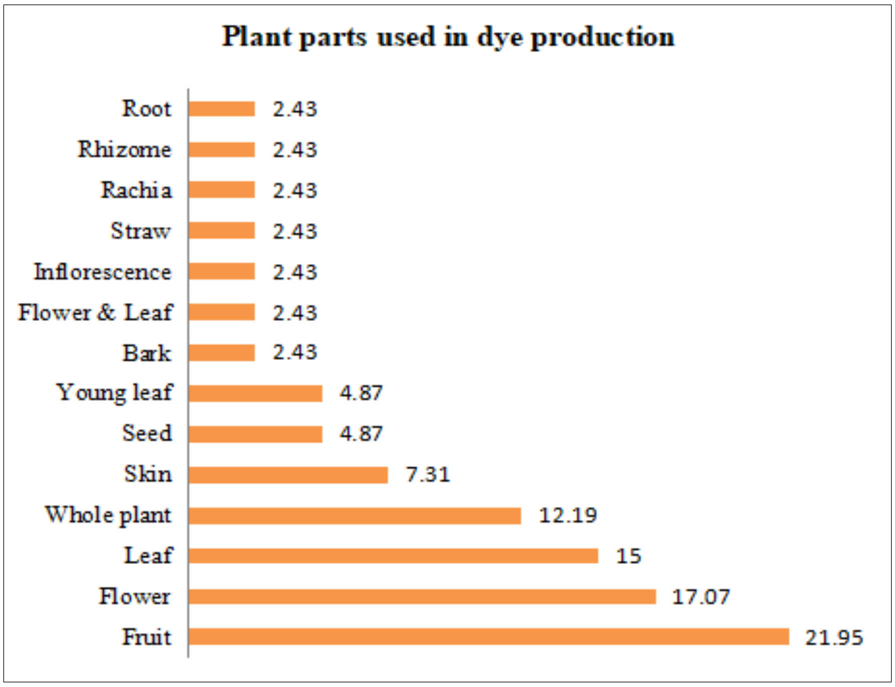

Figure 2. Plant parts used in production of natural dyes

The analysis also revealed that 21 out of 42 species (50%) are native to Assam, India, or the broader Southeast Asian region. This 50% native-to-introduced ratio demonstrates a balanced reliance on both indigenous and culturally adopted plant species in traditional dyeing practices. *Diplazium esculentum* (Retz.) Sw. and *Syzygium cumini* (L.) Skeels are examples of native species of Assam and neighboring regions of Southeast Asia, and *Allium cepa* L. and *Tagetes erecta* L. are two examples of non-native plants but are widely cultivated and culturally significant in India. These findings reinforce the importance of prioritizing conservation for endangered and data-deficient species while recognizing the value of cultivated and non-native plants in dye production and other applications.

Color yield and Heat Stability test

The study yielded 21 unique colors. Out of these 21 colors yellow is most common (18.75 %), followed by cream (15.63%), and red (14. 58%). Other notable shades include Brown (7.29%)**,** Green (6.25%)**,** Pink (6.25%)**,** and Grey (5.21%**)**, which highlights the diversity of secondary colors available. Lighter variants such as Light yellow (4.17%), Light pink (3.13%)**,** and Light green (3.13%) also contribute to the range, suggesting modifications of primary hues through plant part variations or preparation methods (Fig 3). Less frequent but still important shades include Black, Orange, Light brown, Purple, Lilac/Lavender, Mauve, Burgundy, and Deep orange, each below 2-3%. These rare shades demonstrate the breadth of natural dye potential, though they appear more sporadically compared to the dominant hues (Fig 3). The brown and beige colors are very catching similar to the muga (Assam silk) color. Out of the total plant species 63.64% of them are heat stable in all the steps of heat stability step, and 6.6% are not stable in first step of the test**.** 20.4% of the dye-yielding plant samples showed temperature-specific instability during the heat stability test. Heat stability tests revealed that some plant species like *Bixa orellana L.*, *Aegle marmelos* (L.) *Correa*, and *Allium cepa L.* retained their original hues under heat exposure. In contrast, pigments from *Erythrina variegata L.* and *Clitoria ternatea L.* faded noticeably, indicating lower thermal stability (Table 3).

Yellow and brown/beige dyes generally demonstrated better heat stability, retaining their color strength even under high temperatures. Among them, yellow dye is especially valued for its consistency and strong visual appeal. Due to its brightness, cultural significance, and reliability in various dyeing conditions, yellow has become the most commonly used and preferred color in the local area. Its popularity is further supported by its ability to withstand environmental fluctuations better than many other hues.

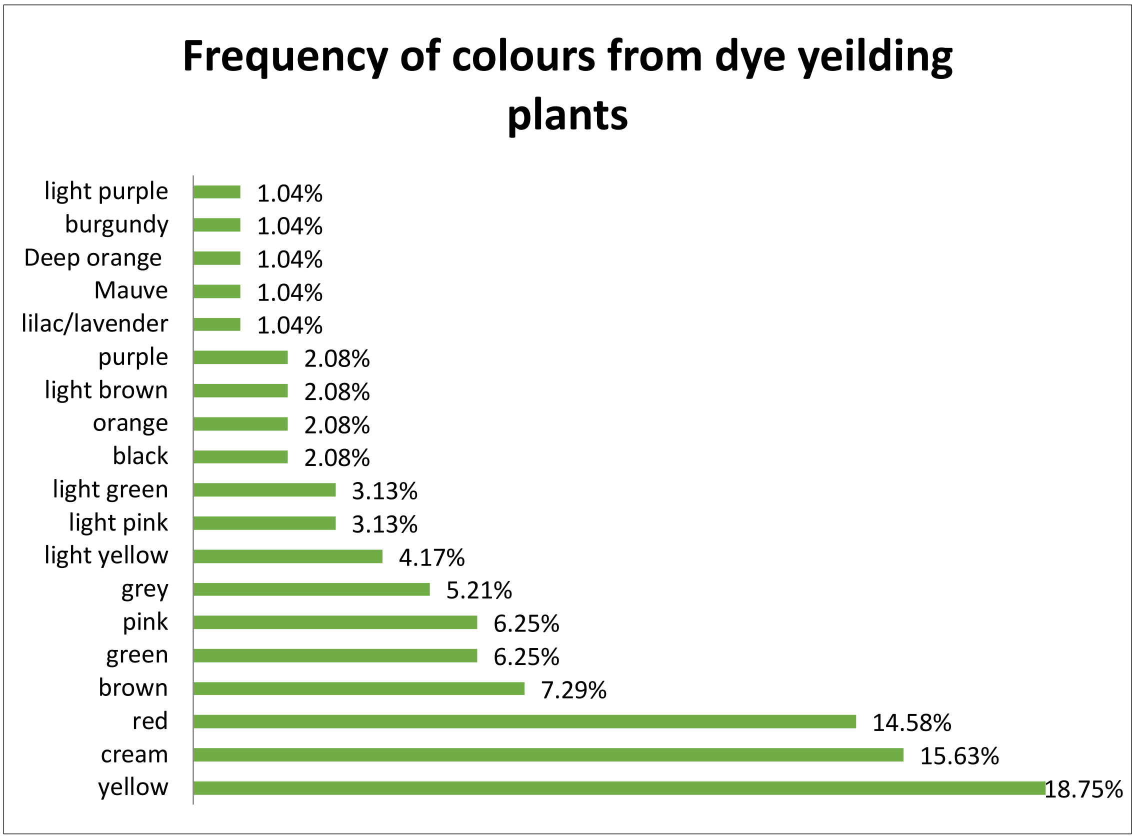

Figure 3. Frequency of colors from dye yielding plants

Dye score of the dye yielding plants

The dye scores ranged from 24 to 84, indicating varying levels of dye performance (Table 3). Among these, *Hibiscus x rosa-sinensis* L. and *Hibiscus sabdariffa* L. achieved the highest dye score of 84, and 78, respectively, showcasing impressive dye yield and excellent stability in both water and heat tests, making it highly promising for textile dyeing. Likewise, *Tagetes erecta* L. (score: 66) and *Musa balbisiana* Colla (score: 62) demonstrated robust dyeing capabilities under different conditions.

Conversely, plants like *Diplazium esculentum* (Retz.) Sw. and *Lagerstroemia speciosa* (L.) Martyn, scored the lowest dye-score. Further examination of solubility and heat stability indicated that species such as *Citrus reticulata* Blanco and *Curcuma longa* L. offered not just rich chemical compositions but also practical reliability due to their stable dye extracts. In contrast, the pigments derived from *Lawsonia inermis* L. and *Erythrina variegata* L. were more heat-sensitive, restricting their use in processes requiring high-temperature dyeing. Species such as *Hibiscus x rosa-sinensis* L. and *Curcuma longa* L. stand out as strong contenders for environmentally friendly textile dyeing, whereas those with lower scores may require further research or alternative applications. An earlier study by Andriamanantena et al. (2023) reported the highest score of 60 for *Thespesia populnea*, whereas in the present study, *Hibiscus rosa-sinensis* achieved the highest score of 84, further underlining its promise in natural dye applications. Dyes from several plant species also faded or dulled over time, with an effective shelf life observed to be around 2 to 4 months in some cases.

Effects of mordant

A selection of five plant species with different color-producing properties was used to test the impact of natural mordants on plant-based pigments. The colors from the plants looked different before and after using the mordant. Without the mordant, the colors were softer and lighter, giving a gentle and smooth look to the fabric. When the mordant was added, the colors became stronger, deeper, and clearer. *Bixa orellana* L., gave a bright orange color that became a bit darker and brownish but still mostly orange with the mordant. *Aegle marmelos* (L.) Correa showed a light cream color that turned richer and deeper with the mordant. The burgundy color from *Allium cepa* L. changed to a warm brown when mordant was used. Meanwhile, *Erythrina variegata* L. had a light pink color that shifted to light brown with the mordant. Lastly, *Clitoria ternatea* L.'s light blue color deepened to a rich, vibrant blue after adding the mordant. These variations offer options for both subtle and bold color preferences in natural dyeing. The mordant's color was stable across all samples. This suggests *Terminalia chebula* Retz mordant can be used effectively in certain natural dyeing applications.

PHOTO PLATE -I

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Brassarda juncea (L.) Su Liu & Z.H.Feng

Ocimum tenuiflorum L.

Ziziphus jujuba Mill.

Kalanchoe pinnata (Lam.) Pers.

Dillenia indica L.

Phyllanthus emblica L.

Mikania micrantha Kunth

Ricinus communis L.

Azadirachta indica A. Juss

Cynodon dactylon (L.) Pers.

Diplazium esculentum (Retz.) Sw.

Citrus reticulata Blanco

Averrhoa carambola L.

Impatiens balsamina L. (flower)

Impatiens balsamina L. (leaf)

Artocarpus heterophyllus Lam. (wood)

Artocarpus heterophyllus Lam. (rachia)

Oryza sativa L.

Aegle marmelos (L.) Correa

Spondias dulcis Parkinson

Corchorus olitorius L.

Cuscuta reflexa Roxb.

Phlogacanthus thyrsiformis (Nees) Nees

Tagetes erecta L. (orange flower)

Tagetes erecta L. (yellow flower)

Curcuma longa L.

Areca catechu L. (seed)

Areca catechu L. (skin)


Coconus nucifera L.


Lawsonia inermis L.


Camellia sinensis (L.) Kuntze


Terminalia chebula Retz.


Terminalia arjuna (Roxb. ex DC.) Wight & Arn.


Senegalia catechu (L.f.) P.J.H.Hurter & Mabb.


Colocasia esculenta (L.) Schott


Erythrina variegata L.


Musa balbisiana Colla


Hibiscus x *rosa-sinensis* L.

Tectona grandis L.f.

Hibiscus sabdariffa L.

Allium cepa L.

Clitoria ternatea L.

Rosa rubiginosa (purple)

Rosa rubiginosa (pink)

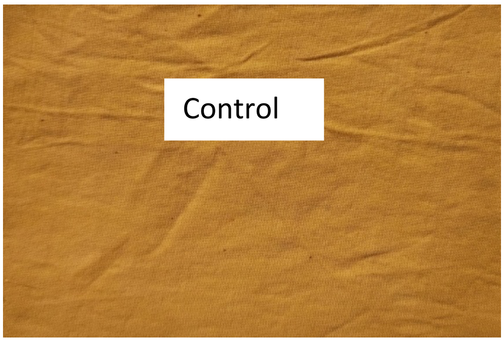
Bixa orellana L.

Lagerstroemia speciosa (L.) Martyn

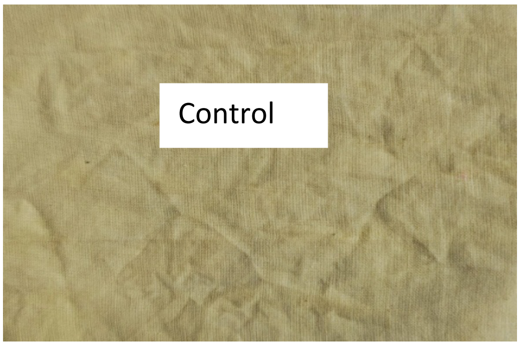
Figure 4. Photo plates showing the colours produced by different colour yielding plants

PHOTO-PLATE-II

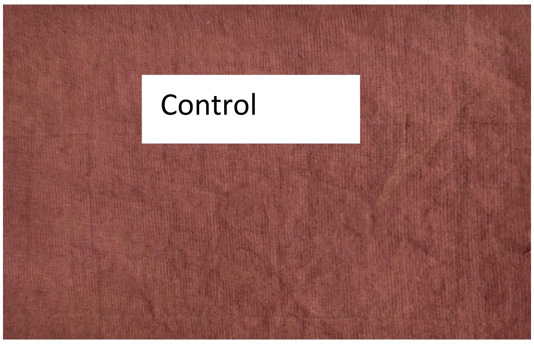
1. *Bixa orellana* L.

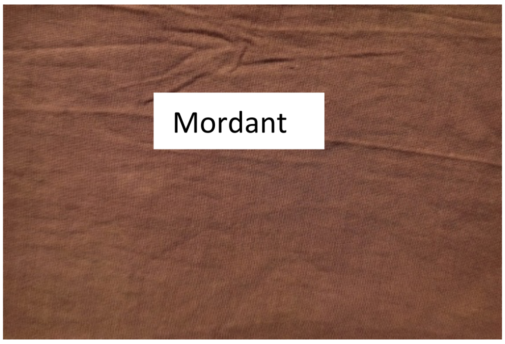


2. *Aegle marmelos* (L.) Correa

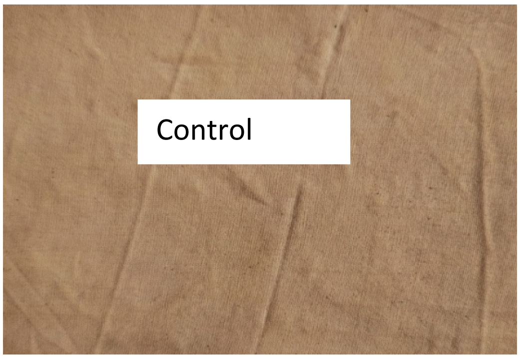


3. *Allium cepa* L.





4. *Erythrina variegata* L.



5. *Clitoria ternatea* L.

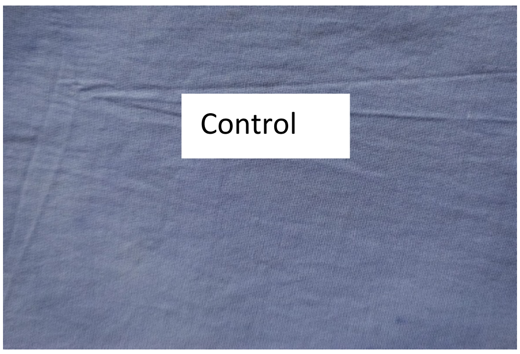


Figure 5. Photo plates showing the comparison of effects of Mordant

Table 2. Field Survey Data of plant species used as dyes in BTR region of Assam, India

SCIENTIFIC NAME	FAMILY	LOCAL NAME	PART USED	NATURAL HABITAT	APPLICATIONS	IUCN RED LIST	NATIVE
Artocarpus heterophyllus Lam. V.No.BUBH101	Moraceae	Khantal	Wood, Rachia	Wild and cultivated	Food, Medicine and wood for construction	Not evaluated	Andaman Is., Assam, Bangladesh, Bismarck
Brassica juncea (L.) Su Liu & Z.H.Feng V.No.BUBH102	Brassicaceae	Besor	All parts	Cultivated	Fabric, Food	Not evaluated	North Caucasus, Transcaucasus
Diplazium esculentum (Retz.) Sw. V.No. BUBH103	Aspleniaceae	Dingkia	All parts	Wild	Fabric, Food	Least Concern (LC)	Assam, Bangladesh, East Himalaya, Andaman Island
Lagerstroemia speciosa (L.) Pres. V.No.BUBH104	Lythraceae	Aowjar	Flower	Wild	Fabric	Least Concern (LC)	Assam, Bangladesh, East Himalaya, Myanmar
Dillenia indica L . V.No.BUBH105	Dilleniaceae	Taigir	Fruit	Cultivated and wild	Fabric, Food	Least Concern (LC)	Assam, Bangladesh, Cambodia, India
Allium cepa L. V.No.BUBH106	Amaryllidaceae	Sambram gwja	Skin	Cultivated	Fabric, Food, Medicine	Not evaluated	Turkmenistan
Kalanchoe pinnata (Lam.) Pers. V.No.BUBH107	Crassulaceae	Pat gaza	Leaf	Cultivated	Fabric, Medicine	Not evaluated	Cook Is., Madagascar
Colocasia esculenta (L.) Schott V.No.BUBH108	Araceae	Taso gwswm	Stem	Wild and cultivated	Fabric, Food, Medicine	Least Concern (LC)	Assam, Bangladesh, Malaya, Nepal
Citrus reticulata Blanco V.No.BUBH109	Rutaceae	Nareng komla	Fruit	Cultivated	Fabric, Food, Traditions	Not evaluated	China & Southeast Asia
Areca catechu L. V.No.BUBH110	Arecaceae	Goi	Young Fruit	Cultivated	Fabric, Food, Traditions	Least Concern (LC)	Philippines
Curcuma longa L. V.No.BUBH111	Zingiberaceae	Haldwi	Tuber, Leaf	Cultivated	Fabric, Food, Medicine, Cosmetic, Traditions	Data Deficient (DD)	India

Ricinus communis L. V.No.BUBH112	Euphorbiaceae	Indi	Leaf	Wild	Fabric, Cosmetic, Medicine	Least Concern (LC)	Eritrea, Ethiopia, Somalia
Lawsonia inermis L. V.No.BUBH113	Lythraceae	Mehendi	Leaf	Cultivated	Fabric, Cosmetic, Medicine	Least Concern (LC)	India, Kenya, Oman, Djibouti
Tectona grandis L.f. V.No.BUBH114	Lamiaceae	Sigun	Young leaf	Cultivated and wild	Fabric, Medicine, Furniture	Endangered (EN)	Assam, Bangladesh, Cambodia, India
Camellia sinensis (L.) Kuntze V.No.BUBH115	Theaceae	Sa pat	Leaf	Cultivated and wild	Fabric, Food, Cosmetic, Medicine	Data Deficient (DD)	Assam, China South-Central, China Southeast, Laos
Hibiscus x *rosa-sinensis* L. V.No.BUBH116	Malvaceae	Joba	Flower	Cultivated	Fabric, Food, Cosmetic, Traditions	Not evaluated	N/A
Terminalia chebula Retz. V.No.BUBH117	Combretaceae	Selekha	Fruit	Cultivated and wild	Fabric, Food, Medicine	Least Concern (LC)	Assam, Bangladesh, Cambodia, India
Phyllanthus emblica L. V.No.BUBH118	Phyllanthaceae	Amlai	Fruit	Cultivated and wild	Fabric, Food, Medicine	Least Concern (LC)	N/A
Aegle marmelos (L.) Corrêa V.No.BUBH119	Rutaceae	Behel	Fruit	Cultivated and wild	Fabric, Food, Traditions	Near Threatened (NT)	Assam, Bangladesh, India, Nepal
Tagetes erecta L. V.No.BUBH120	Asteraceae	Genda	Flower, Leaf	Cultivated	Fabric, Cosmetic, Medicine, Traditions	Not evaluated	Guatemala, Mexico Central, Mexico Gulf, Mexico Northeast
Ocimum tenuiflorum L. V.No.BUBH121	Lamiaceae	Tulsi	Leaf	Cultivated	Fabric, Medicine, Cosmetic, Traditions	Not evaluated	Andaman Is., Assam, Bangladesh, Bismarck
Musa balbisiana Colla V.No.BUBH122	Musaceae	Talir	Young leaf	Cultivated and wild	Fabric, Food, Traditions	Least Concern (LC)	Andaman Is., Assam, Bismarck Archipelago, India
Averrhoa carambola L. V.No.BUBH123	Oxalidaceae	Kamrenga	Fruit	Cultivated	Fabric, Food, Medicine	Data Deficient (DD)	Jawa, Maluku, Sulawesi

Senegalia catechu (L.f.) P.J.H.Hurter & Mabb. V.No.BUBH124	Fabaceae	Khwirw, Khoiar	Root	Wild	Fabric	Least Concern (LC)	Assam, Bangladesh, China South-Central, East Himalaya
Oryza sativa L. V.No.BUBH125	Poaceae	Zigab	Paddy straw	Cultivated	Fabric, Food, Traditions	N/A	China North-Central, China South-Central, China Southeast
Syzygium cumini (L.) Skeels V.No.BUBH126	Myrtaceae	Gwswm jam	Fruit	Wild and cultivated	Fabric, Food, Medicine	Least Concern (LC)	Andaman Is., Assam, Bangladesh, Cambodia
Hibiscus sabdariffa L. V.No.BUBH127	Malvaceae	Mwita	Fruit	Cultivated	Fabric, Food	Not evaluated	Central African Republic, Chad, Congo, Gabon
Clitoria ternatea L. V.No.BUBH128	Fabaceae	Akrazita	Flower, Leaf	Wild and cultivated	Fabric, Medicine, Food, Traditions	Not evaluated	Angola, Benin, Burkina, Burundi
Erythrina variegata L. V.No.BUBH129	Fabaceae	Mandar	Flower	Cultivated and wild	Fabric, Food, Medicine	Least Concern (LC)	Aldabra, Andaman Is., Assam, Bangladesh
Corchorus olitorius L. V.No.BUBH130	Malvaceae	Patw	Leaf	Cultivated	Fabric, Food	Not evaluated	Afghanistan, Andaman Is., Angola, Assam
Bixa orellana L. V.No.BUBH131	Bixaceae	Sindoor	Fruit	Cultivated	Fabric, Medicine, Cosmetic	Least Concern (LC)	Argentina Northeast, Argentina Northwest, Belize, Bolivia
Azadirachta indica A.Juss. V.No.BUBH132	Meliaceae	Neem	Leaf	Cultivated and wild	Fabric, Cosmetic, Medicine	Least Concern (LC)	Assam, Bangladesh, Cambodia, Laos
Spondias dulcis Parkinson V.No.BUBH133	Anacardiaceae	Taisuri	Fruit	Wild and cultivated	Fabric, Food, Medicine	Least Concern (LC)	Bismarck Archipelago, Maluku, New Guinea, Santa Cruz Is.
Cocos nucifera L. V.No.BUBH134	Arecaceae	Narengkol	Dry scale	Cultivated	Fabric, Food, Cosmetic, Traditions	Not evaluated	Bismarck Archipelago, Maluku, New Guinea, Philippines

Terminalia arjuna (Roxb. ex DC.) Wight & Arn. V.No.BUBH135	Combretaceae	Arjun	Wood	Wild and cultivated	Fabric, Food, Medicine	Least Concern (LC)	Assam, Bangladesh, India, Myanmar
Ziziphus jujuba Mill. V.No.BUBH136	Rhamnaceae	Bwigri	Dry fruit	Wild and cultivated	Fabric, Food, Traditions	Least Concern (LC)	China North-Central, China Southeast, Inner Mongolia, Korea
Phlogacanthus thyrsiformis(Nees) Nees V.No.BUBH137	Acanthaceae	Barsika	Flower	Wild	Fabric, Food, Medicine	Not evaluated	Assam, Bangladesh, China South-Central, East Himalaya
Impatiens balsamina L. V.No.BUBH138	Balsaminaceae	Zentoka	Leaf, Flower	Cultivated and wild	Fabric, Cosmetic	Not evaluated	India, Sri Lanka
Rosa rubiginosa L. V.No.BUBH102	Rosaceae	Golab	Flower	Cultivated	Cosmetic, Medicine, Fabric, Traditions	Not evaluated	N/A
Cynodon dactylon (L.) Pers. V.No.BUBH139	Poaceae	Dubri	All parts	Wild	Cosmetic, Medicine, Fabric, Traditions	Not evaluated	Afghanistan, Andaman Is., Angola, Assam
Mikania micrantha Kunth V.No.BUBH140	Asteraceae	Bangri leua	All parts	Wild	Cosmetic, Medicine, Fabric	Not evaluated	Argentina Northeast, Argentina Northwest, Belize, Bolivia
Cuscuta reflexa Roxb. V.No.BUBH141	Convolvulaceae	Leua bendwng	All parts	Wild	Cosmetic, Fabric	Least Concern (LC)	Afghanistan, Assam, Bangladesh, China South-Central

Table 2. Heat stability and Dye score of dye yielding plants

Scientific name	Part used	Material used weight in g/200-500 ml of water	Water Solubility	Color produced	Heat Stability	Dye score (1-100)
Artocarpus heterophyllus Lam.	Wood,	72.8	No	Yellow-Green, Cream	stable	53
	Rachia	56.3	No	Yellow, Cream	not stable	25
Brassarda juncea (L.) Su Liu & Z.H.Feng	Inflorescence	34.5	No	Red, Green, Cream	not stable	39
Diplazium esculentum (Retz.) Sw.	Whole plant	52.7	No	Purple, Pink	stable	24
Dillenia indica L.	Fruit	22.8	Yes	Red, Yellow, Cream	stable	34
Allium cepa L.	Skin	14.6	Yes	Burgundy, Light pink, Light yellow	stable	46
Kalanchoe pinnata (Lam.) Pers.	Leaf	35.3	Yes	Light green, Cream	stable	38
Colocasia esculenta (L.) Schott	Stem	39.2	No	Brown, Grey, Light pink	stable	37
Citrus reticulata Blanco	Fruit	4.7	Yes	Yellow	stable	60
*Areca catechu*L.	Seed	7.9	No	Red, Pink, Brown	stable	42
	Skin	3.6	No	Yellow-Green, Yellow	Not stable	31
Curcuma longa L.	Rhizome	43.2	Yes	Yellow	stable	58
Ricinus communis L.	Leaf	70.2	No	Red-Yellow, Yellow, Brown	stable	42
Lawsonia inermis L.	Leaf	5.7	Yes	Light yellow, Light brown, Red, Grey,Purple	not stable at 70	30
Tectona grandis L.f.	Young Leaf	42.4	No	Red, Brown	stable	60
Camellia sinensis (L.) Kuntze	Leaf	9.1	Yes	Red, Grey, Pink	stable	48
Hibiscus x rosa-sinensis L.	Flower	44.6	Yes	Red, Grey, Brown	stable	84
Terminalia chebula Retz.	Fruit	37.9	Yes	Light yellow, Grey, Cream	stable	30
Phyllanthus emblica L.	Fruit	57.8	Yes	Yellow, Red, Cream	not stable	29
Aegle marmelos (L.) Correa	Fruit	56	Yes	Red-Yellow, Yellow, Orange	not stable at 100	48
Tagetes erecta L.	Flower	59.2	Yes	Light green, Cream	not stable at 100	66
Ocimum tenuiflorum L.	Leaf	8.3	No	Yellow, Light pink	not stable	39
Musa balbisiana Colla	Young Leaf	25	No	Red, Light yellow, Cream	stable	62
Averrhoa carambola L.	Fruit	135.6	Yes	Deep orange, Brown	stable	36

Senegalia catechu (L.f.) P.J.H.Hurter & Mabb.	Root	39.2	No	Yellow	stable	28
Oryza sativa L.	Paddy Straw	24.1	No	Light purple	stable	44
Hibiscus sabdariffa L.	Fruit	179.7	Yes	Light red, Pink	stable	78
Clitoria ternatea L.	Flower	27.7	Yes	Blue	not stable at 30	60
Erythrina variegata L.	Flower	44.9	Yes	Mauve	not stable at 30	26
Corchorus olitorius L.	Dry Leaf	24.7	No	Green, Cream	stable	60
Bixa orellana L.	Seed	68.2	No	Black, Orange	stable	62
Azadirachta indica	Leaf	12.8	No	Light green, Cream	stable	42
Spondias dulcis Parkinson	Fruit	220.6	Yes	Black, Cream	stable	48
Coconus nucifera L.	Skin	19.7	No	Brown	stable	52
Terminalia arjuna (Roxb. ex DC.) Wight & Arn.	Bark	76.8	No	Light brown	stable	27
Ziziphus jujuba Mill.	Fruit	34.7	Yes	Red, Cream	not stable	34
Phlogacanthus curviflorus (Nees) Nees	Flower	46.3	Yes	Yellow	not stable at 70	30
Impatiens balsamina L.	Flower, Leaf	33.7 , 19.3	Yes, Yes	Yellow, Cream	stable, stable	58, 42
Rosa rubiginosa (Red/Pink)	Flower	93.8	Yes	Red/Pink	not stable at 30	33, 33
		122.3	Yes	Red/Pink	stable	
Cynodon dactylon (L.) Pers.	Whole plant	9.3	No	Green, Yellow	not stable	37
Mikania micrantha Kunth	Whole plant	25.3	No	Green, Cream	not stable	28
Cuscuta reflexa Roxb.	Whole plant	33.8	No	Yellow	stable	32
Lagerstroemia speciosa (L.) Martyn	Flower	22	Yes	Lilac or lavender	not stable	24

Discussion

The study finds that accurately following the dye ratio can be challenging, as different plant parts vary in density and weight. The processing of plant materials was also different for different species, and it is essential for to choose the right processing method to ensure optimal dye extraction. Certain species, such as *Colocasia esculenta* produces natural mucilage during boiling, which serves as the primary source of its dye. This mucilage can be lost or diminished if the plant is dried and ground, resulting in lower dye yield. In contrast, plants like *Tectona grandis* and *Terminalia arjuna* contain tannins and other compounds that contribute to their dyeing properties. Temperature sensitivity is another factor that influences dye outcomes. Some colors, like green and pink, can degrade or shift to yellowish tones when exposed to high heat. Although Kar & Borthakur (2008) referred to a pasting method for dye extraction from flowers and leaves, they did not provide sufficient procedural detail. Likewise, Sarma *et al*. (2025) and Yang *et al*. (2023) presented various extraction techniques and measurements, but there is still no clear standard for identifying the best approach. Local water quality and environmental conditions also contribute to final dye characteristics, particularly for more delicate colors. Heat-sensitive dyes often benefit from processing at lower temperatures, but this requires more research. For instance, *Lagerstroemia speciosa* (L.) Martyn produces a unique lavender shade, yet this hue was observed to fade quickly during heat stability tests, underscoring the challenge. Though synthetic mordants such as alum can help preserve these colors, natural dyers in Assam avoid them due to their artificial nature.

Siva (2007) described various synthetic mordants that can help improve color strength, and Andriamanantena et al. (2023) investigated the effects of different mordants on dyeing results. By contrast, Sharma *et al*. (2005) explored two natural mordants—one from alkaline sources and another from citrus fruits—that can enhance or alter dye shades. While *Terminalia chebula* was not included in their study, it has emerged in other regional research as a viable natural mordant (Shabir *et al*. 2016). In the current analysis, *Terminalia chebula* also demonstrated its value as an eco-friendly mordant, adding to its potential in sustainable dyeing practices seen in the present study. Broadening the use of such natural mordants could be especially beneficial in regions like the Bodoland Territorial Region (BTR), where achieving vivid and long-lasting colors remains a challenge. Investigating local, plant-based mordants further may offer new pathways to enhance the quality and durability of natural dyes in these communities.

Research from other regions also supports the growing interest in natural dyes (Chervenkov *et al*. 2024, Tamburini *et al*. 2024). Most of the dye-yielding plants in the region are non-toxic and have medicinal value, suggesting strong potential for safer applications. Although natural dyes show potential, dye stability remains a concern. For example, the color from *Hibiscus rosa-sinensis* changed from grey to pink over time, which is considered a special and desirable hue in the dye industry, while other colors faded and became lighter. This color transformation highlights both the opportunity and challenge in using such dyes.

Conclusion

This study underscores the dyeing potential of 42 plants that are traditionally used for making natural dyes. It focuses on eight main criteria, which were used to calculate a dye score. The study also looked at the conservation status of dye-yielding plants, water solubility of dyes, the color quality and stability change at different temperatures. The study also highlighted the use of eco-frendly mordent *Terminalia chebula* to increase the color stability of natural dyes. The high cost of natural dyes is often linked to their preparation complexity, sensitivity to environmental conditions, and limited color fastness. Advance research is essential to solve these issues, improve efficiency, and make natural dyes more affordable for broader use. Further, it was observed that the transmission of traditional knowledge dye yielding plants of Bodo is has eroded and declined among the general population. Therefore, this documentation has served as an effort to record the invaluable indigenous knowledge of the Bodo and other communities inhabiting the BTR region. Furthermore, the study divulged that 50% of the dye-yielding species are native, indicating that traditional dyeing practices have long been an integral part of the cultural heritage of BTR region. This 50% native-to-introduced ratio demonstrates a balanced reliance on both indigenous and culturally adopted plant species in traditional dyeing practices.

Declarations

List of abbreviations: BTR: Bodoland Territorial Region; POWO: Plants of the World Online

Ethics approval and consent to participate: The participants accepted and singed the free and Informed Consent Form.

Consent for publication: The participants accepted and singed the free and Informed Consent Form

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