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Ecofriendly Dyeing of Silk, Cotton, and Nylon Fabrics Using Red Prickly Pear Fruit Extract and Natural Mordants

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Abstract

Interest in natural dyes has increased as an ecofriendly alternative to synthetic colorants within the textile industry. This study investigates the potential of red prickly pear fruits (*Opuntia Lasiacantha Pfeiffer*) as a novel source of natural dye. The research covers the extraction and chemical characterization of the dye, followed by an evaluation of its application on various textile substrate, including silk, cotton, and nylon fabrics using plant based mordants, pomegranate rind, thuja fruit and moringa leaves to enhance dye fixation and performance. The colorant was obtained through an aqueous based extraction and characterized via UV-VIS spectroscopy and FTIR spectroscopy. Fixation was tested on silk, cotton and nylon using exclusively plant mordant. Spectroscopic analysis emphasis the presence of betacyanin derivatives as the principal chromophore components. The application of dye in conjunction with natural mordants yielded a range of light brown shades on silk, nylon and cotton substrates. Thus, the dyed fabrics exhibited satisfactory light and pressing fastness, indicating adequate superior colorfastness for practical use. this study highlights the significant potential of this entirely sustainable, bio based process, thereby offering a commercially viable environmentally benign solution to replace synthetic dying practices.

Keywords: Red Prickly Pear; Moringa; Colour Fastness; Dyeing; Thuja; Silk: Cotton.

INTRODUCTION

Natural dyes are organic compounds derived and obtained from natural sources that impart coloration to a variety of materials. They are primarily composed of natural compounds (secondary metabolites), such as anthraquinones, flavonoids, tannins, carotenoids, and indigoids, which are responsible for their broad spectrum of colours (Singh, 2025). Natural colorants are thought to be environmentally friendly because they are renewable, biodegradable, non-toxic, and non-allergenic, skin-friendly (Bydoon and Saad, 2023). As a result of global environmental awareness of the dangers caused by synthetic dyes, interest in using natural dyes has recently been renewed (Samanta and Agarwal, 2009). Red prickly pear (*Opuntia Lasacantha Pfeiffer*) is a Xerophytic belonging to the Cactaceae family and the genus Opuntia. This plant is endogens to diverse arid and semiarid regions, particularly across Africa, Australia and the Mediterranean Basin (Ali and El-Mohamedy

,2011). It produces oval-shaped flowers and spiny fruits displaying colours varying from yellow to deep red and purple (Puri, 2024).

The prickly pear fruit is considered a nutritionally complete food. Within the food industry, the juice of the red prickly pear has emerged as a valuable source of natural pigments serving as an eco-friendly alternative to synthetic dye (Ali and El-Mohamedy ,2011). increasing importance as a natural dye extracted from the fruit The fruit exhibits sustainable natural medicinal potinal, as it is rich in vitamins and minerals, constituents. Furthermore, it contains a wide range of bioactive phytochemicals, notably phenolic compounds and flavonoids which significantly contribute to its functional qualities and biological activity (Rodrigues *et al*., 2023). Betalains pigment, comparing yellow betaxanthins and red-violet betacyanins that define the color profile of its extracts (Sadowska-Bartosz and Bartosz 2021).

The main objective is to extract, characterize a natural dye from red prickly pear fruits and evaluate its application on silk, cotton and nylon textiles. This study explores whether red prickly pear fruit extract can be used as an effective and sustainable natural dye for silk, cotton, and nylon fabrics when used with plant-based mordants.

MATERIALS AND METHODS

Plant source: Red prickly pear fruits were collected from Aljelate City in Libya (Figure 1).

Textile substrate: Cotton, nylon, silk fabrics were purchased from local shops in Tripoli and Zawia cities, Libya and fabric samples were cut into 6 × 4 cm.

Natural mordants: *Punicagranatum* (Pomegranate rind), *Moringa oleifera* leaves and *Thuja* fruits were collected and dried in shade.

Figure (1): Red prickly pear fruits

Extraction of dye:

Fresh fruits of red prickly pear were chopped into small pieces and extracted in distilled water (liquor ratio of 60 grams per 500 milliliters) by boiling for one hour to release the pigment. The result extract showed a purple red color and was filtered for immediate use.

Mordanting:

Fabrics samples were treated with different mordants before dyeing. The mordant (3g/500ml) was dissolved in water and boiled for 30 min.

Dyeing:

The mordant fabric samples were dyed with dye extract for 60 min. However, for direct fabric dyeing. Dyeing was done by the conventional dyeing method. After dyeing, the dyed samples were washed with cold water and dried at room temperature (Alsaeh *et al*., 2023).

Color Fastness Tests:
Color fastness tests were conducted on dyed textile samples for sunlight, dry pressure, and wet pressure.

Color Fastness to Light Test
Dyed fabric samples were exposed to sunlight for 24 hours. The colour fastness was assessed by comparing the color change of the exposed portion to the unexposed reference fabric (Paramasivam *et al*., 2022).

Color Fastness to Pressing Test
A dyed fabric sample (5cm x 4cm) was places on a dried white fabric of the same size and pressed with a hot iron for 20 seconds.

Color Fastness under Wet pressing:
The dyed fabric (5 cm × 4 cm) placed between a dried white fabric and a wet white cloth of the equal size, then pressed for 20 seconds. Color change and staining were evaluated using the gray scale (Musa *et al*., 2013).

Spectra Tests:
The absorption spectra of the dye solution were measured using a Photo Lab 7600 UV-VIS spectrometer and an Agilent Gary 630 FTIR spectrometer.

RESULTS AND DISCUSSION

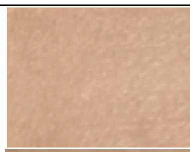
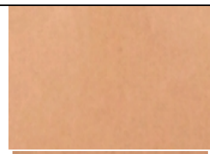
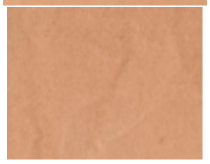
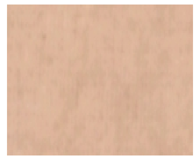
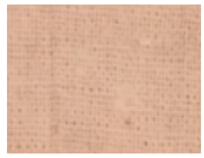
The Colour Shades Obtained:
Pigments extracted from red prickly pear fruits using the traditional method produced bright and soft colour shades, confirming the presence of betalain in the natural dye.

The color intensity depends on the type of mordant used. Mordant, acting as chemical agents that promote bonding between the dye and the fabric, generated different color tons (Patil *et al*., 2016 and Shweta, 2018). Fabrics dyed without mordant exhibited slightly lower color intensity compared to those treated with mordants (Singh *et al*., 2020). Thuja fruits, pomegranate peels, and moringa leaves have been used as mordants.

In this study, aqueous extract produced brown shades on fabric samples without mordant, while natural mordants (pomegranate peels, thuja fruits, and moringa leaves) yielded earthly shades ranged from pale to dark, (Table 1). Silk and nylon showed the brightest color, with higher saturation observed in silk. The variation is attributed to betalains compounds, mainly betacyanin, and phenolic compounds in their plant patterns.

According to Table (1): Deep colour shades were obtained on silk samples with and without all mordants, while lighter colour shades were observed on nylon and cotton samples. This is because silk, a protein fiber possesses high absorbency due to its acidic nature. Conversely, cotton is a cellulosic material with very weak absorbency compared to silk, being basic in nature with fibrous materials closely attached (Das *et al*., 2016).

Table (1): Colour results of fabrics dyed without/with mordant of plant fruit extract.

Mordants	Fabrics		
	Nylon	Silk	Cotton
Without mordant			
Pomegranate rind			
Thuja fruits			
Moringa oleifera leaves			

Results of Color Fastness Properties of Dyed Textile Samples:
Color Fastness Properties of The Aqueous Extract from Red Prickly Pear Fruits:

1. Silk:

- Natural sunlight: The colour fastness of silk fabric dyed with the aqueous extract red prickly pear fruits showed excellent resistance to natural sunlight both, with and without the use of thuja fruits and moringa leaves mordant, will sample treated with pomegranate peel exhibited good fastness. This high level of resistance can be attributed to the formation of dye mordant complex, which protects the chromophore from photo-degradation (Geelani *et al*., 2013) (Table 2).
- In the term of dry and wet pressing, the dyed silk samples demonstrated very good to excellent color change, with negligible staining observed (Table 2).

2. Cotton:

- Natural sunlight: The colour fastness of cotton samples dyed with the aqueous extract displayed very good light fastness with moringa leaves mordant, moderate fastness without mordant, and poor with the other mordants. The relatively low light fastness in some cases is primarily attributed to chromophore photo-oxidation, which can be minimized by forming stable dye metal complex facelifted by with the mordant (Jha *et al*., 2015) (Table 2).
- Dry and wet pressing: The color fastness to dry pressing ranged from poor, for samples without mordant and moringa leaves, to very good, with both pomegranate peels and thuja fruits. In contrast, wet pressing exhibited excellent color fastness across all mordanted samples. This improvement can be attributed to the mordants ability to reduce surface tension, facilitating plays a vital role in breaking the surface tension of the fibers by helping the dye molecules penetrate the fiber core (Singh, 2000). The superior wet pressing fastness relative to dry pressing may be due to the dissoulation of water-soluble dye molecules during pressing, which enhances dye removal from the fiber through friction (Gupta *et al*., 2004). Moreover, fixing agents enhance dye fiber stability by forming larger dye complexes (Geelani *et al*., 2013). No spotting was reported on the cotton samples (Table 2).

3. Nylon:

- Natural sunlight: Color fastness gives effective results with thuja fruits and moringa leaves mordants, moderate with both pomegranate peels and without a mordant. The sample stabilized with pomegranate peels changed colour from sandy to a deeper colour, likely due to the mechanism of light produced by the dye on the fibers (Alam *et al*., 2007) (Table 2).
- Dry and wet pressing: dry pressing fastness ranged from very good to excellent with moringa leaves, pomegranate peels, and thuja fruits, and poor with no mordant, while wet pressing showed very good to excellent performance across treatment (Table 2).

Table (2): The colour fastness properties of fabrics dyed with the aqueous extract of the plant fruits in the presence of mordants and without mordants.

Mordants	Silk Fabric					Nylon Fabrics					Cotton Fabrics				
	Colour fastness degree					Colour fastness degree					Colour fastness degree				
	Sun light	Rubbing				Sun light	Rubbing				Sun light	Rubbing			
		Dry		Wet			Dry		Wet			Dry		Wet	
		CC	CS	CC	CS		CC	CS	CC	CS		CC	CS	CC	CS
Without mordant	4	5	5	5	5	3	1	5	5	5	3	1	5	5	5
Pomegranate rind	5	4	5	5	5	3	5	5	5	5	1	4	5	5	5
Thuja fruits	3	4	5	5	5	4/5	4	5	5	5	1	4	5	5	5
Moringa leaves	5	3	5	5	5	4/5	5	5	4/5	5	4	1	5	4/5	5

CC: Change of Colour, CS: Staining of colour.

Results of the spectra used for red prickly pear fruit samples:

UV-Vis Spectrum Analysis:

The visible absorption spectrum (300-800 nm) of the extract shows a single peak at wave length 576 nm, indicating the prescence of betacyanins, the red-violet subgroup of betalains. These pigments normally show absorption between the 400-600 nm range, attritutble to the colour combination of yellow-orange betaxanthin and red-violet beta-cyanin (Sadowska-Bartosz and Bartosz 2021; and Adenam *et al*., 2020) (figure 2).

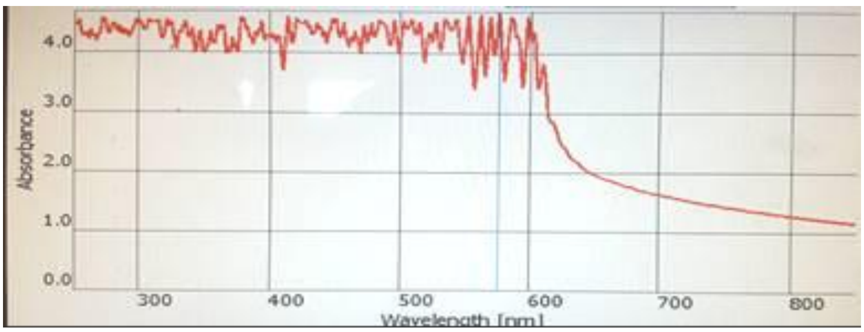


Figure (2): UV- Visible spectra of red prickly pear fruit extract

IR Spectrum Analysis:

The FT-IR spectrum red prickly pear fruit pigments extract Figure (3) recorded between (600-4000 cm^{-1}) region, exhibited characteristic absorption bands confirming the brisance of betalains. A broad peak at 3272.6 cm^{-1} corresponding to O-H and the N-H stretching vibrations associated with intermolecular hydrogen bonding and conjugated double bonds (Maldonado *et al*., 2024; Utami *et al*., 2022). Weaker bands at 2359.4 cm^{-1} and 2132.0 cm^{-1} were attributed to the C=C and C=C stretching, respectively ((Bhandari et al., 2020). A strong absorption band at 1636.3 cm^{-1} indicates C=O and C=N bond stretching, as well as aromatic C=C vibration (AL-Amir *et al*., 2022; Andalo *et* *al*., 2023; Barkociová *et al*., 2021). The weak band near 1062.2 cm^{-1} represented C-O and C-C stretching (Maldonado *et al*., 2024). The presence of hydroxyl and conjugated double bonds confirmed the characteristic structure of betalain pigments. Because the dye possesses OH, COOH, and NH_2, it has an affinity for water and some solubility (AL-Amir *et al*.,2022; Andalo *et al*., 2023).

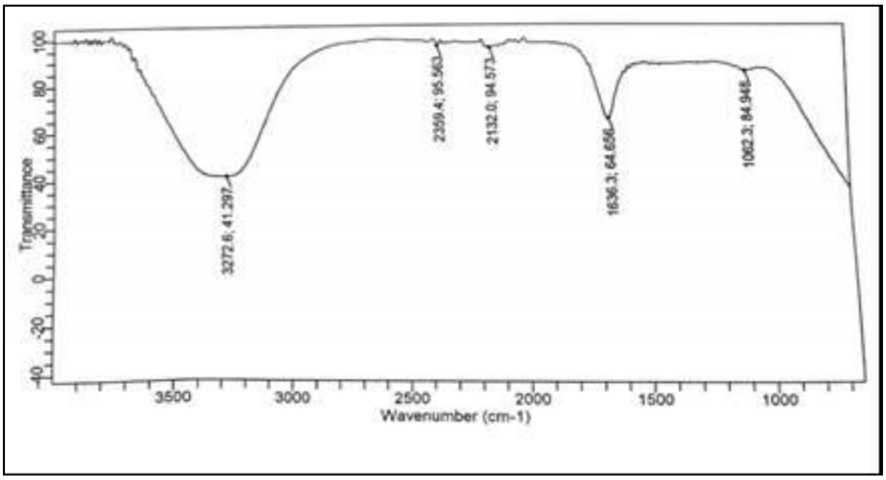


Figure (3): Infrared spectrum of red prickly pear fruit extract

CONCLUSION

This study effectively demonstrated the potential application of red prickly pear fruit extract as a sustainable natural dye for textile coloration. The extraction and dyeing processes were environmentally friendly, yield diverse brown shades depending on the type of natural mordant use. The dyed fabrics exhibited good light and rubbing fastness, attributed mainly to the mordant- dye interactions. Overall, the red prickly pear dye shows considerable potential for commercial adoption in eco-friendly textile dyeing.

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