

Sustainable Natural Dye Extraction: Methods and Sources for Eco-Friendly Applications

W.D.C. Weerasinghe
Department of Materials Technology
Faculty of Technology
Rajarata University of Sri Lanka
Mihintale, Sri Lanka
dcweeras@tec.rjt.ac.lk

P.W.C.L.K. Polkotuwa
Department of Materials Technology
Faculty of Technology
Rajarata University of Sri Lanka
Mihintale, Sri Lanka
chiranga02@gmail.com

E.M.D.A. Ekanayaka
Department of Materials Technology
Faculty of Technology
Rajarata University of Sri Lanka
Mihintale, Sri Lanka
ent1819025@tec.rjt.ac.lk

U.T.P.P. Sri
Department of Materials Technology
Faculty of Technology
Rajarata University of Sri Lanka
Mihintale, Sri Lanka
ent1819087@tec.rjt.ac.lk

P.G.S.M. Dayarathna
Department of Materials Technology
Faculty of Technology
Rajarata University of Sri Lanka
Mihintale, Sri Lanka
ent1819020@tec.rjt.ac.lk

M.A.H. Yasasri
Faculty of Materials Science and
Technology
Technical University Bergakademie
Freiberg, Germany
hariniyasasri@gmail.com

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I. INTRODUCTION

In the prehistoric time of 3000-4000 BC, the Chinese were made dye recipes for obtaining red, black & yellow on silk, at the same time Egyptians made colored mats and hung them on the walls. In Indians religious and social customs dating back to 2500 BC include allusions to gold brocades and colored silk [1]. Natural dyes have been used to color textiles, food, drug, cosmetics, leather and fibers such as wool, silk and cotton. With growing environmental awareness, natural dyes have gained importance due to being non-toxic, nonallergenic, eco-friendly, and produce unique, softer shades [2]. Since the introduction of synthetic dyes in 1856, known for their colorfastness and lower cost, the use of natural dyes declined. But recently there has been renewed interest in natural dyes. Because synthetic dyes are headed to growing environmental hazards such as their water pollution and water disposal problems as well as those are non-biodegradable and carcinogenic [3].

II. MATERIALS AND METHODOLOGY

The extraction of natural dyes involves parts of the plants, minerals, animals with several methods, each with its own advantages and disadvantages including eco-friendly and low yield of the dyes [4].

A. Materials

Ripe *Elaeocarpus serratus* known as Sri Lanka olive or Weralu leaves with red patches were taken and cut into small pieces. One gram (1 g) of chopped leaves was first boiled in water to remove any polar pigments such as anthocyanin that are present in the leaves and identified with UV Visible spectrometer. After filtration, the leaves were boiled again with 2.5 ml of ethanol for 30 minutes at 80°C in a beaker placed in a water bath until the leaves became colorless. After following the extraction, the dye was filtered and collected into a sample bottle. This bottle with dye was wrapped with aluminum foil and keep in a refrigerator at 4°C until used.

The collected Areca catechu powder underwent a sieving process using a 250 µm sieve to achieve a consistent particle

size. 10 g of Areca catechu powder was combined with 200 ml of ethanol (1:20) in a Soxhlet apparatus. The solution obtained through extraction was then concentrated to enhance the concentration of the extracted compounds. Subsequently, the solution was poured into Petri dishes and oven-dried. Then, the dye was scratched out of the petri dishes and collected in powder form.

Flowers, leaves and barks also can be used as sources for natural dye extractions such as *Acalypha hispida* Flowers [5], *Clerodendrum quadriloculare* Leaves [6], Butterfly pea, and roots from Madder, Alkanet, Rhubarb [4]. These alternatives give sustainable solutions for synthetic dyes.

B. Aqueous Extraction

Aqueous extraction is a traditional method where the material containing dye is cut into small particles or powdered and soaked in water. Then boiled the mixture to extract the dye, which is eventually filtered to remove non dye residues [5], [6], [7]. The chosen natural dye plant sources were conditioned, dried in the sun, then ground into powder using a laboratory scale grinding machine. 21 g of powdered dye plant material and 420 ml of distilled water were boiled in a beaker on a hot plate with a temperature regulator for an hour in order to extract the dye. Aluminum foil was placed over the beaker's mouth to stop excessive water loss during extraction. Following the boiling time, the hot dye extract was filtered through fine cotton cloth. After cooling, the filtrate was passed through Whatman filter paper for additional filtering. Under the same conditions, extraction was carried out twice from the same weight of dye material.

C. Acid and Alkali Extraction

Acid and alkali extraction processes use the solubility properties of dyes [8], [9]. The extraction can be followed by use of *Thespesia populnea* (Gan Suriya) and extraction was carried out using 1 L of distilled water and 100g of sun shade dried bark chips. The water bath was heated to 80 °C over 75 minutes. To observe the extraction efficiency and colour yield by the changing pH at the extraction, vinegar and lemon juice were added separately to adjust the pH of the extraction liquor in to the acidic state to keep the pH level as 5 and 3 respectively. NaOH and Na₂CO₃ were added separately to

adjust the pH into the alkaline state to keep the pH as 13-14 and 8-9 respectively [8].

D. Ultrasonic-Assisted Extraction

Ultrasonic assisted extraction is modern and sustainable techniques for extraction of natural dyes from plants that enhance extraction efficiency by reducing solvent use, time, and temperature. It operates typically in the range of 20–40 kHz, where ultrasonic waves generate acoustic cavitation that disrupts plant cell walls and enhances solvent penetration. The process improves extraction yield, reduces processing time, and minimizes solvent usage compared to conventional techniques. Advantages include energy efficiency, eco-friendliness, and suitability for thermally sensitive compounds, while disadvantages include possible degradation of sensitive molecules under prolonged sonication and limited scalability for industrial production. [1], [4].

E. Solvent Extraction

Solvent extraction uses organic solvents (acetone, ethanol and etc.) to dissolve dyes from plant materials to isolate the natural dyes and the type of solvent decided based in the selected based on the polarity of the target dye. The mixture stirred at room temperature or under mild heating conditions to enhance the release of the pigments and the process is followed by the filtration techniques. This method achieves higher yields compared to aqueous extraction and allows easy purification of the dye. But it may pose toxicity issues, and the extracted dyes may not be water soluble [1], [4].

III. RESULTS AND DISCUSSION

Natural materials from various sources give different types of dye pigments which can be used to color the parts. These unique colors for each source have their own mix of dye pigments as shown in Table I.

TABLE I. TABLE 1: SOURCES AND TYPE OF PIGMENTS

Source	Name	Dye Pigments
Plant Leaves	Indigo (<i>Indigofera tinctoria</i>), Spinach (<i>Spinacia oleracea</i>), Henna (<i>Lawsonia inermis</i>)	Indigo Chlorophyll Lawson
Plant Flowers	Marigold (<i>Tagetes erecta</i>), Hibiscus (<i>Hibiscus rosa-sinensis</i>), Rose (<i>Rosa spp.</i>)	Carotenoids Anthocyanins Flavonoids
Plant Roots/Tubers	Turmeric (<i>Curcuma longa</i>) Madder (<i>Rubia tinctorum</i>)	Curcumin Alizarin
Fruits/Seeds	Pomegranate peel (<i>Punica granatum</i>), Annatto seeds (<i>Bixa orellana</i>) Blackberries (<i>Rubus spp.</i>)	Ellagic acid Bixin Anthocyanins
Bark/Wood	Logwood (<i>Haematoxylum campechianum</i>) Cutch (<i>Acacia catechu</i>)	Hematoxilin Catechu tannin
Insects	Cochineal (<i>Dactylopius coccus</i>)	Carminic acid
Minerals	Ochre, Lapis lazuli	Iron oxides, Lazurite

The UV spectrum of the Areca catechu dye solution with a pH value of 4.0 is presented the absorptions in 316 nm and 442 nm regions by UV-Vis Spectroscopy. The peaks of 316 nm show tannin compounds in the dye. This spectrum also shows a peak at 442 nm in the visible zone, indicating the presence of a yellow color in Areca catechu ethanol extract. It can be observed that the Areca catechu dye molecules can easily absorb radiation in the UV-A region (310 - 400 nm) and the visible light region (400 - 700 nm). UV-A makes up

about 95% of the UV radiation that reaches the Earth. Different dye plants were subjected to aqueous extraction, and different dye yields were obtained, as shown in Table II, which presents the range of yields obtained from each material. The amount of the extracted dye and its color is differed from each other based on the method and the parameters such as temperature, time and medium. Based on the final requirements, method can be selected from different sources.

TABLE II. CRUDE DYE YIELD FROM DYE PLANT SOURCES

Local Name	Plant Part	Crude dye yield (%)
Bamiba	Bark	17.64
Dokima	Bark	23.87
Warika	Bark	26.33
Inkoy	Leaves	24.33
Wonbela	Bark	14.14
Abalo	Leaves	17.86
Zana	Leaves	17.09
Gesho	Leaves	24.48
Gimesha	Flower	15.43
Fesson	Flower	20.76

IV. CONCLUSION

The use of natural dyes, while ancient, remains significant due to their eco-friendly properties and non-toxic nature. In this study the extraction of natural dye from plant material such as aqueous, ultrasonic and microwave, solvent extraction etc., each of which can be optimized for different plant materials to maximize dye yield and quality. Advanced techniques such as microwave and ultrasonic extraction offer enhanced efficiency by reducing extraction time, energy consumption, and solvent use, making them more sustainable alternatives. Natural dye sources demonstrate the potential to provide effective dyes for textiles and other applications. These natural alternatives offer significant benefits in reducing pollution, conserving resources, and supporting sustainable practices across various industries.

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