Title: Natural Dyes and their Modern Applications

Literature Review

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1. Introduction

Natural dyes have been used since ancient times and are strongly link with cultural traditions and environmentally friendly practices. For many years, people in different parts of the world used natural materials to make dyes. Natural colorants are obtained from natural sources through various extraction methods following the drying and grinding of plant materials. They used plants, minerals, and other natural substances to create beautiful and long-lasting colors for textiles, artworks, and cosmetics. The selection of an appropriate solvent is based on the specific dye of interest, and extraction is performed using both conventional and advanced techniques (Zhang et al., 1994; Luque de Castro and Garcia-Ayuso, 1998; Sasidharan et al., 2011). The desired compounds, utilized for dyeing applications, are isolated using chromatographic or alternative separation methods. These isolated compounds are subsequently characterized through spectral analysis techniques (Yadav et al., 2023) recently, the heightened focus on sustainability, environmental responsibility, and ethical production has revitalized interest in natural dyes. Newer technologies are now enabling the evolution of this traditional practice into a progressive and sustainable industry (Gala et al., 2018). Present paper suggests a new advanced method grinding assisted microwave extraction of natural dye from biological materials.

2. Sources and Chemical Nature of Natural Dyes

The major sources of these are plants, animals, and minerals.

2.1 Plant-Based Sources

- Plant dyes also contain phenolic compounds that helps in producing a wide range of shades and color variations.
- Different chemical components such as flavonoids, anthraquinones, and carotenoids play and important role in producing various colors.
- Many natural dyes are derived from plants.

2.2 Based Source on Animal

- Natural dyes are obtained from animal source. The main examples includes cochineal, that produces carminic acid, and Tyrian purple. These dyes were highly valued and widely used in ancient times (Brett,2004).

2.3 Mineral Sources

- Natural colors can also come from mineral sources. (Buckley,2004)
- Makeup are made using these chemical dyes and it is important because it affects the strength of the colour.

3. Bridging tradition in natural dye production and applications

From traditional to modern the shift method of natural dye production has addresses various keys of limitation of traditional techniques, such as inconsistent of colour fastness, limited scalability, and environmental concerns. Cultural methods has often relay on long extraction processes, huge amount of water, and toxic mordants. Facilities, like enzymatic extraction, microbial fermentation, and nanotechnology, has enhanced it's dye yield, improve color stability, and reduce environmental impact. Example such as enzymatic extraction allows for more efficient pigment retrieval without hazardous chemicals, while microbial fermentation enables the sustainable production of bio based dyes. Adding, nano-enhanced techniques like dyeing has improved adherence to fabrics, decreasing water and energy of consumption. These innovation has not only secured the cultural heritage but also natural dyeing and has made the process more viable for large-scale, and eco-friendly production of textile. (Yusuf et al., 2016; Gala et al., 2018; Yadav et al., 2023).

4. Natural dye extraction

Cultural method of dyeing and extraction, such as boiling or fermentation of materials of plants, has often posed several challenges (Bart and Pilz, 2011; Pandey et al., 2020). These has include inefficiencies, significance resource consumption, and also inconsistent dye quality due to various of processing condition (Pranta and Rahaman, 2024). The recent technologies has addressed many of this limitations, leading to more efficient, sustainable and reliable processes (Křížová, 2015; Affat, 2021; Hagan and Poulin, 2021; Slama et al., 2021).

4.1 Modern method

Contemporary extraction techniques surpass traditional methods due to their ability to achieve higher yields with reduced costs. Several studies have quantitatively compared modern dye extraction techniques based on yield, efficiency, and product quality. Moreover, supercritical fluid extraction (SFE) using CO_2 has been shown to recover 95–98% of target anthocyanins with minimal thermal degradation (Herrero et al., 2006) Key modern extraction methods are summarized below.

4.2 Solid-phase micro extraction

SPME is a solvent-free extraction technique that integrates sampling, extraction, concentration, and sample introduction into a single step. The method relies on (a) the partitioning of the target analytes between the extraction phase and the sample matrix, and (b) the desorption of the concentrated analytes into the instrument's storage or analytical system. This technique is simple, efficient, and enables the enrichment of analytes while minimizing solvent consumption. However, a limitation of SPME is the limited availability of commercially produced stationary phases (Kataoka et al., 2020).

4.3 Pressurized-liquid extraction

Pressurized-liquid extraction is a technique in which extraction is carried out under elevated temperatures and moderate to high pressure to enhance the efficiency of dye component recovery. This method is time-efficient and requires minimal solvent usage. The process begins by dispersing the sample with inert materials, such as sand, and placing the extraction material into a specialized vessel. (Osorio-Tobón et al., 2013)

4.4 Microwave-assisted extraction

The efficiency of MAE depends on several factors, including the choice of solvent, extraction material, target compound properties, extraction time, temperature, and microwave power. MAE is employed in two configurations: closed-vessel and open-vessel systems.

5. Functional Properties of Natural Dyes

Natural dyes are merely not chromophores, many contains bioactive phytochemicals that is imparted functional performance to dyed substrates. The most significance properties includes antimicrobial activity and antioxidant capacities, both of which are highly relevant in modern textile, and medical, cosmetic, and also food industries.

5.1 Antimicrobial Activity of Natural Dyes

1. Scientific Basis

Antimicrobial activity refers to the ability of a substance to inhibit or kill microorganisms such as:

- Gram-positive bacteria (e.g., *Staphylococcus aureus*)
- Gram-negative bacteria (e.g., *Escherichia coli*)
- Fungi (e.g., *Candida albicans*)

Many natural dyes contain phenolic compounds, flavonoids, tannins, quinones, and essential oils, which disrupt microbial growth.

2. Mechanism of Antimicrobial Action

Natural dye compounds act through several biochemical mechanisms:

(a) Cell Wall Disruption

Phenolic compounds alter membrane permeability, causing leakage of intracellular components.

(b) Protein Denaturation

Tannins bind to microbial enzymes and proteins, deactivating essential metabolic pathways.

(c) DNA Interference

Quinones can interact with nucleic acids, inhibiting replication.

(d) Reactive Oxygen Species (ROS) Generation

Some pigments induce oxidative stress in microbial cells.

3. Major Antimicrobial Natural Dyes

1. Turmeric (*Curcuma longa*) - Active compound curcumin, Strong activity against *S. aureus* and *E. coli*, Mechanism - Membrane disruption + ROS production

2. Henna (*Lawsonia inermis*) -Active compound - Lawsone (2-hydroxy-1,4-naphthoquinone)
Effective against fungal strains
Mechanism: Quinone-mediated enzyme inhibition

3. Neem (*Azadirachta indica*)
Contains flavonoids and limonoids
Broad-spectrum antimicrobial effect

4. Application in Medical and Functional Textiles

Natural dye–treated fabrics demonstrate:

- Reduced bacterial colonization
- Odor resistance
- Improved hygiene performance
- Skin-friendly finishing

Example Applications: Hospital bedding, wound dressing materials, Sportswear, Baby garments

5.2 Antioxidant Properties of Natural Dyes

5.2.1 Scientific Basis

Antioxidants are molecules that neutralize free radicals (unstable oxygen species) responsible for:

Oxidative stress, Cellular damage, Premature aging, Food spoilage. Natural dyes are rich in polyphenolic compounds, which act as antioxidants by donating hydrogen atoms to stabilize free radicals.

5.2.2 Chemical Components Responsible for Antioxidant Activity

(a) Flavonoids

Found in onion skins, marigold, and tea, Exhibit strong radical scavenging activity

(b) Anthocyanins

Present in berries and red cabbage, Provide red, purple, and blue coloration, Possess high ORAC (Oxygen Radical Absorbance Capacity)

(c) Curcuminoids

Found in turmeric, Known for both antioxidant and anti-inflammatory properties.

(d) Tannins

Present in bark and fruit rinds

Exhibit metal chelation properties, reducing oxidation

5.2.3 Mechanism of Antioxidant Action

Natural dye compounds exert antioxidant effects through the following mechanisms:

Donation of hydrogen atoms to neutralize free radicals, Chelation of pro-oxidant metal ions (Fe^{2+}, Cu^{2+}), Inhibition of lipid peroxidation chain reactions

5.2.4 Applications in Modern Industries

A. Functional Textiles

Natural dye-based antioxidant textiles:Reduce oxidative stress on skin, Provide protection against UV-induced damage, used in therapeutic and wellness clothing *Example:* Fabrics dyed with turmeric and pomegranate show measurable DPPH radical scavenging activity.

B. Food Industry

Natural dyes are utilized as: Natural colorants, Shelf-life enhancers, Agents to prevent lipid oxidation, safer alternatives to synthetic dyes such as Tartrazine

C. Cosmetics Industry

Applications include: Lipsticks, Herbal creams, Anti-aging formulations

Benefits:
Skin-safe pigmentation, Reduction of oxidative damage, Provision of natural coloration

6. Modern Applications of Natural Dyes

Natural dyes have transitioned from traditional colorants to multifunctional bioactive materials. Their modern applications extend across textiles, food systems, cosmetics, biomedical science, and renewable energy technologies.

6.1 Application in the Textile Industry

1. Sustainable Eco-Dyeing Systems
The textile sector is one of the largest consumers of synthetic dyes, contributing significantly to water pollution due to, high Chemical Oxygen Demand (COD), Toxic aromatic amines Heavy metal contamination, Non-biodegradable effluents. Natural dyes offer, biodegradability, Reduced toxic discharge, Lower environmental persistence, Compatibility with organic textiles

A. Fibres Commonly Dyed
Cotton (cellulosic), Silk and wool (protein fibers), Linen, Bamboo, Regenerated fibers

Functional Property	Responsible Compound	Example Dye
Antimicrobial	Curcumin, Lawsone	Turmeric, Henna
UV Protection	Flavonoids	Marigold
Antioxidant	Polyphenols	Pomegranate
Deodorizing	Tannins	Myrobalan

(a) Enzymatic Pretreatment
Improves dye uptake and reduces mordant requirement.

(b) Plasma Surface Modification
Enhances fiber–dye bonding without chemicals.

(c) Nano-Encapsulation
Improves wash fastness and color stability.

(d) Biomordants
Tannins, chitosan, and plant extracts replacing metal salts.

4. Market Relevance
Growing demand for sustainable fashion
Used by eco-brands and craft-based labels
Compatible with organic certification standards.

6. Challenges in Adoption

Colorfastness and consistency issues compared to synthetic dyes (Bechtold & Mussak, 2009).
Scalability and costs of extraction and standardization.
Limited color range and seasonal variability of raw materials.

7. Future Prospects

Genetic engineering of dye-producing plants for enhanced yields. Nanotechnology integration to improve stability and functionality. Sustainable mordanting methods using biosourced agents.

8. Conclusion

Modern and innovative methods are more superior to traditional natural dye extraction process. Innovative methods are superior because these techniques make feasible to extract dyes from unconventional and previously underutilized sources obtained from agricultural waste such as byproducts from crops, such as fruit peels, seeds, and stems, which were once discarded, are now valuable sources of natural dyes. Species that pose ecological challenges can be repurposed for dye extraction, turning an environmental problem into a resourceful solution. The intersection of tradition and modern technology is driving a renaissance in natural dye production. By leveraging innovative scientific methods, sustainable practices, and digital tools, the industry is overcoming historical limitations and paving the way for a vibrant future. These innovations not only preserve the cultural legacy of natural dyes but also contribute to a more sustainable and ethical global economy.

Biblography

1. Affat, S. (2021). Classifications, advantages, disadvantages, toxicity effects of natural and synthetic dyes.
2. Ajioka, J., Breslauer, D., and Yarkoni, O. (2017). “Genetically modified microorganisms and uses thereof in the production of pigments,”
3. Alawa, K. S., Ray, S., and Dubey, A. (2013). Dye yielding Plants used by Tribals of Dhar District, Madhya Pradesh, India.
4. Ali, S. Y. (2011). Surfactant-based extraction methods. *Trends Analytical Chem.*
5. Bach, L. and Cannon, D. (2018). Indigo dyeing method and method for making indigo dyed product.
6. Bart, H. J. and Pilz, S. (2011). *Industrial Scale Natural Products Extraction*
7. Bellos, S. (2019). Method of stabilizing and producing plant-based indigo dye for industrial application.
8. Rather, L. J., Shabbir, M., Ali, S., and Zhou, Q. (2024). Natural dyes: green and sustainable alternative for textile colouration. In *Sustainable Textile Chemical Processing*.
9. Chandel, N., Singh, B. B., Dureja, C., Yan, Y. H., and Bhatia, S. K. (2024). Indigo production goes green: a review on opportunities and challenges of fermentative production.
10. Chemat, F., Rombaut, N., Sicaire, A. G., Meullemiestre, A., Fabiano-Tixier, A. S., and Abert-Vian, M. (2017). Ultrasound-assisted extraction of food and natural products. Mechanisms, techniques, combinations, protocols and applications. A review.
11. Frankewich, R. P. and Hinze, W. L. (1994). Evaluation and optimization of the factors affecting nonionic surfactant-mediated phase separations.
12. Gala, S., Sumarno, and Mahfud (2018). Microwave-assisted extraction of natural dyes

from coleus atropurpureus leaves: the effect of solvent.
13. García-Cruz, L., Valadez-Blanco, R., and Zepeda-Vallejo, L. G. (2022). Enzyme-assisted extraction of anthocyanins and flavonoids from plant materials: A review of current advances.
14. Ghosh, S., Sarkar, T., Das, A., and Chakraborty, R. (2022). Natural colorants from plant pigments and their encapsulation: An emerging window for the food industry.
15. Hagan, E. and Poulin, J. (2021). Statistics of the early synthetic dye industry..
16. Herrero, M., Cifuentes, A., and Ibáñez, E. (2006). Sub- and supercritical fluid extraction of functional ingredients from different natural sources: Plants, food-by-products, algae and microalgae.
17. Jiménez-Carmona, M. M., Ubera, J. L., and Luque de Castro, M. D. (1999). Comparison of continuous subcritical water extraction and Soxhlet extraction in the analysis of rosemary essential oils. *J. Chromatogr.*
18. Kataoka, H., Saito, K., and Otsuka, K. (2020). Recent advances in solid-phase microextraction for pharmaceutical and biomedical analysis. *J. Chromatogr.*
19. Křížová, H. (2015). Natural dyes: their past, present, future and sustainability.
20. Liu, S., Li, Z., Guo, C., Wang, Y., and Zhang, H. (2023). Pilot-scale microbial fermentation of indigo by engineered Escherichia coli expressing flavin-containing monooxygenase.
21. Luque de Castro, M. D. and Garcia-Ayuso, L. E. (1998). Soxhlet extraction of solid materials: An outdated technique with a promising innovative future.
22. Manzocco, L., Calligaris, S., and Nicoli, M. C. (2015). Sustainable extraction of bioactive compounds from vegetable by-products.
23. Mohan, R., Geetha, N., and Haritha Jennifer, D. (2020) Venkatasubramanian sivakumar "Studies on natural dye (Pelargonidin) extraction from onion peel and application in dyeing of leather.
24. Osorio-Tobón, J.F., Angela, M., and Meireles, A. (2013). Recent applications of pressurized fluid extraction: curcuminoids extraction with pressurized liquids.
25. Pandey, A., Tripathi, S., and Pandey, R. (2020). Medicinal plants: Chemistry, biological activities, and therapeutic applications.
26. Pranta, A. D. and Rahaman, MD. T. (2024). Extraction of eco-friendly natural dyes and biomordants for textile coloration.
27. Rahaman, MD. T. and Khan, MD. S. H. (2024). Applications of green nano textile materials for environmental sustainability and functional performance: Past, present and future perspectives.
28. Rani, A., Singh, R., and Sharma, S. (2023). Enzyme-assisted extraction of natural dyes from plant sources: A sustainable approach.
29. Routray, W. and Orsat, V. (2012). Microwave-assisted extraction of flavonoids: A review.
30. Sánchez-Camargo, A. P., Parada-Alfonso, F., Ibáñez, E., and Cifuentes, A. (2019). Green processes for the extraction of bioactives from natural sources. *Compr.*
31. Sasidharan, S., Chen, Y., Saravanan, D., Sundram, K. M., Latha, L. Y., and African, J. (2011).