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AGRO-INDUSTRIAL WASTE AS A RESOURCE FOR SUSTAINABLE TEXTILE DYEING: A CIRCULAR ECONOMY PERSPECTIVE

APEC Small and Medium Enterprises Working Group

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Produced by
Arturo Alatrista-Corrales
Angel Jeancarlo Coaquira-Flores

For
Asia-Pacific Economic Cooperation Secretariat
35 Heng Mui Keng Terrace
Singapore 119616
Tel: (65) 68919 600
Fax: (65) 68919 690
Email: info@apec.org
Website: www.apec.org

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CONTENT

KEY ABBREVIATIONS

AITEX	Asociación de Investigación de la Industria Textil (Spain)
BIRAC	Biotechnology Industry Research Assistance Council (India)
CAPES	Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (Brazil)
CITE	Centro de Innovación Productiva y Transferencia Tecnológica (Peru)
CNPq	National Council for Scientific and Technological Development (Brazil)
CSWRI	Central Sheep and Wool Research Institute (India)
EAE	Enzyme-assisted extraction
FAPERJ	Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (Brazil)
GCUF	Government College University Faisalabad (Pakistan)
GHG	Greenhouse gas
ICAR	Indian Council of Agricultural Research (India)
IFPA	Instituto Federal do Pará (Brazil)
INACAL	Instituto Nacional de Calidad (Peru)
ITP	Instituto Tecnológico de Producción (Peru)
LCA	Life cycle assessment
MAE	Microwave-assisted extraction
PAEE	Pressure-assisted dye extraction
PUCP	Pontificia Universidad Católica del Perú (Peru)
SME	Small and medium-sized enterprise
SFE	Supercritical Fluid Extraction
TRL	Technological Readiness Level
UAE	Ultrasound-assisted extraction
UCSM	Universidad Católica de Santa María (Peru)
UNEP	United Nations Environment Programme
UNSA	Universidad Nacional de San Agustín (Peru)
UTP	Universidad Tecnológica del Perú (Peru)

Executive Summary

This study was developed under the APEC Small and Medium Enterprises Working Group (SMEWG) project APEC SMEWG_204_2024, implemented by Peru through the Instituto Tecnológico de la Producción (ITP), via the CITE Textil Camélidos Arequipa, with the co-sponsorship of Canada and Thailand. The study examines the use of agro-industrial waste, including agricultural by-products that remain unvalorized, as a source of natural dyes in the textile sector, with a particular focus on micro, small, and medium-sized enterprises (MSMEs) which constitute the majority of enterprises in the textile sector.

For the purposes of this study, MSMEs are considered within the scope of SME framework of APEC economies. The research addresses two important issues: the negative effects of synthetic dyes, including excessive water use, persistent pollution, and dependence on fossil fuels, and the lack of use of agricultural byproducts. It connects these two problems by considering the residues as underutilized assets that can foster sustainable innovation in the textile industry.

Historically, the textile industry has been linked with the excessive use of resources and the production of toxic waste. The global production of synthetic dyes poses a severe contradiction to the sustainable development goals and the circular economy framework. These challenges disproportionately affect textile SMEs, which often lack the technical capacity and financial resources required to adopt cleaner production technologies. In this context, the valorization of agro-industrial waste within a circular economy framework emerges as a viable and accessible alternative to improve environmental performance while simultaneously enhancing competitiveness.

The study aimed to systematize technical processes, research outcomes and experiences, for extracting and applying natural dyes from agro-industrial residues within the textile industry (with emphasis in APEC economies), while assessing their applicability for SMEs and promoting sustainable innovation. In order to make it possible, we used three strategies for collecting information: (i) a bibliometric analysis to identify gaps and issues within scientific research and its trends; (ii) a review of grey literature to find practical experience that is frequently missing from scholarly publications; and (iii) direct consultation with experts through interviews and questionnaires.

Research output based on the bibliometric analysis indicates that research output worldwide has gradually increased over the last twenty years. Output during that period was concentrated in the Asian and Latin American economies. The majority of research output was achieved in the form of laboratory research which concentrated on the extraction of pigments and the characterization and testing of pigment fastness. Patent analysis demonstrates the immense growth to scale of the industrial patent holders and the technologies they hold patents on. There is a very distinct gap between the academic innovation and the corresponding commercial application.

The analysis of grey literature was useful in completing the research gaps. Commercial information extracted from the internet shows the significant progress made by some international companies, which have managed to develop natural coloring products (some of them based on agro-industrial waste) that meet commercial standards and certification.

Their presence in various patents demonstrates the active role played by the business sector in the development of these innovations. Beyond these cases, the gray literature reveals a large majority of efforts by different actors to find viable uses for natural dyes from agro-industrial waste, but these are the subject of pilot testing, as in cases documented in Indonesia; Peru; and Sri Lanka. The evidence of these experiences suggests that the technological processes are easily replicated, but the system as a whole is lacking in consistency, integration, reproducibility, accessibility, and standardization.

Studies indicate that residues such as husks, peels, and seeds can yield colors with reasonable fastness, as they contain chromophores. Technical feasibility is proved through laboratory investigations, while successful industrial endeavors offer evidence of practical feasibility. Simultaneously, community and small and medium-sized enterprise (SME) led pilot initiatives illustrate residue elimination that is worth more than its simple use and how innovation with culture can integrate the agriculture and textile industries.

Even with this potential, adoption remains slow because of the following gaps.

- **Technical.** The variability with the composition of residues, coupled with the lack of routine techniques, undermines reproducibility and industrial confidence.
- **Economic.** The infrastructure and logistics to transform residues to stable dye formulations are specialized, resulting in the price estimates being more than synthetic dyes.
- **Institutional.** The coordination between the agriculture and textile industries is weak, as observed in pilot demonstrations, with fragmented policy mapping and limited funding.
- **Market related:** At the same time, the demand from the consumers for sustainable textiles keeps on rising, the industries continue to pull back to the slow cautious pace because of the quality, pricing, and whether the global standards will be met.

APEC economies, specially those with large tradition in textile sector, are in an advantageous position to benefit from cross-border technological innovation. Considering several of them have robust agro-industrial bases and dynamic textile sectors, these economies have the necessary conditions to develop residue valorization domestically, while also integrating external knowledge and technology. There is an increasingly market demand for sustainable and environmentally safe (or ecolabeled) products. The regional collaboration, unified regulatory guides, and cooperative research development can assist in the overcoming of fragmentation and technical limitations. In this context, the report provides evidence-based inputs aligned with SMEWG priorities, supporting SME competitiveness, sustainability, and regional integration.

Four issues for future research and action are apparent:

1. The standardization of extraction methodologies, application, and testing for all to be able to guarantee reproducibility.
2. Assessing the complete life cycle in order to measure saved impacts and for the purpose of strengthening eco-labeling.

3. Investigation into increased competitiveness through multifunctional features like antimicrobial and other UV protective capabilities.
4. The pace of industrial implementation will be advanced with techno-economic and scaling studies.

If these challenges are effectively addressed, APEC economies can position themselves on the global map as leaders in sustainable textile innovation. Transforming agro-industrial residues into natural dyes will assist other economies in reducing negative environmental impacts, diversifying their industries, and strengthening cooperative relations, thereby paving the way for increased competition and collaboration across the region.

By providing consolidated empirical evidence and a comparative analysis of experiences across economies, this Research Report contributes to APEC's overarching objectives of promoting green, sustainable, and innovative SMEs. The study supports policy dialogue, technology transfer initiatives, and capacity-building efforts aimed at strengthening the competitiveness and resilience of textile SMEs, while advancing the adoption of circular economy practices across APEC economies.

1 Introduction

1.1 Environmental and Economic Importance of the Textile Sector in APEC Economies

The textile sector is crucial for the economic and social development, employment, and environmental sustainability within APEC economies. The world industry is estimated to be valued at around USD 2.5 trillion. It includes a broad value chain, from the processing of raw materials to the retail outlet, with a significant proportion for the clothing and apparel industry (Sharma Narula, 2020). The prominence of this industry is acknowledged more in certain economies than in others, for example, in the Bangladesh textile industry, which is reported to account for more than 81% of the revenue earned from exports (Miah et al., 2023).

The textile sector provides employment opportunities directly and indirectly. This sector is a livelihood for millions in many developing economies, where handlooms and garments provide crucial sustenance (Dhevan & Ramar, 2024). SMEs make this entire chain available. It is noticed that the operational capacities of such enterprises affect the industry's economic growth and other developmental indicators (Arshad & Arshad, 2019). In addition, the workforce sustainability practice has gained economic and technical efficiency and improved environmental performance (Naz, 2023).

Unmet global sustainability goals continue to be a problem for the textile sector, due to the intensive use of steam, oil, water, and the emission of greenhouse gases during the textile and oil production processes (Filho et al., 2024). On the other hand, the ability to integrate textile recycling stems from the need to eliminate virgin polyester and foster a circular economy within the industry, which is a massive leap forward (Filho et al., 2019). Not only do systemic sustainability changes need to be implemented, but the governance of the entire complex. At the same time consumer behavior, must be altered (Siliņa et al., 2024).

Recent studies on digital technologies have filled the gap on using traceability platforms, digital product passports, and other digital technologies to foster sustainable circulation and close textile value chains (Alves et al., 2023). Achieving a wider change depends on all stakeholders: textile value chain companies, wholesalers, and end consumers (Filho et al., 2024). The long-term vitality of the textile domain in the APEC economies relies heavily on the ability to sustain economic development and the environmental impact of all industry sectors.

In APEC economies, the textile and apparel sector is predominantly composed of micro, small and medium-sized enterprises (SMEs), which play a critical role in employment generation, income creation, and regional development. Despite their economic relevance, these enterprises often operate with limited access to advanced technologies, innovation capabilities, and environmental management systems. As a result, the sustainability transition of the textile sector in the APEC region largely depends on the availability of technical solutions that are economically viable, scalable, and adaptable to the operational realities of SMEs.

1.2 Problematic Use of Synthetic Dyes and Their Environmental Impact

The extensive use of synthetic dyes in the textile industry has raised several issues regarding public health and the environment, especially in the APEC region. Dyes made of synthetic chemicals remain in the environment and are extremely hard to break down like organic compounds. Since the manufacturing industry has one of the largest carbon footprints in the world, about ten to fifteen percent of the synthetic dyes in textile manufacturing perish in wastewater during the production process (Oliveira et al., 2018; Vasdev, 2018; Yue et al., 2019).

The environmental impacts associated with the use of synthetic dyes pose particular challenges for textile SMEs, which frequently lack adequate wastewater treatment infrastructure and the technical capacity required to manage chemical effluents. Increasingly stringent environmental regulations and sustainability requirements in both domestic and international markets may therefore result in higher compliance costs and reduced competitiveness for smaller firms, reinforcing the need for alternative dyeing solutions that are environmentally sound and accessible to SMEs.

The remaining waste in nature predominantly affects the environment and living organisms. Synthetic dyes can significantly damage the environment and living organisms, such as ocean animals (Pekhtasheva et al., 2024). Additionally, some synthetic dyes and associated contaminants have been reported as mutagenic or carcinogenic (Gomes & Soares, 2023; Fobiri, 2022). This is lethal for most living organisms. Synthetic dyes can cause acute immobilization or mortality. Synthetic dyes can enter aquatic food webs via bioaccumulation, affecting higher trophic levels (Nasrin et al, 2022).

Textile wastewater is a good example of a synthetic dye representation, which is known to substantially harm the water quality of rivers and lakes, causing ecological imbalance and adversely affecting the flora and fauna (Nasrin et al., 2022). This issue is most prevalent in the populated and industrial regions of the APEC economies, partly due to a lack of environmental regulations and oversight to match the industrial growth rate.

The very low biodegradability of these dyes significantly hinders a practical remediation approach (Gül, 2020). Conventional wastewater treatment technologies often fail to work in the presence of these dyes' complex molecular structures (Vasdev, 2018). While bioremediation approaches, for example, the use of microorganisms that can degrade the dye (Jamee & Siddique, 2019), have great potential, they have not been widely embraced in industrial practices.

Public and occupational health hazards accompany the environmental impacts of synthetic dyes. Workers in dyeing industries are at higher risk of respiratory diseases, skin conditions, and other health problems arising from dermal absorption and inhalation (Kuffour et al., 2023). Residents near these textile factories are exposed to chronic textile effluents, particularly via contaminated water (Costa et al., 2021).

To summarize, synthetic dyes have far-reaching and complex consequences on public health, such as permanent pollution of waterbodies, harm to critical biological systems, non-biodegradable waste, and dire risks to human life. In APEC economies, improving protective legislation, using advanced technologies to treat wastewater, and incorporating sustainability into the textile dyeing industry are all critical to reducing the impacts.

1.3 Potential of Agro-Industrial Waste as a Source of Natural Dyes

APEC economies have begun recognizing agro-industrial waste as a source of natural dyes due to its eco-friendly approach and economic potential, particularly for SMEs. This helps to further promote sustainability by reducing waste while expanding sources for natural colorants in textile dyeing (Batham & Mandhary, 2023; Haggag et al., 2023).

Several agro-industrial residues can serve as potential sources of dye. Onion skins, discarded by the onion industry, produce bright yellow to brown shades and possess decent fastness when properly extracted and mordanted (Sarwono et al.,2019). Brown shade-producing dyes are also readily available from avocado seeds, which have potential for large-scale utilization due to their color fastness (Ali et al., 2022). Raw beetroot contains a pigment called Betacyanins, which is responsible for its red color; however, its tendency to fade makes the dye easily lost during processing (Samanta, 2020). The natural dye turmeric is abundant in the market. It contains curcumin, producing yellow dyes that can attain high fastness and further enhance when mordanted under light (Handayani et al., 2019).

Extraction methods differ based on the raw material being used and the intended color characteristics. The age-old methods of boiling and soaking have been used for ages. With the traditional methods of boiling and soaking, more modern and eco-friendly techniques like microwave-assisted extraction (MAE) have been developed, which provide more dye and reduce the time spent on dyeing. Mangrove propagule waste has been successfully used with MAE to yield textile-grade, tannin-based dyes (Handayani et al., 2019).

The ability of dyed textiles to withstand fading brought on by light exposure, washing, and different environmental elements is termed color fastness. The product is accepted into the market primarily due to its value. The use of mordanting techniques using agents like alum or other natural metallic salts greatly increases the fixation and adhesion of the dye to the fabric (Sarwono et al., 2019; Ali et al., 2022). Using traditional mordants captures more color intensity and loses the eco-friendly dyeing process.

Relatively, compared to synthetic dyes, dyes obtained from agro-industrial waste are biodegradable, non-toxic, and have a smaller ecological footprint (Rahmadina et al., 2024). The shift toward these dyes upholds circular economy principles by creating value from waste, minimizing disposal to landfills, and mitigating their environmental footprint (Haggag et al., 2023). Also, greater public interest in sustainable textiles increases the market opportunity for SMEs that pursue these sustainable practices (Batham & Mandhary, 2023).

To conclude, agro-industrial waste is a readily available and sustainable source of natural dyes for the textiles industry in APEC economies. New developments in extraction methods, mordanting processes, and dip-dyeing techniques will drive the performance and wider application of these dyes in artisanal and industrial textiles.

1.4 Linkages with Circular Economy, Sustainability, and Innovation Principles

Agro-industrial waste has also been recognized as a natural source of textile dyes, which aligns with the circular economy, sustainability, and innovation across APEC economies. It allows valorization of waste, improves resource efficiency, promotes lowering carbon production, reinforces sustainable value chains, and promotes innovation in value-added production within SMEs.

Valorization of waste and resource efficiency

Agro-industrial by-products such as fruit and vegetable residues can be transformed into potential waste for textile dyeing. This drives down the amount of waste going to landfills and generates a new potential source of revenue for the agro-industrial industry. These efforts are illustrated by the successful dyeing of textiles with pigments extracted from the peels of oranges and the rinds of pomegranates, which are regionally abundant in agriculture (Arista, 2022; Baaka et al., 2024). This is a win-win approach for the economy and the environment, so it should be practiced. It contains fundamental aspects of a circular economy, whereby waste is used to give new life to materials and lessen the impact on the planet.

Low-Carbon Production

Dyes made from agro-industrial waste have a natural advantage because they are economically cheaper than the polishing costs of synthetic dyes, which are petrochemical-sourced abrasives and dyes that are aggressively manufactured and widely used. Natural dyes are also renewable and biodegradable, and help with climate change mitigation in shifting production and greenhouse gas (GHG) emission patterns (Baaka et al., 2024). These practices complement global climate change pledges and satisfy consumer needs for green and sustainable textiles.

Sustainable Value Chains

The production of dyes utilizing agro-industrial waste provides self-contained, sustainable value chains. SMEs can easily obtain raw materials from nearby farms, which signifies another reduction in GHG from transportation and enhances the relationships between the agro and textile industry (Arista, 2022; Baaka et al., 2024). These sustainable value chains offer climate-resilient employment to the rural population and promote eco-friendly farming practices.

Innovation within SMEs

The use of agro-industrial waste for natural dyes warrants the innovation of SMEs. These companies lack the resources to compete with larger companies. Innovations include the development of infusion techniques tailored to particular local waste streams and using various plant-derived residues to obtain new shades (Preetha & Rani, 2023). Improved extraction technologies in the sustainable business innovation process strengthen the company's competitiveness and the environmental performance.

Within the APEC framework, this study is developed in alignment with the objectives of the Small and Medium Enterprises Working Group (SMEWG), which promotes sustainable, innovative, and competitive SMEs across the region. By focusing on the textile sector, one of the key sectors identified in APEC strategies for green and sustainable SMEs, the study provides evidence-based inputs to support policy dialogue, capacity-building initiatives, and cooperation efforts aimed at facilitating the adoption of circular economy practices among textile SMEs in APEC economies.

1.5 Linkages with APEC's Strategic Objectives

Sustainable Economic Growth

New revenue and SME agro-industrial producers benefit from reduced waste management expenses. The transformation of agricultural waste of onion skins, avocado pits, and chickpea husks into dyes supports agricultural producers and SMEs promoting value-added products, enhances profitable ventures, strengthens the resilience of agricultural value chains, and promotes inclusive and environmentally sustainable growth.

Regional Integration and SME Support

The agro-industrial waste value chains in textile dyeing foster integration of farmers, artisans, and textile producers. Sustainable initiatives that SMEs implement improve local economies through enhanced collaboration and participation of community leaders. Such initiatives improve the community's economic conditions and promote sustainable development across the APEC region (Ali et al., 2022; Arista, 2022).

Innovation

Using agro-industrial waste to formulate natural dyes is a step toward innovation and new techniques in both the product and the processing. For instance, the advances in MAE have resulted in maximizing the dye obtained with dyeing and minimizing the environmental harm associated with the process (Baaka et al., 2024). Traditional dyeing practices can be combined with contemporary technologies to formulate unique products, which would help SMEs survive in a sustainability-driven market. (Arista, 2022).

Women's Economic Empowerment

Women have been known to take charge of SMEs and workshops involved in the dyeing of textiles in several APEC economies. It has been observed that the income and skill development opportunities connected with agro-waste valorization economically empower women entrepreneurs, allowing them to improve their socio-economic status. Initiatives that promote the inclusion of women in the sustainable production of dyes have been reported to play a role in achieving APEC's gender equality and economic participation goals (Yadav & Pandey, 2024).

Environmental Sustainability

Using natural dyes that are biodegradable and substituting synthetic and petroleum-based dyes reduces the textile industry's environmental impact. Such industries' practices help to reduce carbon emissions, save resources, and promote the circular economy in which waste is used productively (Baaka et al., 2024; Ali et al., 2022; Arista, 2022). These are some of the goals APEC aims to achieve in sustainable development.

As highlighted before, agricultural industrial residues offer an eco-friendly dye alternative, which aligns with APEC's strategic goals. It promotes APEC's strategic goals and develops a new inclusive economy, stimulating positive social impact and ecological protection.

In this context, the findings of this report directly contribute to SMEWG priorities by providing technical and strategic evidence to support the competitiveness, sustainability, and market integration of SMEs within APEC economies.

2 Objetives

2.1 General Objective of the Study

The study's general objective is to methodically define, dissect, and record the technical processes related to the extraction and use of natural dyes obtained from agro-industrial waste, emphasizing their use in the dyeing industry of the APEC economies. This involves defining the agro-industrial wastes with dyeing potential, determining the extraction processes and their level of technological development, and assessing their applicability for the SMEs sector.

The focused research intends to create a coherent technical baseline to advocate for innovation in dyeing processes to improve the dyeing industry's ecological footprint associated with conventional dye use and advance the adoption of a circular economy framework. The research is aimed at reinforcing knowledge in the region within the APEC economies and, in turn, enhancing collaboration geared towards regional initiatives for improving divergence in the economy, environmental sustainability, and investment in the region.

2.2 Specific Objectives

To obtain the primary goal, the current study focuses on the following goals:

1. Systematize operations for agro-industrial waste processing to extract natural dyes for all conventional, advanced, and emerging approaches, underlining the operational parameters, environmental efficiency, and feasible industrial scaling for each method.

2. Analyzing and categorizing agro-industrial waste that has been proven or has the potential to serve as sources of natural dyes based on its chemical makeup, color spectrum, and general availability, with emphasis in the APEC region.

3. Assessing the current methods of extraction and utilization of similar procedures and their applicability in small and SMEs in the textile sector based on their Technological Readiness Levels (TRLs) and the overall ease of integrating them into the prevailing production frameworks.

4. Compile evidence and relevant case studies related to practical proactive learnings/actions, especially in APEC economies, and capture lessons learned, barriers, and opportunities.

2.3 Scope and Delimitations of the Study

This research examines the engineering aspects of extracting and applying natural dyes from agro-industrial wastes and their potential use in the textile industry, with emphasis in the APEC economies. This study includes:

1. **Geographical scope**: Emphasis in APEC member economies, focusing on areas with significant agro-industrial waste and an economically viable textile industry.
2. **Thematic scope**: The extraction and application of natural dyes, including characterization of the materials, extraction, exhaustion, dye-fiber interaction, colorfastness, eco-friendliness, and other technical and operational parameters.
3. **Focus**: On the textile value chain of SMEs, which are often neglected players in a region's production ecosystem, and they are heavily burdened with technological and resource limitations.

This study excludes:

1. The economic and financial viability of large-scale industrial applications (which will be developed in a subsequent phase of this project)
2. Regulatory, or trade policy areas outside the boundaries required to frame the technical aspects.

The study does not include experimental laboratory development of new dyes; instead, it is based on a systematic review and analysis of existing technical knowledge and case studies.

3 Methodology

3.1 General Approach

This investigation adopts a technical-applied research design. It integrates systematic review techniques and targeted data analysis to develop a full understanding of the extraction and use of natural dyes from agro-industrial waste, with emphasis in APEC economies. The approach considers both quantitative and qualitative aspects to make a grounded and well-rounded assessment.

The research process consists of three interrelated elements: bibliometric analysis, systematic review of non-indexed literature, and expert consultation. The bibliometric analysis helps to determine the global and regional scope of natural textile dye, maturity level, and other key players within a specific scope of technology. The systematic review of non-indexed literature helps uncover other relevant domain areas such as technical reports, theses, institution-based research, and even some pilot studies done in APEC economies. Here, expert consultation complements the desk research by offering real-world insights into practical use, technological challenges, and market-adoption barriers.

This study employs defined scope boundaries to limit the research scope and horizon. In addition, data is collected, classified, and arranged using standard frameworks. These measures place extreme focus on the textile industry, along with eco-sustainability and innovation, to triage the outcomes more precisely. In addition, the outcomes of this design focus on small and medium-sized enterprises, which are the target in this case. This main pattern supports the emphasis of circular economy plans within the region, reaching the target.

3.2 Methodological Components

The methodological framework of this study rests on three interconnected elements, each aimed at achieving a distinct set of objectives and ensuring a thorough technical evaluation of the utilization of waste generated from agro-industries as natural dyes in textiles, with emphasis in APEC economies.

A. Bibliometric Analysis (Scopus and Patents)

This part of the analysis focuses on the systematic extraction, organization, and analysis of scholarly publications (Scopus) and patents from 2010 to 2025. The objective is to locate research outcomes that satisfy certain defined relevance, certainty, technical applicability, and technological readiness (TRL) frameworks. The bibliometric analysis yields quantitative data on temporal distribution, geographic concentration, and thematic clustering. The analysis of patents enhances this approach by uncovering the dynamics of technological innovation and the corresponding changes in intellectual property.

B. Systematic Analysis of Non-Indexed Resources

The study presents a systematic analysis of 'grey literature' such as theses, technical reports, institutional studies, and documentation of pilot projects in APEC economies, which assists in supplementing the indexed literature. This literature review is based on a systematic search, selection, and assessment approach, guaranteeing that only substantiated and technically relevant materials are considered. The focus is to derive practical experiences and context-based innovations that are documented and may not be available on indexed sources.

C. Expert Consultations

This part uses practitioner knowledge and contextual leverage via semi-structured interviews and questionnaires with academics, domain experts, practitioners, and other players in the APEC economies. The consultation analyzes expert knowledge on assessing the technological challenge, operational and adoption barriers, and other barriers, including the gaps in case studies. Responses are thematically analyzed to derive recurrent themes and actionable recommendations.

3.3 Analysis Variables

The conceptual framework of this study relies on a set of defined variables that facilitate orderly and methodical categorization of all gathered information, irrespective of the source (indexed and grey literature or experts' data). These variables focus on the relevant technical, operational, and contextual aspects of extracting and applying natural dyes from agro-industrial wastes.

1. Type of Agro-Industrial Residue

The classification of the raw material is based on the source, e.g., fruit peels, seeds, leaves, roots, and barks, and the particular agro-industrial process, e.g., food, beverages, and oil. This variable also notes the availability and abundance of extracted residue within APEC economies.

2. Extraction Technique

Specify the method of extraction of dye compounds, traditional, e.g., maceration, boiling, soaking, and more developed, e.g., microwave-assisted, ultrasound, and enzymatic extraction. Operational data and other factors, e.g., temperature, time, solvent, and energy, are recorded where possible.

3. Textile Application

Describe the fiber type, natural or synthetic, to which the dye is applied, and the use of the dye, e.g., immersion dyeing, printing, or coating. Comments on the process and compatibility optimization are also reported.

4. Technological Readiness Level (TRL)

Estimation of technology maturity using the TRL scale from lack of technology (TRL 1-2) to technology fully embedded and operational commercially (TRL 9) enables estimation of each technique's probable adoption by SMEs.

5. Level of Documentation in APEC Economies

The documentation and the level of evidence-based documentation in APEC economies. This variable distinguishes between techniques and methods with substantial local documentation and poorly documented or undocumented ones.

6. Applicability in SMEs

Assessment of the rationale and practicality of the technique for small and medium-sized enterprises in terms of the financial implications, available skills, infrastructure, and ease of scaling.

The use of these variables ensures that all findings are comparable optimally, making it easier to determine patterns, technology deficits, and innovative potential for the textiles industry in terms of sustainability

3.4 Tools and Sources

The study combines various data sources and tools for specialized datasets and institutional repositories, along with tools for careful data collection and structured analysis for isolating and utilizing natural dyes from dye agro-industrial waste for systematic data processing. These resources follow the three methodology logical structures defined in the preceding pages.

A. Indexed Literature and Patent Databases

1. Scopus database: Retrieves peer-reviewed scientific publications based on defined relevance threshold, delivering research direction mainly from academia.
2. LENS: Patents on natural dye extraction (application technologies) – spying on innovation, IP (intellectual property) strategies, and patent analysis.

B. Grey Literature Repositories

1. University digital libraries and economy-wide thesis repositories for unindexed academic research and dissertations.
2. Institutional and organizational archives: technical reports and feasibility studies on pilot projects in APEC economies.
3. Sector-specific portals and bulletins – for case studies and operational manuals for textile sector SMEs.

C. Data Processing and Bibliometric Tools

1. Tools for reference management, citation and annotation retrieval, for APA 7 compliance.
2. Bibliometric analysis and statistical software: Used for data coding, classifying variables, performing frequency analysis, and graphical representation of trends and relationships among variables.

D. Consultation with Experts

Semi-structured interviews and online surveys were used to gather narratives of experiences from practitioners, researchers, and stakeholders to obtain rich, domain-specific, nuanced perspectives. The tools employed in these cases aid in standardizing the data while also permitting the exploration of new avenues.

4 International Overview of Natural Dyeing Practices and Methods

4.1 Introduction

Natural dye extraction from agro-industrial waste for textiles has recently garnered special interest, ditching traditional production to favor more sustainability. Generally, techniques for extraction can be classified as either 'conventional' or 'advanced'. Each category of dye use comes with its own implications for dye yield, quality of color, sustainability, resource use, environmental impact, and potential use in SMEs.

One of most used traditional methods is Maceration, which involves soaking the plant in either water or a solvent at a lower temperature for prolonged periods. It is a sit-and-wait extraction method that is cheaper and takes fewer resources (equipment). It is suitable for small and medium enterprises. However, it is inefficient compared to other techniques because it takes a long time (often hours to days) and does not achieve high yields. For instance, onion skin dyes acquired via maceration have achieved coloration, yet consistency in lightfastness is limited (Ebrahimi & Gashti, 2016).

On the other hand, boiling and decoction methods use temperature to expedite the release of dye from the substrate, with decoction helpful with tougher plant parts like roots and bark. Both methods are also commonly used during traditional dyeing techniques since they produce bright, vibrant colors. They are economically friendly and can be scaled for larger batches; however, their energy and water use is higher (Gita et al., 2018).

Soaking is also a traditional method well spread. It requires less time than maceration and works better with softer materials. While faster than boiling and decoction, the colors acquired from soaking are often less saturated, thus making it less ideal for delicate textiles.

Modern techniques have been developed to increase efficiency and quality for dyeing. Microwave-Assisted Extraction (MAE) utilizes microwave energy to accelerate the heating of the solvent, therefore improving the effectiveness of the extraction and saving time, water, and energy in the process. The yields are reported to be significantly greater than those from traditional extraction methods. At the same time the equipment used is modular and have low operating costs (Moosavi et al., 2021).

Ultrasound Extraction utilizes the principles of high-frequency sound to facilitate the movement of the solvent into the plant matrix, thereby increasing the yield of the dye and decreasing the time it takes to process the plant. This technique is effective in energy and water conservation, benefiting small and medium enterprises that strive for efficient resource use (Peter et al., 2021) (Abidin et al., 2015).

Enzymatic extraction advancement utilizes certain enzymes to break down the plant cell walls surrounding the dye, releasing it with mild, solvent-free extraction techniques. This method increases the dye quality while lowering the process's ecological impact.

Supercritical Fluid Extraction (SFE) leaves behind very low solvent residues since it employs supercritical carbon dioxide as a solvent for extraction. As a result, it produces high-concentration, high-purity dyes. However, the equipment costs may hinder the widespread adoption of SME. Nonetheless, it has been successfully applied to extract dyes from specific agro-industrial waste (Micó-Vicent et al., 2020).

The method chosen for extraction directly relates to the quality, yield, and environmental effectiveness of the dye. While techniques such as boiling and maceration are easily accessible to SME, they are less effective than other techniques such as MAE and Ultrasound.

As far as methods of application of the dyes are concerned, these span from the traditional methods like immersion dyeing, to more sophisticated like coating and printing. With printing techniques like block printing and discharge printing, it is possible to place dyes in distinct patterns precisely. This is ideal for ornamental purposes and has been successfully applied using marigold pigments on lyocell fabrics to yield vibrance with environmental sustainability (Rashdi et al., 2020).

Coating consists of applying a layer of dye to the fabric's surface. This could increase the fabric's color and longevity. Functional coatings using *Apocynum venetum* extract have been applied without mordants and have been shown to adhere strongly to wool fibers, thus decreasing environmental impact (Xu et al., 2020).

4.2 Main Agro-Industrial Residues Used as Natural Dyes

4.2.1 Onion Skins and Avocado Seeds

The peels of onions and the seeds of avocado are increasingly accepted agro-industrial residues with the potential to create natural dyes in textiles. They also provide substantial sustainability advantages by converting waste and minimizing the use of fossil fuels for dyes.

Chemical Composition of Colorants

Onion skins contain large quantities of the flavonoid quercetin and other polyphenolic compounds that give the yellowish to brownish range and antimicrobial effects with the potential to improve the functionality of textiles (Deveoglu, 2022; Kumar et al., 2021; Şapcı et al., 2017). Tannin and flavonoid-rich avocado seeds are light brownish polyphenolic dyed textiles and exhibit antioxidant properties (Utami et al., 2021; Kim & Bui, 2022).

Extraction Methods

Onion skins are often subjected to boiling or simmering techniques. For example, the optimal color was achieved by drying and boiling the skins at 100 °C for 20 to 25 minutes in a 1:30 dye bath (Bui & Hue, 2019). Ultrasonic-assisted extraction of avocado seeds yields better efficiency and shorter extraction time while also improving the dye uptake on cellulose fibers as compared to conventional dyeing techniques (Utami et al., 2021).

Tile Yield and Color Properties

Avocado seeds have a moderate dye yield compared to onion skin, which even can improve yield in acid medium (Kim & Bui, 2022; Hinze & Clarke-Sather, 2024). Onion skin dye can attain a spectrum from light yellow to a very dark brown as a result of different extraction and mordanting techniques, making possible to obtain a wider range of tones compared to avocado seed dye, which is softer and muted (Üren, 2024).

Colorfastness

- Wash Fastness: The dye from onion skin can achieve wash fastness from moderate to low, depending on the mordanting, while avocado seed, on the other hand, has a better wash-to-color fastness (around 2–3) when proper mordanting is applied (Hinze & Clarke-Sather, 2024).

- Light fastness: Onion skin dyes tend to fade very fast compared to avocado seed dyes, which are more stable under light exposure (Ladekarl et al., 2023).
- Rubbing fastness: Onion skins perform better in dry rubbing than wet rubbing (Tatman & Gunaydin, 2021), and avocado seed, when applied using optimum techniques, can achieve good to excellent rubbing fastness (Utami et al., 2021; Kim & Bui, 2022).

Environmental Impact

The by-products of agriculture, like onion skins and avocado seeds, can also be used as dyes because they are biodegradable, non-toxic, and have little agricultural value. Their use decreases landfill contribution, lessens ecological damage, and encourages using local materials (Şapcı et al., 2017; Wijayapala & Peiris, 2017).

Case Studies

A comparative study on dyeing wool with onion skins found that iron-based mordants improved the color depth and brightness (Hinze & Clarke-Sather, 2024). In Viet Nam, optimized ultrasonic extraction from avocado seeds produced excellent-quality dye and cotton fabric with bright color and low ecological footprints (Kim & Bui, 2022).

4.2.2 Other Relevant Residues: Beetroot, Turmeric, Pomegranate Rind, Coffee Husk, and Mango Peels

Since some agroindustrial by-products such as beetroot (*Beta vulgaris*), turmeric (*Curcuma longa*), and pomegranate (*Punica granatum*) rinds, coffee husk, and mango (*Mangifera indica*) peels have been reported as potential natural sources of dye for textiles, their usage in such applications is gaining popularity. These by-products fit within the sustainability frameworks of APEC economies, as the recovery and use are aimed at reducing waste.

Chemical Composition of Pigments

1. **Beetroot** – The principal pigments in beetroot are betalains, which are responsible for vivid red and violet hues. These are further classified into betacyanins (e.g., betanin) and betaxanthins, both known for their antioxidant properties, which can enhance the functional value of dyed textiles (Das et al., 2023).
2. **Turmeric** – Turmeric's primary coloring agent is curcumin, a polyphenolic compound that produces an intense yellow color. Curcumin exhibits antimicrobial and antioxidant properties, particularly suitable for functional and protective textiles (Hanafy & El-Hennawi, 2022; Ly Do et al., 2024).
3. **Pomegranate Rind** – Rich in tannins and anthocyanins, pomegranate rind produces deep reddish-brown tones. These polyphenolic compounds also contribute antioxidant benefits that may extend textile longevity (Ahire et al., 2024; Habeebunissa et al., 2024).
4. **Coffee Husk** – Coffee husk contains chlorogenic acids and other polyphenols that generate earthy brown shades. While less documented than other residues,

research highlights its potential as a low-cost, sustainable colorant (Canpolat & Merdan, 2015).

5. **Mango Peels** – Pigments in mango peels are primarily carotenoids and flavonoids, producing bright yellow to orange hues. Their application in textiles has shown potential for vibrant coloration with minimal environmental impact (Awode et al., 2023; Helmy & Shakour, 2015).

Extraction Methods

- **Beetroot** – Commonly processed through boiling or soaking, with optimal pigment release occurring at high temperatures after 20–30 minutes. Yields can exceed 20% under favorable conditions (Das et al., 2023; Canpolat & Merdan, 2015).
- **Turmeric** – Extracted by boiling powdered rhizomes in water or ethanol. This method produces dye rich in curcumin and adaptable to various textile substrates (Hanafy & El-Hennawi, 2022; Ly Do et al., 2024).
- **Pomegranate Rind** – Typically macerated or boiled in hot water. A sequential process combining cold soaking followed by boiling has been shown to enhance yield efficiency (Ahire et al., 2024).
- **Coffee Husk** – Traditionally boiled to release colorants, with emerging techniques to improve yield and stability (Canpolat & Merdan, 2015).
- **Mango Peels** – Boiling and solvent-based extraction (ethanol or methanol) effectively produce concentrated dye solutions (Awode et al., 2023).

Dye Yield and Color Properties

Yields vary significantly by residue and method. Beetroot can provide yields exceeding 20%, turmeric typically 10–15%, and pomegranate rind under 10% unless optimized. Colors range from vibrant reds (beetroot) and yellows (turmeric, mango peels) to earthy browns (coffee husk, pomegranate rind). Mordanting with alum or iron often enhances color vibrancy and stability (Ahire et al., 2024; Hanafy & El-Hennawi, 2022).

Colorfastness

- **Washing Fastness** – Turmeric and pomegranate dyes generally exhibit better wash fastness than beetroot, which is prone to fading unless properly mordanted (Ahire et al., 2024; Hanafy & El-Hennawi, 2022).
- **Light Fastness** – Pomegranate rind and turmeric typically outperform beetroot, which is more light-sensitive (Ahire et al., 2024).
- **Rubbing Fastness** – Moderate for most residues; turmeric and pomegranate often perform better than beetroot, which benefits significantly from optimized fixation (Ramadhany et al., 2020).

Environmental Performance

These dyes are biodegradable, renewable, and less polluting than synthetic alternatives. Their use promotes waste valorization and aligns with low-impact manufacturing strategies, making them highly relevant for SMEs in APEC economies seeking sustainable production (Awode et al., 2023; Habeebunissa et al., 2024).

Case Studies

1. **Beetroot on Cotton** – Demonstrated successful coloration with various mordants, achieving vivid shades and retaining eco-friendly labels (Canpolat & Merdan, 2015).
2. **Turmeric Dyeing** – Applied to cotton and silk, yielding strong colorfastness when paired with natural mordants (Hanafy & El-Hennawi, 2022; Das et al., 2023).
3. **Pomegranate Rind on Cotton** – Produced rich, stable colors with commendable light and wash fastness, while contributing to waste reduction (Ahire et al., 2024; Habeebunissa, et al., 2024).
4. **Mango Peel Application** – Achieved vibrant hues and exemplified circular economy principles through waste utilization (Awode et al., 2023; Helmy & Shakour, 2015).

4.3 Types of Extraction Methods of natural dyes obtained from Agro-Industrial Residues

4.3.1 Conventional Extraction Methods

The basic and traditional methods of dye extraction − maceration, soaking, boiling, and decoction − still suffice for the extraction of natural dyes from agro-industrial waste because of their ease of use and their versatility, as well as potential for scale-up for SMEs. These methods differ in the amount of dye they produce, the color quality, the environmental impact, and the resources needed. These methods effectively extract value from waste materials like onion skins, avocado seeds, pomegranate rind, beetroot, turmeric, coffee husk, and mango peels.

4.3.1.1 Maceration

Maceration is a process of soaking plant material in a solvent, such as water, for a long time. While doing so, it is left in an open vessel at room temperature. Slow soaking methods always consume less energy and are economical as well. However, it is more disadvantageous than more rigorous methods of dye production, which involve the application of heat. The maceration of turmeric results in the capture of high yellow toners due to the presence of curcumin; however, it is far less than the quantities of curcumin captured when using the boiling method.

4.3.1.2 Soaking

Soaking is a quicker version of maceration, usually done at room temperature for a shorter time. Although the dye yields are satisfactory, subsequent heat treatments are often needed to enhance pigment release. Soaking pomegranate rinds, for example, yields a satisfactory first color but improves with boiling to enhance extraction (Ahire et al., 2024). Soaking mango peels is also known to produce bright colors for dyeing textiles, but they have a low ecological footprint because of low water and energy usage (Helmy & Shakour, 2015).

4.3.1.3 Boiling

Soak/boil the plants in water and heat them to let the pigment diffuse efficiently. This method is proven to have greater yields, even better than soaking and maceration. This is proven in the case of beetroot, which yields blistering records of above 20% during optimized boiling (Das et al., 2023). Boiling does use a substantial amount of water and energy, but the footprint can be lowered by reducing the times through optimized processes, and the color intensity is preserved.

4.3.1.4 Decoction

Decoction involves boiling down pomegranate rinds to separate and solubilize otherwise unattainable portions of pigment. Indirectly boiling aids in heat retention and actually dissolves the pigment. These colorants remain concentrated and stable, particularly useful for natural dyes. Decoction aids in high-value coloring and still fulfills the circular economy's eco-friendly and economic strategic goals. It provides energy that removes pigment waste attached to agro-industrial waste. It takes a lot of energy to accomplish, but in the end, it achieves what it sets out to do.

4.3.1.5 Comparative Evaluation

The choice of extraction method affects both the yield and the functional performance of the dyes. While boiling and decoction give richer and more stable colors, maceration and soaking offer SMEs more resources and cost efficiency. Mordant application is still crucial in improving color intensity and fastness for all methods. With suitable mordants, the washing fastness for turmeric and pomegranate-derived dyes for example, can achieve 4-5 ratings. Similarly, decoction-derived pigments tend to have the highest lightfastness (Hanafy & El-Hennawi, 2022; Ahire et al., 2024).

4.3.2 Advanced Extraction Methods

Technical progress has contributed to increase eficiency rate, improved preservation quality, and intensified the eco-friendliness of natural dyes from agroindustrial residues. This section focuses on ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), enzyme-assisted extraction (EAE), and supercritical fluid extraction (SFE) and their use on agro residues: onion skins, avocado seeds, pomegranate rind, beetroot, turmeric, coffee husk, and mango peels, especially in the APEC region.

4.3.2.1 Ultrasound-Assisted Extraction (UAE)

By using ultrasound, it is possible to gain higher ultrasonication frequencies while aiming cavitation bubbles at a target. This optimizes the plosive impact, increasing the rate at which plant cell walls break and colors escape. Compared to the boiling or maceration methods, ultrasonic extraction is quicker and more effective at boosting dye yields and enhancing the color. For example, UAE on pomegranate rind and turmeric increased the concentrations of anthocyanins and curcumin, resulting in more vivid colors (Variyana et al., 2024). Furthermore, the technique has been used on avocado seeds to produce a higher intensity and quality dye. UAE is one of the best methods for having the shortest extraction time and least energy use, which is favorable, particularly for small and medium enterprises. However, in practice, the price of ultrasonic technology remains a concern.

4.3.2.2 Microwave-Assisted Extraction (MAE)

MAE, just like other uses of microwave technology, heats solvents with microwave technology, increasing the dissolution and pigment release rate. However, microwave-assisted extraction or MAE techniques provide better yields and color vibrancy than other traditional techniques. For example, turmeric extraction using MAE developed improved yields of 20% greater than traditional techniques. On the other hand, application of MAE in high oleic and oilseed sunflower cultivars - known to be pigment-rich, appears to have higher pigment yields than the conventional boiling method, with even better color preservation (Devi et al., 2020). There are also notable advances in the method, like reduced water utilization and the time needed to perform the task; however, technology costs could be still high (Moosavi et al., 2021).

4.3.2.3 Enzyme-Assisted Extraction (EAE)

The use of enzymatic methods breaks down the cellular structures using certain enzymes, which helps release pigments without extreme chemicals. EAE has successfully extracted dyes from raw, fibrous residues such as mango peels and from other raw residues like coffee husk (Russdi et al., 2020) (Ramadhany et al., 2020). EAE methods tend to improve the extraction yield and the dye uptake, but there are other issues to consider, such as enzyme specificity, stability, and cost for bulk use. Still, the overall target reduction per chemical input definitely assists in achieving sustainable goals (Ramadhany et al., 2020).

4.3.2.4 Supercritical Fluid Extraction (SFE)

SFE employs supercritical CO_2 fluids as solvents, allowing pigment extraction without leftover organic solvents. This also helps to maintain the pigment's yield and integrity, as was the case for the highly concentrated beetroot extractions, where color was preserved with minimal degradation, for example, studies on the pigments of mango peels have shown SFE can produce stable and high-quality colorants (Batubara et al., 2025). SFE also has environmental benefits as the CO_2 is biodegradable and non-toxic. The major drawback is the technology cost (Micó-Vicent et al., 2020), which limits the use of SFE for small and medium enterprises.

4.3.2.5 Comparison with Conventional Methods

As shown in (Variyana et al., 2024; Devi et al., 2020), and others, advanced methods of extraction outperform even boiling, soaking, and maceration by providing a higher concentration of a dye, shorter times of extraction, and better stability of color. Removing and Ultimate Extraction (MAE and UAE) methods offer brighter shades with lightfastness, while EAE and SFE value green chemistry. Regarding SMEs, advanced extraction methods depend more on the ability to capital investments and the training needed to operate the technology.

4.4 Fixation Methods and Performance of Natural Dyes from Agro-Industrial Residues

Natural dyes used on products like onion skins or avocado seeds need precise fixation techniques for maximum dye absorption and dye retention properties. Fixation can be accomplished by several methods, including, but not limited to, the application of natural and metallic mordants. Other fixation techniques, such as pH or enzymatic methods, also exist. These methods impact critical loss of color metrics to washing, light, and abrasion—major parameters for determining the commercial and hand workmanship viability of dyed materials.

Natural vs. Metallic Mordants

Metallic mordants such as alum and iron remain common due to their consistent performance in enhancing color uptake and fastness in cotton and wool. However, bio-mordants from plant materials (e.g., pomegranate rind, coffee husk) are emerging as sustainable alternatives. These bio-mordants have demonstrated color strength and fastness results approaching those of metallic mordants, while reducing environmental impact (Vankar & Begum, 2023; Adeel et al., 2019).

4.4.1 Mordanting Techniques

Pre-mordanting

In pre-mordanting, the mordant is applied to the textile before dyeing. This process increases fibers' affinity for dye molecules, enhancing both color depth and durability. For example, alum pre-mordanting of cotton before dyeing with onion skin extracts has been shown to produce deeper shades and improve wash fastness ratings (Adeel et al., 2019).

Post-mordanting

Applied after the dyeing process, post-mordanting can intensify shades and improve fastness. Turmeric-dyed wool treated with iron salts post-dyeing exhibited richer colors and superior durability than pre-mordanting alone (Geelani et al., 2015; Vankar & Begum, 2023).

Simultaneous (Meta-) Mordanting

In simultaneous mordanting, mordants are added directly to the dye bath, enabling concurrent uptake of dye and mordant. This approach balances shade depth and fastness, with performance comparable to pre- and post-mordanting methods in specific applications (Manicketh & Francis, 2020).

Alternative Fixation Methods

1. pH Adjustment

Modifying the pH of the dye bath can influence dye solubility and binding. Acidic conditions generally enhance pigment absorption for vegetable-based dyes (Rotich, Wangila, & Cherutoi, 2022).

2. Enzymatic Treatment

Enzyme-based treatments can improve dye penetration and fixation without the environmental drawbacks of metallic mordants. When combined with bio-mordants, enzymatic methods can confer additional properties, such as antibacterial effects (Rashdi et al., 2020; Vankar & Begum, 2023).

4.4.2 Impact on Colorfastness Properties

- **Washing Fastness**—Pre and post-mordanting typically yield higher wash fastness ratings. For instance, turmeric-dyed cotton treated with mordants achieved ratings of 4–5, compared to 2–3 without mordants (Mulec & Gorjanc, 2015).

- **Light Fastness**—Mordanting can significantly improve resistance to fading. Avocado seed–dyed wool showed markedly enhanced lightfastness when post-mordanted (Abidin et al., 2015; Rather et al., 2016).
- **Rubbing Fastness** – The use of bio-mordants has been linked to better dry and wet rubbing fastness, particularly in cotton dyed with beetroot and turmeric extracts (Vankar & Begum, 2023; Mulec & Gorjanc, 2015).

Case Studies

- **Onion Skins** – Alum pre-mordanting of wool before dyeing produced vivid yellows with enhanced fastness, suitable for artisan production in APEC contexts (Adeel et al., 2019).
- **Avocado Seeds**—Pre- and post-mordanting with iron salts improved color intensity and wash fastness in cotton dyed with avocado seed extracts (Vankar & Begum, 2023).
- **Turmeric** – Post-mordanted wool and cotton retained superior color depth and stability (Geelani et al., 2015).
- **Pomegranate Rind**—Pre-mordanting with natural tannins from the rind yielded fabrics with excellent washability and lightfastness (Habeebunissa et al., 2024).

Conclusion

The fixation methods, from metallic mordants to enzymes and bi-fixation, affect the technical efficacy of agro-industrial waste products as natural dyes. Specialized methods for specific fiber types and constructed color properties improve naturally dyed textiles' ecological and functional properties as required.

4.5 Application of Natural Dyes to Textile Fibers: Cotton, Wool, Blends, and Animal Fibers

4.5.1 Chemical Interactions Between Dyes and Fibers

Natural dyes exhibit compatibility with animal and plant fibers primarily due to hydrogen bonding, ionic interactions, and van der Waals forces. The hydroxyl and amine groups present in the structure of cellulose in cotton and proteins in wool facilitate hydrogen bonding with dye molecules, enhancing dye uptake (Rather et al., 2020; Kumar et al., 2021).

- Onion Skins: The flavonoids extracted from onion skins form hydrogen bonds with hydroxyl groups in cotton, leading to improved color retention and depth of hue. Using mordants such as alum further enhances the binding abilities, yielding more intense colors on wool and cotton fabrics (Hanafy & El-Hennawi, 2022; Rather et al., 2016).
- Avocado Seeds: The polyphenolic compounds within avocado seeds also interact similarly with fibers. Studies show that the fibrous structure complements the dyeing process, resulting in better color adherence when treated with metal mordants (Islam et al., 2024; Rosyida et al., 2021).
- Pomegranate Rind and Turmeric: Colorants from pomegranate rind (predominantly tannins) and turmeric (curcumin) interact effectively with both natural and synthetic fibers. The binding capacities of these dyes can be

significantly increased with mordants, particularly on protein fibers like wool, enhancing dye yield and fastness properties (Ahire et al., 2024; Islam et al., 2024).

4.5.2 Role of Mordants

Mordants are critical in improving color intensity and fastness across various fibers. They enhance the dye-fiber bond and can also modify the shade of the dye.

- **Wool**: Research shows that wool treated with tannin-rich mordants from sources such as pomegranate rind yields vibrant colors with better fastness properties (Rather et al., 2020; Islam et al., 2024). The formation of coordination complexes between dye molecules and metal ions leads to enhanced dye retention (Islam et al., 2024).
- **Cotton**: Cotton fabrics dyed with natural dyes often require mordants for satisfactory color depth and shade variation. The application of alum or iron improves both color units and colorfastness, especially crucial for commercial use in textiles (Rosyida et al., 2021; Islam et al., 2024).
- **Blended Fabrics**: Due to synthetic fibers, natural dye uptake tends to be lower in blended fabrics. However, studies indicate that suitable mordants can optimize dye uptake and color intensity even in synthetic blends (Rosyida et al., 2021).

4.5.3 Comparative Performance Among Fiber Types

1. **Dye Uptake**: Natural fibers like cotton and wool generally exhibit higher dye uptake than synthetic blends. For instance, studies have indicated that cotton can absorb more dye when using avocado seeds or beetroot than wool (Afonso et al., 2023). Conversely, blends often demonstrate lower uptake, with dye yields sometimes halving due to the nature of synthetic fibers inhibiting dye penetration (Helmy & Shakour, 2015).
2. **Color Quality**: The color achieved on natural fibers tends to be more vibrant and complex. Natural dyes derived from turmeric or beetroot produce striking shades on cotton and wool, while the color intensity can be muted in blended fabrics (Variyana et al., 2024).
3. **Fastness Properties**: Natural fibers treated with appropriate mordants tend to have better light and wash fastness properties than synthetic blends. For example, lightfastness ratings on wool dyed with natural dyes can reach 4-5. At the same time, blended fabrics may achieve lower ratings due to the lesser affinity of the dye molecules for synthetic fibers (Rather et al., 2016).

4.5.4 Case Studies with emphasis in APEC Economies

1. **Onion Skin Dyeing**: A study demonstrated successful dyeing of wool fabrics with onion skin dye using alum as a mordant, yielding vibrant colors with excellent colorfastness properties (Hanafy & El-Hennawi, 2022).
2. **Avocado Seed Applications**: Research performed in Viet Nam utilized avocado seed extracts to dye cotton fabrics, resulting in high color depth and improved fastness. This is especially notable due to the economic viability of using food waste for dye production (Variyana et al., 2024; Islam et al., 2024).
3. **Turmeric and Pomegranate Rind**: Both dyes have been investigated in multiple APEC regions for their efficacy on cotton and wool. Studies report good color

uptake and durability on untreated fabric, highlighting the potential of these resources to drive sustainable practices within local economies (Ahire et al., 2024; Habeebunissa et al., 2024).

4. **Beetroot Dyeing**: Case studies show that beetroot can be used effectively on wool, achieving deep red hues with the aid of chamomile as a natural mordant, further emphasizing the eco-friendly attributes of these practices (Ramadhany et al., 2020; Devi et al., 2020).

4.5.5 Application of Natural Dyes from Agro-Industrial Residues to Animal Fibers, with a Focus on Alpaca

Onion skins, avocado seeds, pomegranate rinds, beetroot, turmeric, coffee husk, and mango peels are known agro-industrial residues. They are considered natural dyes with a strong affinity for some animal fibers, particularly wool and alpaca (Huacaya and Suri breeds). These animal protein-containing fibers have peculiar structural features that enable them to bind with considerable strength to dye species and thus fulfill sustainability requirements, along with high-quality dyes for the textile industry.

4.5.5.1 Dye Uptake Mechanisms and Compatibility

Due to the unique structural formation of animal fibers, their protein content allows them to bind natural dyes of any woof or warp by means of hydrogen bonds, van der Waals bonds, and even ionic bonds. Keratin has polar and charged amino acid residues, which increases its attraction to the dye molecules (Kovačević et al., 2021).

1. Alpaca and Wool: The two fibers have an almost equal capacity for high dye uptake, which is further increased by the use of mordants or bio-mordants. Results show that wool and alpaca offer higher yield and a more intense color when dyed with pigments derived from agro-waste compared to plant-based fibers (Kovačević et al., 2021; Rusmini et al., 2020).

2. Silk: Silk, another protein-based fiber, has similar dye-binding properties. However, the dyeing process has to be done cautiously because silk's smooth surface morphology requires the fixation parameters to be controlled carefully to achieve the same color intensity and fastness as the other substrates (Patel et al., 2023)

4.5.5.2 Fixation Methods

The method for fixation changes the performance of the dye on animal fibers:

- Pre-mordanting with aluminum salts on wool promoted the uptake of onion skin pigments, yielding deeper hues with superior wash fastness (Correia et al., 2021).
- Post-mordanting permits controlled modifications of colors; wool dyed with avocado seed and then post-mordanted with ferrous salts attained richer shades and greater fastness (Pei et al., 2023; Rusmini et al., 2020).
- Simultaneous mordanting supports dyeing with turmeric as it permits the simultaneous absorption of dye and mordant (Kovačević et al., 2021).

Comparing Natural and Synthetic Mordants

Among plant-based mordants, tannins in pomegranate rind have been shown to improve the uptake and colorfastness of the dye while possessing a lower environmental impact. Though metallic mordants yield greater fastness ratings, bio-mordants are a viable, sustainable option with comparable performance (Pei et al., 2023; Rusmini et al., 2020).

Other Methods of Fixation

- Patel et al. (2023) and Kovačević et al. (2021) demonstrated that adjusting pH levels to more acidic (4-5) conditions allows certain dye compounds to bond with the substrate more easily and, therefore, result in higher yields of turmeric and mango peel dyes.
- Pei et al. (2023) and Kovačević et al. (2021) report that the application of proteolytic enzymes is capable of increasing the accessibility of dye sites in the color-printed wool and silk fabrics and, therefore, contributes to color improvements in depth and uniformity.

4.5.5.3 Colorfastness Properties

For the practical use of textiles, colorfastness is an important factor to be considered:

- Washing fastness: Rusmini et al. (2020) reported that wool dyed with pomegranate rind and pre-mordanted with aluminum sulfate has achieved launderability ratings of 4–5, which is an excellent level of resistance to laundering.
- Light fastness: Pei et al. (2023) and Rusmini et al. (2020) reported that ferrous sulfate mordants improved the stability of wool dyed with avocado seed at light.
- Rubbing fastness: Rather et al. (2016) found that bio-mordants improved dry and wet rubbing fastness, making them a suitable replacement for metallic mordants in environmentally conscious dyeing.

4.5.5.4 Conclusion

The application of agro-industrial waste-derived dyes on animal fibers, especially alpaca, is a technically and ecologically solution for sustainable textile production. The technical ease of fixation for natural dyes on protein fibers, coupled with fixation methods like traditional mordanting and modern enzymatic fixation, and their eco-friendly coloration processes, provides remarkable positive outcomes.

5 Relevant International Experiences, emphasis on APEC Economies

5.1 Introduction

This chapter focuses on the experiences of APEC economies that represent various aspects of natural dye development from agro-industrial wastes, that are published in non-indexed literature like technical reports, commercial documentation, websites, particular events among others. This variety of sources makes it possible to explore knowledge often absent from the scholarly records and record practical applications based on creative advancements.

The APEC region is of great importance to the global textile industry. It includes economies within its fold whose traditions span generations in natural dyeing and those at cutting-edge technology in sustainable textile production. Economies like Indonesia; Japan; Peru; Thailand and Viet Nam, for instance, have long histories of employing natural dyes and other agro-industrial and agricultural residues, like the cochineal dyeing of alpaca fibre in the Andes, batik in Indonesia with plant-based pigments, and the Shibori indigo dyeing techniques in Japan. At the same time, other APEC members like China; Korea and the United States are also engaged in the development of biotechnological and industrial approaches, natural dye production via synthetic biology, enzymatic and agro-waste processes, and downscaled industrial processes of biowaste valorization.

In the case of APEC, the re-emergence of natural dyes can be researched as a unique laboratory. Artisanal and community practices can illustrate the cultural value of dyeing and its local adaptation, more often than not relating it to biodiversity and the principles of a circular economy. On the other side, technological solutions to the issues of colour fastness, standardisation, and industrial scale are being developed for regional enterprises and research centres. The intertwining of heritage and innovation in the APEC context makes it particularly suitable for study on the transformation of agro-industrial residues into sustainable sources of textile colourants.

Throughout the study, commonly cited agro-industrial wastes are the rinds of pomegranates, onion skins, walnut husks, grape pomace, and tomato waste. These residues are already well-known for being rich in tannins and other phenolic compounds, which beautifully and functionally provide antibacterial and UV-protective properties integrated into the dyes. These qualities are also pointed out in technical reports and artisan manuals (Instituto Tecnológico de Producción (ITP), 2023; Kraftkolour, 2017).

Many reports also explore residue-based dyes and other extraction methods to maximize dye yield. Theses and manuals feature bio-mordants of plant tannins as substitutes for metal salts and microwave—or ultrasound-assisted extraction (Karuppuchamy & Annapoorani, 2019). Although not yet standardized on an industrial level, these methods highlight the resourcefulness present in grey literature as an early response to the anticipated sustainability issues.

Importantly, grey sources also analyze the practical incorporation of residues into artisanal and semi-industrial contexts. Descriptions and case studies from the Latin American and Asian regions highlight the use of kitchen organic waste (such as avocado pits, maize husks, and citrus peels) in community workshops and cooperative ventures, wherein the waste residues transform into cost-effective and accessible dye sources (Maiwa – Canada, 2024; Ponce-Cano et al., 2023). At the same time, corporate reports and patents indicate that companies like Archroma and Colorifix have drawn inspiration from such feedstocks to develop scalable, traceable, and certified commercial products (Archroma, 2020; Cambridge Patent the US 11,781,265 B2 2023).

5.2 Natural Dyes in the World: A Geographical and Historical Overview

5.2.1 Historical Background

The historical narrative of natural dyes is closely linked with the development of agriculture and the different cultures of weaving and textiles. These records and archaeological findings confirm the use of different materials such as plants, insects, and even minerals for dyeing in different civilizations on different continents. For instance, garments and ceremonial textiles in ancient Mesopotamia and Egypt were made with madder roots (*Rubia tinctorum*), saffron, and indigo. In India and China, domestic production and long-distance Silk Road trade were associated with dyeing indigo and turmeric. Peru pre-Inca cultures, such as the Paracas, provided extraordinary evidence of colorful textiles dyed with natural dyes dating back more than two thousand years. Other mesoamerican civilizations such as the Maya and Aztecs had also advanced cochineal dye (*Dactylopius coccus*) cultivation, which would later decimate the world's textiles market. (Bechtold et al., 2023).

From the earliest times, dyeing was not solely from cultivated species, but also from agricultural by-products and residues. Tree barks, fruit skins, husks, and leaves, which are often thrown away after harvest or food preparation, were used widely in dye baths. Onion skins, pomegranate rinds, and walnut shells are examples of what today are called agro-industrial residues, but which were already used in a variety of recipes throughout Eurasia and the Mediterranean in the past (Baaka et al., 2017; Karuppuchamy & Annapoorani, 2019). To this extent, the agricultural waste valorization for dyeing is not a contemporary development; rather, it is a continuity of ancient practices now reframed in the current sustainability discourse.

The global diffusion of natural dyes is associated with expanding trading routes. In the early modern period, indigo and cochineal were of the highest value, and they supported the economic web that connected Asia, the Americas, and Europe. In particular, between the sixteenth and nineteenth centuries, cochineal imported from Mexico and Peru was the most sought-after worldwide due to its brilliant red color and strong dyeing properties (Bechtold et al., 2023). Simultaneously, local practices also used agricultural residues, such as maize husks, avocado skins, and grape pomace, which reveals the strong interconnection between agriculture and textile dyeing.

The course of history was altered when William Perkins synthesized the first coal-tar aniline dye, mauveine, in 1856. Synthetic dyes became widely available after their debut. The shift from authentic to synthetic dyes was primarily due to their affordability, reproducibility, and durability (Popescu et al., 2021). Because of this, the use of natural dyes and agro-residue valorization in textile applications faced a gradual decline.

Natural dyes were, however, reintroduced in the late twentieth to twenty-first century due to the focus on environmental sustainability, eco-friendly fabrics, and free market regulations. Numerous publications from different economies, academic writings, and the renowned artisan community have recorded this reintroduction. Guides such as *The Maiwa Guide to Natural Dyes* and *Natural Dyeing for the Artisan Dyer* promote the use of onion skins, pomegranate peels, and avocado pits as intensely green and readily available sources of dye (Maiwa - Canada, 2024; Kraftkolour, 2017). These publications illustrate grassroots efforts' role in preserving and reimagining residue-based dyeing techniques.

Histories of natural dyes tell us two things. First, agro-industrial waste for textile dyeing has been employed throughout history, from ancient times to the modern world. Second, the 'return' of such practices reflects both a yearning for the past and a purposeful engagement with the current sustainability practices. These two angles of seeing things—tradition and modernity—make it possible to analyze the emerging trends and the spread in the use of natural dyes across the world, particularly in the APEC region.

5.2.2 Global and Regional Distribution

5.2.2.1 Asia and the Pacific

Asia and the Pacific regions have been and continue to be innovators and trendsetters in colorant practices in textile technology and culture. The region's practices exemplify the importance of culture around dyes and dyes derived from agricultural by-products, which today would be called agro-industrial residues, as the key materials for sustainable coloration.

In the case of India and the trade in indigo (Tinctorial indigo), indigo came to be one of the most sought dye commodities in world trade. In the case of turmeric (Curcuma longa), it came to be extensively used not only as a dye for textiles but also for foods. Importantly in the case of turmeric dyeing, not only the high-grade rhizomes were used, but also leaves, surplus roots, and powders which were not fit for culinary application. In the same way, the pomegranate rinds and onion skin indigo dyed from food waste from food cooking are a part of India's traditional dye practices, which is a step toward agro residue utilization (Karuppuchamy & Annapoorani, 2019).

In Japan, paintings and silk cloth using indigo dyeing (aizome) and techniques such as shibori resist-dyeing achieved sophistication and were sometimes mastered by these art forms and crafts, which were admired and sought after worldwide. Beyond indigo leaves, Japanese traditions used persimmon peels (kakishibu) and sake lees as mordants and finishing agents, and they were by-products of the dyeing, agriculture, or fermentation processes. These crafts showed how, long before sustainability was even considered, Japanese artisans incorporated and masterfully crafted waste minimization techniques into their dyeing and even crafted reuse systems (Bechtold et al., 2023).

The Korean dyeing traditions shed light on incorporating and dependence on agricultural residues. Walnut shells, acorn husks, and barks drawn from the forestry residues are incorporated and furnish the tannins used as mordants and auxiliaries. All these contributed to the advanced and broader Korean textiles chromatic diversity, which fostered and reinforced the value of cultural resource efficiency, which is becoming more relevant nowadays.

Indonesia and Thailand are the only economies in the region still using natural dyes on silk and batik cloth. Thai craftspeople have historically used lac and the residue from turmeric processing. More recently documented sources attest to the use of wastewater from the fermentation of legumes, discarded mango peels, and the waste from the food processing of the mangosteen, all of which are currently in the food industry. Indonesia, during the batik-making process, used the other parts of the plant, such as bark and the peels of some fruits, as well as leaves that were left after harvesting, thereby integrating art and agriculture (Bechtold et al., 2023; Baaka et al., 2024).

Practitioners today still understand the importance of these residues. Books such as The Maiwa Guide to Natural Dyes stipulate that artisans use first discarded plant residues, such as the skins of onions, the pits of avocados, or the peels of pomegranates, and only later move to more specially grown dye plants (Maiwa, n.d). This supporting literature shows the blending of traditional artisanal practices with modern sustainable practices.

In the Asia and Pacific regions, the use of residues for dyeing is not a novel practice but a long-standing one. The APEC economies that incorporated agro-industrial by-products into their textile practices are now a case study for the modern renaissance of agro-residue dyeing, illustrating the seamless merger of cultural legacy with green practices.

5.2.2.2 Europe and the Mediterranean

Equally important in the art and practice of natural dyeing, the European and Mediterranean region seemed to have given the art of dyeing its due recognition through the cultivated dye plants and the by-products of agriculture, even down to its fibers and its pigments of cloth. The cultivated dye plants and the by-products of agriculture are more than sufficient to explain the peculiar synergy everywhere in the region. The dyeing of viticulture, olive, and nuts alone more than attests to the boundless and rich potential of natural dyeing.

As discussed in historical European dyeing practices, beyond the well-known plant sources such as madder (Rubia tinctorum), woad (Isatis tinctoria), and saffron (Crocus sativus), a wide variety of agricultural and plant-based residues were also traditionally used as dye precursors. These included by-products from crops cultivated alongside olives, nuts (particularly macadamia), and grapes—staples of Mediterranean agriculture. Olive residues were especially valued for their deep earthy tones, while walnut shells and husks provided rich browns and blacks (Baaka et al., 2017). Similarly, grape pomace and skins yielded reddish to purplish hues reminiscent of vintage wines. In these practices, the intensity of color often increased with the degree of crushing or fermentation, revealing the close relationship between agrarian by-products and the palette of natural dyes in early European craftsmanship.

Some of the earliest recorded circularities in dyeing practices are seen in the Mediterranean model. Farmers and artisans incorporated food-processing waste into the dyeing process, which reduced waste while increasing the number of colors available. Farmers and artisans integrated agriculture and textiles in Italy and Spain, which had constant by-products from viticulture and olive oil production used in artisanal workshops. Such practices show that agro-residue valorization is a historical fact, not a recent innovation.

Mediterranean dyes were not restricted to the region alone. By the fifteenth century, ports like Venice and Sevilla were important trading centers for madder, walnut, and cochineal imported from the Americas, connecting Europe's traditions to the world. The economy and agro-residue circulation demonstrate how natural dyes cultivated local economies and constructed international trade systems.

Currently, artisan manuals refer to these remnants as convenient and easily obtainable resources for sustainable dyeing. The Maiwa Guide to Natural Dyes and Natural

Dyeing for the Artisan Dyer recommends walnut husks, pomegranate peels, and grape reminents as residue dyes, keeping the tie to the historical dyeing practices from the Mediterranean alive (Kraftkolour, 2017; Maiwa—Canada, 2024).

5.2.2.3 The Americas and Africa

In the Americas and Africa, natural dyeing was more than just an agricultural activity; it was woven into the societal fabric. Here, dyeing with natural substances was not restricted only to enricher crops but also incorporated waste materials like husks, shells, peels, and fermentation residues.

In Mesoamerica, Mexico became the cochineal (Dactylopius coccus), cultivation and cochineal feeding as a plant insect in the center of the world, and cochineal was extensively exported to Europe after the sixteenth century. In addition to cochineal, local communities incorporated walnut husks, pomegranate rinds, and marigold flowers, which were regarded as agricultural waste, seasonal surplus, or strong support for upper layers to enrich their dyeing palettes (Bechtold et al., 2023). These practices demonstrate a strong precedent in the circular artisanal dyeing of farming byproducts.

In the Andean region, especially in Peru, alpaca and cotton textiles have historically been dyed with cochineal and diverse agro-residues. Ethnobotanical uses of onion skins, avocado peels, and purple maize husks, common agro-food remnants, have been documented (Baaka et al., 2024). Aside from variety and functional attributes such as the antibacterial from pomegranate and UV protective maize anthocyanins, these residues also contributed diverse shades. Such practices are still present in rural cooperatives, where community-based innovations in dyeing include agricultural residues.

While the United States may have historically been limited in using natural dyes compared to Latin America, current practices show strong innovation with residues. Artisanal movements and start-ups have encouraged using corn husks, soy residues, and fruit peels as sustainable dye sources (Kraftkolour, 2017; Maiwa - Canada, 2024).

The art of using natural dyes is understood to have deep historical roots in Africa, especially in Indigo fermentation in West Africa, where indigo resist-dyeing is still in practice. Aside from the indigo, the dye baths utilized in resistance dyeing included the barks, seeds, and leaves of other plants, many of which were agricultural and forestry wastes collected in a season (Bechtold et al., 2023). These auxiliaries are said to have constructed tannins that were a mordant, increasing the practicality of dye wastes and ensuring their availability and the strengthened dye fastness.

In contrast, the cochineal and maize husks of Peru, the walnut shells of Mexico, and the bark extracts of West Africa are examples of agricultural byproducts that were used in traditional dyeing and illustrate the natural dyes and agro-residues cultural association that has also been documented in Africa and the Americas. These methods have been passed on culturally, with a sustainability model, reinforcing textiles' unbroken historical line of residue-based coloration.

5.2.3 Emerging Trends in APEC Economies

5.2.3.1 Traditional Knowledge and Agro-Residue Valorization

A prominent trend is the revitalization of traditional dyeing practices and their use of agro-industrial residue within APEC economies. Rather than being a new practice, the use of agricultural byproducts is culturally embedded and now discussed in the context of sustainability and a circular economy.

In Latin America, Mexico and Peru beautifully demonstrate this fusion of tradition and waste valorization. Peru's traditional textile history is paired with the famous cochineal dyeing on alpaca and cotton. However, ethnographic and technical reports also document the use of onion skins, avocado peels, and purple maize husks, which provide yellow, green, and purple shades (Baaka et al., 2024). These practices showcase the purposeful incorporation of food-processing byproducts into the dyeing process, which aligns with contemporary waste minimization aims. So too in Mexico, while cochineal is still symbolic, waste materials such as walnut husks, pomegranate rinds, and marigold flowers, which are the byproducts of agriculture, are central to artisanal dyeing and still support rural communities (Bechtold et al., 2023).

The skillful integration of natural dyes in traditional Southeast Asian textile practices—such as Thai silk painting and Indonesian batik (Bechtold et al., 2023)—illustrates a deep knowledge of agro-based resources and fermentation processes. In these traditions, plant residues and natural extracts from beans, grains, and fruits are commonly used as dye sources or mordants. For instance, lichens serve as both colorants and fabric modifiers, while residues from indigo fermentation are reused together with sake lees and *kakishibu* (fermented persimmon solution) to enhance dye stability and tone. In Korea, artisans have historically employed decoctions made from walnut shells and acorns to produce deep brown hues, often applied to silk or crepe fabrics using immersion or resist-dyeing techniques.

5.2.3.2 Challenges and Opportunities for Scaling

APEC economies have a long history of integrating agricultural residue into textile dyeing; however, the primary shift from artisanal to industrial-grade production remains a significant challenge. Grey literature and practitioner reports continuously document the technical, logistical, and market barriers that have to be overcome for agro-industrial residue natural dyes to be used as natural dyes in the mainstream textile industry.

Among the most frequently cited challenges are the issues of poor color fastness, tonal variation, and limited reproducibility. Natural dyes extracted from residues such as onion skins, pomegranate peels, and maize husks often display unstable chromatic behavior, as their final hues depend on seasonal variations, geographical origin, and extraction techniques. These inherent fluctuations make consistent comparisons with synthetic dyes difficult, since the latter deliver standardized and predictable results (Dobreva, 2025). Although bio-mordants derived from plant biomass or biochemical sources are far less harmful to the environment, they still fall short of meeting the industrial requirements for color durability and uniformity (Sustainability Directory, 2025).

A different challenge deals with consistency in the supply of residues and their scalability. Furthermore, the byproducts of fermentation, nut husks, and some fruit peels, arise in discontinuously dispersed regions and in fluctuating proportions. This makes establishing an uninterrupted supply on an industrial level highly difficult. The concerns of some regional firms differ from those of local artisans, who are more flexible and willing to work with seasonal resources to survive. The local artisans work in a survival economy, while the larger corporations are operating in a wide economy, requiring consistent supply, reliable processed materials, and specific supply routes (Baaka et al., 2024).

These problems are a microcosm of the bigger picture, wherein economic considerations are still lacking and unconstrained. The cost of processing, collecting, storing, pre-processing, and quality control becomes paramount. Although residues originate from the land or are considered free in the source region, and are regarded as eco-friendly, such expenses render their free nature redundant and expensive on a larger scale (Sustainability Directory, 2025).

While some of the opportunities are glaring, the scope for improvement still lies. Growing environmental concerns, coupled with an increase in the market for sustainable, eco-friendly textiles, drive the firms dealing in agro-residue dyes to explore their products. Positive initial results by some economies, such as Japan; Peru; and Thailand, indicate the potential for the residues to be used for artisan-focused, specialized, eco-friendly industrial applications. Reports and commentaries suggest a bonanza for the economies where artisans, along with brands and researchers, are willing to work together in order to bring the traditional methods over the growing heritage while also bridging the gap, and the scale at which they are accurate to modern textiles (Dobreva, 2025).

To conclude, the APEC region has the dual challenge of overcoming the barriers of residue-based dyeing traditions with technical and logistical limitations. If such barriers are surmounted, APEC economies will likely be the first to develop sustainable models for dye production that, within the framework of a circular economy, contribute to the ecological transformation of the global textile industry.

5.3 Technological Development and Business Innovation

5.3.1 Introduction: Business Innovation in Natural Dyes

The industrial uptake of natural dyes derived from agro industrial residues hinges less on discovering new chromophores than firms' ability to convert heterogeneous bio feedstocks into repeatable, certifiable, and traceable color solutions at scale. In practice, this requires solving four interlocking problems that academic studies and artisanal manuals rarely need to address simultaneously: (i) batch to batch consistency (including colour strength and shade reproducibility), (ii) performance against industry test methods (e.g., wash, rub, and light fastness), (iii) supply assurance and quality control of residue streams (moisture, phenolic profile, contaminants), and (iv) regulatory, certification, and brand compliance (restricted substances, worker safety, LCA/traceability).

Corporate materials and patent filings from leading actors indicate that competitive advantage emerges from integrated business–technology models rather than isolated laboratory techniques. Three complementary pathways can be distinguished:

- **Residue to dye process platforms**. These systems transform agricultural and food processing byproducts (e.g., nutshells, fruit peels, plant trimmings) into standardized dyestuffs with documented provenance and process control. In corporate brochures and sustainability reports, this approach is framed around traceability and circularity claims, pairing chemistry and supply chain management so that variable residues can be converted into spec grade products acceptable to global brands (Archroma, 2023; Archroma, 2024; Archroma, 2025).

- **Microbial dyeing and biosynthesis**. Here, colour molecules (or dye precursors) are generated by engineered microorganisms and applied through aqueous processes under industrial conditions. Company disclosures and a patent document show an emphasis on process intensification (reduced water/energy inputs), the possibility of using sugar rich byproducts as fermentation substrates, and IP protected strain/process control to deliver consistent shades at mill scale (Cambridge Patent nº the US 11,781,265 B2, 2023; Colorifix, 2022; Colorifix, 2025).
- **Niche market enablement and capability building**. Specialist suppliers oriented to the artisan/SME segment lower adoption barriers by curating natural dye ranges, auxiliaries, and know how for consistent small to medium runs. Although not equivalent to large scale chemical vendors, they bridge practice and market, expand demand for residue based colourants, and create stepping stones for regional ecosystems (Kraftcolour, 2025; Fashion for Good, 2022).

Across these models, firms converge on industrial validation as the key currency of credibility. Beyond spectral profiles and lab recipes, what persuades brand partners is evidence of repeatability under production constraints (e.g., substrate variability, line speed, liquor ratio), alignment with certification frameworks (e.g., organic textile standards and restricted substance lists referenced in corporate materials and practitioner guides), and traceable material stories that survive supply chain audits (Archroma, 2023; Fashion for good, 2022; Cambridge Patent nº the US 11,781,265 B2, 2023). Patents function as legal protection and as signals of process maturity, documenting unit operations, control parameters, and claims around feedstocks or microbial pathways (UK Patent nº the US 11,781,265 B2, 2023).

From a strategic viewpoint, the firms in focus demonstrate how business design (feedstock contracting, QA protocols, certification roadmaps, brand integration) is inseparable from technological design (extraction trains, microbial platforms, application methods). Residue based colourants become viable for the fashion and home textile sectors when companies can guarantee specification stability and compliance at scale, not merely when a pigment can be extracted.

5.3.2 Archroma and the EarthColors® Innovation

Archroma incorporates agro-industrial residues in dye production managed by SK Capital Partners (United States), headquartered in Switzerland. Archroma has developed a remarkable reputation for converting agricultural and food waste into dyes for critical international textile manufacturers, becoming one of the leading dye manufacturers in the world, utilizing food and agro-industrial waste.

EarthColors is Archroma's flagship technology. It is a patented process of converting otherwise waste residues from the agricultural and herbal industries, such as almond shells, saw palmetto, rosemary, bitter orange peels, beet residues, and cotton byproducts, into fully traceable dyes (Archroma, 2023; Archroma, 2024). The difference between EarthColors and traditional methods is that the former uses a systematic, controlled chemical process to extract and stabilize dyes, yielding consistent and reproducible shade outputs.

One of the most unique features of EarthColors® is the integration of traceability and transparency into the product offering. Archroma explains that products developed under this platform include a digital traceability system that allows brands and consumers to track the precise agricultural source of the residue feedstock. This has appealed to large international textile firms wanting to substantiate their sustainability claims, and has enabled the EarthColors® offering to be woven into the United States, Europe, and Asia (Archroma, 2024).

From a performance point of view, Archroma highlights that the EarthColors® dyes can be used with the existing dyeing infrastructure and provide the fastness and durability properties of international compliance. In addition, the EarthColors® dyes have several eco-certifications, including GOTS, Bluesign®, and Cradle to Cradle® (C2C), which further enhances their competitive position with brands that are sustainability compliant (Archroma, 2025).

Thanks to Archroma, EarthColors® is an innovation that proves that overcoming natural dye barriers, such as reproducibility, fastness, and regulatory acceptance, is possible. Archroma's patent, certification, and embedded agro-residue valorization processes streamline industrial credibility alongside sustainability. This illustrates that even APEC companies headquartered outside the region but US-owned and working in Asia can influence the region's sustainable dyeing practices.

5.3.3 Colorifix and Microbial Dyeing

One of the most revolutionary business models in sustainable textile dyes is Colorifix Ltd., a biotech start-up based in the United Kingdom. While not in an APEC economy, the company works globally, including in the United States and Asia. As a result of its approach to technology, it demonstrates the industrial pathways of transformational potential bio dyeing. Colorifix is a spinout company from the University of Cambridge. It has been funded by Cambridge Enterprise and the H&M CO: LAB, which illustrates the robust connections of academic research, venture capital, and global fashion companies (Colorifix, 2022; Colorifix, 2025).

Built into the foundation of Colorifix's innovation is the patented biosynthesis of dyes with engineered microorganisms. Pigments are not synthesized from petroleum precursors chemically, but rather from fermentation, as Colorifix inserts the DNA sequences that encode natural color molecules into microbes that reproduce the dye. The microbes can be fed with low-value sugar streams, including food and agricultural industry residues, integrating waste valorization directly into the production process (Cambridge Patent nº US 11,781,265 B2, 2023). The principle of circularity is the paradigm of waste being turned into a valuable input. This approach turns the synthesis process from chemical to biological and embodies circularity.

Environmental performance is key to Colorifix's business. Data from Colorifix show that their process of dyeing textiles using microbes saves 49% on water, 35% on electricity, and 31% on CO_2 dyeing emissions compared to traditional dyeing methods (Colorifix, 2022). These data, pilot projects, and partnerships with brands lend credibility in an era when sustainability claims are being examined more closely.

From a business perspective, adopting Colorifix technology is more attractive when integrated with dyeing shops than constructing new ones. This decreases the capital cost of adoption and increases the availability of the DI solution. Also, her IP (e.g., the US Patent 11,781,265 B2) on proprietary microbial methods of dyeing still is cryptic in the industry's fabric, confirming the cardiolytic readiness.

In contrast to large firms like Archroma, Colorifix showcases a different style of leadership. Colorifix shows the efficacy of bypassing chemical synthesis through a biotechnological approach, using agricultural waste for microbial dyes, while Archroma optimizes color extraction and chemical stabilization of agro-residue. In the case of APEC economies, the cornerstone of Colorifix lies in its model transferability. Regions with a high concentration of sugar and carbohydrate agricultural residues and industry, like some economies in South Asia or Latin America, are ideal for deploying microbial dyeing technologies.

5.3.4 Fashion for Good: Pioneering Sustainable Innovation in the Textile Industry

Fashion for Good is a global innovation platform that disrupts the fashion industry by improving its climate and social footprint. The goal of such an organization, founded in 2017, is to stimulate and focus on a closed-loop, sophisticated system of fashion, enabling regenerative and breakthrough innovations. At the center of his innovation is a systems approach and vertical integration of the entire value chain of collaboration with the brands, manufacturers, innovators, and financiers to adopt sustainable solutions (Fashion for Good, 2025).

One of the innovation focal points is the development of sustainable materials and processes, emphasizing dyeing and finishing textiles, which is the most environmentally burdensome. The Innovation Platform of the Fashion for Good organization scouts, supports, and finances emerging (bio-based, recycled, and waste-converted) technologies. Among others, Fashion for Good has pioneered the valorization of agro-industrial waste through the Agriwaste Natural Fibres and Untapped Agricultural Waste Projects, and has demonstrated the technical and economic practicability of agricultural residues workshops (Fashion for Good, 2025).

Altough, no flagship project has yet been aimed at natural dyes from agro-industrial waste, Microbial Dyeing startups of APEC economies have been recognized such Sodhani Biotech Private Limited, from India. By fostering partnerships, funding, and sharing knowledge, Fashion for Good facilitates the shift towards a circular, low-impact textile industry. This will allow the broader adoption of natural dyes procured from agro-industrial waste (Fashion for Goods Website, 2025).

5.3.5 Kraftkolour: A Sustainable SME Model Bridging Craft and Innovation

Another noteworthy reference is Kraftkolour (Australia), a long-established supplier and educator in the field of sustainable textile dyeing. The company has specialized in the commercialization of natural dyes and auxiliaries, offering plant-based pigments and eco-friendly mordants adapted for both artisanal and semi-industrial applications. Beyond sales, Kraftkolour has developed training programs, technical manuals, and demonstration kits, contributing to capacity building in the textile sector. Its approach represents an important bridge between craft-based traditions and modern market demands, emphasizing product traceability, safety, and reproducibility. This model demonstrates how a medium-sized enterprise can sustain innovation through education, environmental responsibility, and close engagement with the creative industries — values fully aligned with APEC’s circular economy principles.

5.3.6 Concluding Remarks

The examples of Archroma, Colorifix, and Kraftkolour show how the shift from natural dyeing techniques to practical and industrialized solutions is not futuristic anymore but a reality due to the vision of entrepreneurs. Each of these companies shows a different model of innovation. Archroma, a Swiss company predominantly owned by the US capital, demonstrates how a multinational can utilize the agro-industrial waste with

EarthColors® to provide certified and traceable products that fulfill international performance standards. As a biotechnology start-up, Colorifix is an example of how microbial dyeing and the valorization of low-value sugar streams can change the production paradigm while enhancing eco-sustainability. Kraftkolour is an Australian company operating in the APEC region, demonstrating how smaller companies can serve a niche market, develop capabilities, and widen the constituency base for residue-based dyes.

Understanding these cases is crucial for APEC economies. They demonstrate that success stems from having the patents and technologies to integrate and trace certified processes and residues into patented supply chains.

5.4 Case Studies in APEC Economies

5.4.1 Indonesia: Batik Heritage and the Transition to Agro-Residue Dyeing

5.4.1.1 Cultural and Traditional Dimension

Batik is renowned for its exquisite artistry and serves as a lasting symbol of Javanese culture and its influence throughout the archipelago. UNESCO has recognized the craft as a piece of the world's intangible heritage. The intricate designs of batiks and their woven stories illustrate the spirit of Indonesia. The cloth serves as a cultural and historical narrative that transports the storyteller and her audience to the heart of Java and other representative regions.

However, starting in the late 19th century, natural colorants began to be replaced by synthetic dyes. Cheaper prices, faster processing times, and the ease of reproduction drove the appeal of synthetic materials. Consequently, many batik producers abandoned natural recipes, and knowledge of residue-based dyeing fell out of fashion (Widiawati, 2009). Nonetheless, the last few decades have seen a revival movement fueled by cultural pride and a concern for the environment. Artisans and cooperatives are progressively re-adding natural residue-based dye recipes to batik production, framing natural dyeing as a means of preserving heritage and tackling global ecological issues (Yuniati et al., 2025).

5.4.1.2 Scientific Advances and Contemporary Challenges

In Indonesia, batik culture was connected to modern science, research, and policy efforts that tried to explore the potential of agro-industrial byproducts to produce sustainable dyes for textiles. Producer and academic investigations demonstrate significant breakthroughs and stubbornly persistent hurdles to more widespread use.

Advanced and applied research has concentrated on improving the fastness of natural dyes, which is one of their most significant drawbacks compared to synthetics. One study on the application of natural dyes on cotton showcased that the treatment with chitosan, a bio-based polymer from the crustacean shell, significantly enhanced the wash, rub, and light fastness after the chitosan was used (Febri et al., 2021). This bio-finishing type can substantially improve agro-residue dyes' color stability, thus enhancing their competitiveness in contemporary textile value chains.

Other studies have reevaluated the dyeing ability of tropical byproducts like mango leaves, mangosteen peels, and coffee husks for their colors and environmental values (Yuniati et al., 2025). Such studies have proven the residues' ability to yield varied shades of yellow, brown, and red, thereby helping in the waste management of the agricultural sector of Indonesia. The researchers still point out the unreliability of the results due to seasonality and extraction techniques, which makes industrial reproduction pricier.

At the socio-economic level, surveys conducted with batik producers (over 200 in total) have reported that the dependence of the adoption of natural dyes on technical proficiency is superficial. The willingness to use natural dyes hinges on the appreciation of the environment, cultural pride, and social values, while being constricted by the fear of the expenses involved, time required, and the overall profitability in the market (Kusumastuti et al., 2022). This evidence indicates that Indonesia needs to offer producers natural dyes that have been simplified for use in the globally interconnected textile supply chains alongside the necessary technological innovations.

These difficulties notwithstanding, the prospects continue to grow. The revival of batik with natural dyes puts Indonesia at the forefront of the sustainable practice of marrying heritage conservation with residue-based heritage preservation. Suppose technical improvements such as chitosan pre-treatment and optimized extraction are scaled, and supportive policies promoting certification and branding are in place. In that case, Indonesian natural dyes can supply niche international markets seeking eco-certified and culturally unique textiles.

5.4.2 Japan: Tradition, Innovation, and Resource Circulation

5.4.2.1 Heritage and Traditional Practices

Japan's inclusion in the global history of natural dyeing is illustrated using the dorozome technique in the Ōshima Tsumugi silk tradition from Amami Ōshima, Japan. This technique allows the silk to obtain beautifully deep and lustrous black and brown colors from the mud by mixing the mud with the tannin acids derived from the techigi tree, which is also known as the Yeddo hawthorn (Linton, 2024). This technique, along with the durability of the silk, allows the garments to be featured in high-end luxury clothing. This craftsmanship, called Ōshima Tsumugi, highly appreciates the local ecology, artisanal skill, and culture.

Perhaps the most interesting point from the view of a circular economy is pre-dyeing techigi wood, which came from the dyeing techniques used with the wood from the tree. This wood was not wasted, as it was chipped and boiled, capturing an early circular resource economy (Linton, 2024). This approach of Japanese craft, where waste got value, was centuries ahead of its time, considering it was deep in the history of industrial sustainable practices.

In addition to its functional use, dorozome has expansive cultural significance. The interaction between the tannin of trees and the island's volcanic mud symbolizes balance between the elements and the artistry of humankind. These textiles served as pieces of clothing and a means of expressing oneself, social rank, and the culture's heritage. The present survival of Ōshima Tsumugi attests to the enduring traditions of natural dyeing, even when synthetic dyeing reigns over the world's textile industry.

Other reports indicate materials such as techigi wood are becoming increasingly difficult to obtain, particularly due to land use changes and a general lack of forestry production. Recent reports indicate the tension between maintaining the tradition and the constant available supply of the materials needed to sustain the artistry, raising issues about how crafts of the past are positioned in the present-day context of environmental resource management (Linton, 2024).

In the case of Japan, the historical dimension and the practices of circularity, which are rooted in utilizing wood waste, are alongside the more recent difficulty of implementing these practices in a world of scarce ecological resources and an integrated global textile industry

5.4.2.2 Scientific Innovations and Circular Economy

As attested to by its masteries in crafts, heritage, and innovation, Japan is a focus of scientific progress in the integration of agro and industrial residues and biomass wastes, particularly in dyeing systems. These advances in dyeing are part of domestic policies that aim to establish frameworks of resource circulation, where waste is 'recycled' as a production input in eco-friendly systems (METI, 2024).

An area of innovation is the attempt to dye leather using biomass residues. For example, in 2018, a study 'feathered' eco-friendly tanning and dyeing by utilizing pigments derived from agricultural and forestry byproducts demonstrated minimized chemical input and lowered ecosystem toxicity compared to traditional procedures (Shin, 2018). This research exemplifies how waste residues that could be discarded into waste streams can be valorized into high-value, purposeful products without loss to the Japan economy.

Recent leather research has extended the range of natural dyes to include invasive species of plants, particularly the Japanese Knotweed (*Fallopia japonica*), which many parts of the world consider an ecological nuisance. Experiments with printing textiles with extracts from this invasive plant species give encouraging results in rich color and desirable functional features (Klančnik, 2024), encouraging the enthusiastic transformation of ecological liabilities to engineered resources of sustainable design. Although knotweed, an invasive plant species, is not an agro-industrial residue, its usage by design serves a principle of constituents: the local, abundant, and available overstock of biomass serves to replace synthetic materials.

The latest technologies are centered around Japan's policies on closed resource circulation systems, including policies that minimize raw material imports, curb carbon emissions, and bolster self-sufficiency in core industries (METI, 2024). Still, researchers and policymakers point to ongoing issues: the biomass quality problem, the inability to scale pilot projects, and the conflict between advanced techno-industrial processes and the preservation of artisanal crafts, such as dorozome.

Overall, contemporary Japan's approach to natural dyeing represents a complex duality: on the one hand, heritage crafts continue to honor the use of forestry residues like techigi wood with craft-centered systems; on the other hand, scientific research, coupled with economy-wide policy, seeks to incorporate biomass wastes and even invasive plants to integrate dyeing into closed-loop systems. This combination of cultural resilience and industrial innovation makes Japan a remarkable case in the APEC region, highlighting the intersection of tradition and sustainability of resource circulation.

5.4.3 Thailand: Silk Heritage and the Bio-Circular-Green Transition

5.4.3.1 Cultural Heritage and Agro-Residues

Thailand's long-standing tradition in silk weaving is remarkable in its textile identity, particularly Thai silk and eri silk, which encapsulate regional craftsmanship and cultural artistry. Ethnographic and historic data document Thailand's dye biodiversity as constructed from lac, turmeric, indigo, and extracts of certain hardwoods (Thailand Foundation, 2025). In conjunction with locally sourced mordants, these resulted in the dynamic dyeing practices associated with ceremonial and artistic textiles across the economy.

Recent studies have highlighted the many residues of the agro industry and their dyeing. Experimental work on eri silk yarns illustrates the fastness of specific blends from agro waste, including mango peel, tamarind seed, and mangosteen husk, which produce yellows, browns, and soft-red tones (Phanichphant et al., 2020). These byproducts, which were once disregarded as agricultural waste, are now recognized for their alignment with sustainable practices and their dyeing potential.

These practices rely on the function of communities, as you noted. For instance, artisans in the northeastern Isan region still use traditional dye recipes, sometimes incorporating residues from local food processing. This practice enhances the cultural adaptive capacity of Thailand's silk dyeing heritage and the practical usefulness of residue dyeing. (Roengthanapiboon et al., 2024).

In this regard, Thailand is an example of how a silk cultural heritage has expanded its agro-industrial dyeing residues chromatic palette as a basis for present-day initiatives to weave natural dyes into its sustainability frameworks

5.4.3.2 Sustainability and the Bio-Circular-Green (BCG) Policy

Incorporating natural dyes aligns with the bioeconomy policy framework through the BCG strategy policy line. The strategy, adopted in 2021, sets out Thailand's plans to become the regional hub for the sustainable management of solar industries (textiles) along with other circular economy initiatives (United Nations Environment Programme (UNEP), 2020). This strategy establishes activities for Thailand to close the green production cycle as the economy expands across textiles and other dominantly eco-friendly industries. This policy provision identifies agro-industrial residues and Thailand's silk weaving traditions as the key sources of dyes.

Silk can be dyed using residues like mango peels, mangosteen husks, and tamarind seeds to achieve BCG framework goals without strong chemicals. This and other studies have shown how much silk dyeing could benefit and how much synthetic chemicals could be minimized (Phanichphant et al., 2020). Results from initiatives from Universities and cooperatives show that dyes with strong fastness and easy use can be manufactured from these residues. However, industrial models to achieve these results still need to be developed (Thailand Foundation, 2025).

Simultaneously, Thailand is under pressure. Reports along the textile value chain identify the economy's persistence in importing cotton and synthetic fibres. Issues with scalability and certification continue to exist (UNEP, 2020). Variability of fastness and uninterrupted supply of residues are still obstacles to integrating into export markets where compliance with GOTS, EU Ecolabel, and other similar certifications is obligatory. Nonetheless, the government of Thailand and private sector stakeholders are keen on marketing the ecolabels, such as “Green Label Thailand”, to encourage domestic use and instill confidence in sustainable textile products (UNEP, 2020).

In the context of the BCG framework, the ecosystem for policy and innovations fosters an environment in which the agro-residues for dyeing are valued and valorized. Coupling the silk heritage with the current sustainable framework, Thailand illustrates the repositioning of cultural assets in global markets as high-end, eco-certified, and value-added that blends in history with modern-day innovations

5.4.4 Peru: Alpaca, Cultural Dyeing Traditions, and Agro-Residue Innovation

5.4.4.1 Cultural and Traditional Dimension

Peru's textile industry was developed in the Andean Highland throughout history because of the culture surrounding alpaca fibre. Also, in this case, natural dyeing is more than a rudimentary craft; rather, it is a component of the material culture that shapes community identities, aesthetic norms, and knowledge passed down from one generation to the next. Peruvian practitioners and historical documents show that the dyes produced from alpaca fur, rich in deep red, brown, olive, and gold colors, were manufactured using natural species, wild plants, and kitchen or on-farm products (Antúnez-de-Mayolo, 1988; Pazos & Soluciones Prácticas, 2017).

An important aspect in the Peruvian tradition is the combination of protein fibres (yarns and fabrics made from alpacas) and tannin and phenolic dense botanical materials that enable fixation. There are manuals and procedure sheets that detail recipes that use walnut husks (nogal) to create strong and robust brown to almost black colors, and molle (Schinus molle) to obtain yellowish olive hues, and often with the addition of alum or tannins from plants to improve the durability (Guerra-Buenaño et al., 2022; Carrasco-Bocangel et al., 2022). These sources also describe artisanal sequencing techniques in great detail, such as the gentle washing of the fibre (scouring), specific ratios of fibre and water (liquor), long periods of submersion and in some cases simmering in the water, and airing after the last bath—applied to the specific alpaca fibre cuticles and their unique warmth sensitivity (Manuela Ramos-Economistas sin Fronteras-Union Europea, 2012; Sucasaca-Quispe & Guevara-Garnica, 2022).

The overarching reasoning of this set of practices consists of symbolic and ecological dimensions. The construction of the dyestuffs is best understood in relation to the Andean landscape (tree barks, leaves, and husks) and the agriculture-related byproducts available at different seasons. When these materials are brought together with ancient techniques of over-dyeing and tone alteration through mineral or plant mordants, a reliable and recognizable set of colors, used in garments, blankets, and ritual textiles, is produced (Antúnez-de-Mayolo, 1988; Pazos & Soluciones Practicas, 2017). Significantly, several of these dyestuff precursors, like walnut husks or some fruit peels, are contemporary agro-residues used ingeniously in the dye kitchen, pointing to an early form of circularity long before contemporary sustainability stories.

Beyond the technical aspects, the documentation also underscores the social organization of dyeing practices in Peru. These include household-based and women’s cooperative labor, the codification of dyeing recipes by master dyers, and community workshops where knowledge is transmitted through hands-on learning. Such collective arrangements help sustain livelihoods and foster resilience through adaptation—for example, by fine-tuning water temperature and timing to local conditions, managing plant scarcity, or adjusting color preferences to the different grades of alpaca fiber (e.g., baby, superfine). Recent technical bulletins from regional institutions further support this legacy by compiling species catalogs and practical dyeing recipes that community members may selectively adopt, thus reinforcing Peru's dyework heritage as a dynamic and living tradition (Instituto Tecnológico de Producción – CITEtextil Camélidos Cusco, 2023).

5.4.4.2 Scientific and Technological Advances

In recent years, enhanced efforts have been made to systematize and innovate Peru's dyeing activities. This has been achieved through some form of applied research and the corresponding support of various public and private institutions. Technical reports and manuals distributed by some centers of scientific institutions and universities aim to synergize the previously mentioned traditional system with its scientific and industrial validation. This is placed on the importance of the remains produced from agro-industries.

The research on the native and Andean tree Schinus molle has been documented as the experimental use as color source. It has been observed and documented that using the native and Andean tree Schinus molle to extract some yellowish-greenish color dyes from the leaves and berries using traditional methods. This involves boiling the leaves and berries to form the Schinus molle dye. More advanced scientific methods, such as the pressure-assisted dye extraction (PAEE) system, have been implemented to increase the reproducibility of the traditional methods (Carrasco-Bocangel et al, 2023). Using natural mordants has been shown to improve the color produced during the dyeing process of some fibers. This is particularly true for the alpaca fibers when compared with synthetic mordants such as aluminum salts or tannin-bearing extracts (Manuela Ramos, 2012). This is a typical proof of how the scientific process can improve artisanal systems without losing the rich cultural aspect that they offer.

Onion skins, purple maize husks, avocado peels, beet residues, and some citrus byproducts are classified as food and agricultural residue and are being evaluated as dye source materials. A recent CITE (Centro de Innovación Productiva y Transferencia Tecnológica) Bulletin (2023) reports multiple case studies where these residues provided uniform and repeatable coloration on alpaca and sheep wool. Beyond coloration, the bulletin provides wash and light fastness results, which are important operational metrics for international trade in textiles and overseas sub-export. In these cases, the dyeing is done by a circular economy system, in which the residues from the Agri-food chains of Peru are converted into sustainable dyeing residues. Circular economy principles are being applied in Peru for these agri-food chains, as the dyes used are usually discarded residues. The results are a set of sustainable dyes produced on a circular economy basis that can be used in Peru.

A further innovation is the elimination of metallic mordants from wool and other textile dyeing formulas in favor of a bio mordant made from pomegranate peels and walnut husks (ITP— CITEtextil Camélidos Cusco, 2023). Not only is the dye fixation improved and bio certified, but the certified GOTS schemes for heavy metal reduction have become operational.

Many challenges remain regardless of these advancements. Scaling artisanal results or tests in a laboratory to industrial dyehouses remains a struggle, particularly as it relates to batch-to-batch reproducibility and the durability required by export markets (ITP – CITE textil Camélidos Cusco, 2023). Furthermore, the infrastructure for processing and stabilizing residues into standardized dye intermediates remains scarce, compromising the supply chain reliability. Also, while cooperatives and CITE centers have piloted the residues dyeing technique, its integration into the large-scale alpaca export industries is still in its infancy.

To summarize, the case of Peru is one of ongoing knowledge convergence in which ancestral practices and scientific innovations coexist. The work about molle, onion skins, purple maize, and other residues serves as an example of the technical possibility of residue-based dyeing, but also reaffirms the necessity of investment in scalability, certification, industrial adoption, and the realignment of Peru's cultural and ecological resources into competitively sustainable textiles on a global level.

5.4.5 Other Case Studies (Korea; Malaysia; Mexico)

5.4.5.1 Korea: Wood Residues and Tannin Extraction

Recent studies have shown that wood residues can be used as a sustainable source of natural dyes for plant-based dyeing, thus broadening the scope of the economy's plant dyeing tradition. Merbau (Intsia bijuga) sawdust, a waste material from the timber and furniture industries, is a good example of a tannin-rich material used for textile dyeing (Mindaryani et al., 2023).

The study's authors showed that under optimized solid–solvent ratios and temperatures, aqueous extraction of merbau sawdust would yield concentrated tannin solutions that can dye cotton and silk fibers in stable brown and reddish shades. Unlike most dyeing processes, these colors were achieved without using synthetic mordants, which are deemed harmful. The tannins served as mordants and effective fixing agents (Mindaryani et al., 2023). Such a finding aligns with a global movement to reduce or eliminate the use of heavy metal mordants in natural dyeing and improve the sustainability of the practice.

Merbau is also a good example of the valorization of industrial byproducts. Merbau sawdust, which is regarded as waste or low-value fuel, becomes a resource of high economic value in the context of textile dyeing. Such a practice parallels Korea's efforts to implement environmentally sustainable textile technologies in compliance with the economy's environmental policy and sustainable growth objectives.

Merbau residues, however, face challenges in upscaling production, maintaining batch consistency, and evaluating long-term color retention in industrial settings despite existing at the laboratory scale. Nonetheless, this study offers an illustrative example of redirecting residues from the wood-processing and forestry industries into dyeing textiles, thereby gaining economic and ecological advantages.

5.4.5.2 Malaysia: Zero-Waste Plant Dyeing

Alongside cultivating this practice, Malaysia has also become the focus of an experiment on systems of zero-waste dyeing. Such systems seek not only the substitution of synthetic dyes but also the elimination of waste at every step of the process. A case study on the market of plant dyes used on textiles describes the incorporation of agro-industrial wastes like fruit peels, seeds, stems, and leaves. These are combined with other residues stemming from the cultivation and processing of plants, as described in Mo et al. (2024), to achieve a circular economy with positive environmental and economic outcomes.

The waste outcomes within circular economy principles are most visible in agricultural residues like the mango skin, banana peel, and pomegranate husk, which are otherwise considered refuse. The byproducts can be transformed into dye extracts to create a broad spectrum of colors ranging from yellows, browns, reds, and greens. The process in question applied a zero-waste principle, wherein the plant material left after the dye extraction was composted or converted into biogas, thus closing the cycle (Mo et al., 2024). Such a process is a step further than simply applying circular concepts to the production of the dye since it embeds operational and closed-loop principles within the value chain.

The trials' insights elucidated that the levels of fastness achieved are comparable to those of conventional natural dyeing, especially when using mordants such as tannin-rich plant extracts. Though still in the developmental phase, these trials demonstrate Malaysia's ability to integrate its rich biodiversity and circular-economy thinking to address the sustainability challenges in the textile industry.

Malaysia's case emphasizes the value of a more systemic approach, such as valorizing agro-residues as a source of dyes and as part of an integrated ecosystem for waste minimization. It thus offers a complementary perspective to larger APEC economies, showcasing the capacity of small and medium enterprises to design value-driven novel paradigms in the context of global sustainability.

5.4.5.3 Mexico: Indigenous Heritage and Agro-Residues

The historic legacy of Mexico regarding natural dyes starts with Oaxaca, where cochineal (Dactylopius coccus), indigo, and Brazilwood have been fundamental to the region's care of its textile traditions. The prickly pear cacti spawned cochineal, which became the most sought-after dyestuffs in the early modern global trade. Its indigo and Brazilwood counterparts also added to the diverse and flourishing chromatic set tied to the region's identity and ceremonial textiles (Dekel, 2025). Natural dyes, especially cochineal and indigo, have been and still are significant. Natural dyes color the fabric of life with harmony of beauty, signifying the wonderful status of the society, unique rituals, and rich shared history.

Incorporating agro-industrial residues in modern Mexican dyeing and agro-industrial residues exposes and integrates Mexico's rich history. Sustainable dyeing experiments, based on the natural dyes, were successful upon the use of walnut husks, avocado pits, and onion skins on cotton and wool and yielded brilliant, durable shades of brown, red, and yellow (Ponce-Cano et al., 2023). The dying of textiles remains a direct link to the community, and while these residues come from the agro and food processing industries, they impact the circular economy. The Ponce (2023) dyeing tests have shown, in addition to being cost-effective, agro-residue-based dyes are technically satisfactory to meet the niche textile markets' requirements with sufficient fastness properties to washing and light.

Mexico is an example of an economy with an artisanal sector based on indigenous culture and symbolism, exemplified by the traditions of Oaxaca, and a burgeoning sector that turns Agro Res Shreded into value-added products. At the same time, artisanal production remains a puzzle. The ability to scale beyond artisanal production, to assure reproducibility, and to obtain the requisite certifications for international trade is a persisting challenge for global commerce.

6 Results of the Bibliometric and Technological Analysis

Having reviewed, in previous chapter, economy-level case studies that highlight both traditional practices and emerging applications of agro-industrial residues, this chapter expands the scope of analysis by examining indexed scientific literature and technological trends. This transition provides a quantitative and global perspective on how research outputs, patent activity, and technological maturity shape the potential for scaling natural dyes within the textile sector.

6.1 Bibliometric Analysis based on SCOPUS

6.1.1 Bibliometric Methodology

For the present study, a bibliometric analysis was conducted in the Scopus database, which is considered one of the primary sources of scientific information internationally. The search strategy used was the following:

("natural dyes" OR "bio-based dyes") AND

("textile industry" OR "textile dyeing" OR "textile production") AND

("agro-industrial waste" OR "agricultural residues" OR "agro-waste") AND

("sustainability" OR "environmental impact" OR "clean production")

The search, conducted with a cut-off date of August 2025, yielded 169 documents. A filtering process was subsequently applied, which consisted of: (i) eliminating duplicate records, (ii) discarding those not directly related to the objective of the study, and (iii) excluding documents with incomplete metadata or outside the defined thematic scope. After this filtering, a final sample of 44 documents was obtained for analysis.

It was also identified that some of the results corresponded to review articles, which allowed for the consultation of the works cited in these reviews. This procedure expanded and enriched the reference universe, ensuring a more robust overview of the application of natural dyes derived from agro-industrial waste in the textile industry. Tools such as Microsoft Excel (for descriptive analysis) and VOSviewer (for constructing co-authorship maps, keyword co-occurrence maps, and citation networks) were used for data processing and results visualization.

6.1.2 Bibliometric results

The results of the bibliometric review on natural dyes obtained from agro-industrial waste applied to the textile industry, prepared using information compiled in the Scopus database, are presented graphically below. The graphs visualize the main trends in scientific production, identify the most relevant authors and institutions, and identify the thematic areas, economies, and publication sources that have contributed to the development of this line of research linked to sustainability and textile innovation.

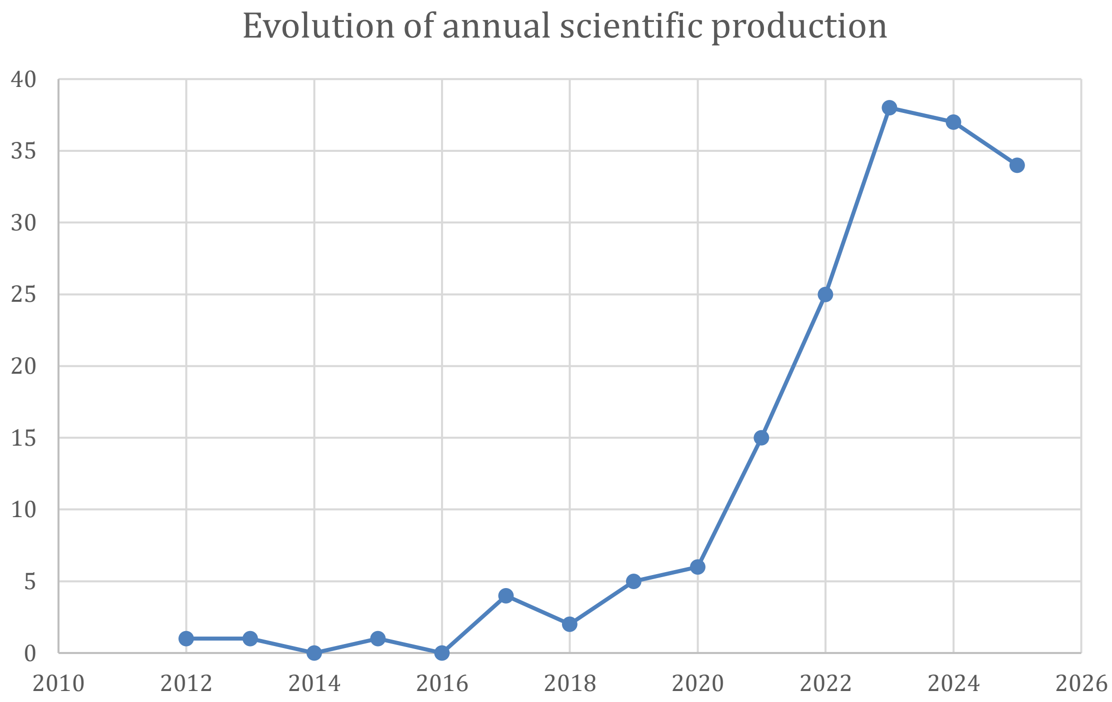

Figure 1 Evolution of annual scientific production

The evolution of scientific production on natural dyes from agro-industrial waste applied to the textile sector shows an upward trend over the last decade. Between 2010 and 2016, production was practically zero, reflecting a nascent and dispersed interest. However, starting in 2017, a progressive growth was observed that intensified in 2021, when the number of publications increased rapidly, reaching a peak of 38 documents in 2023. This trend demonstrates that the topic has moved from being a marginal field to becoming a priority line of research within the scientific agenda linked to sustainability, textile innovation, and the circular economy.

In more recent years (2024–2025), a slight decline in production has been recorded, although levels remain much higher than those of the initial stage. This relative stabilization can be interpreted as a natural readjustment after accelerated expansion, indicating that the topic has reached consolidation and recognition within the research community. In terms of public policy and international cooperation, this trend confirms the growing strategic importance of utilizing agro-industrial waste in sustainable dyeing processes, aligning with global commitments to reducing environmental impact in the textile industry.

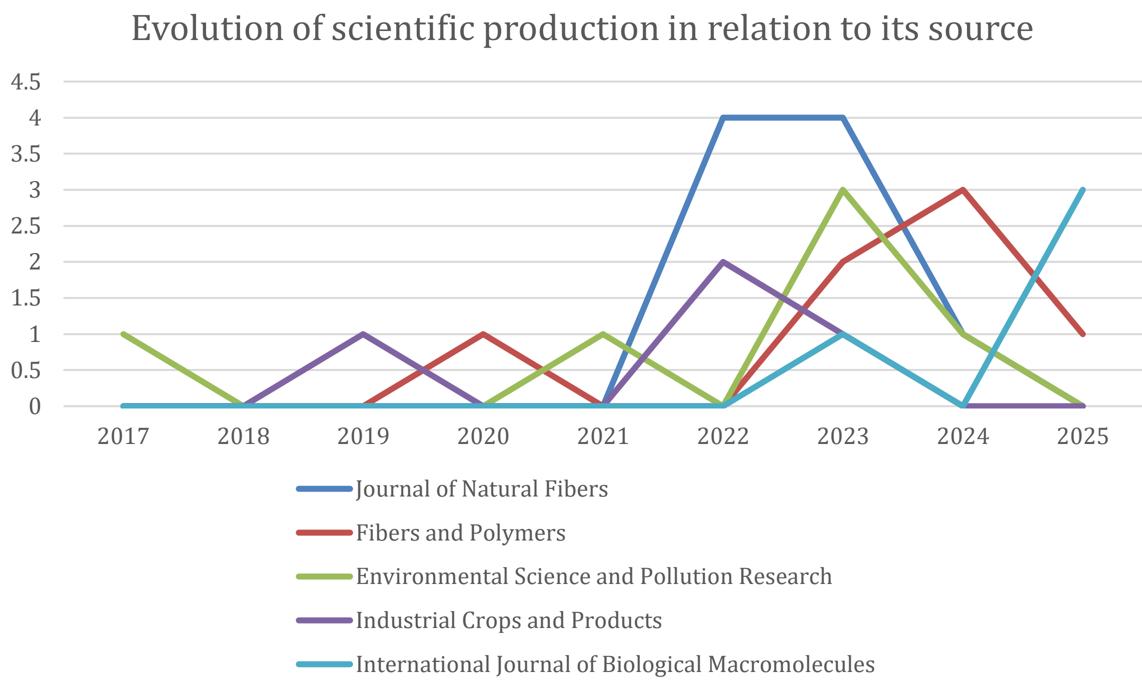

Figure 2 Evolution of scientific production in relation to its source

Scientific production on natural dyes derived from agro-industrial waste for textiles has shown an evolution marked by the consolidation of leading journals and the diversification of publication venues. In the initial years (2017–2020), articles appeared scattered in journals such as *Environmental Science and Pollution Research*, *Industrial Crops and Products*, and *Fibers and Polymers*, reflecting a still nascent and exploratory interest. Beginning in 2021, the *Journal of Natural Fibers* emerged as the central dissemination platform, reaching its peak in 2022 and 2023, confirming the topic's positioning within the textile sustainability agenda.

In the most recent period (2023–2025), sources were diversified, with the strengthening of *Fibers and Polymers* and the incorporation of the *International Journal of Biological Macromolecules*. This dynamic reflects the field's expansion toward more specialized approaches in biomaterials and molecular applications, while maintaining relevance in established textile journals. Overall, the evidence indicates that the topic has moved from an exploratory phase to one of consolidation and strategic diversification, reinforcing its importance in the context of sustainable innovation for the textile industry.

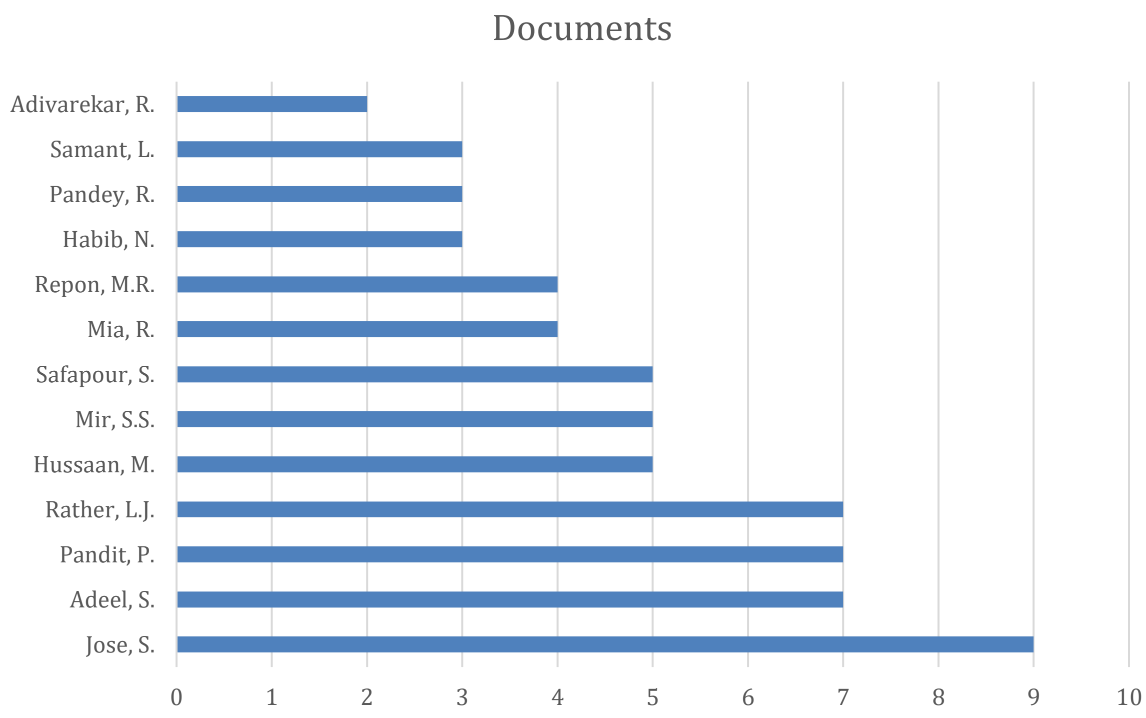

Figure 3 List of authors with the most publications on natural dyes based on agro-industrial waste

The authorship analysis reveals the presence of a core of researchers leading the scientific production on natural dyes derived from agro-industrial waste applied to the textile sector. Jose S. stands out with nine publications, followed by Adeel S., Pandit P., and Rather L.J., with seven papers each. These authors comprise the most influential group, contributing steadily to the development of the field and consolidating research networks that strengthen the topic's international visibility and impact.

At a second level are researchers such as Hussaan M., Mir S.S., and Safapour S. (with five publications each), along with Repon M.R. and Mia R. (with four papers), reflecting their ongoing and complementary participation. Finally, an emerging group with a smaller number of publications is observed, made up of authors such as Habib, N., Pandey, R., Samant, L., and Adivarekar, R. Overall, the evidence shows a characteristic pattern of consolidating fields, where a strong core of leaders drives the research agenda. At the same time, new actors contribute to diversifying and expanding the scope of studies.

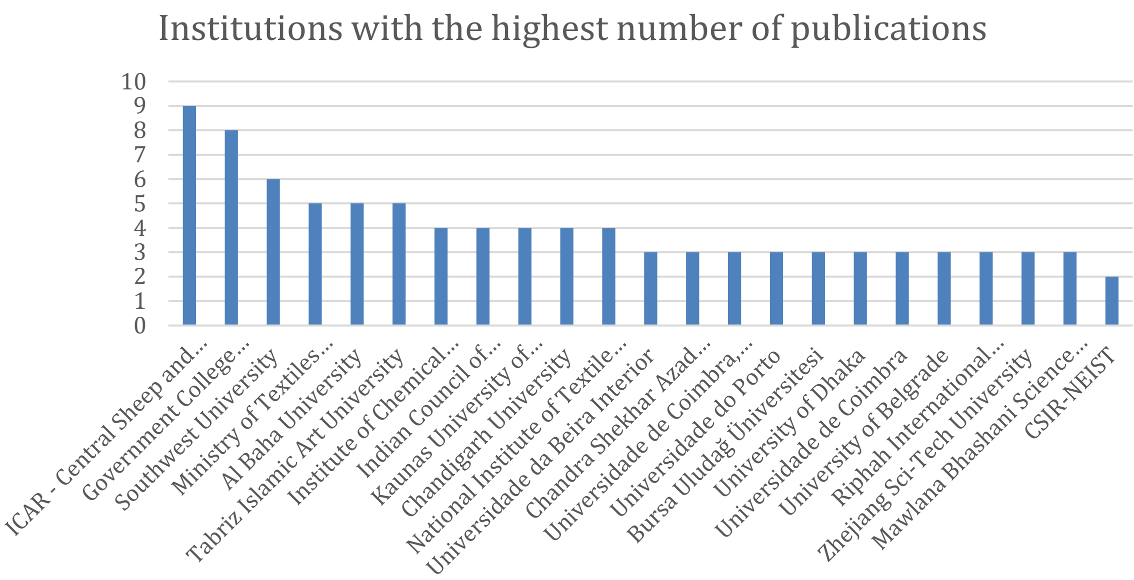

Figure 4 Institutions with the highest number of publications

Scientific production on natural dyes derived from agro-industrial waste for textiles is mainly concentrated in Asian institutions. The ICAR (Central Sheep and Wool Research Institute, India) leads the way with nine publications, followed by Government College University Faisalabad (Pakistan) with eight. At the second level, universities such as Southwest University (China), the Ministry of Textiles, Government of India, Al Baha University (Saudi Arabia), and Tabriz Islamic Art University (Iran) stand out, demonstrating Asia's regional relevance in applied research on sustainable fibers and dyeing processes.

At the same time, there is an intermediate core of institutions with three to five publications, such as the Institute of Chemical Technology (India), the Indian Council of Agricultural Research, Kaunas University of Technology (Lithuania), Chandigarh University (India), and the National Institute of Textile Engineering and Research (Bangladesh). Finally, the participation of European and other regional universities—such as the University of Beira Interior, the University of Porto, the University of Dhaka, and Zhejiang Sci-Tech University, among others—is observed. Although smaller in size, this demonstrates the international expansion of the topic. Overall, the data reflect an intense concentration in Asia with progressive global diversification, opening up opportunities for interregional scientific cooperation in sustainable textile innovation.

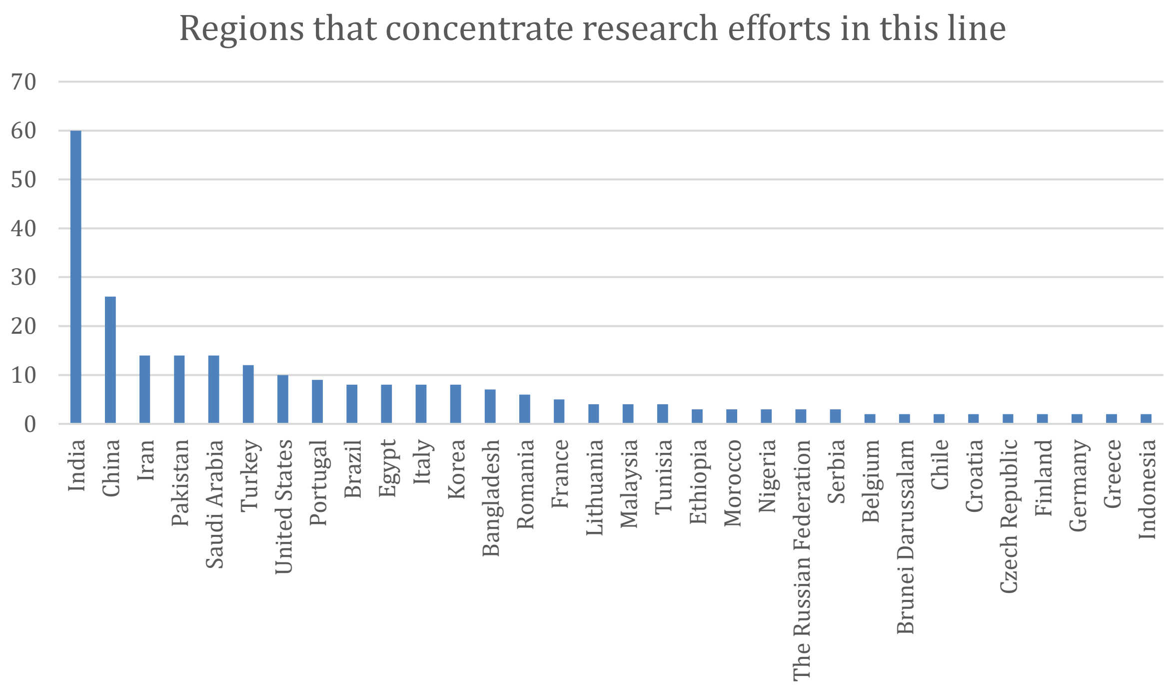

Figure 5 Regions that concentrate research efforts in this line

Scientific production on natural dyes derived from agro-industrial waste for textiles is heavily concentrated in Asia. India leads the field with 60 publications, followed by China with 26. Iran, Pakistan, and Saudi Arabia are in second place with 14 publications each, while Turkey contributes 12 and the United States 10. This core of economies represents the epicenter of research, reflecting the strategic importance of Asia and, to a lesser extent, North America in the development of sustainable alternatives for the textile industry.

At an intermediate level, Portugal (9) stands out, as well as Brazil, Egypt, Italy, and Korea with eight publications each, along with Bangladesh (7) and Romania (6). Other European economies, such as France (5), Lithuania; Malaysia; and Tunisia (4 each), in addition to a group of economies with 2 to 3 publications—including Belgium; Chile; Ethiopia; Germany; Greece; Indonesia; Morocco; Nigeria; the Russian Federation; Serbia, among others—contribute to the international diversification of the field. Overall, the data show that, although Asia holds the absolute leadership, there is growing participation from Europe, Latin America, and Africa, consolidating global interest in research into sustainable dyes and opening up opportunities to strengthen international cooperation within the circular economy framework.

It should be added that, of the top ten economies with the largest scientific output on natural dyes derived from agro-industrial waste, only two—China and the United States—are members of APEC. Together, these two economies contribute 34 publications, representing approximately 20% of the total research generated by the top 10. This demonstrates that the APEC region still has a limited presence compared to Asia as a whole, but has strategic potential to expand its leadership in this field.

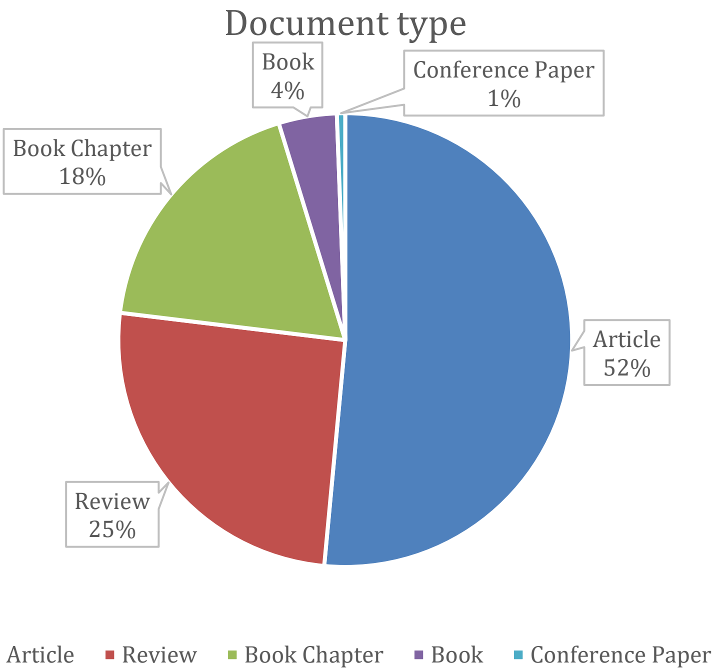

Figure 6 Classification of publications on natural dyes based on agro-industrial waste

Scientific production related to natural dyes derived from agro-industrial waste for textiles is concentrated mainly in research articles (52%), demonstrating an expanding field focused on presenting original results and experimental advances. This category is followed by reviews (25%), which play a fundamental role in synthesizing existing knowledge and providing a framework for future research, as well as book chapters (18%), reflecting the interest in integrating this topic into broader academic compilations and conceptual frameworks.

To a lesser extent, full-length books (4%) and conference presentations (1%) are also present, indicating that although there are dissemination efforts in longer formats and in academic exchange spaces, these are not yet the main channels. Overall, the evidence shows that research in this field is undergoing consolidation, with a clear emphasis on articles and reviews and a progressive diversification toward collective and educational publications, strengthening its visibility and positioning on the international scientific agenda.

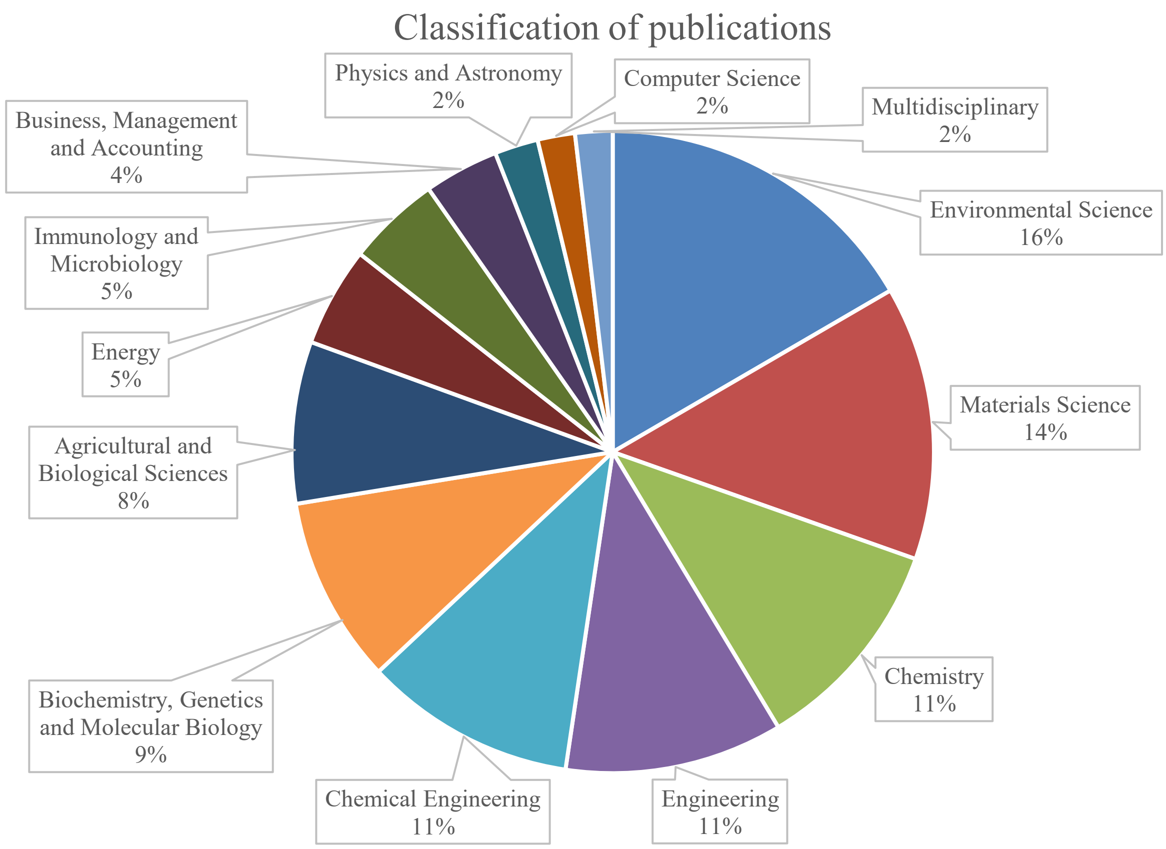

Figure 7 Classification of publications on natural dyes based on agro-industrial waste, considering the areas of study

Scientific output on natural dyes derived from agro-industrial waste for textiles is characterized by a marked interdisciplinary approach. Environmental sciences (53 documents) clearly predominate, followed by materials science (44), chemistry (35), engineering (35), and chemical engineering (34). This core reflects the focus of research on sustainability and the development of new materials and processes, confirming the topic's relevance in mitigating environmental impact and in technological innovation applied to the textile industry.

In addition, areas such as biochemistry and molecular biology (30 documents), agricultural and biological sciences (26), as well as energy (16), and immunology and microbiology (15) demonstrate that the field also benefits from contributions related to biomass valorization, the characterization of natural compounds, and their applications beyond dyeing. To a lesser extent, disciplines such as management and business (12), physics (7), and computer science (6), along with multidisciplinary studies (6), show a growing interest in economic evaluation, advanced characterization, and integration of digital technologies. Overall, the evidence confirms that this is a transversal and strategic field of research, capable of articulating environmental sustainability with industrial innovation and global competitiveness.

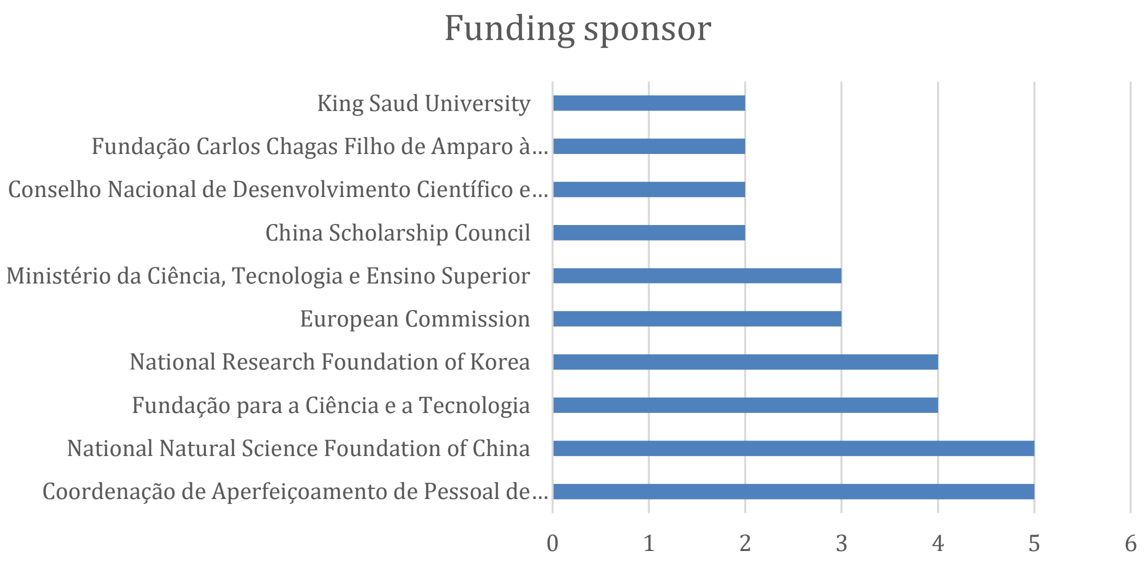

Figure 8 Funding sponsor

Funding for research on natural dyes derived from agro-industrial waste for textiles is led by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior (CAPES, Brazil) and the National Natural Science Foundation of China, each with support for five publications. At the second level are the Fundação para a Ciência e a Tecnologia (Portugal) and the National Research Foundation of Korea, with four publications each, reflecting the interest in Asia and Europe in consolidating this field of research.

Likewise, organizations such as the European Commission and the Ministry of Science, Technology, and Higher Education (Portugal) have funded three publications. In contrast, institutions such as the China Scholarship Council, the National Council for Scientific and Technological Development (CNPq, Brazil), Fundação Carlos Chagas Filho de Amparo à Pesquisa do Estado do Rio de Janeiro (FAPERJ), and King Saud University (Saudi Arabia) each have funded two publications. Together, these data demonstrate diverse international support, with a strong presence in Latin America and Asia, accompanied by the European Union, reinforcing the global and collaborative dimension of research in sustainable textile innovation.

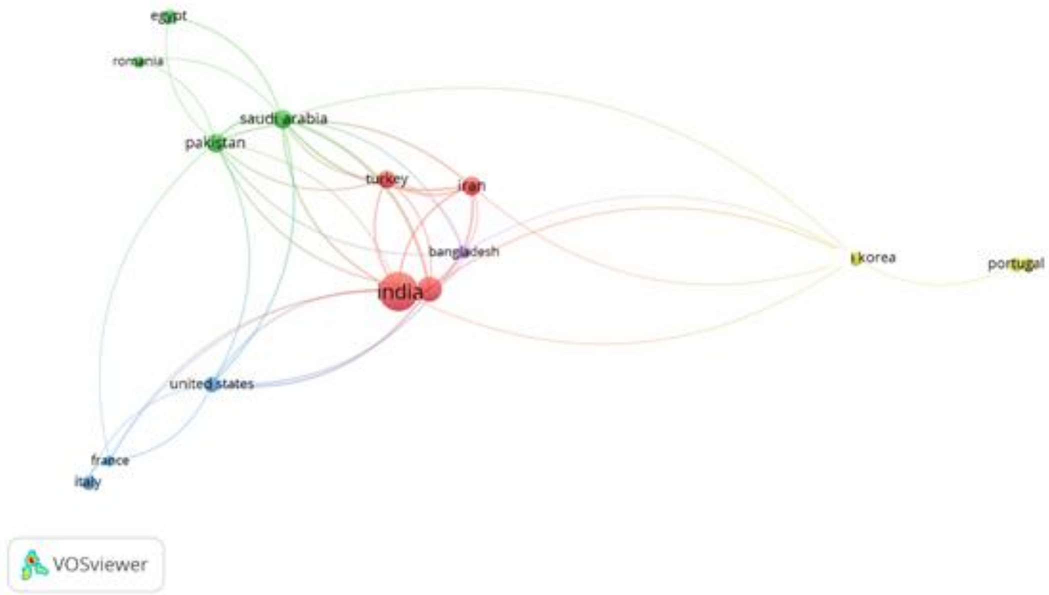

Figure 9 Co-authorship network across economies

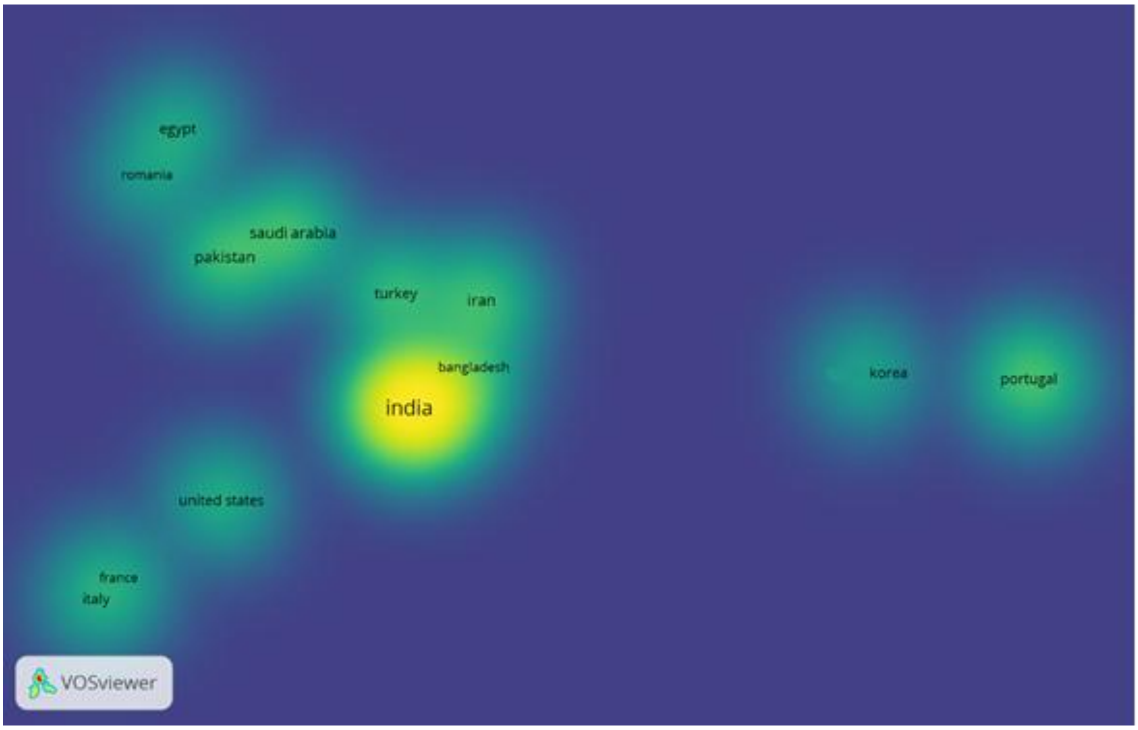

Figure 10 Co-authorship across economies – density visualization

The co-authorship network across economies shows that India, the central node with the highest volume of publications and collaborative links, leads research on natural dyes derived from agro-industrial waste for textiles. Strong networks are structured around it with Iran, Turkey, Bangladesh, Pakistan, and Saudi Arabia, demonstrating that Asia concentrates the main scientific cooperation efforts in this field. Likewise, the participation of economies in the Middle East and Eastern Europe, such as Egypt and Romania, is observed, strengthening the regional dimension of collaborations.

In addition, connections are identified with the United States, France, and Italy, which, although less dense, reflect the openness to intercontinental collaborations. The link between Korea and Portugal is also notable, suggesting focused bilateral projects. Overall, the network confirms that the global research structure is dominated by Asia, with India as the central hub, but with increasing diversification toward international alliances that enhance the global reach of sustainable textile innovation.

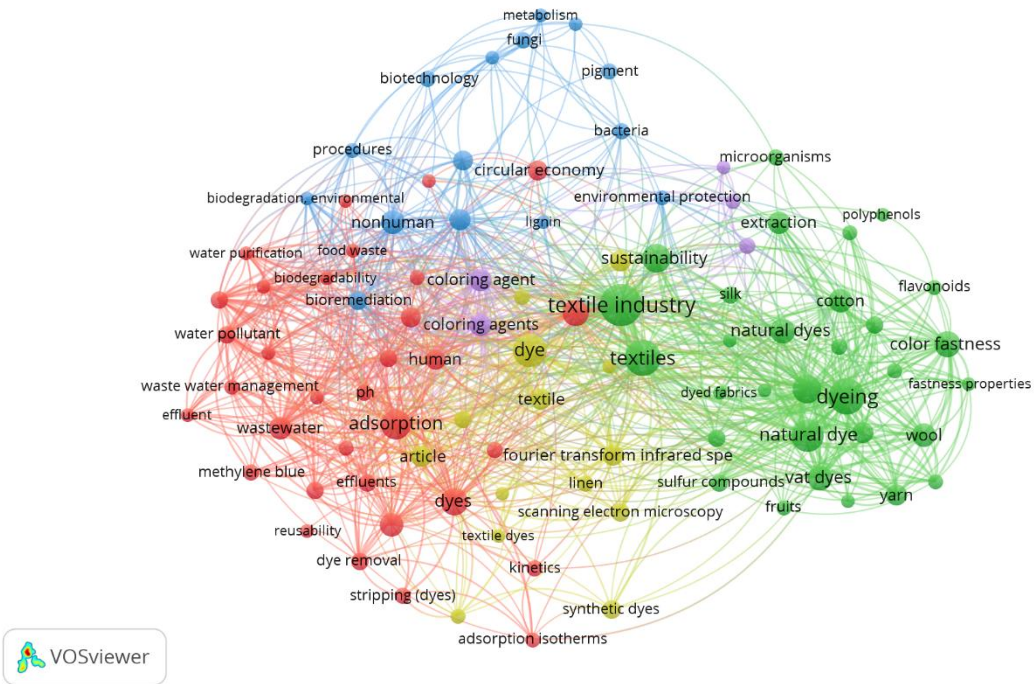

Figure 11 The co-occurrence analysis of author keywords

The co-occurrence analysis of author keywords shows that research on natural dyes derived from agro-industrial waste for textiles is organized around a central core composed of terms such as "textile industry," "textiles," "dyes," and "natural dyes," confirming that the field is primarily oriented toward the development of sustainable alternatives applied to the textile sector. From this core, relevant subtopics are identified: on the one hand, studies focused on fibers and their dyeing properties (cotton, silk, wool, yarn, color fastness); and on the other, studies related to the processes for obtaining natural dyes from bioactive compounds such as flavonoids and polyphenols.

Complementarily, two transversal approaches are distinguished. The first, linked to effluent treatment and environmental remediation, includes terms such as adsorption, wastewater, effluents, dye removal, and water purification, which demonstrate concern about the impact of dyes and the search for mitigation technologies. The second, related to biotechnology and the circular economy, incorporates concepts such as biotechnology, lignin, fungi, bacteria, and the circular economy, focused on using agro-industrial waste and biological processes to obtain sustainable dyes. Overall, the map reflects an interdisciplinary field where textile innovation, chemistry, biotechnology, and environmental management converge, aligned with global trends in sustainability and circular innovation.

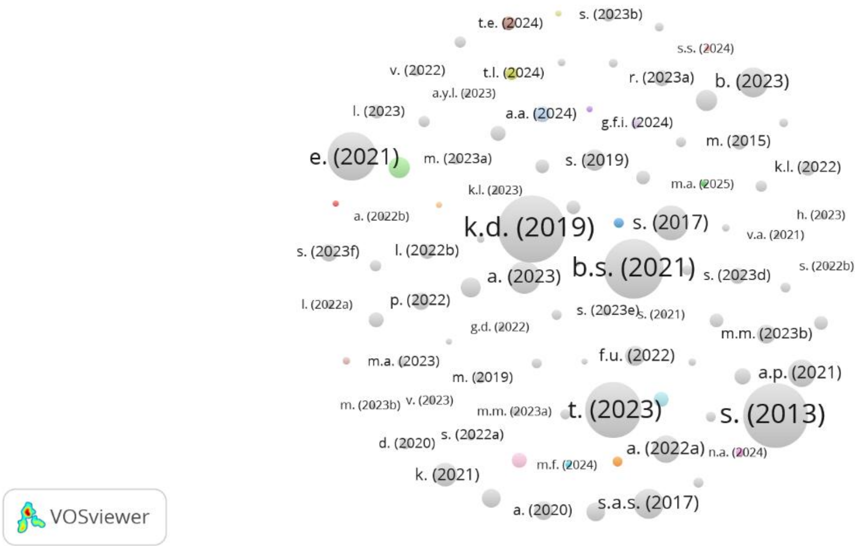

Figure 12 The document-by-document citation analysis

The document-by-document citation analysis shows that some works have impacted research on natural dyes derived from agro-industrial waste for textiles. Publications such as s. (2013)[1], k.d. (2019)[2], e. (2021)[3], b.s. (2021)[4], and t. (2023)[5] stand out, appearing as the largest nodes, reflecting their high influence in terms of citations. These articles can be considered key references or methodological and experimental anchor points, around which much of subsequent scientific production has been structured.

Furthermore, the graph reveals a balance between foundational documents—such as the one from 2013—and recent works published between 2021 and 2023, confirming this field's vitality and rapid evolution. The coexistence of established literature with emerging contributions demonstrates that the topic rapidly expands, generating publications that rapidly gain relevance in the scientific community. Taken together, this pattern indicates that research into natural dyes has a solid foundation and continues to incorporate innovations that strengthen its impact on the sustainability of the textile industry.

The following section analyzes the selected documentation, consisting of 44 documents. This results from a filtering process applied to the initial information provided by the Scopus database, which initially yielded 169 records. This corpus was previously subject

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[1] Olive mill wastes: Biochemical characterizations and valorization strategies. https://doi.org/10.1016/j.procbio.2013.07.010

[2] The amazing potential of fungi: 50 ways we can exploit fungi industrially. https://doi.org/10.1007/s13225-019-00430-9

[3] Factors Affecting Synthetic Dye Adsorption; Desorption Studies: A Review of Results from the Last Five Years (2017–2021). https://doi.org/10.3390/molecules26175419

[4] Critical review on hazardous pollutants in water environment: Occurrence, monitoring, fate, removal technologies and risk assessment. https://doi.org/10.1016/j.scitotenv.2021.149134

[5] Impact of textile dyes on health and ecosystem: a review of structure, causes, and potential solutions. https://doi.org/10.1007/s11356-022-24398-3

to a preliminary analysis using statistical graphs provided by Scopus and visualization maps generated with VOSviewer. This allowed us to identify trends, collaboration networks, and thematic areas related to using natural dyes derived from agro-industrial waste in the textile industry.

6.1.3 Analysis of the refined scientific production

The 44 documents selected in the bibliometric review generated a table with 70 natural dyes obtained from agroindustrial waste used in textile dyeing. The complete table is available in the appendices to this report; however, to provide greater clarity and fluidity in the presentation of results, the most representative cases were selected and presented in the following summary table.

Table 1 Summary table of the bibliometric result

DENOMINATION	EXTRACTION METHOD	ECONOMY	TRL	
Corn cob	Solvent extraction	China	6	Demonstration of a prototype in a relevant environment
Peanut skins	Aqueous extraction	Egypt	4	Laboratory component validation
Olive mill wastewater (olive oil)	Aqueous extraction	Italy	5	Validation in relevant environment
Olive pomace	Aqueous extraction	Turkey	5	Validation in relevant environment
Olive tree leaves	Aqueous extraction	Turkey	6	Demonstration of the technology in a relevant environment
Grape pomace	Aqueous extraction	Tunisia	5	Validation in relevant environment
Anthocyanins from blueberry waste	Aqueous extraction	Belgium	4	Laboratory component validation
Chickpea husk	Aqueous extraction	India	4	Laboratory component validation
Common walnut	Aqueous extraction	Belgium	4	Laboratory component validation
Beetroot peels	Green / Emerging method	India	4	Laboratory component validation
Areca nut husk	Aqueous extraction	Malaysia	5	Validation in relevant environment
Carotenoids from tomato processing wastes	Solvent extraction	Pakistan	5	Validation in relevant environment
Peanut Red Skin	Microwave-assisted extraction (MAE)	Egypt	6	Demonstration of the technology in a relevant environment
The dry rind of the pomegranate	Aqueous extraction	India	4	Laboratory component validation

DENOMINATION	EXTRACTION METHOD	ECONOMY	TRL	
Onion skin	Aqueous extraction	India	5	Validation in relevant environment
Gunda Gundo (Citrus sinensis) orange peels	Soxhlet extraction	Ethiopia	5	Validation in relevant environment
Black rice	Ultrasound-assisted extraction (UAE)	China	4	Laboratory component validation
Avocado Seed and Peel Extracts	Aqueous extraction	Turkey	4	Laboratory component validation
Mango seed	Aqueous extraction	Bangladesh	4	Laboratory component validation
Groundnut Testa	Aqueous extraction	India	5	Validation in relevant environment
Pumpkin	Ultrasound-assisted extraction (UAE)	China	5	Validation in relevant environment
Coconut	Microwave-assisted extraction (MAE)	Malaysia	5	Validation in relevant environment
Almond skin	Aqueous extraction	Spain	5	Validation in relevant environment
Chestnut shell	Green / Emerging method	China	5	Validation in relevant environment
Date pits	Solvent extraction	Tunisia	3	Proof of concept in the laboratory
Watermelon rind	Aqueous extraction	Bangladesh	4	Laboratory component validation

The main findings from this bibliographic section, which includes the analysis of the refined scientific production, are presented below in graphic form. These visualizations synthesize and clearly communicate the most relevant trends, patterns, and relationships identified in the study.

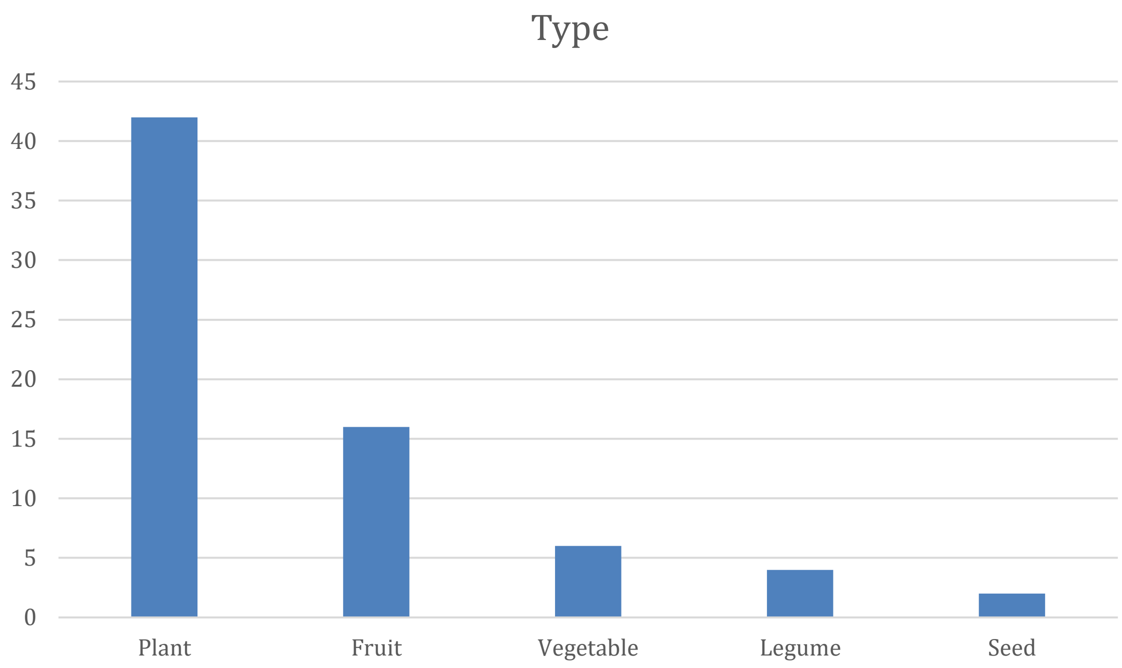

Figure 13 Analysis of agro-industrial waste used to generate natural dyes

The analysis of the Type category reveals a clear predominance of plant waste (42 cases) as the primary source for obtaining natural dyes used in textiles. This result confirms that scientific research focuses on plant-based materials due to their high availability and abundant coloring compounds such as flavonoids, tannins, and anthocyanins. At a second level are fruit waste (16) and specific vegetable waste (6), reflecting the interest in utilizing agri-food byproducts—mainly peels and pulp—as part of sustainability and circular economy initiatives.

Studies on legumes (4) and seeds (2) appear to a lesser extent, representing emerging areas with little potential. The low frequency in these categories could be explained by the lower concentration of useful pigments or the need for more complex extraction processes. Overall, the evidence shows that research into natural dyes derived from agro-industrial waste prioritizes highly available and efficiently utilized sources, while opening up opportunities to diversify into new agro-industrial matrices.

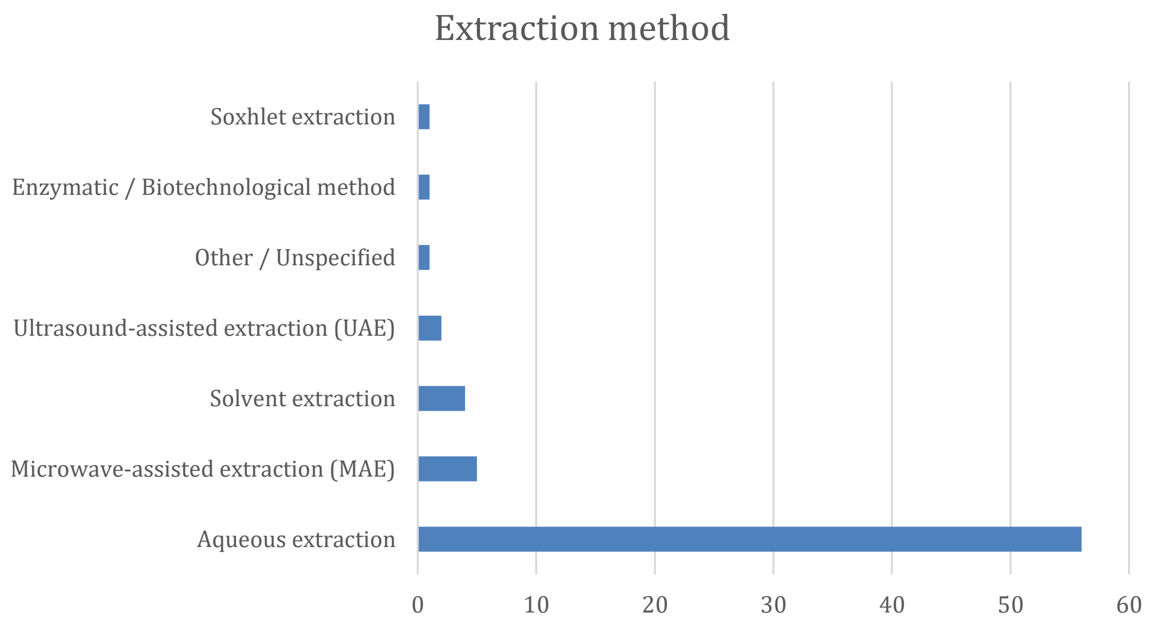

Figure 14 Analysis of natural dye extraction methods based on agro-industrial waste

The analysis of the methods used in the reviewed studies shows a clear predominance of aqueous extraction (56 cases), established as the most widely used technique for obtaining natural dyes from agro-industrial waste. Its widespread adoption is due to its ease of application, low cost, and alignment with sustainability principles, as it dispenses with toxic solvents and is adaptable to laboratory settings and industrial processes. This result confirms that research in the field favors replicable and straightforward solutions that promote waste recovery within the circular economy framework.

In contrast, other extraction methods are much more prevalent. Microwave-assisted extraction (5 cases), solvent extraction (4 cases), and ultrasound-assisted extraction (2 cases) reflect attempts to innovate in efficiency and time reduction, although still in their infancy. Enzymatic/biotechnological extraction and the Soxhlet technique are reported marginally, suggesting areas that remain largely unexplored. Overall, the picture indicates that, although aqueous extraction dominates the literature, emerging methods offer opportunities for technological development that could strengthen the sustainability and competitiveness of this field.

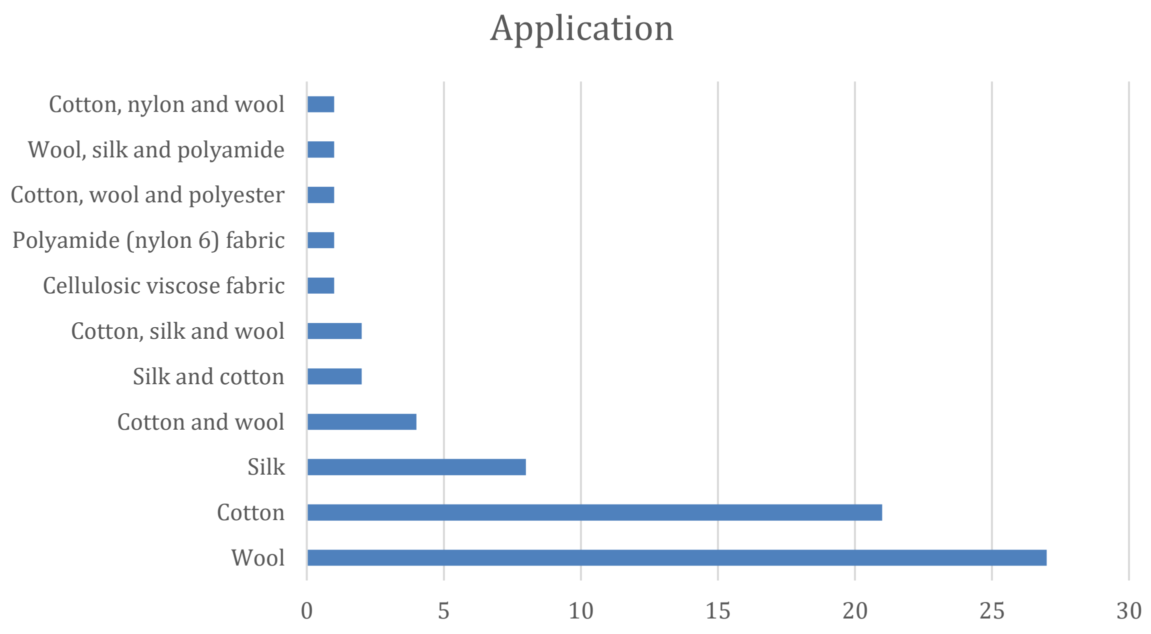

Figure 15 Main textiles on which natural dyes based on agro-industrial waste were applied

The analysis of applications shows a clear predominance of wool (27 cases) and cotton (21 cases) as the primary textile fibers used to evaluate natural dyes derived from agro-industrial waste. Both represent most of the studies due to their relevance to the global industry, availability, and favorable properties for fixing dye compounds. Silk appears to a lesser extent (8 cases), reflecting an interest in higher value-added fibers with applications in specialized textile market segments.

Furthermore, some literature has explored the comparative application of dyes to different fibers, including cotton, silk, wool, cellulose viscose, and polyamide (nylon 6). These tests do not involve mixtures, but rather differentiated tests to determine the efficiency of natural dyes on various substrates. This trend reveals an effort to expand the scope and validate the versatility of dyes across different types of fibers, both natural and regenerated or synthetic, which constitutes a significant step toward their future adoption in a broader range of textile applications.

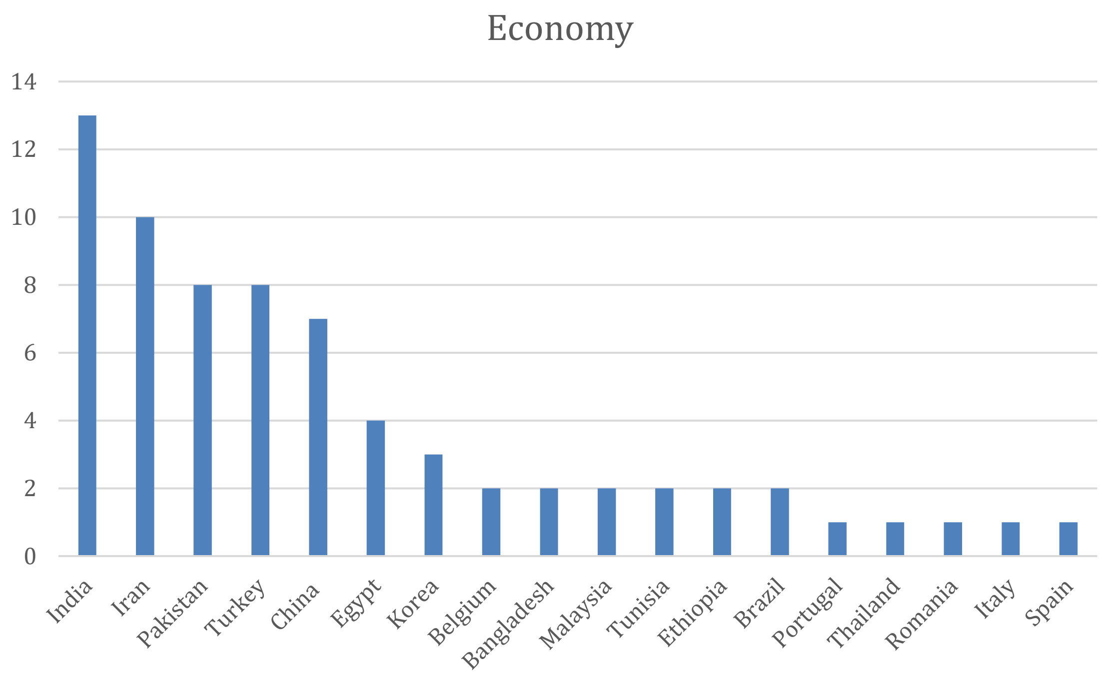

Figure 16 Ranking of economies with the most publications on natural dyes based on agro-industrial waste

India maintains its leadership in scientific production (13 publications), consolidating its position as the economy with the most significant contribution to applying natural dyes from agro-industrial waste in textiles. It is followed by Iran (10), Pakistan (8), Turkey (8), and China (7), forming an Asian bloc that concentrates the majority of studies. This regional predominance is due to the strong presence of the textile industry in these economies and the abundance of agro-industrial waste, which represents a viable source for developing sustainable dyes.

Egypt (4) and Korea (3) follow these leading economies while Belgium; Bangladesh; Malaysia; Tunisia; Ethiopia; and Brazil each report two publications. Finally, Portugal; Thailand; Romania; Italy; and Spain each contribute one publication, reflecting a growing, though still incipient, interest compared to the Asian leadership. This distribution confirms that, although there is global interest in natural dyes and textile sustainability, the focus of research is on Asia, with occasional contributions from Europe, Africa, and Latin America, broadening the scope of the topic internationally.

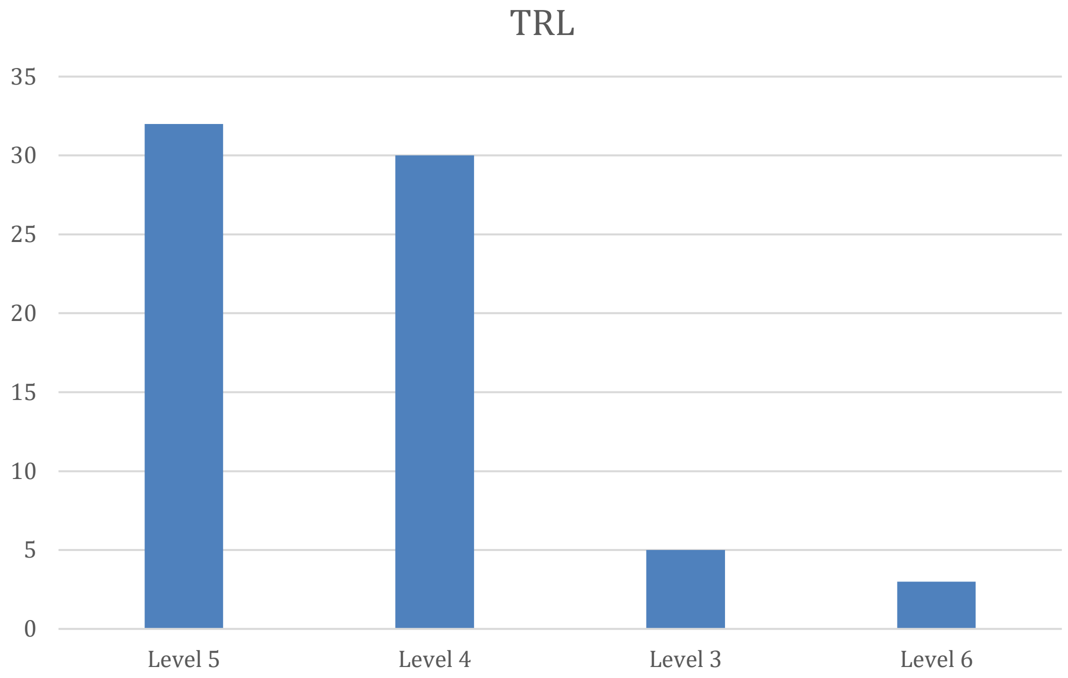

Figure 17 TRL analysis of research on natural dyes based on agro-industrial waste

The analysis shows a clear concentration at the intermediate technological maturity levels, predominance in TRL 5 (32 cases) and TRL 4 (30 cases). This indicates that most studies on natural dyes from agro-industrial waste have reached a validation stage in relevant, advanced laboratory environments, confirming that these technologies have already surpassed the initial proof-of-concept phases and are at a solid level of experimental development. The fact that the bulk of the literature is concentrated at these intermediate levels demonstrates a consolidating field, with the potential to be scaled toward industrial applications, which still requires adjustments and optimization to reach commercial phases.

In contrast, the initial levels (TRL 3, with 5 cases) and the highest levels (TRL 6, with three instances) appear marginal. This suggests that, while nascent efforts aimed at proof of concept and a few cases have advanced to demonstrations in simulated or real industrial environments, the gap toward mass adoption remains wide. The predominance of levels 4 and 5 confirms that current research is at a critical point: sufficiently mature to demonstrate viability, but still facing technical and economic limitations that prevent large-scale deployment. This finding highlights the need to strengthen technology transfer projects, investment in scaling, and industry-academic collaboration, so that natural dyes derived from agroindustrial waste can move toward more technologically mature levels and establish themselves as competitive alternatives to traditional synthetic dyes.

General Summary of the Bibliometric Analysis

The bibliometric analysis conducted on 44 documents selected from the Scopus database provided a comprehensive overview of the scientific literature on natural dyes derived from agro-industrial waste for applications in the textile industry. The results demonstrate growing academic and technological interest in this field, with a sustained increase in publications over the last decade and a clear leadership from Asian economies, particularly China; India; Iran; Pakistan; and Turkey, which account for most of the research.

Regarding sources, studies focus primarily on using plant and fruit waste, while categories such as legumes and seeds remain largely unexplored. The most widely used extraction method is aqueous extraction due to its low cost and ease of implementation. However, innovative techniques such as MAE, UAE, and biotechnological approaches are beginning to emerge, which could increase the efficiency and sustainability of the processes. Regarding applications, tests on traditional fibers such as wool, cotton, and silk predominate, although regenerated and synthetic fibers have also been tested, broadening the spectrum of potential uses.

Finally, the TRL analysis reveals that most studies are at intermediate levels (4 and 5), confirming a sufficient level of development to validate the viability of these dyes in relevant environments, but still far from large-scale industrial adoption. These results together reflect that the field of natural dyes based on agro-industrial waste is undergoing a period of consolidation, with strong scientific and academic support, but still requires technology transfer efforts, investment in scaling, and collaboration with industry to reach full commercial maturity.

Having completed the bibliometric analysis of scientific output, it is pertinent to complement this study with a review of the patent landscape of using natural dyes derived from agro-industrial waste for the textile industry. Unlike academic literature, patents constitute a direct indicator of the level of innovation and technology transfer, allowing us to identify the actors—companies, universities, and research centers—leading the development of applied solutions, as well as emerging technical trends and potential areas of opportunity for industrial scaling. In this sense, patent analysis becomes a key input for understanding the current landscape of intellectual property in this field and guiding technological development and international cooperation strategies.

6.2 Bibliometric Analysis based on patents on natural dyes from agro-industrial waste

6.2.1 Patent Analysis Methodology

To identify and analyze the universe of patents related to natural dyes based on agro-industrial waste applied to textiles, the Lens.org database was used, and it was recognized for its broad coverage of intellectual property and scientific literature. The procedure was structured in three successive search and filtering stages:

General universe of dyes (natural and synthetic): the search equation

(dye OR dyes OR dyestuff OR colorant* OR pigment* OR "coloring agent" OR "coloring agents") AND (textile* OR fabric* OR cloth* OR fiber* OR fiber* OR yarn* OR garment*)*

was applied, resulting in 1,304,568 patents. This initial search allowed us to gauge the total volume of technological developments related to dyes applied to the textile sector.

Natural dyes in general: the equation

("natural dye" OR "natural dyes" OR "natural colorant" OR "plant-based dye*" OR "botanical dye*" OR "bio-based dye*" OR "organic dye*") AND (textile* OR fabric* OR cloth* OR fiber* OR fiber* OR yarn* OR garment*)*

was then used, identifying 40,784 patents. This second level of filtering allowed us to narrow down the set of innovations specifically linked to natural dyes in the textile sector.

Natural dyes from agro-industrial waste: Finally, the equation

(("natural dye" OR "plant-based dye" OR "biological dye" OR "eco-friendly dye" OR "natural pigment" OR "biopigment") AND ("textile" OR "fabric" OR "cloth" OR "textile fiber" OR "garment") AND ("agro-industrial waste" OR "agricultural waste" OR "agro waste" OR "agroindustrial residue" OR "food waste" OR "fruit waste" OR "vegetable waste" OR "plant waste" OR "organic residue"))

was used, resulting in 301 results. After manual filtering and relevance review, it was found that only 15 patents were directly related to the use of natural dyes derived from agro-industrial waste in the textile industry.

Overall, this progressive search strategy allowed us to move from a broad universe of textile dye developments to a narrow, focused set of technologies incorporating agro-industrial waste as a sustainable source of natural dyes.

6.2.2 Analysis of patent results

Below are a series of graphs summarizing the results of patent searches related to natural dyes obtained from agroindustrial waste for application in textiles. These graphs clearly visualize the distribution, characteristics, and main trends in technological innovation identified in this field, thus facilitating comparative analysis with scientific output and its potential for transfer and industrial scaling.

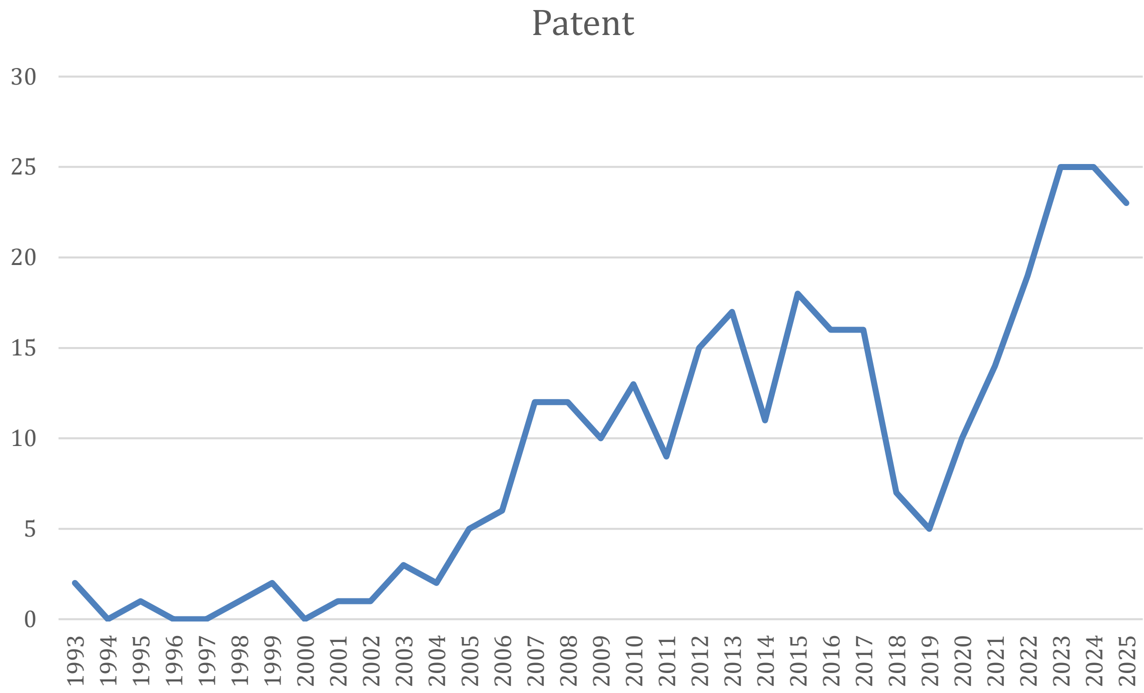

Figure 18 Annual evolution of patent management

An analysis of the annual evolution of patents shows that activity was marginal during the initial years (1993–2003), with sporadic and low-frequency registrations. This initial trend reflects that natural dyes obtained from agro-industrial waste were not a technological priority but an exploratory field with isolated contributions.

From 2004 onward, progressive growth was observed, reaching a sustained number of annual applications in the range of 15 to 18 between 2012 and 2016. This period is the consolidation of interest in this technology, driven by greater environmental awareness and the need for alternatives to synthetic dyes. Subsequently, between 2017 and 2019, a decline in patenting was recorded, suggesting technical or circumstantial difficulties that limited the momentum achieved.

Since 2020, the trend has changed radically, showing a sustained upswing that will reach a peak of 25 applications in 2023. This recent increase is aligned with global sustainability policies, the circular economy, and pressure from the international textile market to adopt cleaner processes. Overall, the evolution demonstrates that the topic has gone from marginal to consolidating as an emerging field with increasing technological maturity and significant potential for industrial transfer.

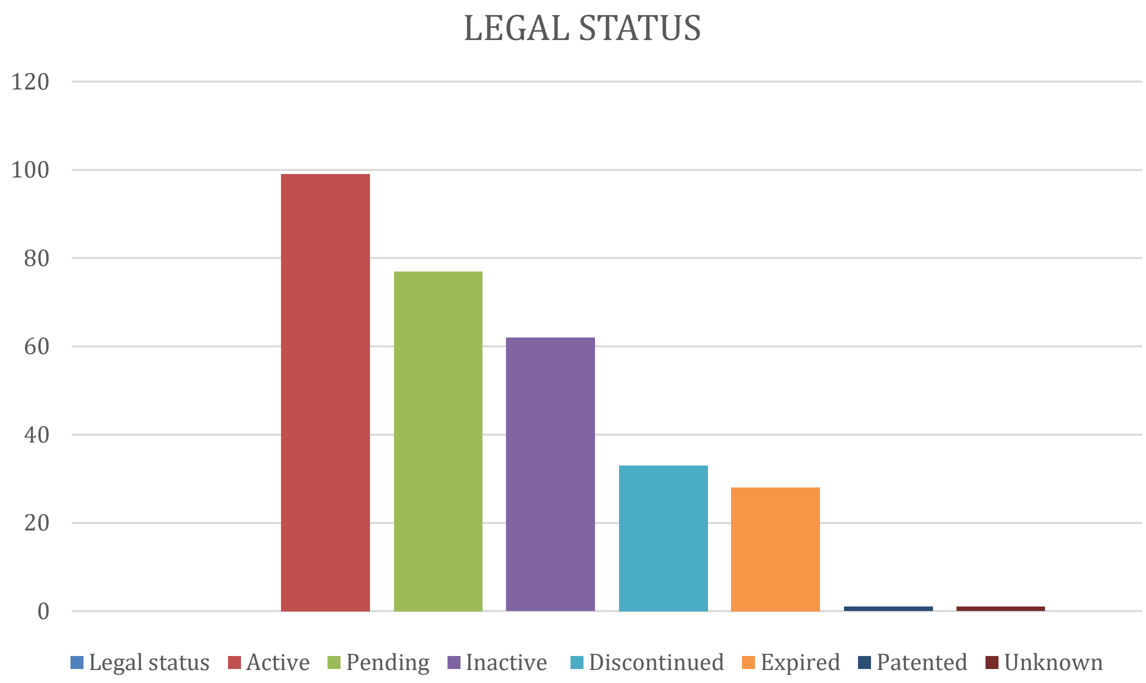

Figure 19 Analysis of the legal status of patents on natural dyes based on agro-industrial waste

An analysis of the legal status of the patents shows that most of them are active (99 cases) or in the application process/pending (77 cases). This situation reflects a dynamic technological field, in which already protected developments coexist with a constant flow of new applications under evaluation. The high proportion of current and pending patents confirms that natural dyes derived from agro-industrial waste for textiles constitute a growing and strategic topic of interest within sustainable innovation.

In a second tier are inactive patents (62 cases), along with those classified as discontinued (33 cases) or expired (28 cases). These results suggest that a significant portion of the developments failed to consolidate over time due to a lack of continuity in protection, technical difficulties in their application, or a lack of commercial interest. However, this pattern is typical in emerging areas, where initial experimentation does not always translate into scalable solutions.

Finally, the coexistence of a significant volume of active and pending patents with a group of expired or discontinued technologies opens up an interesting scenario. While ensuring the protection of recent innovations, it also creates opportunities for unrestricted technological use that new researchers and companies can exploit. Overall, this outlook confirms that the sector is in a consolidation phase, with strong momentum in generating applicable knowledge and clear opportunities to advance its transfer to the textile industry.

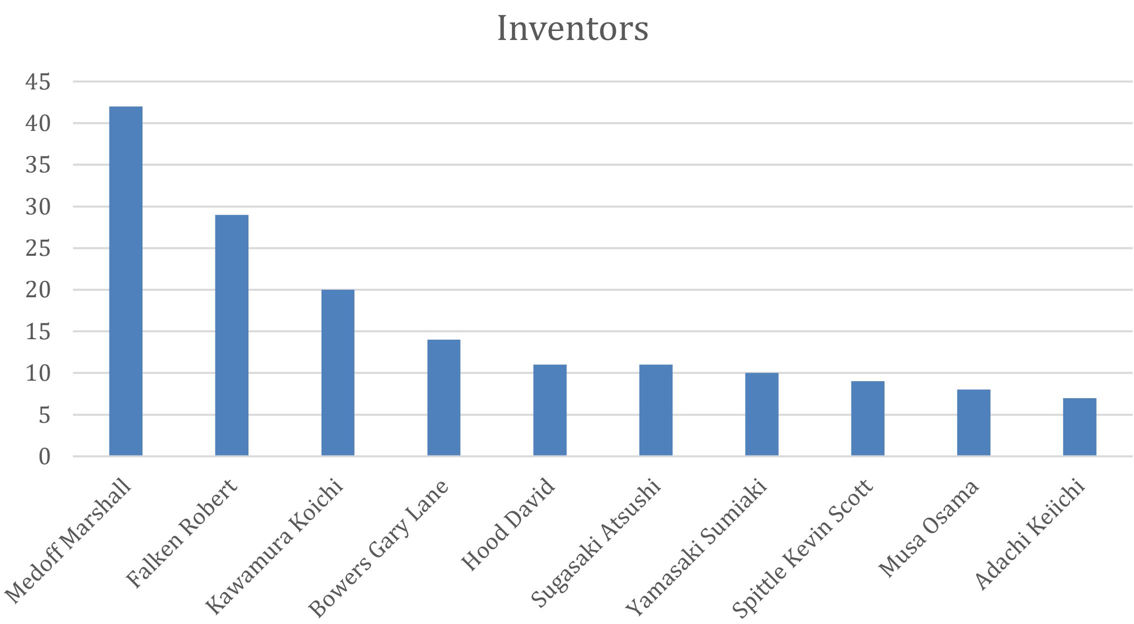

Figure 20 Ranking of the creators with the most patents on natural dyes based on agro-industrial waste

An analysis of the primary inventors reveals a clear leadership by Medoff Marshall, with 42 registrations, making him the most influential player in developing patents related to natural dyes from agro-industrial waste for textiles. He is followed by Falken Robert (29) and Kawamura Koichi (20), forming a core of researchers who concentrate the majority of technological innovation in this field, reflecting consolidated lines of research and sustained continuity over time.

At a second level are inventors such as Bowers Gary Lane, Hood David, Sugasaki Atsushi, and Yamasaki Sumiaki, with between 10 and 14 registrations, in addition to collaborators such as Spittle Kevin Scott, Musa Osama, and Adachi Keiichi, who contribute with a smaller number of applications. This distribution shows that, while leadership is concentrated among a few inventors, there is also a growing diversification of contributions, strengthening the innovation ecosystem and opening up opportunities for international cooperation and knowledge transfer to the textile industry.

In summary, the inventor landscape reflects both the existence of established leaders and a growing base of collaborators who strengthen innovation in natural dyes derived from agro-industrial waste for textiles. This context is key to understanding the concentration of knowledge and the most influential actors in technological development in this area. Along these lines, and to delve deeper into the results obtained, a table[6] is presented below, along with the 15 findings identified that are directly and effectively related to the topic. These findings constitute the most representative basis for analyzing trends and opportunities for technology transfer.

[6] The full version of the table, with details of all the patents reviewed, is available in the Annexes to this report.

Table 2 Summary table of patents related to natural dyes based on agro-industrial waste

NAME	INVENTORS	ECONOMY	STATUS
Yarns, Fabrics, And Garments Including Lignin As A Primary Dye Agent And Methods Of Dyeing Textiles With Lignin	Agarwal Dhruv , Pardeshi Akash	United States	Active
Method of Dyeing Textiles with Lignin	Agarwal Dhruv , Pardeshi Akash	United States	Active
Method for producing natural dyeing assistant by using danhua flower and pericarp	Zhu Yiming	China	Discontinued
Ampelopsis grossedentata tea agricultural waste plant dye and application of preparation method thereof in cloth dyeing	Wang Qiong , Xu Zenglai , Chen Yongmei	China	Active
A Process For The Production Of A Phytoderivative	Mele Antonio	Italy	Pending
Psychrophilic enzymes compositions and methods for making and using same	Chakraborty Krishanu , Mukhopadhyay Arka , Dutta Nalok , Dasgupta Anjan Kr	India	Inactive (Has Terminal Disclaimer (US only))
Enzyme Stabilization By Carbon Nanotubes	Dasgupta Anjan Kr , Bhattacharyya Tamoghna , Mukhopadhyay Arka , Dutta Nalok , Chakraborty Krishanu	India	Inactive
Tobacco Plant Derived Dye and Process of Making the Same	Devall Suzanne M	United States	Inactive
Method for dyeing cotton fabric dye prepared from black corncob	Shi Baoli , Jia Lina , Bo Jialu	China	Pending
Method Of Extraction From Plant And Algal Material, And Extracts Therefrom	Schneider Luke Valentine	New Zealand	Pending
Methods And Systems For Plasma Colouration And Pigment Fixation	Hussey Thomas , Alker Nathaniel , Chen Zhiqiang , Volpe Robert , Whitby Scott , Parhizkar Marzieh , Han Mingyu , Patil Amol , Sutti Alessandra , Subianto Surya , Lotz Oliver	Australia	Pending
Integrated Process Extraction Of Pineapple Biomass Into Fibers And Natural Products	Baez-Vasquez Marco A , Putilin Betty	United States	Discontinued

NAME	INVENTORS	ECONOMY	STATUS
Naturally dyed mulch and growing media	Spittle Kevin Scott , Bowers Gary Lane	United States	Active (Has Terminal Disclaimer (US only))
Gram-positive alkaliphilic microorganisms	Jones Brian Edward , Grant William Duncan , Collins Nadine Claire	United States	Expired
Nucleic Acids And Proteins And Methods For Making And Using Them	Chang Cathy , Mathur Eric J , Cayouette Michelle , Robertson Dan E , Hugenholtz Philip , Warnecke Falk , Leadbetter Jared , Ivanova Natalia , Luginbuhl Peter , Hutchison Don	United States	Pending

An analysis of the 15 patents' legal status shows that most are active or pending, reflecting a consolidating field with a constant flow of ongoing innovations. However, there are also cases of inactive, discontinued, and expired patents, common in emerging areas, where not all developments remain current or reach commercial stages.

Regarding geographic distribution, the United States clearly leads the way (7 registrations), followed by China (3) and India (2), while economies such as Australia; Italy; and New Zealand contribute less. This pattern demonstrates that major economies with established textile industries and innovation capabilities lead the generation of patents, although there is growing interest in other regions.

Finally, the analysis of inventors reveals the recurring participation of researchers such as Agarwal Dhruv, Pardeshi Akash, Chakraborty Krishanu, Mukhopadhyay Arka, Dutta Nalok, and Dasgupta Anjan Kr, each with two registered patents. This core of inventors reflects the existence of consolidated work teams driving technological advancement in the area. In contrast, other inventors who made a single contribution demonstrated the opening of the field to new players. These results confirm that innovation in natural dyes derived from agro-industrial waste is still a specialized niche, but one with growing dynamism and potential for global expansion.

7 Comprehensive View of Expert Perceptions

The results obtained from two complementary areas of data collection are presented below: a survey of natural dye experts, which identified general trends; and a summary of interviews with various specialists, which provide a more in-depth and qualitative analysis of the collected perceptions. The integration of both sources offers a more complete view of the development and challenges associated with the use of natural dyes derived from agro-industrial waste in the textile sector.

7.1 Analysis of expert interviews

7.1.1 Perceptions of experts and actors in the textile sector

This section will characterize the interviewed experts, detailing their profiles and the relevance of their participation to the topic of natural dyes derived from agro-industrial waste for textiles. The results of the interviews will then be presented, highlighting the main findings, similarities, and differences in their perspectives. This qualitative evidence enriches the overall analysis of the study and complements the bibliometric and technological insights previously reviewed.

7.1.2 Characterization of experts

The experts who were interviewed were:

Full name	Padma S. Vankar
Position	Independent Research Consultant
Years of experience in the textile sector	30 years
Economy	India

Full name	Sidhant Sodhani
Position	Managing Director at Sodhani Biotech Private Limited
Years of experience in the textile sector	12 years
Economy	India

Full name	José Luis León Tiznado
Position	Technical Manager of Andes Yar SAC
Years of experience in the textile sector	21 years
Economy	Peru

Full name	Gilberto Colina Andrade

Position	Research professor at Universidad Católica de Santa María (UCSM)
Years of experience in the textile sector	5 years
Economy	Venezuela

Full name	Elvis Gilmar Gonzales Condori
Position	Research professor at Universidad Tecnológica del Perú (UTP)
Years of experience in the textile sector	5 years
Economy	Peru

Full name	Mercedes Durand Zamalloa
Position	Coordinator in the Textile Area of the Awamaki Organization
Years of experience in the textile sector	15 years
Economy	Peru

Full name	Ruly Terán Hilares
Position	Research professor at UCSM
Years of experience in the textile sector	10 years
Economy	Peru

Full name	Suyeon Kim de Aguilar
Position	Director of the Master's Program in Biomedical Engineering and Professor of Biomedical Engineering at Pontificia Universidad Católica del Perú (PUCP)
Years of experience in the textile sector	20 years
Economy	Korea

Full name	Raúl Lazarte Gamero
Position	Independent Professional

Years of experience in the textile sector	20 years
Economy	Peru

Full name	Claudia Fuentes Meza
Position	Alpaca Garment Marketing Specialist
Years of experience in the textile sector	15 years
Economy	Peru

Full name	José Luis Carrasco Bocangel
Position	Wet Processing and Dyeing Specialist, at Center for Productive Innovation and Technology Transfer specialized in Camelid Textiles, Arequipa (CITEtextil Camélidos Arequipa)
Years of experience in the textile sector	23 years
Economy	Peru

Full name	Lucía del Carmen Martínez Pujadas
Position	Applied R&D Researcher for SMEs at CITEtextil Camélidos Arequipa
Years of experience in the textile sector	6 years
Economy	Peru

Full name	Fernanda Soncco
Position	Laboratory Analyst at CITEtextil Camélidos Arequipa
Years of experience in the textile sector	5 years
Economy	Peru

Below is a systematic summary of the interview results, organized question by question. This structure allows for a clear and organized presentation of the experts' perceptions, identifying similarities and discrepancies in their responses. This facilitates comparative interpretation and generates relevant input to complement the bibliometric and patent analysis findings.

7.1.3 Results of Perceptions of experts and actors in the textile sector

Regarding the question: Do you have experience or know of initiatives for using natural dyes in your economy or region?

The interviews confirmed that most experts and stakeholders in the sector had direct experience or knowledge of initiatives using natural dyes in their respective contexts. In the Peruvian case, projects promoted by CITEtextil Camélidos Arequipa, UCSM, and Andes Yarn SAC stood out, which had worked with agro-industrial waste, plants, and microorganisms for the production of biopigments. Likewise, at the international level, the experience of India—referred to by researcher Padma Shree Vankar—demonstrated the pioneering role played by that economy following the ban on azo dyes in the 1990s.

A second group of responses showed that the use of natural dyes was at different stages of technological maturity. While some experts reported successful experiences in the artisanal and small-scale sectors (e.g., Awamaki, Mitchell & Cía SA, Andes Yarn SAC in artisanal processes), others emphasized the limitations for industrial production, mainly due to the lack of standardization of shades, the variability of results, and the absence of reliable suppliers. These factors prevented certain business projects from consolidating stable production lines, despite the market interest shown.

Finally, several responses highlighted the diversity of approaches: from academic studies on biopigments (UCSM and UTP), to industrial export projects (Mitchell & Cía SA), and even applications for functional purposes in health (PUCP). This heterogeneity confirmed that natural dyes derived from agro-industrial waste constituted an expanding field, with significant local and international experience, but with structural challenges still pending to achieve scalability and competitiveness compared to synthetic dyes.

Regarding the question: Are agro-industrial wastes used as an input for dyes? Which ones?

The experts' responses unanimously confirmed that agro-industrial waste was indeed used as input for obtaining natural dyes, with a remarkable diversity of sources used. Among the most frequently mentioned examples were onion peels, avocado seeds, purple corn, grape pomace, and potato peels, as well as other plant products such as eucalyptus, oregano, and achiote. In several cases, the interviewees emphasized that these raw materials came from food or agricultural processing waste, reflecting the concrete application of circular economy principles.

A relevant aspect was the scalability and logistics associated with the use of these wastes. For example, the experience of the Andes Yarn SAC company dyeing 500 polo shirts with onion peels showed the need to collect between 600 and 700 kilos of input, which represented an operational challenge. Situations like this highlighted that, although waste utilization was viable in small volumes or pilot projects, its transfer to an industrial scale required organized collection systems and reliable suppliers that guaranteed continuity of supply.

Furthermore, a diversification of technological approaches was observed. While some experts used waste directly in artisanal or semi-industrial dyeing processes, others explored more sophisticated routes, such as the use of microorganisms that transformed carbohydrates present in the waste into biopigments (UCSM case). Internationally, experiences such as those in India showed a broader utilization, including industrial byproducts such as lac wastewater or unmarketed flowers. Overall, the interviews showed that agro-industrial waste represented a strategic source of inputs for natural dyes, although challenges remained in standardization, color sustainability, and large-scale supply.

Regarding the question: What extraction methods do you know or are used locally?

The responses agreed that boiling in water was the most widespread local extraction method. This traditional and straightforward technique allowed for obtaining a dye liquor from plants, seeds, or peels. This procedure was widely used in artisanal communities and small businesses, as it did not require complex infrastructure and was well-suited to transmitting traditional knowledge. Several experts also highlighted the role of mordants (e.g., metallic salts, lemon salt), which fixed the color and allowed for varying shades obtained from the same raw material, as with onion peels.

However, the analysis also moved toward more diversified and specialized methods. In some cases, maceration processes with common compounds such as sodium chloride or ethanol were used, as were techniques to concentrate and stabilize the pigments. Other researchers explored ultrasound-assisted extraction, using green solvents (DES), and supercritical fluid or CO_2 extraction to increase efficiency, reduce environmental impacts, and obtain more stable pigments. These innovations demonstrated how scientific research was expanding the boundaries of a historically artisanal field toward more sustainable and technologically advanced approaches.

Finally, some experts highlighted that, beyond direct extraction, there was growing interest in biotechnological processes that used agroindustrial waste as a substrate for microorganisms capable of producing biopigments. This approach represented a more versatile and scalable alternative, as it utilized any carbohydrate-containing waste and converted it into an indirect source of dyes. Overall, the interviews reflected a dual landscape: on the one hand, the persistence of low-cost, artisanal, and applicable traditional methods; and on the other, the consolidation of innovative techniques that sought to standardize natural dyes and make them more competitive compared to synthetic ones.

Regarding the question: Have processes been adapted for use in SMEs or textile workshops?

The interviews showed that dyeing processes using natural dyes had been adapted for SMEs and textile workshops, primarily through technology transfer and training led by CITEs (Centers for Productive Innovation and Technology Transfer) and universities. The most widely used methods in this field were boiling or decoction, due to their accessibility and low cost, as they did not require specialized equipment. These procedures were taught in workshops and courses, allowing entrepreneurs and artisans to apply the knowledge with available resources in their production environments.

However, the testimonies also showed that the transfer was still incipient and faced significant challenges. Cases like that of Andes Yarn SAC showed that companies had to implement separate areas for natural dyeing processes because they required different handling than synthetic dyes. Other experts mentioned that transfer projects had not yet resulted in fully optimized products, pointing to problems such as poor light fastness and the instability of biopigments, which limited their full adoption by micro and small businesses.

Finally, international experience (India) and research comments agreed that, although many SMEs worked with natural dyes, most focused on the artisanal or semi-industrial dyeing phase, while very few participated in dye extraction. This suggested that innovation was concentrated in academic and research settings, while more traditional practices predominated in the business world. Overall, the results reflected a gap between research and productive application, with significant progress but insufficient to consolidate a solid ecosystem for technology transfer to textile SMEs.

Regarding the question: What technical factors have facilitated or hindered using these dyes?

The experts' responses highlighted the issue of lightfastness and stability of natural dyes, especially in the face of solar radiation, as the primary technical obstacle. Unlike synthetic dyes, natural pigments tended to oxidize and degrade rapidly, causing loss of hue and limiting their durability. Both researchers and entrepreneurs mentioned this challenge and agreed that lightfastness was the most difficult variable to control. They also highlighted that color intensity was usually low, and that when greater intensity was achieved, deficiencies in the dye's resistance often appeared.

Another recurring issue was the lack of standardization and reproducibility in the extraction and application processes. The proportions varied depending on the type of residue or plant used, and factors such as pH, harvest season, or the type of mordant influenced the results, generating inconsistencies in the colors obtained. This, which could be tolerated in artisanal production, became a critical barrier when seeking to scale up to industrial levels, where customers demanded uniformity and consistency in large volumes. In this sense, the gap between artisanal and industrial production was highlighted as a fundamental technical obstacle.

Finally, other factors that influenced the advancement of natural dyes were identified: the scarcity or rising prices of certain raw materials (e.g., cochineal, seasonal mosses), and the need for more sophisticated extraction technologies (ultrasound, supercritical fluids, green solvents) that improved the efficiency and sustainability of the process. Although some experts, such as Padma Shree Vankar, emphasized that the field offered enormous and still underexplored potential, most agreed that overcoming technical obstacles required more applied research, financing, and technology transfer to bring laboratory advances closer to the production reality of textile SMEs.

Regarding the question: Are there problems with quality, fixation, toxicity, and durability?

The interviews confirmed that the main technical challenge with natural dyes related to color fastness and durability, particularly in sunlight. Several experts (Lucía Martínez, José Luis Carrasco, Elvis Gonzales, Ruly Terán, among others) pointed out that natural pigments tended to degrade rapidly when exposed to ultraviolet radiation, causing loss of intensity and hue over short periods of time. Although some cases showed good performance in rubbing and washing fastness tests, light fastness remained the most critical challenge, limiting the competitiveness of natural dyes compared to synthetic ones in markets that demanded uniformity and durability.

Secondly, problems with fixation and reproducibility were identified. Results depended largely on the type of fiber (e.g., alpaca vs. cotton), the nature of the pigment, and the mordant used, making it difficult to standardize processes and obtain consistent colors in large volumes. This limitation, tolerable in artisanal production, became a significant barrier to industrialization, as batch-to-batch variations undermined the confidence of international customers. Likewise, the need for greater technical training in companies was emphasized, given that basic errors in the preparation and washing processes directly affected the quality of the dye.

Regarding toxicity, most experts agreed that natural pigments did not pose significant risks, given that many came from edible ingredients. However, the problem lay in the mordants used, some of which (such as copper sulfate or alum in high proportions) could have negative impacts. At this point, the role of regulations such as GOTS, which established strict limits for metals and fixatives, was highlighted. However, standardization in the criteria applicable to organic ingredients was still lacking. Overall, the findings showed that natural dyes offered an environmental and safety advantage over synthetic dyes, but required technical optimization, clear regulations, and certification processes to ensure their quality, fixation, and durability reliability.

Regarding the question: Are there any necessary equipment or materials that are difficult to obtain locally?

The responses showed that the processes for obtaining and applying natural dyes generally did not require sophisticated equipment, as they could be developed using basic artisanal methods (pots, stoves, strainers, heat sources) or with small-scale textile machinery available on the market. This facilitated experimentation and the work of workshops or SMEs, which found technical simplicity an advantage in introducing themselves to the practice of natural dyeing. However, when seeking to move toward more standardized and efficient processes, apparent limitations arose regarding access to specialized equipment such as freeze-dryers, sonicators, rotary evaporators, or supercritical fluid extractors, which were mentioned as necessary for pigment extraction and stabilization innovations.

A second challenge related to the availability of inputs and mordants, rather than the equipment itself. Experts such as José Luis Carrasco pointed out that products such as alum, widely used in dyeing processes, had begun to become scarce with the expansion of natural dyes, posing an even greater risk if attempts were made to scale up to an industrial level. Furthermore, plant-based raw materials presented problems of seasonality and degradation upon drying, which impacted the continuity of processes. This forced them to rely on collection networks, collaboration with local communities, or biotechnological alternatives that reduced pressure on natural resources.

Finally, the testimonies highlighted that the difficulty accessing certain materials and technologies created a gap between academic research and practical production. While laboratories experimented with green solvents, bioprocesses, and advanced techniques, local companies resorted to simple methods that did not always guarantee reproducibility, stability, or scalability. This difference in technological and logistical access reflected the need to strengthen applied research infrastructure, develop agro-industrial waste supply chains, and facilitate the transfer of equipment and methodologies to textile workshops and SMEs to consolidate a more solid and sustainable productive ecosystem.

Regarding the question: Are public institutions, NGOs, or innovation centers involved?

The interviews showed that public institutions, NGOs, and innovation centers were involved in developing natural dyes, although their presence was still incipient and dispersed. In the Peruvian case, the Textile CITEs were the primary references, playing a key role in training, technical assistance, and the accreditation of quality tests (e.g., fastness to rubbing and washing, with the support of Instituto Nacional de Calidad (INACAL)). Universities such as UCSM, UTP, and PUCP also actively participated, contributing applied research and connecting with companies to explore extraction processes and technology transfer. However, several experts agreed that there were still no specialized centers for natural dyes in Peru, which contrasted with international experiences such as Asociación de Investigación de la Industria Textil (AITEX) in Spain, government centers in China, or associations such as Biotechnology Industry Research Assistance Council (BIRAC) in India.

Another important finding was that collaboration between academia, companies, and innovation centers still faced structural and continuity limitations. Projects such as those funded by Prociencia had enabled progress in developing biopigments and forming consortia. Still, many of these initiatives ended when funding ran out, preventing long-term consolidation. At the same time, it was evident that NGOs and community-based organizations played a role in preserving artisanal knowledge and promoting natural dyeing in regions such as the Sacred Valley of the Incas, although their reach was often limited.

Finally, greater institutionalization and government support were observed at the international level. In India, for example, incubation programs such as those at the University of Delhi allowed startups access to laboratories, expensive equipment, and low-cost consulting, significantly reducing barriers to entry. This difference highlighted the need, in the Peruvian case, to strengthen public policies and partnerships between the government, universities, and companies to ensure the sustainability of these initiatives, promote international certification, and foster knowledge transfer to SMEs and artisanal communities.

Regarding the question: Are there collaboration networks between academia, businesses, or the government?

The responses showed that collaborative efforts between academia, businesses, and the government existed, although their level of consolidation was still incipient. The CITEtextil Camélidos Arequipa played a central coordinating role, serving as a bridge between universities and microentrepreneurs to align research with the real problems of the sector. This intermediary role was key, as it allowed academia to gain firsthand knowledge of the technical limitations of natural dyes (e.g., difficulty in obtaining specific colors) and allowed companies to access knowledge that could improve their processes.

On the other hand, several interviewees highlighted the importance of government programs such as Prociencia, which funded research projects and value chains. However, limitations were also noted: the financial requirements established in the calls for proposals excluded many SMEs, even though they should have been priority players in this ecosystem. This showed that, although there were development policies, they were not yet fully adapted to the Peruvian productive reality. In contrast, international experiences (India and other economies) showed how ministries and government agencies actively facilitated technology transfer and connections between researchers and companies. In some cases, collaborations depended on paid agreements between companies and universities.

Finally, testimonies confirmed that tripartite coordination (academia-business-government) was essential for developing natural dyes. Concrete examples, such as collaborative projects in Arequipa between universities, textile companies, and CITEtextil Camélidos Arequipa, showed that significant advances in applied research and innovation were achieved when these networks worked. However, the lack of continuity, dependence on external funding, and the absence of consolidated networks remained obstacles. The standard recommendation was to strengthen collaboration platforms, make mechanisms for accessing funds more flexible, and promote international partnerships that complemented local efforts.

Regarding the question: What is needed for these solutions to be viable for SMEs?

Interviewees agreed that the viability of natural dyes for SMEs depended on combining solid research with practical scalability. Academia and technology centers emphasized the need for more accessible funding sources that did not exclude micro and small businesses, and for progress in transferring results from laboratory to plant. Several experts emphasized that much research remained on paper and was never tested under real-life production conditions, creating a gap between theory and practice. Pigment stability, light resistance, and fixation capacity remained critical issues that required applied research.

Furthermore, it was emphasized that SMEs required accessible technology, affordable inputs, and technical training. Current extraction times and costs represented a significant obstacle, so simplifying processes and ensuring a constant supply of raw materials were fundamental conditions. They also mentioned the need to standardize formulas and processes (proportions of plants, water, and fiber) so that results were reproducible and consistent. The main constraints to entry into international markets were the lack of color consistency and the difficulty scaling from artisanal to industrial production.

Finally, the importance of multisectoral coordination and collaboration was highlighted. For solutions to be sustainable, SMEs needed support in research, capacity building, supplier networks, and technical assistance. Furthermore, a cultural shift was required: entrepreneurs and artisans had to perceive these innovations not as impositions but as tools that improved their products' quality and added value. At the same time, the development of powdered pigments, the stabilization of dyes, and the standardization of processes were essential technological milestones for using natural dyes from agro-industrial waste to become a viable and competitive option in the textile industry.

Regarding the question: What experiences or cases would you highlight as examples?

The interviewed experts highlighted both international leaders and leaders within their economies who had paved the way for using natural dyes in textiles. Globally, companies such as Sodani (India), Colorifix (United Kingdom), and Dyegon (Chile) were mentioned, standing out for their commitment to innovation and sustainability. In Peru, the work of Andes Yarn SAC, a company committed to research and collaboration with CITEtextil Camélidos Arequipa and universities, was highlighted, as were other emerging initiatives in Huancayo and microenterprises such as Simonson SAC, which focused on agro-industrial waste such as avocado seeds. These examples demonstrated that, although the ecosystem was still developing, there were pioneering initiatives with the potential to consolidate.

Likewise, the advances made in technical processes that could serve as models to follow were valued. These included transforming pigments into powder, which facilitated their conservation and transportation; creating catalogs of stable colors in complex fibers such as alpaca; and demonstrating that dried vegetables could produce reproducible results, breaking the paradigm that only fresh vegetables were useful. These achievements showed how applied research and practical validation could overcome barriers such as plant seasonality or limited pigment intensity.

Finally, alliances between academia, companies, and innovation centers were highlighted as valuable experiences. Cases such as the joint project between UCSM, CITEtextil Camélidos Arequipa, and local companies, or the collaborations between universities and small companies like Mater, demonstrated the importance of cooperation in generating concrete solutions. However, it was also noted that these advances still needed to be further disseminated and systematized, as many initiatives remained scattered or lacked continuity. These experiences offered clear clues about the direction the sector needed to follow: focusing on standardization, scalability, and multisector collaboration as the key to consolidating a market for natural dyes based on agro-industrial waste.

Regarding the question, is there any aspect we have not addressed that you consider essential for this study?

The interviewees agreed that the development of natural dyes from agro-industrial waste still faced structural challenges that had not been sufficiently discussed. Among the most notable points was the need to promote biotechnology as a sustainable path, using waste as substrates to produce biopigments without resorting to genetic modification, which facilitated international certifications such as GOTS. They also pointed out that research had to be accompanied by a regulatory framework and official certifications in Peru, as the lack of clear standards limited market and consumer confidence.

Another key issue highlighted was strengthening the relationship between academia, businesses, and artisans. Several experts emphasized that projects often remained academic and failed to scale to industrial practice. Reversing this situation required fostering feedback from entrepreneurs, generating greater investment in joint projects, and ensuring the active participation of SMEs. Furthermore, the urgency of systematizing technical information and experiences was highlighted: the literature available in Peru was limited, and most references came from abroad, which prevented the full utilization of strategic fibers such as alpaca or even the exploration of new ones such as vicuña.

Finally, the interviewees emphasized considering environmental and social sustainability as central criteria. From preventing negative impacts such as deforestation to training highland artisan women, a sustainable approach was considered indispensable. Furthermore, some experts emphasized that natural dyes offered color and bioactive properties with potential health benefits, opening up a new field of applied research. In short, the conclusion of the interviews pointed to the same goal: the viability of these solutions would depend on sustained research, progressive technological development, and the development of certification and collaboration frameworks that ensured their real impact on the textile industry and producing communities.

7.1.4 Conclusion of interviews

The interviews showed a consensus on the potential of natural dyes from agro-industrial waste. Still, they agreed that the path to their consolidation faced technical and market challenges. Among the main limitations were variability in color fastness, especially in sunlight, the difficulty of achieving reproducibility in large volumes, and the lack of clear regulations or official certifications in Peru. Despite this, experts emphasized that research and technological development around new extraction techniques, the incorporation of biotechnology, and the sustainable use of waste could help overcome these barriers.

Likewise, key factors were identified to ensure the viability of these solutions for SMEs: stable financing, effective technology transfer, process standardization, and specialized training. The coordination between academia, business, and the government was identified as necessary for research to transcend the academic sphere and become solutions applicable in practical production. In this sense, the CITEs were consolidating as strategic institutions that allowed scientific knowledge to be brought closer to the sector's needs, while artisans and small businesses contributed their experience and tradition of natural dyeing.

Finally, the experts highlighted the importance of international references and local experiences. At the global level, India was identified as the most relevant case due to its leadership in certifications, productive scaling, and coordination between research and business. In the case of Peru, although a fully consolidated ecosystem did not yet exist, enormous potential was recognized due to its biodiversity, emblematic fibers such as alpaca, and the growing demand for sustainable fashion. In conclusion, this field is emerging as a strategic opportunity for the economy, integrating innovation, sustainability, and inclusive development in the textile industry.

7.2 Analysis of the survey applied to experts

7.2.1 Characterization of the experts

The experts who participated in the survey come from a wide range of institutional and geographic backgrounds, reinforcing the study's validity by integrating perspectives from diverse academic, productive, and governmental contexts. In total, representatives from Latin America, Asia, and the Middle East were identified, allowing for the coverage of contrasting realities surrounding the research and application of natural dyes in the textile industry.

On the international level, institutions from Iran (Tabriz Islamic Art University), India (Indian Council of Agricultural Research (ICAR) - Central Sheep and Wool Research Institute (CSWRI)), Pakistan (Government College University Faisalabad (GCUF)), and Thailand (Rajamangala University of Technology Phra Nakhon and Kasetsart University) participated, economies with a well-established tradition in the use of natural fibers and the development of textile processes. These contributions provide a perspective from regions with extensive experience in wool, silk, and cotton fibers.

On the Latin American side, experts from Brazil (Universidade Estadual de Maringá and Instituto Federal do Pará (IFPA)), Costa Rica (Universidad de Costa Rica), Argentina (Universidad Internacional Iberoamericana), and Ecuador (Escuela Superior Politécnica de Chimborazo) were included. This representation reflects a growing regional interest in linking academic research with sustainable and circular economy practices, especially around agro-industrial waste.

Peru's participation was particularly significant, with representatives from the Ministry of Production, UNSA, UCSP, and Inca Tops SA. This concentration demonstrates the economy's active role in developing natural dyes linked to the South American camelid value chain, which combines government, private, and academic efforts.

Overall, the characterization shows that the survey included a group of experts with diverse and complementary backgrounds, which enriches the analysis by integrating academic research perspectives, practical experiences from the textile industry, and public policies aimed at sustainable innovation.

7.2.2 Methodology

A structured survey was designed and administered to international textile, chemical, and sustainable innovation experts to gather specialized information on practices and experiences related to using natural dyes from agro-industrial waste. The questionnaire was developed digitally using Google Forms and distributed through institutional channels and academic networks, ensuring the participation of stakeholders from diverse production and geographic contexts.

The survey consisted of nine main questions and a description section, covering aspects such as:

- Types of agro-industrial waste used to obtain dyes.
- Extraction techniques used or recommended.
- Textile materials to which the dyes were applied.
- Average extraction yields.
- Fixation and stability levels achieved.
- Technical advantages over synthetic dyes.
- Degree of replicability for textile SMEs.
- Main technical and logistical barriers to small-scale adoption.
- Application potential in APEC economies.

Twenty experts from academic institutions, research centers, government entities, and private companies in Latin America, Asia, and the Middle East completed the survey. This diversity of profiles provided a broad and representative overview, integrating the scientific perspective and the practical experience and needs of the productive sector.

The results were systematized and analyzed qualitatively and quantitatively to identify common patterns, divergences, and strategic opportunities to promote sustainable textile innovation in APEC economies.

7.2.3 Analysis of survey results

Below is a detailed analysis of the experts' responses, organized question by question. This approach provides a more transparent and understandable explanation for the reader, highlighting the similarities and differences in participants' perceptions. This ensures a comprehensive view of the findings, facilitating the identification of trends, challenges, and opportunities linked to using natural dyes derived from agro-industrial waste in the textile sector.

Regarding the question: What was the main agro-industrial residue used in your study?

The responses revealed a wide variety of agro-industrial waste used as sources for obtaining natural dyes. Plant-based materials such as pomegranate, onion, rice peels, leaves from various species (mango, roselle, mangosteen, and native trees), and fruit waste such as pineapple are prominent. Also mentioned are colored wood waste, medicinal plants, microalgal biomass, and spirulina microalgae, reflecting the sector's ability to utilize traditional agricultural waste and emerging biotechnology resources. This heterogeneity demonstrates that the field of natural dyes is not restricted to a single type of input, but instead draws on ecological richness and the regional availability of waste.

Another relevant aspect is incorporating non-conventional waste, such as aqueous contaminants containing heavy metals or previously synthesized dyes. These responses, although a minority, revealed an orientation toward experimental research that seeks to broaden the horizons of sustainable dyeing, exploring solutions that could contribute to environmental remediation. Likewise, the reference to native plants of the Patagonian steppe illustrates the potential to transform spaces degraded by extractive activities into new sources of value for the textile industry, thus contributing to ecological restoration strategies with a productive impact.

Overall, the findings suggest that innovation in natural dyes within APEC economies is characterized by a comprehensive waste utilization approach, ranging from the most common agro-industrial byproducts to the exploration of cutting-edge materials such as microalgae. This diversity constitutes a solid starting point for designing circular economy policies that integrate agricultural and urban waste management with the textile value chain, fostering environmental sustainability and the competitiveness of textile SMEs through access to low-cost inputs with high valorization potential.

Regarding the question: Which extraction technique did you use or recommend?

The responses showed a clear preference for traditional and accessible techniques, primarily decoction and maceration, which appeared to be the most commonly used by experts. This confirmed that, in the field of natural dyes, the most widely used methods continued to be those of low technical complexity, widely known by artisans and small textile producers. Their popularity was explained by their ease of application and low equipment requirements, making them especially suitable for textile SMEs in APEC economies seeking sustainable and replicable solutions.

At the same time, some responses referred to emerging and more sophisticated techniques, such as microwaves, ultrasound, and enzymatic methods. These approaches reflected a growing interest in optimizing extraction efficiency, improving color fixation, and reducing water and energy consumption. Methods such as fermentation and solid-liquid extraction also pointed to a hybridization process between traditional techniques and modern scientific approaches, opening the door to innovations applicable on artisanal and industrial scales.

In summary, the results suggested that innovation in natural dyes moved along a spectrum ranging from preserving ancestral techniques to gradually incorporating advanced technologies. This finding reinforced the need to promote technology transfer programs that disseminated modern best practices and respected and strengthened traditional knowledge for public policy and international cooperation purposes. This combination would allow textile SMEs to take advantage of both the accessibility of conventional methods and the efficiency and sustainability advantages of new techniques.

Regarding the question: To what type of textile material were the dyes applied?

The responses showed that natural dyes were applied to various natural and synthetic fibers, reflecting the interest in evaluating their versatility and performance on different substrates. The most frequently mentioned fibers were wool, silk, and cotton, which were traditional artisanal and academic dyeing materials. References also appeared to less conventional fibers such as nylon 66, hemp, and pineapple leaf fiber, demonstrating the desire to expand the scope of sustainable dyeing to include fibers with different origins and physical properties. This finding suggested that natural dyes could be adapted to various substrates, albeit with fixation and stability variations requiring more detailed studies.

A second relevant aspect was the presence of fibers linked to local and regional identity, such as alpaca fiber, mentioned in several responses, and second-quality silk cocoons, demonstrating how waste from the textile industry itself could also be converted into testing materials. Likewise, plant-based fibers such as pineapple and materials generally described as "natural fibers" were mentioned, reinforcing the idea that research was not limited to conventional textile fibers but encompassed alternative resources and, in many cases, byproducts.

Regarding sustainability and projection for APEC economies, the diversity of materials tested indicated that natural dyes had transversal potential that could benefit both the large-scale textile industry and SMEs. The possibility of applying these dyes to animal, plant, and synthetic fibers suggested that innovation and technology transfer programs should include differentiated guidelines for each group of materials. In this way, environmental and economic benefits could be maximized while ensuring that the adoption of natural dyes was viable in different textile market segments.

Regarding the question: What was the average extraction yield per kg of residue? (if applicable)

The responses showed wide variability in extraction yields, reflecting the influence of factors such as the type of waste, processing conditions, and the methodology used. Some experts reported specific quantitative values, such as 50–300 g/kg of waste, 22%, 15%, or 120 g from 1 kg of pomegranate peel. In contrast, others expressed yields in ratios of dyeing material to dyed fiber, for example, 300 g of waste per 100 g of merino wool. Others reported average yields of 5% or even comparative trials with 50%, 100%, and 200% concentrations, highlighting different experimental approaches.

Another group of responses indicated that yield depended mainly on the characteristics of the plant material and its dyeing potential, making it difficult to establish a standard value. In fact, some participants clarified that the parameter was not considered in their trials or that it was not applicable in cases where small quantities of material were used (e.g., 100 g). This methodological diversity highlighted a challenge for standardizing performance indicators, as laboratory conditions, biomass quality, and the type of fiber used generated significant variations in the results.

Overall, the findings suggested no consensus on the average extraction yield for natural dyes. However, most reports agreed that the values were moderate and highly dependent on the raw material and technique. From a policy and innovation perspective in APEC economies, this aspect highlighted the importance of developing comparative protocols and standardization guides that allowed textile SMEs to assess the efficiency of agro-industrial waste as dye sources more accurately. Consolidating these parameters would improve the replicability, scalability, and commercial viability of sustainable dyeing processes.

Regarding the question: What level of fixation and stability was achieved in the dyeing tests?

The results reported by the experts showed wide variability in fixation and stability levels, reflecting the diversity of dyeing materials used and the testing conditions. Some participants mentioned quantitative values, for example, 80–85%, 90%, and 70% fixation in alpaca fibers, while others reported more modest results, such as 50% or grayscale values, with ratings of 4 to 5, considered good to very good and exceeding the minimum accepted commercial standard of 3. These figures suggested that, in general, natural dyes could achieve competitive fixation levels compared to synthetic dyes, although with significant dependence on factors such as fiber type and mordant use.

Other specialists offered qualitative descriptions, indicating everything from "good fixation" and "moderate to high level of stability" to lower-performance results where fixation was low despite some color stability. Likewise, cases were reported where prolonged sun exposure caused color deterioration, confirming that the lightfastness of natural dyes remained a technical challenge. Specific tests, such as boiling dyeing for 45–60 minutes and using statistical methods and mordanting to optimize fixation, were also mentioned, indicating an effort to systematize processes and achieve reproducible standards.

In summary, the findings reflected that, although there was a wide range of results, most experiences showed adequate fixation levels for textile applications, in some cases even exceeding the minimum required by the industry. For APEC economies, this situation raised the need to advance standardization protocols and comparative testing to validate the performance of natural dyes on different fibers and conditions of use. This could strengthen confidence in their commercial application, while ensuring their contribution to the sustainability of the textile sector.

Regarding the question: What technical advantages did you find compared to synthetic dyes?

The experts identified a broad set of technical advantages of natural dyes over synthetic ones, including their biodegradability, lower toxicity, and greater compatibility with natural fibers. Frequently mentioned were benefits such as reduced environmental impact, safety for human health, and the possibility of obtaining unique and diverse shades, which were difficult to reproduce with industrial dyes. Additional functional properties, such as antibacterial, antifungal, insect repellent, and UV protection, were also highlighted, conferring significant added value to textile products dyed with natural pigments. These technical attributes reinforced the idea that using agro-industrial waste as raw material not only replaces synthetic dyes but also expanded the performance of the final textile.

Another key aspect was the socioeconomic sustainability associated with natural dyes. Several experts emphasized that using these inputs promoted the circular economy by utilizing agro-industrial byproducts and could contribute to community income generation in rural areas. Specific examples included the revaluation of local waste in Peru and the large-scale cultivation of dye-producing plants, which allowed sustainable textile production to be linked to regional development. Furthermore, the simplicity of processes such as decoction and maceration was highlighted as a technical advantage, as they facilitated the replicability of methods in artisanal workshops and SMEs, reducing dependence on complex chemicals and specialized equipment.

While some participants indicated that they found no specific advantages, most responses agreed that natural dyes represented a more resilient and safer alternative to synthetic dyes, both from a technical and environmental perspective. The combination of attributes such as low cost, availability of raw materials, less polluting processes, and consumer health benefits reinforced these dyes' potential to be integrated into sustainable value chains within APEC economies. This created a favorable framework for innovation and green certification programs that legitimized their advantages over the conventional industry.

Regarding the question: Do you consider your method replicable by textile SMEs?

Most of the experts consulted agreed that the methods for extracting and applying natural dyes were replicable by textile SMEs. This trend demonstrated that, in principle, the procedures described did not require highly sophisticated infrastructure and could be adapted to smaller-scale contexts. The use of accessible techniques such as decoction or maceration contributed to this perception, given that these methods did not require specialized equipment and could be implemented in artisanal workshops or small production plants.

However, some respondents qualified this feasibility by pointing out that replicability depended on certain factors. In particular, it was mentioned that prior technical validation, the incorporation of batch biodigesters, or specific adjustments based on the raw material and local conditions would be necessary. Likewise, some experts indicated that their method would not be replicable in SMEs, reflecting that not all developments had achieved the simplicity or standardization required for immediate technology transfer.

In summary, the findings suggested a high potential for replicability, but it was neither universal nor automatic. To turn this expectation into reality, APEC economies must promote validation, training, and technical support programs enabling SMEs to incorporate these innovations effectively. Such programs should consider both the simplicity of more traditional processes and the need for basic infrastructure in more complex cases, thus ensuring that the benefits of natural dyes can be distributed equitably throughout the textile ecosystem.

Regarding the question: What technical or logistical barriers do you perceive for small-scale adoption?

The experts' responses highlighted recurring barriers that hindered the adoption of natural dyes at the SME level. One of the most frequently cited limitations was variability in color quality and shade reproducibility, which created batch-to-batch consistency issues and reduced confidence in the final product. Difficulties associated with color fastness, remarkably light and washing, and the dependence on using mordants that required complex pretreatment and standardization processes were also mentioned. These technical factors represented a significant obstacle to scaling production competitively with synthetic dyes.

Another group of barriers identified relates to the availability and quality of raw materials. The experts pointed to the seasonality of agro-industrial waste, the adulteration of materials in the markets (for example, products sold with mixtures that made dyeing difficult), and the need for access to certified inputs. Added to this was the lack of standardized technical information regarding parameters such as pH, temperature, and extraction times, making replicating results in different contexts difficult. Problems with financing, access to specialized equipment, and infrastructure limitations were also highlighted, which restricted the ability of small businesses to adopt these technologies efficiently.

Overall, the findings reflected that small-scale adoption depended on the availability of agro-industrial waste and institutional, technological, and market conditions. For APEC economies, this implied the need to promote support policies that include technical training, financing access, quality standards development, and strengthening supply chains. Overcoming these barriers is key for SMEs to harness the potential of natural dyes, transforming a readily available resource into a sustainable competitive advantage.

Regarding the question: Could your development have applications in APEC economies?

The responses reflected a high degree of positive consensus regarding the potential application of natural dyes in APEC economies. Most experts responded affirmatively, noting that these technologies were suitable for a wide range of natural fibers and allowed for the valorization of local agro-industrial waste, while strengthening sustainable textile practices among SMEs. Furthermore, it was highlighted that this type of development fit with trends in eco-friendly textile production, the circular economy, and the generation of community-based added value, making it a relevant alternative for the region's markets.

Some participants emphasized that, to consolidate these applications, specific challenges of scalability and standardization had to be overcome so that the products could be internationally competitive. Consistency in shade quality and performance was also key to building consumer confidence and expanding target markets. Responses such as the possibility of moving toward pilot prototypes suggested that intermediate stages had to be covered before full adoption, but the development direction was favorable.

The findings showed that natural dyes derived from agro-industrial waste were technically viable and had strategic potential in APEC economies, simultaneously contributing to environmental sustainability, strengthening local production chains, and market differentiation. For these applications to materialize, it is essential to support their development with standardization programs, technological validation, and support for scalability, so that the benefits can be widely disseminated throughout the region.

7.2.4 Summary of survey findings

The survey of 20 experts from different economies showed that natural dyes derived from agro-industrial waste had high application potential in APEC economies. However, they faced significant technical and logistical challenges. Participants reported using various inputs, such as pomegranate, onion, rice peels, mango leaves, pineapple fibers, microalgae, and byproducts from the silk and alpaca industries. The most commonly used techniques were decoction and maceration, which were recognized for their simplicity and low cost. However, innovative methods such as ultrasound, microwave, and enzymatic methods were also mentioned, offering improved yields and energy efficiency. In terms of application, the natural dyes were tested on wool, cotton, silk, alpaca, and alternative fibers, achieving fixation levels above the minimum industry standard in several cases, with up to 80–90% values.

However, the survey also highlighted critical limitations to small-scale adoption, including variability in color quality, dependence on mordants, the seasonality of agro-industrial waste, a lack of standardized technical parameters, and the costs associated with specialized equipment. Despite this, most experts agreed that the methods were replicable by SMEs, provided they were accompanied by training and validation processes. Among the advantages noted over synthetic dyes were their biodegradability, lower toxicity, compatibility with natural fibers, functional properties (antibacterial, antifungal, UV protection), and contribution to the circular economy. Overall, the findings suggested that natural dyes represented a viable and sustainable alternative, whose consolidation in APEC economies will depend on technology transfer programs, process standardization, and support for the scalability of textile SMEs.

8 Conclusions

8.1 Synthesis of the Research Context

The textile industry within APEC economies drives economic growth and contributes to environmental damage. Chief among them is the widespread application of synthetic dyes used in effluent streams, increasing the volume of water used to dye textiles, and intensifying water consumption during the dyeing process. These issues have been brought to the fore in the scientific and technical literature, which seeks to answer a key sustainability question within the industry—worldwide, pollution from dyes is described as one of the most serious sustainability threats. The reliance on petrochemical dyes severely undercuts the environmental performance of textile industries and their ability to respond to a global sustainability agenda.

In this context, realizing the potential of residue agro-industrial residues as a source of sustainable innovation has become more significant. Like many agro-industrial residues, fruit peels, husks, and leaves contain naturally occurring chromophores that can be extracted and used to dye textiles. In contrast to traditional crops used for dyeing, this method does not compete for resources with food production and uses less land and water. These agro-industrial residues, which research and pilot studies have shown can be transformed into high-value colorants, stand to create new, environmentally sustainable business opportunities (Baaka et al., 2017; Carrasco-Bocangel et al., 2022).

It has been demonstrated in industrial endeavors how coupling innovation with technological advancement can facilitate application at scale. As with the Archroma EarthColors® project, which demonstrates the transformation of agri-food waste into commercially viable dyes for contemporary textiles (Archroma, 2023), similar endeavors in APEC economies, such as those spearheaded in Peru by the ITP–CITE Textil Camélidos, demonstrate the need to integrate the valorization of agri-industrial waste with local textile tradition and SME promotion (ITP, 2023).

By combining these assorted insights, this report seeks to emphasize that residue-based dyes should not be seen as peripheral, rudimentary, or artisanal methods. Rather, they are essential instruments to enhance the circular economy, augment regional value chains, and propel APEC economies to the frontline of sustainably disruptive innovations in textiles.

This synthesis is grounded in the integrated analysis of scientific publications, patent activity, grey literature, and expert consultations, ensuring that the conclusions reflect both technological maturity and practical feasibility within APEC economies.

8.2 Key Findings from Bibliometric Analysis

The bibliometric analysis conducted in this study revealed strong patterns and disparities in the scientific production connected to natural dyes from agro-industrial residues. Since the beginning of the 2000s, publications addressing this field have increased, irrespective of the research capacity within the APEC region. The literature represents China;

Indonesia; and Peru well, while other economies with strong agro-industrial bases are notably underrepresented. This reflects both the challenges and opportunities for cross-regional cooperation in addressing the imbalances in regional knowledge.

Much of the literature focuses on the laboratory scale, particularly extracting and characterizing chromophores and applying natural dyes to fibers. For example, Baaka et al. (2017) reported promising color fastness with agro-residue dyes at the experimental level, but did not advance to pilot-scale demonstration. Likewise, Kusumawati et al. (2020) and Wijayapala and Peiris (2017) identified particular local materials and dyeing practices, illustrating the range of raw materials, yet a common deficiency in robust practices.

A study on patents also showed that innovation is not limited to academic circles. Companies like Archroma have taken the lead in valorizing agricultural waste into scalable dye solutions (Archroma, 2023). This highlights a crucial imbalance, with academia focusing on material identification and basic process optimization, whereas industry handles the upscaling and commercialization. The bibliometric evidence, therefore, emphasizes two main aspects.

The first aspect is that APEC economies increasingly acknowledge the technical potential of recovering natural dyes from industrial residues. The second is that the economy needs strong linkages between research, small and medium-sized enterprises, and multinational corporations because the shift from scientific knowledge to practical application is still too weak. These insights help justify the need for coordinated efforts that blend scientific development with industrial innovation and policy frameworks.

8.3 Insights from Grey Literature

The review of grey literature complements the bibliometric analysis since it illuminates previously unindexed practices, projects, and institutional attempts recorded in visualized knowledge. These prove that agro-industrial residues are the subjects of laboratory study and, more importantly, employed as constituents in textile projects at the community, SME, and institution levels across the APEC region.

Peru offers several experiences that exemplify this. Carrasco-Bocangel et al. (2022) documented one such case, the dyeing of alpaca fibers using Schinus molle extracts, and showcased the utility of agro-ecosystem and other native agro-resources in textile value-adding. Sucasaca-Quispe and Guevara-Garnica (2022) also studied the application of cabbage red residues on alpaca wool and dyeing and textile fastness. The ITP also documents the institutional initiatives – CITEtextil Camélidos Cusco (2023) that merge agro-wastes' valorization with technical and cultural skill training, further emphasizing the growing involvement of local SMEs and cooperatives in sustainable practices.

Several comparable initiatives are available in other APEC contexts. In Indonesia, Kusumawati et al. (2020) investigated the potential of plant-based residues to achieve innovative coloration processes, stressing the significance of grassroots innovation. In Sri Lanka et al. (2017) documented the use of naturally sourced dyes in traditional fiber systems, highlighting the cultural significance and practical challenges in scaling such practices. More encompassing reviews, such as Baaka and colleagues (2023, 2024), confirm that agro residues stemming from food industries are increasingly being recognized as potential sources of dye, despite most initiatives still being fragmented and at the pilot phase.

In their totality, grey literature illustrates a common phenomenon: while localized and institutional projects prove the technical viability of residue-based dyes, persistent challenges—such as irregular supply chains, unstandardized processes, and poor market visibility—are still widely prevalent. These findings further support the need for institutional backing, regional cooperation, and cooperation in building support services for scaling beyond localized successes towards region-wide adoptions within APEC.

8.4 Technological Pathways and Innovations Identified

The analysis indicates various methods of residue extraction and usage as natural dyes for textiles and technological advancements that transform agro-industrial residues into natural dyes for the textile industry. While traditional aqueous extraction is still considered the most well-documented method, there is a shift to novel, resource-efficient methods that improve yield, stability, industrial process compatibility, and process optimization.

One of the most important advancements is waterless dyeing. Hossain et al. (2021) provide evidence for incorporating agro-residue dyes into low-impact dyeing systems using cacao shell extracts in waterless colorations. Much like Hossain et al. (2021) about cacao shell extracts, Hou et al. (2017) investigated the functionality of sorghum waste extracts, using them as colorants and bioactive agents with UV-protective properties. All residue-based dyes have multifunctionality and a tendency toward broader textile innovations, like in the above cases, which extend the dye's value.

Other technological approaches include advanced pretreatments and fiber modifications to optimize dye absorption. Correia et al. (2021) tackled the issue of cotton fibers' cationic pre-treatment and attributed the high affinity of cotton fabrics residue colorants with fast dyeing to swift cationization of cotton. This innovation is not only in the dye lines but also in the interface between the dye and the substrate, combining chemical and enzymatic strategies for improved performance.

Analyzing the extracts of phenolic compounds derived from food by-products, as illustrated by Afonso et al. (2023), reveals the potential of crafted functional textiles. Similarly, Kovačević et al. (2021) demonstrated the application of *Spartium junceum* extracts to fibers, encouraging stability outcomes. The progress highlighted in these studies demonstrates the growing interdisciplinary technological advancements and their potential to be applied in practical, scalable contexts.

The focus of Chapter 4 is on shifts in research frontiers. A first clear tendency is the ongoing merger of green chemistry and textile engineering, evidenced by studies concentrating on using eco-friendly solvents, enzymatic adjuncts, and reducing energy use in extraction. Another tendency is the increasing interest in multifunctional performance, where agro-residue dyes are recognized for their coloration and antimicrobial and UV protective characteristics. Such shifts elevate natural dyes' status from being considered alternative materials to being advanced materials in their own right.

Lastly, the industry review highlighted the movement from solely artisanal and laboratory experimentation to now including semi-industrial and pilot-scale demonstrations. Such progress indicates the innovation path emerging to meet the still prevalent challenges of reproducibility, standardization, and quality control. In the context where technological approaches are matched to industrial needs, APEC economies can benefit from the stronger connections emerging from academic research to innovation in SMEs and the production of textiles at large.

8.5 Opportunities for APEC Economies

The outcome of this investigation presents important openings for APEC economies regarding the use of agro-industrial remains for innovative textile styles. The region has a distinct overlap of significant agricultural production and a dynamic textile industry. Such a position permits the synergistic integration of traditional waste outcomes for high-value additions, strengthening the alignment of APEC textile systems' sustainability along with innovative circular economy principles on dye technologies.

One opportunity is the expansion of agro-residue valorization within Indonesia; Peru; and Viet Nam. These economies generate large amounts of agro-industrial waste that can be added to new textile value chains. Evidence by Carrasco-Bocangel et al. (2022) showcases that even regional, localized pilot schemes help generate new value for SMEs and rural producers while differentiating textile products within emerging market niches. These examples of 'fast followers' provide fertile ground for regional scaling based on rich knowledge and capacity building. For SMEs, these opportunities translate into differentiated products, improved access to niche markets, and enhanced resilience through value-added diversification.

Integrating natural dyes into broader sustainability frameworks, eco-labels, and circular fashion systems is another key opportunity. Reviews like Bechtold et al. (2023) and Samanta et al. (2020) emphasize that consumer-oriented demand is increasingly focused on transparency and having environmental responsibility. APEC economies can take advantage of this trend by reconciling residue-based dyeing with international standards and implementing residue-based dyeing processes. This allows APEC economies to be more competitive in international and export markets. In addition, Siliņa et al. (2024) emphasize that there is a systemic shift in the textile industry towards sustainability and that circular economy systems will be critical.

Opportunities also arise from collaboration at the regional scale. Shared testing platforms, harmonized workflows, and collaborative R&D initiatives can accelerate the deployment of these systems and tools, helping to minimize the duplication of efforts. Broader assessments like that of Baaka et al. (2024) suggest that agro-residues are plentiful in the region but lack proper use. This indicates that collaborative efforts can achieve better economies of scale. These kinds of opportunities will help APEC economies deal with pressing environmental issues while at the same time improving resilience, diversification of industry, and their position in the international market for sustainable textiles. Such regional collaboration mechanisms are particularly relevant for supporting SME participation and reducing entry barriers to sustainable textile innovation.

8.6 Challenges and Barriers

The introduction of agro-residue-based dyes helps increase sustainability in multiple sectors. However, their use in APEC economies is likely to be limited. These issues pertain to institutional readiness as well as economic viability and performance.

Reproducibility is a key issue. The natural residues as agro-dyes may change in composition due to geography, cultivation techniques, and seasonal change. Varying composition makes standardization of processes for extraction and dyeing to achieve a semblance of a given standard exceedingly difficult. Bechtold et al. (2023) point out the lack of testing protocols for fastness, shade safety, and their ambiguity makes it next to impossible to compare results from various laboratories and industries. Similarly, Siliņa et al. (2024) emphasized that residue-based dyes are practically impossible to use in global supply chains due to poor quality standardization. These technical barriers were consistently highlighted by experts and industry stakeholders consulted during this study, particularly in relation to SME-scale operations.

The economic aspects of the problem are equally, if not more, important. Despite the large availability of residues, the costs involved in collection, storage, and dye manufacturing make it cheaper to use synthetic dyes. Baaka et al. (2024) suggest that extracting concentrates is exquisitely expensive due to the need for specialized equipment and storage, which is out of reach for most SMEs. Furthermore, the large production capacity of synthetic dyes and the reduced prices due to lowered production costs make it difficult to compete.

The institutional and governance problems have a layer of difficulty all their own. Samanta et al. (2020) observe that the absence of cohesive policies and support for pilot tests suffices to demonstrate the translation of the lab's creativity to industrial practice. Whenever a set of economies operates under a framework that is still developing, such a framework does not refine the influence imposed on the industries to abandon conventional residue solutions and adopt residue-based ones. Also, the agriculture and textile industries' cooperation is minimal and monocentric, restricting the formation of thin value-adding chains.

The absence of adequate policies is the main reason why these barriers to technical feasibility persist. Furthermore, the lack of standardization constitutes another barrier, which remains the core factor restricting the potential of agro-residue dyes to small-scale and experimental initiatives within APEC economies. Addressing these challenges requires coordinated policy support, targeted capacity building, and institutional mechanisms aligned with SMEWG priorities.

8.7 Implications for SMEs in APEC Economies

The findings of this study indicate that natural dyes derived from agro-industrial waste can represent real opportunities for SMEs in APEC economies. These practices allow for product differentiation through attributes of sustainability, cultural identity, and traceability, which are increasingly valued in niche and export markets (both domestic and international). By adding value to locally available waste, SMEs can reduce their dependence on imported synthetic dyes, strengthen the links between agricultural and textile value chains, and improve resilience through diversification and value-added processing of their products.

However, several barriers limit adoption and scaling up. SMEs face challenges related to waste variability, a lack of standardized extraction and dyeing protocols, and limited access to the equipment and infrastructure needed to achieve consistent quality standards over time. Economic constraints, including higher initial costs and restricted access to financing, further hinder implementation. These barriers were identified and confirmed through expert interviews and surveys.

The minimum technical capabilities required for SMEs include basic knowledge of waste preparation, pigment extraction, dye application, and colorfastness testing. Additional capabilities related to environmental management, traceability, and compliance with sustainability standards are increasingly important for accessing higher-value markets. While these requirements may exceed the capabilities of individual SMEs, they can be addressed through shared facilities, training, and institutional support.

In this context, technology centers such as CITE Textil Camélidos Arequipa (Peru) play a relevant role by providing pilot-scale validation, technical training, process standardization, and access to testing and certification services. These centers facilitate collaboration among SMEs, researchers, and policymakers, reducing technological and market risks while supporting inclusive and sustainable innovation, in line with the priorities of the SMEWG.

8.8 Future Research Directions

The analysis provided in this report has shown the potential and drawbacks of agro-residues-based dyes in textile use. Sufficient research has to be done, and the technical, commercial, and administrative issues need to be worked on to progress from promising laboratory results to widespread implementation in the APEC economies.

A major research focus is the standardization of the methodologies. As noted by Bechtold et al. (2023), there are no unified and standardized protocols in place for extraction, dyeing, and fastness that are set, and this is the reason there are so many differences in the studies, which makes the comparison difficult. The focus of research should be to formulate reference protocols that give specific outcomes that the industries can use as benchmarks. This includes forming collaborative systems that allow scientific research testing within schools, SMEs, and larger textile companies in APEC.

Another vital area is the life cycle assessment (LCA), which assesses the system's environmental performance. Although several studies focus on the dye's color characteristics, there is a significant lack of sophisticated studies that analyze the water, energy, and carbon footprint. As Siliņa et al. 2024 have pointed out, without quantifiable sustainability metrics, the value of residue-based dyes is uncertain. These studies should be broader and assess the environmental claims to improve eco-labeling and certification schemes.

Research gaps remain regarding multifunctionality. Afonso et al. (2023) demonstrate the bioactive properties—such as UV shielding and antimicrobial action—bestowed by phenolic compounds derived from food residue. Further advancing this line of inquiry could shift the position of agro-residue dyes from functional replacements to truly advanced functional materials.

Moreover, all future research should encompass the development of scaling strategies and techno-economic assessments. Samanta et al. (2020) and Baaka et al. (2024) stress the importance of innovation-centered models for laboratory-pilot-scale translation. Resemblance to residue collection logistics, dyeing system cost optimization, residue collection network logistics, and dyeing unit integration will be vital for industrial implementation.

Lastly, greater emphasis should be placed on interdisciplinary cooperation. Collaboration with policy makers, environmental economists, and textile engineers will ensure APEC economies remain at the forefront of sustainable textile innovation while maximizing the available agro-industrial residues and shifting them to a strategic resource.

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10 Annexes

INTERVIEW ANNEX

To enhance this study, interviews were conducted with economy-level and international experts involved in developing natural dyes, textile sustainability, and agro-industrial waste management. These interviews are part of a methodological process to identify perceptions, experiences, and projections regarding using natural dyes in APEC economies, emphasizing their applicability to small and medium-sized enterprises in the textile sector.

Participants were selected based on their academic and professional backgrounds and their direct involvement in technological innovation, sustainability, and knowledge transfer projects in the textile industry. Various specialists from different economies were contacted, and effective responses were received from a representative group of experts, whose contributions were considered valuable for the prospective analysis.

The interviews were systematized based on the responses provided by the experts, fully preserving the meaning and content of their contributions. Only minor adjustments to the wording and textual consistency were made, aiming to facilitate reading and understanding without altering the meaning of the ideas expressed. Thus, this appendix transparently reflects the perspectives collected, complementing the main report's findings.

This document differentiates the participation of the interviewer from that of the experts interviewed to facilitate the identification of the interventions. Thus, the questions and comments posed by the interviewer appear in *italics*, while the specialists' responses are presented in plain text.

INTERVIEW APPLIED TO PADMA S. VANKAR

CHARACTERIZATION OF THE INTERVIEWEE

- Full name: Padma S. Vankar
- Current position or role: Independent Research Consultant
- Type of organization: Independent Research and Consulting Practice
- Years of experience in the textile sector or related fields: 30 years
- Mumbai / India

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1. Local context and topic awareness

- Do you have experience with or knowledge of initiatives using natural dyes in your economy or region?

I have worked for 30 years, but let me share a small story. I am basically an organic chemist, and I did my PhD in organic chemistry. At that time, I had nothing to do with natural dyes. However, in 1996 there was a German ban on azo dyes, and soon after, India also banned them because some were carcinogenic. As a result, the textile ministry began launching projects to find alternative colorants for fabric dyeing. That is how I first became involved in natural dyeing.

- Are agro-industrial residues used as inputs for dyes? Which ones?

Yes, we have only worked with agro-industrial waste. For example, we have used pomegranate skin. In the juice industry, pomegranate and orange peels are usually discarded, but we have extracted color from them.

2. Technologies and techniques used

- What extraction methods do you know of or are used locally?

Usually, people use the conventional method of boiling in water, an aqueous extraction done locally. However, we have developed many new techniques depending on the plant and the specific requirements, since our focus has been on improving the extraction methods.

- Have processes been adapted for use in SMEs or textile workshops?

Yes, I usually demonstrate this during dyeing presentations. I show the difference between simple aqueous dyeing and more sophisticated extraction methods, highlighting the variation in dye content between them.

3. Technical and organizational feasibility

- What technical factors have facilitated or hindered the use of these dyes?

There are no real hindrances. I feel this is a very challenging field with so much potential. I have only touched the tip of the iceberg. There is such a wide variety of plants and so many colorants that still need to be explored.

- Are there issues related to quality, fixation, toxicity, or durability?

Yes, that standardization slide I showed is very important. Every process must be standardized so it can be repeated, and that is what we have achieved. Now, when we provide the technology to a company or dyers, we give them a step-by-step procedure to follow, and they obtain the same result. The issue of repeatability—where dye shades would differ after two runs—has now been resolved because we have standardized the process.

- Are there any necessary equipment or materials that are difficult to obtain locally?

Yes, certain equipment is essential in the laboratory. You need a sonicator and a good rotary evaporator. If a supercritical fluid extractor is available, that is even better. Otherwise, the basic laboratory setup should at least include UV-visible or color scan machines.

4. Ecosystem and dissemination

- Are there public institutions, NGOs, or innovation centers involved?

In Bombay? Yes. Every laboratory has some basic equipment. For example, I was a research advisor at the Bombay Textile Research Association (BTRA), and they have excellent textile facilities. Their laboratories are fully equipped for testing, including fastness properties.

- Are there networks of collaboration between academia, companies, or government?

Yes, there are initiatives underway, and that is precisely what we are trying to promote through the Ministry of Textiles. The Ministry is bringing together academicians and industrialists so that whatever is developed in the academic field can be effectively transferred and applied in the industry.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

Well, better interaction is needed. People must collaborate and try things out. Each organization requires small R&D efforts and proper training of its staff. That is how progress is achieved. Simply handing over the know-how does not work; you actually have to demonstrate it, run experiments, and show them how it should be done. Theory is different from practice—you will agree with me.

- *What experiences or cases would you highlight as examples to follow?*

Well, the first and most important step is to determine the dye content of any new plant. Once that is established, the next step is to understand the colors and the structure of the colorant, because only then can you know how it will adhere to the fabric and what subsequent steps need to be followed.

As for whether there are aspects not covered in this study, I would say no. It is more of an interactive process. As we go along, new questions will arise, and when they do, we will be able to address them.

INTERVIEW APPLIED TO SIDHANT SODHANI

CHARACTERIZATION OF THE INTERVIEWEE

- **Full name**: Sidhant Sodhani
- **Current position or role**: Managing Director at Sodhani Biotech Private Limited
- **Type of organization**: Private Limited Company
- **Years of experience in the textile sector or related field**s: 12 years
- Jaipur / India

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1. Local context and topic awareness

- Do you have experience with or knowledge of initiatives using natural dyes in your economy or region?

Yes, I am aware of the initiatives taking place in our economy related to natural dyes.

- Are agro-industrial residues used as inputs for dyes? Which ones?

Yes. For example, in our company we use many products derived from waste. Not all of them come from agricultural waste—some are industrial wastes that we also convert into dyes. From agricultural sources, the main products we use are pomegranate peels, areca nut, walnut shells, and onion peels. We also use marigold flowers. While not strictly waste, in India, which is a major producer of these flowers, large quantities often remain unsold because they quickly lose freshness. We procure these unsold flowers and use them for natural dye processing.

In addition, we use wastewater from the processing of lac (*Laccifer lacca*), an insect widely used in India for producing lacquer in paints and varnishes. During lacquer preparation, significant washing takes place, generating wastewater that we repurpose for dye production.

Furthermore, India's vast flora and fauna are heavily utilized in the pharmaceutical industry, where specific compounds are extracted from plants. After extraction, the remaining raw material is usually considered waste and sold as fertilizer or boiler fuel. Our team continuously researches such residues, identifying which ones contain color content. We then collaborate with extraction companies to collect this material and extract dyes from it.

2. Technologies and techniques used

- What extraction methods do you know of or are used locally?

There are multiple ways of extracting a product. Some methods are manual, while others are machine-based. For example, in India, certain products like indigo are still largely extracted manually, and although many companies are trying to shift toward machine-based extraction, they have not yet succeeded.

In machine-based extraction, there are several methods. The three main categories are solvent extraction, water extraction, and CO_2 extraction. Among these, we primarily focus on solvent extraction because it yields a more purified product compared to the other methods.

One of the biggest advantages of solvent extraction is that we are able to recover close to 95% of the solvent at the end of the process.

(There was an audio problem)

Yes. One of the main advantages of solvent extraction is that it produces a more purified product. In addition, we are able to recover close to 95% of the solvent at the end of the process, which makes it a very circular method.

- Have processes been adapted for use in SMEs or textile workshops?

There are not many companies in India currently extracting natural colors. There are many SMEs involved in dyeing with natural extracts, and several companies conduct textile workshops using them. However, very few companies are actually engaged in the extraction of natural colorants themselves

Thank you so much for that. Because here in Peru, the companies that I have been asking for some of these questions told me that they have made the traditional or conventional methods that are, for example, maceration or decoction.

Often people take fruit peels or parts of the fruit and boil them like tea. This is a simple form of water extraction. However, with water alone it is not possible to extract all kinds of compounds, since natural products contain many different components.

Without using solvents, it becomes very difficult to purify the product. For example, if a material contains around 100 compounds, extracting the one that provides the color requires several rounds of processing. It may take three or four successive extractions with different solvents to isolate the desired compound.

3. Technical and organizational feasibility

- What technical factors have facilitated or hindered the use of these dyes?

One of the biggest factors is the stability or fastness of the dyes. While most types of fastness can be managed, light fastness remains the biggest challenge. Compared to synthetic dyes, natural colors tend to fade much faster under sunlight, and that continues to be one of our main challenges as a company.

- Are there issues related to quality, fixation, toxicity, or durability?

Quality-wise, I would say that after working with natural dyes for 12 years, I would rank our company at around 7 out of 10. That is reasonably good, but not perfect, and I believe it will take another seven or eight years to reach a higher level.

Fixation remains a challenge, particularly light fastness, which continues to be the main issue. Toxicity, however, is not a problem. We have conducted multiple analyses, including a carbon footprint assessment and COD-BOD analysis of our dyes. Compared to synthetic dyes, our natural dyes show a much lower carbon footprint and significantly lower COD-BOD values. This reduces water treatment costs by nearly 80%.

In terms of durability, our dyes perform more or less the same as synthetics, and durability can be further improved with enzymes, which some companies are already producing for this purpose. In my view, the only major issue that remains is light fastness.

- Are there any necessary equipment or materials that are difficult to obtain locally?

For example, we extract most of the colors using machine-based methods, with specific equipment designed for that purpose. In India, this is not a problem because large-scale extraction is already common in the pharmaceutical sector. However, I am not sure how difficult it might be in Peru.

4. Ecosystem and dissemination

- Are there public institutions, NGOs, or innovation centers involved?

Yes. In India, there is a body called BIRAC (Biotechnology Industry Research Assistance Council). For our bacteria-based colors, which involve synthetic biology, BIRAC has provided significant support to our company.

We have also collaborated with NGOs in the past—for example, one helped us increase the cultivation of a raw material that posed challenges in our supply chain. Additionally, there are many innovation centers across India. In our case, for the bacteria-based dyes, we are incubated at the University of Delhi, where we conduct all of our research.

This incubation is crucial because otherwise research would be extremely costly. Starting independently might require an initial investment of around two to two and a half million dollars, due to the expensive equipment needed. Instead, through the incubation program, we pay only a minimal rent—around USD350 a month for the space—and an additional USD150–250 for equipment usage, totaling about USD500–600 monthly.

All of this infrastructure has been developed by the Government of India, which shows there is strong institutional support for these kinds of initiatives.

- Are there networks of collaboration between academia, companies, or government?

Yes, there is considerable collaboration between academia and companies, but it is mostly paid—meaning we have to pay academic institutes to conduct research for us. It is not a free collaboration as it might be with the government.

As for government collaboration, we haven't worked directly with them on projects. However, the government does support us by inviting us to trade shows or providing free spaces in events, especially those related to sustainability.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

I think one of the most important issues is cost, because many people back out for that reason. The problem is that demand is still small, which keeps the cost high.

For example, if we look back 20 years, solar panels were very expensive. But now, because they are sustainable and widely incentivized by the government in India, everyone uses them. In the same way, if our technology is sustainable, there is strong interest. However, many people still withdraw because the costs remain too high.

- What experiences or cases would you highlight as examples to follow?

For us, as a company, the main objective has always been commercialization. SMEs are important, but unless you can operate at a commercial level, scaling becomes a major challenge. Large companies like H&M or Levi's would need to purchase at bulk scale for products to truly grow.

In the past, we have worked with multiple brands—including Diesel, Target, and H&M—who have produced pilot collections using our dyes. However, these are mostly small-scale pilots rather than full-fledged collections, and they have not replaced conventional dyes with natural ones.

The key issue is the lack of circular demand. For example, Target purchased about 20 metric tons of dyes from us in 2022, but there has been no repeat order since then. We are expecting a new order this year, but without consistent demand, scaling remains a significant challenge

6. Closing

- Is there any aspect we have not covered that you consider important for this study?

In my 12–13 years of experience, what I have understood is that the development of synthetic dyes took nearly 70–80 years to perfect. It did not happen in a single day or even within a decade. When synthetic dyes were introduced, their main competition was natural dyes.

If natural dyes are to be adopted at a mass scale today, the same principle applies—it will take time. Research and development is a long journey and cannot be completed in just a few years. Moreover, unless demand increases from major brands, it will be difficult for the industry to grow.

Over the years, we have also observed that natural dyes work particularly well with certain fibers. Wool is the best fiber for natural dyes, followed by nylon, jute, linen, silk, and lastly cotton.

INTERVIEW WITH JOSÉ LUIS LEÓN TIZNADO

CHARACTERIZATION OF THE INTERVIEWEE

- Name and surname: José Luis León Tiznado
- Current position or function: Technical Manager
- Type of Organization: Andes Yarn SAC Company
- Years of Experience: 21 years
- Socabaya / Arequipa / Peru

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1. Local context and knowledge of the subject

- Do you have experience or know of any initiatives using natural dyes in your economy or region?

Yes, we are a company specializing in industrial and artisanal dyeing. We use organic and synthetic dyes and work with plant pigments and cochineal. This emerged as a way to expand our work into the artisanal field.

Based on our experience in industrial processes and artisanal dyeing with synthetic dyes, we also had the foundation to work with natural pigments. We conducted research within the company and received training; we even traveled to Cusco to learn from artisans who master traditional dyeing techniques passed down through generations. There, we discovered several small businesses dedicated to these processes.

The drawback with natural dyes is the lack of color sustainability, as the same shades are not always achieved in large orders. Small, artisanal productions work well because there are fewer demands. However, for larger volumes, color variability is a problem. That's why we've worked to standardize processes, although we maintain a fairly limited color range.

- Are agroindustrial wastes used as input for dyes? Which ones?

Yes, we've worked with agro-industrial waste like onion peels. We used them in a large order of about 500 polo shirts for a company in Arequipa. To do this, we needed between 350 and 400 grams of peel per garment, which meant collecting around 600 to 700 kilos of peel in total. It was complicated because we had to source it directly from the markets where the onion harvest arrives.

Another ingredient is avocado seeds, which allow us to achieve attractive colors. However, we don't use them much because it's more challenging to obtain sufficient quantities. In this case, we've been in contact with the Productive Innovation and

Technology Transfer Center for Agroindustry (CITE Agroindustrial) located in La Joya, which has a supplier network and could facilitate our access.

You can also work with products like passion fruit. A university has even researched grape seeds as a possible additive for sewage lines, demonstrating the diverse applications of these waste products. That's why it's important to form groups or entities that act as a link between researchers, companies, and producers to strengthen this emerging market for organic and natural products.

2. Technologies and techniques used

- *What extraction methods do you know or are used locally?*

The most common method is boiling, similar to preparing a mate: the products are boiled to extract the pigment, which is the most commonly used.

At a fair in Lima, we met a company from Huancayo already working on concentrating pigments and transforming them into powder. We even requested some samples, and they worked well. The process involves some dehydration, although I don't know the details. At that time, they offered about four colors.

All of this is part of the research, and achieving a greater variety of powdered pigments would be a great advantage because it would strengthen the development of this industry.

- *Have processes been adapted for use in SMEs or textile workshops?*

Yes, natural dyeing should be done separately from industrial or synthetic processes. In our company, we have implemented it in a separate area, completely isolated from other production sections.

3. Technical and organizational feasibility

- *What technical factors have facilitated or hindered the use of these dyes?*

It's not easy; we've had to overcome several barriers. The first was obtaining the necessary inputs, as obtaining the required plants is not always easy. Even the price of cochineal bug has risen significantly. A few years ago, a kilo cost USD60, and now it's around USD120, which makes a big difference in costs.

Furthermore, many of the plants we use in our menu come from Cusco, and some are difficult to obtain because they only appear during the rainy season. For example, certain mosses that allow us to achieve orange hues only grow during this time.

Farmers need to understand the demand to take advantage of these opportunities. Better coordination throughout the supply chain is also necessary to ensure supply.

- Are there any problems with quality, fixation, toxicity, or durability?

Natural dyes don't achieve the same durability as synthetic dyes; they're always a step below. In our research and testing with different plants, we've identified a more stable range, although others with pigments aren't suitable because they fade easily in the sun or when washed. That's why it's key to work with plants that offer pigments with the necessary durability and that are also in demand in the market.

When we provide services, we always inform clients that natural dyes are less fast-drying than synthetic dyes. This is already known internationally, and according to new regulations, the products are accepted because they do not cause skin problems.

Even so, there is much to investigate. In ancient times, for example, the colors of the Paracas have been preserved to this day. However, some natural products can no longer be used because they are harmful. This creates restrictions that we must also consider.

- Are any necessary equipment or materials difficult to obtain locally?

No, the processes we carry out at our company aren't complicated, as we use pots, stoves, and strainers. However, more complexity would be required if we wanted to convert the pigments into powder, as is the case with the Huancayo company, which surely has special equipment.

4. Ecosystem and diffusion

- Are there any public institutions, NGOs, or innovation centers involved?

It is worth highlighting that natural dyeing workshops have been held at the CITEtextil Camélidos Arequipa, where we have participated.

- Are there collaboration networks between academia, businesses, or the government?

Although a consolidated network has been proposed, it hasn't been created yet. The first steps were taken last year, but didn't move forward due to economic issues; in that sense, the government could play an essential role in coordinating and funding these initiatives.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

Improved technology is essential. Our extraction process is currently time-consuming and labor-intensive. We could reduce the time and cost if the necessary inputs were more readily available. It's critical to remember that natural dyes aren't cheap, so one way to make the process more affordable is to have more accessible and affordable inputs.

- *What experiences or cases would you highlight as examples to follow?*

The company from Huancayo that converted the pigment into powder, was a significant advance.

On the other hand, our company strives to continue researching and expanding our color range. We currently have a color chart of 14 shades, but we often receive requests for more. We've preferred to stick to a limited range, prioritizing color stability.

6. Closing

- *In closing, is there any aspect we haven't addressed that you consider essential for this study?*

There is no official certification for organic products or dyes in Peru, and there are no regulations. Several companies have asked us for a guarantee and told us, 'Okay, your product is natural and organic, but what certifies it?'

Faced with this situation, as a company, we prepared a letter of commitment for a demanding company and presented photographs as proof that the product had been naturally dyed. However, we know this isn't the appropriate approach. That's why it's necessary to have an entity that can issue an official certificate. We even looked for options abroad, but didn't find anything specific.

INTERVIEW APPLIED TO GILBERTO COLINA ANDRADE

CHARACTERIZATION OF THE INTERVIEWEE

- Name and surname: Gilberto Colina Andrade
- Current position or function: Research professor at UCSM
- Type of Organization: University
- Years of Experience: 5 years
- Arequipa/Peru

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1. Local context and knowledge of the subject

- Do you have experience or know of any initiatives using natural dyes in your economy or region?

I have a PhD in Environmental Engineering, so I analyze various environmental issues. Within that framework, I study natural pigments. When we presented our proposal on natural dyes, we had been working on the topic for several years, especially concerning biopigments at the corporate level, albeit from other sources.

- Are agroindustrial wastes used as input for dyes? Which ones?

As far as I know, certain agro-industrial wastes are used to dye materials like alpaca fiber or cotton. Onion waste is frequently used, and cochineal is a natural source of dye.

Approximately 10% of the textile industry's production line uses natural dyes.

2. Technologies and techniques used

- What extraction methods do you know or are used locally?

In my specific case, our source is not directly agro-industrial waste, but algae and microalgae. We work through a Prociencia project, a consortium of several entities, in which we develop processes for extracting pigments from these sources.

We have applied environmentally friendly extraction methods for microalgae, utilizing green technologies. For example, we employ maceration processes with commonly used substances such as sodium chloride to stabilize the pigment. At this stage, we use compounds such as sucrose, which is also widely used and poses no risks to the ecosystem or human health.

- Have processes been adapted for use in SMEs or textile workshops?

So far, we've worked in consortia with institutions such as the CITEtextil Camélidos of Arequipa and Puno, private companies, and regional governments. This collaborative effort has allowed us to advance in the development of biopigments.

We are currently stabilizing these pigments to subsequently establish a schedule and coordinate workshops that will allow us to disseminate these technologies, which are quite accessible to the population.

3. Technical and organizational feasibility

- What technical factors have facilitated or hindered the use of these dyes?

A lot is going for it, because very little research has been done on the extraction of biopigments from algae or microalgae in our region; perhaps some progress has been made internationally, but many aspects remain to be developed.

The idea is to present eco-friendly extraction and stabilization protocols. Among the main challenges we've faced are pigment stability and its performance in tests such as sun exposure or friction on fabric. These aspects are more complex because, unlike synthetic dyes, which adhere more strongly to the fiber, biopigments typically generate more pastel or softer colors.

The main challenge is ensuring the pigment remains stable in the fiber over time and can pass standardized quality tests.

- Are there any problems with quality, fixation, toxicity, or durability?

Some of the challenges relate to stability and fixation. In our case, we worked with phycocyanin, a process we are perfecting on alpaca fiber, and the fixation has been positive.

The important thing is that there is no toxicity. Unlike synthetic dyes, which can generate toxic processes both in the garment and in the textile process—especially in effluents and wastewater—we use natural dyes. This guarantees no significant risks to the ecosystem or the user who will wear the garment.

- Are any necessary equipment or materials difficult to obtain locally?

No, as I mentioned earlier, we work with commonly used reagents and compounds in these processes. It's important to remember that it's not just a matter of dyeing by placing the biopigment on the fabric; it involves several stages: extraction, pigment stabilization, and dyeing.

In the latter, mordants are necessary to help fix the biopigment to the fabric. We use accessible and non-toxic substances, avoiding dangerous organic solvents. We primarily work with inorganic compounds, especially sucrose or sodium chloride, especially in the case of microalgae. All are commonly used reagents on the market and do not require special permits, as they are not controlled.

4. Ecosystem and diffusion

- Are there any public institutions, NGOs, or innovation centers involved?

Not at the moment. When I mentioned the consortium, I was referring to being part of a Prociencia project with a defined duration and officially concluded in December. During that time, we worked with the Regional Government to locate institutions that work with microalgae, to establish effective sampling systems for private companies, and to count on the support of the CITE (Centers for Productive Innovation and Technology Transfer) in quality control and in evaluating the quality of the staining.

That process formally concluded in March of this year, when the technological package was completed. However, we continue working informally, with the same desire to move forward. Once this package is more consolidated, there will be invitations to share the results. In fact, I've already been invited to several Prociencia conferences to present at venues where various organizations participate. So, although the official project is over, we're always open to inviting and joining other institutions.

- Are there collaboration networks between academia, businesses, or the government?

There is fluid communication between private companies, research centers, and academia. We've achieved a fairly efficient coordination, and that's essential because the entire biopigment extraction process begins in laboratories. Ultimately, both the business owner and the end user must give their approval, and this coordination is necessary to ensure a quality product.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

Working with algae and microalgae, we've developed a small color catalog. This material is important because, when presenting results at meetings, we can show something more concrete and useful to companies.

We're putting together this catalog with colors that are visually appealing and highly stable in alpaca fiber, which is unique due to its medullary structure. This makes the biopigment impregnation different. The idea is to offer organizations a stable product and a catalog of colors that appeal to the business sector.

- What experiences or cases would you highlight as examples to follow?

There are several opportunities. As I mentioned, Peru has an interesting market, both domestically and internationally, due to the type of fiber and garments we offer. The European market, particularly, is beautiful because it supports and consumes sustainable fashion.

In recent years, I've noticed a joint effort between companies and academia to increase the use of natural pigments. A good example is cochineal, which is already used on an industrial scale. Another example is onion peel, which offers an interesting color and is also an agro-industrial waste with potential for reuse.

This background motivates us to investigate other sources, such as algae and microalgae, which represent a promising alternative.

6. Closing

- *In closing, is there any aspect we haven't addressed that you consider essential for this study?*

The survey has addressed key issues, and I don't see anything beyond what was discussed. It is essential to expand, diversify, and support this area, promoting the use of different sources of biopigments, while always ensuring biodiversity and without affecting other areas, so that it is entirely sustainable. To achieve this, we must work together: academia, the government, and business.

Initiatives like those developed by Prociencia are very valuable because, in the end, they generate a valid and quality product for everyone through projects that involve both public and private institutions.

INTERVIEW WITH ELVIS GILMAR GONZALES CONDORI

CHARACTERIZATION OF THE INTERVIEWEE

- Name and surname: Elvis Gilmar Gonzales Condori
- Current position or function: Research professor at UTP
- Type of Organization: University
- Years of Experience: 5 years
- Arequipa/Peru

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1. Local context and knowledge of the subject

- Do you have experience or know of any initiatives using natural dyes in your economy or region?

I've heard of some companies that use natural dyes made from agro-industrial waste, such as seeds and shells. These companies have begun dyeing various textile fibers, such as alpaca fiber and cotton, with good results. They have even developed color and pattern charts, which have allowed them to sell products based on these natural dyes.

We were recently interested in a call for proposals for value chains, but we encountered a problem submitting the project. However, we continue working on natural dyes and plan to continue along these lines.

- Are agroindustrial wastes used as input for dyes? Which ones?

We've worked with avocado pits, onion peels, and algae pigments. The ingredient that most catches my attention is avocado pits, because we've already been working with them in the laboratory. I even know that a company in Lima already sells garments, such as polo shirts, dyed with avocado pits.

2. Technologies and techniques used

- What extraction methods do you know or are used locally?

Typically, industries work with seeds, which are often pulverized or reduced in size and then extracted by boiling them in water. Water acts as a solvent with an affinity for these compounds, facilitating their extraction.

In short, the process involves boiling the seeds with water to obtain the pigment, which is then used in dyeing the fibers.

- Have processes been adapted for use in SMEs or textile workshops?

I don't think there's been much of an impact on small businesses yet. For example, the microenterprise we were planning to submit a project with sells avocado seed-dyed polo shirts. However, it doesn't yet have a developed scientific component, and that's precisely why we were interested in establishing a collaboration between the university and the company. The idea was to consolidate that scientific base and, eventually, obtain a patent.

3. Technical and organizational feasibility

- What technical factors have facilitated or hindered the use of these dyes?

The dyeing process itself is not problematic, as it has been developed for many years and is quite well-known. However, natural dyes are sensitive to light. One of the main technical problems is solar radiation, as the pigments begin to degrade: their chemical structures are destroyed by ultraviolet radiation or the sun's intensity, causing the garments' initial color to deteriorate gradually over time.

This is the main limitation currently facing companies and laboratories developing natural pigments. Therefore, research seeks to answer the question: how can we make these pigments more resistant to degradation caused by the sun?

- Are there any problems with quality, fixation, toxicity, or durability?

Durability is one of the issues, but toxicity is practically nonexistent because these natural pigments are in the environment and are part of our food. Only in particular cases could allergic reactions occur in people sensitive to a component, although no studies or reports confirm this. They do not pose a danger to people, even in dermal contact.

I haven't seen all the controls up close regarding quality, but the CITEtextil Camélidos Arequipa is the institution that most supports companies in this regard. They've reported that the main difficulty with natural dyes is fixing the color to the fiber, which creates quality issues, as the garments lose color over time.

- Are any necessary equipment or materials difficult to obtain locally?

Not really, because the boiling process is quite simple. Traditionally, in artisanal dyeing, they can be done in a pot of water, using ground seeds. A decoction and simple filtration are then carried out, for example, by passing the extract through a cloth, which allows for a solution without seeds but with all the pigments.

The problem arises when attempting to take this to the industrial level. Initial studies show that extraction is simple and pigmentation is easy, but exporting the pigments in liquid form is not feasible, since using water as a solvent quickly causes the growth of microorganisms—such as fungi—that deteriorate the product.

The only way to preserve them is to turn them into powder. For this, other technical aspects come into play: solvents such as ethanol extract pigments more efficiently and, after recovery, allow them to be dried and transformed into powder. Processes such as freeze-drying can optimize drying and preserve the pigment's properties until its use in industry.

This path is just beginning, as there are no established processes in this area yet. We are currently investigating which solvents could help overcome these limitations and how to obtain stable powdered pigments.

4. Ecosystem and diffusion

- Are there any public institutions, NGOs, or innovation centers involved?

Yes. The only center I know of that's working on this topic is CITEtextil Camélidos Arequipa. At Technological University of Peru, we're just beginning to engage with the industry because previously, all our studies were done exclusively in laboratories. Dyeing a garment under controlled conditions is relatively easy, but doing it in a company, with production batches and high costs, is much more complex.

In this approach, the CITEtextil Camélidos Arequipa —through the Ministry of Production—has played a key role as a link between the university and industry. It has an accredited laboratory for the quality control of textile fibers. It provides this service, technical assistance, and support to companies to solve practical problems with which they already have experience.

As far as I know, the Ministry of Production actively supports these initiatives.

- Are there collaboration networks between academia, businesses, or the government?

The university is increasingly entering this field, and right now, the government—through PROCIENCIA—will fund 81 value chain projects. One focuses on the textile and alpaca fiber sector, significantly strengthening the collaboration between academia, industry, and the government. This alliance will undoubtedly bear many fruits.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

The first step in ensuring the viability of these projects is to verify that they work in the laboratory, that is, to complete the academic phase. Once validated, patents can be generated to protect the dyeing or pigment extraction processes.

When we obtain powdered pigment, it will be much more feasible and viable for companies to use it in garment dyeing and even for export. I imagine there are foreign companies interested in acquiring powdered pigments because education and industrial development are currently geared toward sustainability and the circular economy. In that context, the utilization of waste has a huge impact.

- What experiences or cases would you highlight as examples to follow?

The company we've been in contact with is Simonson SAC. I highly value their courage in starting to dye polo shirts with avocado seeds and other garments made with this pigment. It's a microenterprise, but it's very ambitious in developing and optimizing dyeing processes, as they've identified several challenges that need to be addressed.

Now that we've established close contact, we'll begin future joint projects to perfect their processes. From academia, we'll obtain scientific products and even patents, and the company will also be able to generate its own patents, improving its visibility at the regional, domestic, and even international levels.

It's a company with great potential for expansion because it has invested in this innovation. At the same time, in Arequipa and other parts of Peru, universities are already researching the use of agro-industrial waste to extract natural pigments and bacteria and algae, stressing them to produce pigments of various, very striking colors. However, the challenge remains fixing these pigments in the fibers; once we resolve this limitation at the university level, we will be able to support companies like Simonson SAC to generate greater revenue from these innovative ideas.

6. Closing

- In closing, is there any aspect we haven't addressed that you consider essential for this study?

Yes, universities should focus their most significant investment on research, but internal projects should also involve companies. We have worked solely in the laboratory for many years, achieving exciting results and publications in prestigious journals. However, when we contact companies, we find that many of these processes are not scalable.

Scalability will only be achieved if universities invest in internal projects that integrate the business sector and the government allocates more funding to research, fostering this university-business connection. In this way, we will grow as universities and as an economy, making better use of resources. In Peru, we have a large amount of waste that is currently undervalued and that can serve not only as a source of natural pigments but also as the origin of future molecules with applications in medicine and other fields.

INTERVIEW WITH MERCEDES DURAND ZAMALLOA

CHARACTERIZATION OF THE INTERVIEWEE

- Name and surname: Mercedes Durand Zamalloa
- Current position or function: Coordinator in the Textile Area of the Awamaki Organization.
- Type of Organization: Civil Association
- Years of Experience: 15 years
- Urubamba/Cusco/Peru

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1. Local context and knowledge of the subject

- Do you have experience or know of any initiatives using natural dyes in your economy or region?

Yes, although my practical experience is not yet extensive, I have some knowledge of working with natural dyes.

- Are agroindustrial wastes used as input for dyes? Which ones?

Well, cochineal, as well as various plants and vegetables, are used for dyeing. Mordants such as alum stone and lemon salt are the two fundamental elements for lightening or fixing the color.

2. Technologies and techniques used

- What extraction methods do you know or are used locally?

I don't have much experience with extraction methods. When we need to work with a plant—for example, chilca—we simply go to the site, collect what we need, and use it directly. In the case of cochineal, we usually buy it in stores by the kilo, so I don't know much about the extraction process.

Excuse me, but do you use the traditional method, which is boiling?

Of course, all our work is entirely handmade, without standardized formulas. Therefore, colors may vary from production to production: they may be similar, but never the same.

- Have processes been adapted for use in SMEs or textile workshops?

No, we don't produce for third parties; we only carry out the process for our production.

3. Technical and organizational feasibility

- What technical factors have facilitated or hindered the use of these dyes?

One of the main obstacles is the scarcity of raw materials, as it's not always possible to find the right dye plant, especially when it's not in season. However, from a technical perspective, we don't face major difficulties, as it's a completely artisanal process, meaning we don't rely on specific technologies that could cause complications.

- Are there any problems with quality, fixation, toxicity, or durability?

Yes, there are some challenges related to color durability, specifically its proper fixation in the wool. Occasionally, the dye can fade during weaving, washing, or use. However, these problems are usually corrected by observing what's happening and adjusting the process accordingly.

- Are any necessary equipment or materials difficult to obtain locally?

In our case, we have not had that experience.

4. Ecosystem and diffusion

- Are there any public institutions, NGOs, or innovation centers involved?

I know of some initiatives in the Valley, although not many. Foreign organizations promote natural dyeing; for example, in Calca, there's a young woman working on this, probably the only one in the area. We also encourage the practice of artisanal dyeing.

- Are there collaboration networks between academia, businesses, or the government?

I've seen the government provide support for dyeing in other communities through local governments or municipalities. These processes are also artisanal, involving people with experience in traditional dyeing.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

It would be essential to advance toward greater technical development in dyeing, without resorting to chemicals, but instead working with our plants. For example, establishing explicit formulas: if a 20-liter pot requires 2 kilos of chilca, the result should be a specific color that can be reproduced in each process. This doesn't occur because artisanal dyeing is usually done empirically, by calculation, without exact measurements. It would be advisable to standardize aspects such as the quantity of plant, water, or wool to be used to achieve uniformity and reproducibility in colors.

- What experiences or cases would you highlight as examples to follow?

I believe artisanal dyeing should continue to be strengthened. I know of a young woman working in this field, although I don't have many details about her methods or remember the exact name of her initiative. However, I think it would be valuable to continue and support these types of efforts.

6. Closing

- In closing, is there any aspect we haven't addressed that you consider essential for this study?

A very important aspect is that artisanal dyeing is closely linked to artisanal weaving and consequently to the work of high Andean women's groups who depend on this knowledge. It would be essential to train these artisans so they can replicate and continue this practice.

However, the process should advance toward greater technical development by defining explicit formulas, such as establishing how many kilos of vegetables (chilca, colli, among others) correspond to certain liters of water and a certain amount of wool. This would avoid working solely by calculation and would ensure greater precision and consistency in the results. Furthermore, I believe that women artisans fully deserve access to this knowledge, which would strengthen the sustainability of artisanal work.

INTERVIEW APPLIED TO SUYEON KIM DE AGUILAR

CHARACTERIZATION OF THE INTERVIEWEE

- First and last name: Suyeon Kim de Aguilar
- Current position or function: Director of the Master's Program in Biomedical Engineering and Professor of Biomedical Engineering at PUCP
- Type of Organization: University
- Years of Experience: 20 years
- Daegu / Korea

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1. Local context and knowledge of the subject

- Do you have experience or know of any initiatives using natural dyes in your economy or region?

Yes. In the early stages of my work, during my master's degree, we focused on using natural indigo dye (Indigofera). We were looking not only to dye fabrics, but also to add effects with potential health benefits.

- Are agroindustrial wastes used as input for dyes? Which ones?

Of course. We generally consider fruits and plants with coloring compounds as candidates for dyes. We currently work with purple corn—both the kernel and the cob—and with fruit peels. We also use winemaking waste (grape pomace/bagasse) to extract compounds that can be used as dyes.

2. Technologies and techniques used

- What extraction methods do you know or are used locally?

Our research group is focused on improving extraction techniques. We seek to avoid toxic solvents that can harm the environment. We are currently working with deep eutectic solvents (DES), a type of low-toxicity, reusable "green" solvent. In parallel, we employ mechanical routes—for example, ultrasound-assisted extraction—to reduce or eliminate the use of organic solvents.

- Have processes been adapted for use in SMEs or textile workshops?

I've worked on projects with companies looking for readily available plants as color sources. We were responsible for extracting their compounds (pigments) and evaluating their functionality as dyes.

3. Technical and organizational feasibility

- What technical factors have facilitated or hindered the use of these dyes?

More than "facilitating," we optimize natural dyeing processes to minimize the use of chemical inputs. Using natural dyes doesn't mean eliminating auxiliaries or mordants; color performance is often lower without this support. Our goal is to minimize the chemical load when using natural dyes. We have improved, but bringing them to the plant is challenging: the industrial process differs from the laboratory process. We continue working and already have publications on more effective applications with fewer additives.

- Are there any problems with quality, fixation, toxicity, or durability?

Finding natural sources of pigments—plants, fruits, bark, and even some insects—isn't the most difficult part; there are many attractive colors. The real challenge is demonstrating their performance and bringing them to industry: reproducibility, color fastness, and user safety. Synthetic dyes can be toxic or cause allergies in some people; since clothing is in direct contact with the skin, the dyes must meet safety criteria. This requires a multidisciplinary team (textile/materials, chemistry, toxicology, engineering). In my experience, about 90% of natural sources don't offer good durability (e.g., poor fastness to washing, light, or rubbing). In short, there's still much to be developed.

- Are any necessary equipment or materials difficult to obtain locally?

Of course, at the local level. We currently work with the Mater company; in those cases, we can directly obtain and use their waste, facilitating the process. However, when companies want inputs that only grow in the jungle or other regions, obtaining them from Lima and managing the transportation logistics isn't easy. It's easier with local sources like purple corn or purple potatoes, but if we're dealing with species unique to the jungle, we need community support for the collection; otherwise, it becomes complicated. This applies not only to dyes but also to other raw materials we seek to develop.

4. Ecosystem and diffusion

- Are there any public institutions, NGOs, or innovation centers involved?

I know of institutions and textile centers working alongside private companies in this area. For now, I only collaborate with companies. I have no direct contact with the alpaca textile sector; I'm not yet familiar with that topic. However, I know some organizations do address it.

- Are there collaboration networks between academia, businesses, or the government?

Yes, I do work with companies. However, I'm a foreigner, and my focus isn't entirely on natural dyes or textiles; I'm currently also focused on other topics. That's why I don't have many active connections in that sector. Still, I participate in events to maintain and expand contacts.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

In general, developing these types of projects without financial support from SMEs is difficult. Many depend on external funding. In my experience, public funds (e.g., ProInnóvate) often have very short deadlines—sometimes around a year—and high demands, complicating collaborative work. Companies rush ahead, expecting quick results (activating a machine and obtaining a product), while in academia, we must rigorously validate projects and undertake multiple trials. This creates tension and makes thesis students suffer due to unrealistic deadlines.

Furthermore, the funds offer little support for partners and assistants, limiting operational capacity. Typically, no one approaches the project with their own resources; when a problem arises, we define the solution and "apply to a fund." However, resources are almost always scarce, and conditions don't favor fluid collaboration between academia and business.

- What experiences or cases would you highlight as examples to follow?

Yes. We're currently working with Mater, a small, highly focused company. In this case, their team communicates constantly with us and shares information. Generally, communication is difficult in projects with companies. For example, even when we won an Innóvate project, we were never invited to meetings, and no one knew how things were progressing. It would be helpful for us to understand the process with the company. Still, communication is often closed: they focus only on deliverables and results, with no opportunities for open exchange.

6. Closing

- In closing, is there any aspect we haven't addressed that you consider essential for this study?

As I said, working with natural dyes in textiles isn't just about 'adding color' to a fabric. We can extract a green, blue, or red dye in 6–8 months, but that's not enough. Natural dyes have added value— bioactivity and potential health benefits—that we must study in depth. Many companies only look for the final color, without considering the fabric, use, or user. We want to further validate safety and performance, for example, in textiles for sensitive skin or hospital use. This requires more flexible and longer-term funding, and companies with a more open vision. Respecting the scientific process and maintaining fluid communication throughout the project is also key.

INTERVIEW WITH RULY TERÁN HILARES

CHARACTERIZATION OF THE INTERVIEWEE

- Name and surname: Ruly Terán Hilares
- Current position or function: Research professor at UCSM
- Type of Organization: University
- Years of Experience: 10 years
- Arequipa/Peru

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1. Local context and knowledge of the subject

- Do you have experience or know of any initiatives using natural dyes in your economy or region?

Yes, we have participated in a project funded by Prociencia to develop natural dyes from macroalgae and microalgae. The main objective was the dyeing of alpaca fibers.

Subsequently, we conducted laboratory studies that also focused on alpaca fiber, but this time, we used natural dyes obtained through biotechnology. Specifically, we used waste to produce pigments from certain fungi, which were evaluated as dyes suitable for these fibers. The university funded this project.

We are currently in the final stage, conducting dye tests primarily in red shades and obtaining preliminary results in orange and yellow. Our next goal is to get more complex shades like purple and blue.

To this end, we are working on identifying and using microorganisms capable of producing these pigments, with the aim of applying them in the dyeing of alpaca fibers.

- Are agroindustrial wastes used as input for dyes? Which ones?

In our case, we use waste as a raw material to generate sugars, which serve as a carbon source for the growth of microorganisms. These, in turn, transform these sugars into natural colorants.

Various applications use plants or waste directly for dyeing, extracting, and applying the dye. However, each approach has advantages and disadvantages, particularly regarding resource availability.

The difference in our case is that, by working through biotechnological processes, we can utilize virtually any type of waste since its structure always contains carbohydrates. These are transformed into sugars, and microorganisms then produce the colorants more versatilely.

2. Technologies and techniques used

- What extraction methods do you know or are used locally?

Typically, the extraction method depends on the nature of the compound and its solubility. Water can be used as a solvent to extract water-soluble pigments and then apply them directly.

For example, I used to watch my mother extract pigments from walnut or prickly pear trees: she would boil the plant, extract the pigment, and apply it to fibers, usually sheep's wool, achieving shades of brown or other colors. This shows how the technique varies depending on the compound and its solubility.

Solvents such as alcohol or ethanol are often used for pigments that are poorly soluble in water. In some of our projects, we have used water, alcohol, or even mixtures of both to facilitate extraction. The pigments are then concentrated before application to achieve better adhesion and action on the fiber.

- Have processes been adapted for use in SMEs or textile workshops?

In the project we participated in with Prociencia, we collaborated with a company, and some tests were conducted through CITEtextil Camélidos Arequipa. This was the most advanced level we've reached in terms of engagement with the productive sector.

However, a real technology transfer has not yet materialized since, although significant progress has been made, a product ready for application has not yet been delivered to the company. This is due to the fact that optimization steps remain pending, especially in the extraction processes and in the preservation of certain properties, such as light stability. Since these are natural pigments, they are much more susceptible to degradation.

3. Technical and organizational feasibility

- What technical factors have facilitated or hindered the use of these dyes?

One of the main obstacles lies in the very nature of natural pigments. While present in the plant, they are protected within cellular structures, but when extracted, they tend to oxidize and degrade rapidly, especially under the influence of light. This considerably limits their durability and stability, as radiation can cause accelerated loss of hue. Both plant-derived pigments and those produced by microorganisms are highly susceptible to degradation, unlike chemical pigments, which are generally much more stable.

Another major obstacle is the extraction process, which depends mainly on the type of pigment and the solvents used. Some solvents, such as ethanol, offer the advantage of being recoverable through evaporation and condensation for reincorporation into the process. However, in the case of plant pigments, the raw material often needs to be subjected to crushing and cell wall rupture processes to release the compounds, which increases the complexity.

The choice of extraction technology is crucial to ensuring sustainability and efficiency, as it must allow pigments to be obtained without degrading them. Currently, several alternatives exist, such as ultrasound-assisted extraction or the use of supercritical fluids, among other advanced techniques. However, their technical and economic viability, as well as their scaling potential, must be carefully evaluated.

- *Are there any problems with quality, fixation, toxicity, or durability?*

In the case of fixation, several factors come into play. First, the nature of the pigments themselves varies significantly depending on the microorganism or plant of origin. Added to this are the conditions of the dyeing process: temperature, the type of mordant used, and whether pre-mordanting, post-mordanting, or direct mordanting is used.

It has been observed that color fixation is possible in natural dyes, but it does not reach the intensity offered by chemical pigments. The color is fixed, although with less vibrancy or durability.

On the other hand, stability is another critical challenge. Pigments usually behave well in shaded conditions; however, they quickly lose hue and intensity when exposed to light.

All this shows that the process of fixation and stability in natural dyes is complex and requires further optimization of both the methods and the inputs used.

There is still much to be done regarding toxicity, as I haven't seen conclusive studies determining whether these pigments can cause allergies or other adverse reactions. However, this is an aspect we must address if we pursue the commercialization of natural dyes.

We are currently in the development stage, working on the technology and the process. We have obtained the pigments, applied them, and tested their performance. However, the next phase, essential for obtaining certifications and moving toward the market, will be conducting toxicity studies, including allergenicity tests.

In principle, I don't consider them to pose a significant risk of toxicity, as these are not products intended for consumption, like food. Furthermore, many of the pigments used are edible, reducing the possibility of toxic effects. However, when applied to textiles, the primary concern will not be systemic toxicity, but rather the potential for allergies or other skin problems.

- *Are any necessary equipment or materials difficult to obtain locally?*

The use of plants as a source of pigments presents several limitations. It is not always possible to have plant material available year-round to supply companies sustainably. Furthermore, when dried, many pigments in leaves or other plant parts tend to degrade, reducing their quality. Even if fresh plants were used, associated problems would arise, such as deforestation or other environmental impacts that would question the sustainability of the process. Therefore, the availability of raw plant materials is a limiting factor in developing these technologies.

Biotechnology is emerging as an interesting alternative, as it does not depend on seasonality or plant availability. It allows for using different types of waste and their combination as substrates. However, it also presents challenges: it requires appropriate selection of microorganisms, scaling up production in bioreactors, and meeting the initial costs of these infrastructures, which are often high.

Despite these limitations, we can gradually advance the development and maturity of biotechnology, making it increasingly viable and sustainable over time.

4. Ecosystem and diffusion

- Are there any public institutions, NGOs, or innovation centers involved?

When we arrived in Peru in 2019, we met with an NGO dedicated to working in the alpaca value chain in Arequipa. They had already expressed interest in developing natural and sustainable dyes at that time.

In addition to these initiatives, we have the collaboration of the CITEs, which are our closest allies, as they play a key role in strengthening the textile value chain. Within this process, pigments and dyeing are particularly central, and the CITEs are the ones who can most strongly promote their dissemination.

On the other hand, the university also plays a vital role through its innovation office and marketing departments. When a project demonstrates relevance and impact, these bodies can significantly contribute to its promotion and positioning.

- Are there collaboration networks between academia, businesses, or the government?

Various stakeholders participated in the project we developed. On the one hand, academia is represented by our team; on the other, a local Arequipa company dedicated to fiber processing, which traditionally works with chemical dyes but showed great interest in natural dyes. As an organization linked to the government, CITE played a key coordinating role. This way, all three sectors—academia, business, and the government—were involved.

Furthermore, in recent years, we have been promoting collaborations with universities, both domestic and foreign, to encourage them to join these initiatives and contribute to the development of new ideas and approaches in the field of natural dyes.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

The first step in making this type of project viable is properly stabilizing the natural pigments without losing quality. This is a critical aspect, as simply obtaining the pigment and applying it is not enough; it requires modifications and treatments to ensure its stability.

In this sense, research plays a fundamental role. The market will continually evaluate the quality of the final product: a garment that fades quickly or loses color upon exposure to sunlight will not be accepted, no matter how attractive the concept of using natural dyes in the industry may be.

Therefore, technological development must be worked on gradually, advancing step by step, scaling up processes, and adapting them until they reach industrial levels. In conclusion, the main challenge lies in research aimed at obtaining stable pigments, since once this point is resolved, they can be used without major problems in textile applications.

- What experiences or cases would you highlight as examples to follow?

We've always highlighted our natural dye project, developed in conjunction with a company and the CITE, as it allowed us to reach the stage of demonstrative testing on textile garments such as gloves, scarves, and caps. It was a very valuable experience, and I consider it a successful conclusion.

I haven't seen many similar initiatives beyond this project. Proposals have been submitted to PROCIENCIA to use waste as a source of sustainable dyes, but as far as I know, none have seen significant development beyond the initial stage.

It's true that traditional dyeing practices have been passed down in regions like Cusco and Puno since ancient times, but these are primarily artisanal techniques. There is usually no scientific basis or systematic study behind them.

I have not identified any other relevant experiences at the level of science—and technology-based projects to date, or perhaps there is a lack of wider dissemination of the progress achieved.

6. Closing

- In closing, is there any aspect we haven't addressed that you consider essential for this study?

When developing natural dyes, it's essential to be very careful when selecting the resources. For example, if working with marine macroalgae, it's necessary to comply with current legislation and obtain the appropriate permits. The same applies when using plant resources: we can't promote a line of natural dyes at the expense of contributing to deforestation or other environmental impacts.

Therefore, opting for sustainable alternatives that do not harm the environment or endanger protected species is essential. Biotechnology represents an up-and-coming option for pigment production, as it offers a fascinating field of development and viable experiences already implemented in other economies.

While the direct use of waste can be an attractive alternative, its availability is not always guaranteed, which limits its long-term sustainability. For these reasons, the strategic focus should be on biotechnological solutions that allow for the stable and responsible generation of pigments.

<u>**INTERVIEW WITH RAÚL LAZARTE GAMERO**</u>

CHARACTERIZATION OF THE INTERVIEWEE

- Name and surname: Raúl Lazarte Gamero
- Current position or role: Independent Professional
- Type of Organization: Independent Professional
- Years of Experience: 20 years
- Arequipa/Peru

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1. Local context and knowledge of the subject

- Do you have experience or know of any initiatives using natural dyes in your economy or region?

I'm passionate about natural knowledge. Throughout my career, I've worked with around 50 plants and experimented with nearly 80, exploring their possibilities in artisanal dyeing.

This type of knowledge is better applied in artisanal rather than industrial settings. In the industrial setting, the process is much more standardized: color charts are used, customer requirements are directly addressed, and quality aspects such as finish strength, light and sun resistance, and other technical parameters are prioritized.

Thanks to years of experience, we've developed more suitable dyes, not only for their aesthetic qualities but also for the quality they guarantee in various tests. This has allowed us to establish ourselves as pioneers in alpaca dyeing.

Today, Michell & Cía SA is recognized as the leading textile producer in Peru, with a significant position in exports. We have worked with sectors such as the Lima cotton growers, and today we are leaders in the textile sector and pioneers in the use of alpaca fiber.

- Are agroindustrial wastes used as input for dyes? Which ones?

Potato peel, oregano, among others.

2. Technologies and techniques used

- What extraction methods do you know or are used locally?

No, it is not necessary to extract the dye prior to application. For example, potato peels can be used directly in the dyeing process without requiring an intermediate pigment extraction step.

(…)

Dyeing with plants can be done directly without the need to extract the dyes first. For example, cochineal is enough to dry and be used directly; it's unnecessary to isolate the carminic acid for dyeing. The same is true for plants such as oregano and achiote, among many other species found in Peru.

Each plant offers different possibilities, as in some cases several parts can be used: leaves, stems, fruits, or branches, all with dyeing properties. However, not all plants can be used in their entirety; some can, others can't. This demonstrates the diversity of natural resources available in different regions—mountains, jungle, and coast—making Peru a territory with significant dyeing potential.

A key aspect for the artisan is planning the supply: it's not enough to identify plants with coloring properties; it's also important to ensure where to obtain them and who can consistently supply them. This way, colors can be reproduced consistently, although always with slight variations of 10 to 20%.

In this sense, natural dyeing is more oriented toward artisanal production, where the artisan must be involved, research, and passionate about natural colors. Success lies in knowing the technique and ensuring the availability of raw materials.

(…)

Dyeing must be done in water, using an immersion bath. It is not possible to do this using microwaves or other methods. The process involves preparing a water bath into which the natural dyes, the necessary chemical agents, and the material to be dyed are added.

The technique is similar to dyeing other fibers, such as wool or silk. The temperature is gradually raised, the material is gently stirred, and the dye is left in the bath for approximately half an hour to an hour. Finally, it is rinsed and allowed to cool, thus obtaining a uniform and stable dye.

- *Have processes been adapted for use in SMEs or textile workshops?*

I believe artisans should continue working with natural dyes. However, they clearly face limitations. In many cases, their garments are presented as dyed with natural dyes, but in reality, some colors come from other processes or unnatural dyes.

I've observed, for example, in Cusco, that although color palettes associated with natural materials are displayed, many of them don't actually correspond to artisanal pigments. Still, I think it's essential that crafts remain linked to natural dyes and that those who practice them develop a deeper understanding of dyeing: it's not enough to apply a dye, but to fully understand the process.

3. Technical and organizational feasibility

- *Are there any problems with quality, fixation, toxicity, or durability?*

In the artisanal sector, achieving uniform color reproduction is not always possible. There is always some variation, which represents a market limitation, as many customers require identical colors in each production.

Another key aspect is fastness. In my experience, rubbing fastness can be high, as can washing fastness, which can be improved in some cases through certain adjustments. However, light fastness is a greater challenge: it depends on the structure of the dye itself and cannot be modified by adding external products.

In many cases, handcrafted colors lack lightfastness, which is a significant limitation to their wider application. This factor clearly differentiates them from more standardized processes, which achieve greater consistency and durability.

- Are any necessary equipment or materials difficult to obtain locally?

Various heat sources, such as firewood, can be used in the dyeing process, although industrial stoves are also currently used. In some cases, small equipment, with a capacity of one or two kilos, can be incorporated, which is often purchased secondhand in Europe. These machines run on electricity, can be installed relatively easily, and are a viable alternative for small-scale processes.

Some companies have already implemented this equipment, such as Cori, which specializes in working with fine fibers—vicuña, sheep, and alpaca. They have two small machines, adapted for finishing processes, with capacities of two to three kilos maximum. Although they do not have a large production capacity, they represent a practical option for starting dyeing processes with a more technical approach. They also rely on electric industrial ovens to heat and develop the process.

4. Ecosystem and diffusion

- Are there any public institutions, NGOs, or innovation centers involved?

I don't have any precise knowledge about current initiatives. I know that in areas like Chinchero, some work is done with natural dyes, although these are very limited. I haven't seen them widely marketed, nor are many products available.

For example, none of the participants used natural dyes at a recent fair for small designers and producers at the Alliance Française language academy of Arequipa. They all worked with alpaca purchased from Michell & Cía SA to make their garments. I didn't find anyone who highlighted the use of natural dyes in their processes.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

Training is essential for SMEs. They often know about the existence of natural dyes but don't know how to use them or understand the reasons for each step of the process. Adequate training should provide the practical experience and the technical foundations that allow them to apply the procedures knowledgeably and reproduce them correctly.

Currently, most SMEs do not use natural dyes. For example, they often purchase yarn from companies like Michell & Cía SA and use it to make various garments—shawls, sweaters, and scarves, among others—but they have not been seen using their own natural dyeing processes.

This represents an interesting opportunity: international markets are very interested in products linked to ecology and sustainability. Therefore, it would be advisable to study the potential acceptance of garments dyed with natural dyes, considering that there are currently no companies or stores in the economy that offer this type of clothing.

INTERVIEW WITH CLAUDIA FUENTES MEZA

CHARACTERIZATION OF THE INTERVIEWEE

- Name and surname: Claudia Fuentes Meza
- Current position or role: Alpaca Garment Marketing Specialist
- Type of Organization: Company
- Years of Experience: 15 years
- Arequipa/Peru

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1. Local context and knowledge of the subject

- Do you have experience or know of any initiatives using natural dyes in your economy or region?

A few years ago, we conducted tests to introduce garments made with yarns dyed with natural dyes. At that time, we launched a small collection and received orders, but couldn't consolidate the experience. The main problem was the lack of color consistency: there was no uniformity in the shades and a limited supply. Customers, who were not yet ready to accept such variations inherent in the artisanal process, did not welcome the results.

We once had a large order of sweaters dyed with natural dyes, but the dyeing was so uneven that the pieces couldn't be shipped: on one garment, the sleeve was different from the body. The entire order remained undelivered. Later, the same customer requested accessories and blankets with natural dyes, but the results were unsatisfactory.

While consumers are now more flexible regarding color variations, the lack of consistency and reliable suppliers remains the central problem. We attempted to work with a supplier in Cusco, but the samples didn't match the requested color charts. Faced with this difficulty, we decided to dye the products in our own plant, which already had experience with hand-printing, although not with natural dyes.

During this process, we obtained some colors, such as eucalyptus green and yellow, from another herb, but the supply was minimal. This highlighted a key obstacle: dependence on artisanal suppliers with limited standardization, which creates uncertainty regarding delivery times, supply, and fulfillment of commitments to international clients who demand consistent quality and on-time deliveries.

For these reasons, we did not consolidate production with natural dyes, despite our initial intention to specialize and form a team to carry out systematic tests within the plant.

- Are agroindustrial wastes used as input for dyes? Which ones?

Although there is no official list of agro-industrial waste used as raw materials, we have worked with artisans and suppliers who use natural dyes extracted from plants and insects. For example, in the initial testing stages, the use of eucalyptus and cochineal was identified to produce dyes. The documentation process was collaborative, with artisans sharing their traditional knowledge of the plants used, although a detailed technical explanation of the methods was not always available.

2. Technologies and techniques used

- *What extraction methods do you know or are used locally?*

No, detailed technical information on extraction methods was not within the scope of our commercial management. These specific details may have been provided directly to our designers or specialized dyeing staff, who handle the technical and operational aspects of the process.

3. Technical and organizational feasibility

- *What technical factors have facilitated or hindered the use of these dyes?*

The main factor that has hindered its implementation on an industrial scale is the impossibility of guaranteeing color uniformity and the scalability of the dyeing process. While satisfactory results are achieved at the artisanal level in tiny batches (e.g., 500-gram skeins), this inherent irregularity is magnified when projected to industrial volumes, where hundreds of kilos of yarn in a single shade are required. The artisanal technique, which produces variations between batches and then blends the results, is viable for limited orders (such as 20 garments), but does not meet the standards of homogeneity and consistency demanded by markets, especially export markets. In short, the fundamental technical barrier is the gap between artisanal production methods and the standardization requirements of the large-scale textile industry.

5. Recommendations

- *What is needed to make these solutions viable for SMEs?*

Two fundamental pillars are required. First, it's crucial to ensure a consistent supply of raw materials. We experienced production interruptions because colors disappeared due to a lack of reliable supplies of the necessary plants or insects, making it impossible to start projects. Second, it's vital to work on the consistency and scalability of production. Although the client may understand some irregularity due to the artisanal process, it's necessary to be able to create larger, more consistent batches for it to be a real and sustainable solution for the industry.

INTERVIEW WITH THE ISO/IEC 17025 ACCREDITED CAMELID LABORATORY OF THE CENTER FOR PRODUCTIVE INNOVATION AND TECHNOLOGY TRANSFER – TEXTILE CAMELIDS, AREQUIPA

INTERVIEW APPLIED TO JOSÉ LUIS CARRASCO BOCANGEL

CHARACTERIZATION OF THE INTERVIEWEE

- Name and surname: José Luis Carrasco Bocangel
- Current position or function: Wet Processing and Dyeing Specialist, at CITEtextil Camélidos Arequipa
- Type of Organization: CITE
- Years of Experience: Approximately 23 years
- Arequipa/Peru

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1. Local context and knowledge of the subject

- Do you have experience or know of any initiatives using natural dyes in your economy or region?

Yes, well, what's more, here at CITEtextil Camélidos Arequipa, we do natural dyeing, whether with plant-based ingredients or agro-industrial waste.

- Are agroindustrial wastes used as input for dyes? Which ones?

We have worked with various natural sources such as molle, eucalyptus, turmeric, and purple corn. Among agroindustrial waste, we have worked with onion peels, achiote, and tara.

Based on these experiences, we have developed small collections and created a color chart to share with entrepreneurs. We also show them our methodologies for the different dyes so that they can replicate them in their own businesses.

2. Technologies and techniques used

- What extraction methods do you know or are used locally?

Here in Arequipa and some communities in southern Peru, the extraction method used is boiling. The plant is boiled to release the pigment, obtaining a liquor, which is then used in dyeing with the help of a mordant. The mordant acts as a fixative and, at the same time, directs the color toward a specific hue.

For example, depending on the mordant used, onion peel can produce shades ranging from yellow to orange and even a grayish green. Each mordant has the unique ability to shift the color toward a different horizon.

- Have processes been adapted for use in SMEs or textile workshops?

Yes, we've shared this information primarily through training courses developed over the years at our facilities and through technical assistance in our workshops. In these spaces, we teach entrepreneurs and artisans how to perform this dyeing with whatever available materials, from more artisanal techniques to slightly more technical processes, depending on each individual's skills and abilities.

3. Technical and organizational feasibility

- What technical factors have facilitated or hindered the use of these dyes?

Deforestation is one of the main obstacles to scaling up these techniques to a more industrial level. Many plants and ingredients used to obtain pigments are also used in home remedies, such as eucalyptus or tara, to treat colds, among other medicinal uses. Therefore, there is competition for the same plant resources, which creates a barrier, since scaling up the process could encourage deforestation, something the company is trying to avoid.

Therefore, we are adopting an alternative that uses agro-industrial waste, such as onion peels, avocado seeds, and camu-camu husks, among others. These byproducts or waste can be used as dye without generating a negative environmental impact.

- Are there any problems with quality, fixation, toxicity, or durability?

The main enemy of natural dyes is sunlight fastness. In contrast, rubbing fastness—which measures color transfer in the laboratory—is usually quite good. For example, onion peels achieve values close to 4 on a scale of 1 to 5, where 1 is very poor and 5 is very good.

The parameters regarding wash fastness are usually around 3. Commercially, although it is not a strict rule, many exporting companies require that fastness not fall below this value, which is considered regular or intermediate.

The problem arises with sunlight fastness: in some cases, values of 2 are obtained, and with specific plant inputs, they even reach 1. Studies are currently underway to test mordants that can improve this aspect. This is one of the industry's main challenges: increasing sunlight fastness.

Chemical ingredients make it possible, but if you're committed to sustainability and organic dyes, the ideal would be to find more natural solutions and not rely on chemical additives.

During the presentation on GOTS certification, you pointed out that using agro-industrial waste to obtain natural dyes could lead to toxicity problems. This is due to the frequent use of chemical inputs during the cultivation stage, which could eventually be transferred to the final product, i.e., the dyed garment.

It's important for me to understand this aspect. Many strong pesticides are used in agribusiness to combat pests, and my concern is focused on that. I believe it's essential to review this entire aspect because we're also surrounded by activities like informal mining that generate pollution. In some cases, this waste ends up in irrigated land and crops from which natural pigments are obtained. This means that we could already have relatively contaminated products from the outset.

Ensuring that the product is entirely natural and contamination-free is crucial for business owners. Certifications play a fundamental role in achieving these goals. However, achieving this requires analysis and traceability: identifying where the product is grown and harvested, what ingredients were used in the vegetable production process, and even what type of water was used to produce the crops. All this information must be compiled and analyzed to ensure that the product is genuinely free of contamination.

- Are any necessary equipment or materials difficult to obtain locally?

Yes. A couple of years ago, when natural dyeing began to gain popularity in the area, there was already a shortage of some ingredients, such as alum. It used to be easy to obtain, even in its crushed stone form, for dyeing. However, with attempts to industrialize these processes, this ingredient began to become scarce, which affected us significantly, as it is one of the most commonly used because it helps prevent the colors from shifting. That's why it's often used in both pre-mordanting and post-mordanting processes.

If we've already had supply problems on a relatively small scale, imagine what would happen if we moved to an industrial scale with vegetables. That's why I believe it's important to focus efforts on the use of agro-industrial waste and not rely solely on scarce natural inputs.

But are there any complex equipment or materials to obtain regarding this topic?

This is a good point because these processes can be carried out even in the most traditional way, even using firewood, without sophisticated equipment. The real challenge lies in achieving color reproducibility, so precise and controlled processes are essential.

If you don't know, for example, how long it took to extract the liquor, or if one batch was made in one hour and another in two or three, you can't standardize. The same goes for the temperature reached during boiling, the speed at which it rose, or the exact amount of mordant used for a particular fiber or yarn. All of this information is key to obtaining consistent results.

Here at CITEtextil Camélidos Arequipa, although we have extracted the dye by boiling, we have also worked with artisanal liquors and applied them on an industrial scale using dyeing machines. Thanks to specialized equipment, the goal is to reduce the problems typical of manual processes, such as barring, and improve the fixation and penetration of the dye into the fiber.

In that sense, I believe there are no limitations: you can work both artisanally and more technically with the support of machinery.

4. Ecosystem and diffusion

- Are there any public institutions, NGOs, or innovation centers involved?

Yes, we've actually begun working with universities because they have laboratories available to students where pigments or liquors can be obtained using different techniques. Boiling extraction is just one method, but there are others, such as pressurization, the use of water, ethanol, or various alcohols. Universities can experiment with these methodologies at the laboratory level.

The idea is to move on to a second stage, in which, after validating the results in the laboratory, the process can be scaled up to companies interested in using these liquors. The limitations lie in the quantity that can be extracted, the cost, and the profitability. In this regard, universities play a key role because they concentrate the specialists who can validate the tests and determine whether they are feasible for industrial scale.

We also have allies like CITEtextil Camélidos Arequipa, which works with handicrafts and is dedicated to collecting and disseminating ancestral techniques. However, the focus is on university research because we have proven that obtaining liquor by boiling is not the same as doing it in a laboratory with specific equipment. At certain temperatures and with certain mordants, the dye can degrade.

Therefore, instead of boiling dyeing, lowering the temperature to 80, 70, or 60 degrees Celsius is possible to avoid this degradation. This is very important. It's sometimes thought that the same laboratory dyeing process can be applied directly to production, but it doesn't always work, at least not with all plants. It must first be validated before scaling up.

- Are there collaboration networks between academia, businesses, or the government?

Yes, we're now trying to engage more with academia to achieve our goals and take advantage of the available competitive funds. Many funds aren't known to employers and universities, and we're trying to build a connection to access them.

You'll talk to Lucía later, who will be able to explain this topic in more detail, as she's actively involved with us. Fernanda, who's been doing some work, will also be able to give you her perspective on the matter.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

The most important thing is for SMEs to be willing to adopt the new technologies being researched and promoted. Changing artisans' mindsets is sometimes tricky because they've worked with specific methods. Therefore, it's first necessary to demonstrate to them that this research and technology are designed to help them, improve their processes, ensure that the color doesn't run after dyeing, and enhance its lightfastness.

Not all vegetables are resistant to sunlight. Part of our work is to identify which ones offer the best results in rubbing, washing, and sun exposure, and to recommend to business owners which vegetable inputs they should use.

- *What experiences or cases would you highlight as examples to follow?*

At this point, we've developed some small collections that we exhibited a few years ago at Peru Moda, where we demonstrated that color reproducibility is indeed possible. Previously, the paradigm existed that dyeing could only be achieved with fresh vegetables, but we've demonstrated that very similar results can also be achieved, within tolerance, using dried vegetables.

This opens up a new possibility: harvesting a plant product that isn't produced year-round, storing it, and using it during non-harvest periods. For us, this is a significant challenge that we have already overcome and promoted at fairs, with the participation of artisans, which is key to showcasing the progress achieved through our research.

6. Closing

- *In closing, is there any aspect we haven't addressed that you consider essential for this study?*

As I mentioned, it's essential to focus efforts on agroindustrial waste, rather than on plants or inputs that produce a specific color. Otherwise, we would be generating deforestation problems, which is precisely what we want to avoid. That's why focusing research on agroindustrial waste is the right path to prevent these conflicts with nature.

INTERVIEW WITH LUCÍA DEL CARMEN MARTÍNEZ PUJADAS

CHARACTERIZATION OF THE INTERVIEWEE

- Name and surname: Lucía del Carmen Martínez Pujadas
- Current position or function: Applied R&D Researcher for SMEs at CITEtextil Camélidos Arequipa
- Type of Organization: CITE
- Years of Experience: Approximately 6 years
- Arequipa/Peru

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1. Local context and knowledge of the subject

- Do you have experience or know of any initiatives using natural dyes in your economy or region?

Yes, in natural dyes. I first learned about CITEtextil Camélidos Arequipa through the sustainable dyes project developed with the Catholic University of Santa Maria. Our initial contact with CITEtextil Camélidos Arequipa was precisely through that project, where I discovered that they not only had general expertise in dyes but specifically in natural dyes derived from agro-industrial waste. This knowledge greatly facilitated our research and improved our understanding of biopigment behavior.

I am a biotechnology engineer and have participated in international research related to biopigments. In particular, I completed a research stay in Spain working with phycocyanin, exploring its extraction, stabilization, and application as a natural dye. In collaboration with Andes Yarn, I served as a co-researcher in a project focused on microbial dyes applicable to alpaca fiber, specifically working with phycocyanin blue and Haematococcus pluvialis red from microalgae. This work has resulted in a patent and provided me with valuable experience as a technology manager, overseeing intellectual property protection and the transfer of these developments to the productive sector.

Throughout this year, I have continued my involvement in the topic through the APEC project, focusing on gathering international references on natural dyes to support the academic content of our event. According to GOTS' mapping of global certifications in natural dyes, India stands out as the economy with the highest number of certifications. Furthermore, last Monday, we had the opportunity to conduct an interview with one of the leading international experts in this field, which offered highly valuable insights for our research.

- Are agroindustrial wastes used as input for dyes? Which ones?

Yes, of course. In Peru, our center is developing a new project focused on using grape pomace as a base for producing natural dyes.

2. Technologies and techniques used

- What extraction methods do you know or are used locally?

Regarding extraction methods, boiling remains the most commonly used approach locally. However, current research is exploring alternative techniques to improve efficiency and pigment stability. In our work with biopigments, we employ aqueous extraction without applying heat, as these protein-based compounds are prone to thermal degradation. Instead, extraction relies on principles of polarity and molecular affinity, often using salts to facilitate pigment recovery.

Emerging approaches in the field include supercritical fluid extraction and ultrasound-assisted extraction. In addition, we are investigating the use of agro-industrial waste as a substrate for cultivating microorganisms that produce a variety of pigments. In this model, the color is not extracted directly from the waste; rather, the waste serves as a growth medium, enabling the sustainable production of biopigments within a circular economy framework. This strategy allows for the valorization of by-products while supporting more stable and versatile pigment generation for textile applications.

- Have processes been adapted for use in SMEs or textile workshops?

Regarding biopigments, the technology transfer of the extraction process to Andes Yarn, the company with which we initiated the project, has been ongoing since last year. A patent has been registered, although it is still pending approval by Instituto Nacional de Defensa de la Competencia y de la Protección de la Propiedad Intelectual (Indecopi), as processes of this type typically take time to complete. UCSM requested this registration and has allocated internal funds to support the transfer.

One of the main challenges identified is lightfastness, as biopigments exhibit oxidative degradation issues and do not behave like traditional plant-based dyes, being more sensitive to environmental conditions. Therefore, this year we are specifically working on improving the light stability of biopigments to effectively complete the technology transfer; otherwise, it would be impractical for companies to use a pigment that degrades easily when exposed to light.

3. Technical and organizational feasibility

- What technical factors have facilitated or hindered the use of these dyes?

There is a clear lack of research projects on natural dyes. Currently, several international trends could be applied, such as the use of agro-industrial waste not only to obtain colorants but also as mordants to improve pigment fixation, an aspect still underdeveloped due to limited local research.

It is also necessary to innovate in dyeing techniques that avoid high temperatures, which tend to degrade natural pigments. For example, proteins or enzymes could be employed to open alpaca fibers without damaging them, thereby facilitating dye penetration. Products such as tara or tannic acid show great potential as biopigment fixatives.

There is significant development potential in this field, especially concerning sustainable fashion, but progress requires increased funding, as research cannot be sustained without resources. At CITEtextil Camélidos Arequipa, we promote initiatives at universities to foster research on our essential raw material, alpaca fiber, and we seek to disseminate projects developed in areas such as circular economy, sustainable dyes, and traceability. Our goal is to act as a bridge between academia and industry so that research does not remain confined to publications but has a tangible impact when companies apply these results in their production processes.

- *Are there any problems with quality, fixation, toxicity, or durability?*

The main issue identified is lightfastness. Regarding certifications, toxicity associated with the use of certain mordants is also addressed, as the industry frequently uses metals to fix synthetic and natural dyes, posing significant risks. In this sense, GOTS certification establishes clear parameters for the maximum allowable limits of certain metals, and it would be interesting to assess whether criteria also apply to organic inputs such as alum, an aspect still underdeveloped. These guidelines are essential to ensure that the product can genuinely be marketed as a sustainable dye.

- *Are any necessary equipment or materials difficult to obtain locally?*

Regarding innovative trends, certain limitations have been identified. For example, we recently attempted to obtain enzymes for a test as part of a Prociencia application, but this was not straightforward; even universities did not have them available. In this context, we resorted to more accessible alternative methods, such as pineapple peel to obtain enzymes.

Innovative extraction methods also include procedures using controlled solvents, which represents another limitation due to regulations and restricted access. These aspects highlight the need to continue developing viable and sustainable options for research in natural dyes.

4. Ecosystem and diffusion

- *Are there any public institutions, NGOs, or innovation centers involved?*

Information remains limited in the field of sustainable dyes, even among certification agencies, as this topic is only beginning to gain relevance. Although there is an ancestral tradition of using natural dyes, this practice has been displaced by synthetic colorants. The current challenge is not only to revalue this knowledge but also to adapt it to an industrial context that respects the ecosystem and prevents pollution.

There are no specialized centers in Peru; however, in Spain, AITEX coordinates industry and academia in a manner similar to our model. In China, there is also a government-linked natural dyeing center, although access to its information is more restricted.

- Are there collaboration networks between academia, businesses, or the government?

Our institution promotes networking, and Prociencia also encourages it in its calls for proposals. However, limitations have been identified, such as minimum UIT requirements for companies to apply for funding, which significantly restricts the participation of SMEs, which constitute the predominant productive force in Peru.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

To make these projects viable, it is essential to strengthen funding for research calls. Innovation is difficult to sustain if it does not start from a foundation of prior research. Adjusting and expanding calls to include micro and small enterprises, which represent the majority of the productive sector within the economy, is key to sustainable development.

- What experiences or cases would you highlight as examples to follow?

Leading companies in natural dyes include Sodhani Biotech (India), Colorifix (United Kingdom), Dyegon (Chile), and Andes Yarn (Peru), all committed to research and innovation. Other relevant actors include Archroma Color. Specialization varies depending on the type of fiber: some focus on denim, while others work primarily with natural fibers such as cotton or wool, each developing its own niche based on the fiber type.

6. Closing

- In closing, is there any aspect we haven't addressed that you consider essential for this study?

The main innovation lies in using agro-industrial waste as a fermentation or culture medium to obtain biopigments without requiring genetic modification of the microorganisms. This enables compliance with sustainable dye certifications such as GOTS. Microorganisms can be cultivated directly in agro-industrial waste, generating color naturally and sustainably.

INTERVIEW APPLIED TO FERNANDA SONCCO

CHARACTERIZATION OF THE INTERVIEWEE

- Name and surname: Fernanda Soncco
- Current position or function: Laboratory Analyst at CITEtextil Camélidos Arequipa.
- Type of Organization: CITE
- Years of Experience: 5 years
- Arequipa/Peru

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1. Local context and knowledge of the subject

- Do you have experience or know of any initiatives using natural dyes in your economy or region?

Yeah.

- Are agroindustrial wastes used as input for dyes? Which ones?

I've observed that natural dyes use agro-industrial waste such as avocado seeds and onion peels. Various plants that don't necessarily come from waste are also used. However, with the current focus on the circular economy, the reuse of agro-industrial waste as raw materials for dye production is increasingly promoted, thereby contributing to achieving sustainability goals.

2. Technologies and techniques used

- What extraction methods do you know or are used locally?

The boiling method is the most widely used by entrepreneurs, facilitating the dyeing process. I have observed that various companies primarily use this method. However, considerable work is currently being done at universities in the field of natural dyes, implementing new methods for obtaining the liquor or dye, both in powder and liquid form. This represents a significant contribution, as it allows for improved dyeing parameters and is reflected in better results in quality control tests applied to dyed fabrics.

- Have processes been adapted for use in SMEs or textile workshops?

Yes, courses have been offered, and the boiling method is generally taught, as it is the most accessible and manageable for entrepreneurs. Other methods require specialized equipment, which many entrepreneurs lack, so the boiling method remains the most common. For this reason, this method is also used in training sessions, as it is the most widely available.

3. Technical and organizational feasibility

- What technical factors have facilitated or hindered the use of these dyes?

One of the main challenges is the literature and available knowledge. While much information can be found in books and articles, it often falls short regarding practical applications, whether in trials or at the plant level.

A critical point in natural dyes is color intensity. These dyes generally have low intensities; when greater intensities are achieved, problems with fastness arise. Results are usually positive regarding fastness to rubbing—both wet and dry—and washing, but most present difficulties with sunlight fastness, which is not always met. Only some agro-industrial residues or plants achieve good results in this regard.

Another issue is the proportions. There is no standardized method: the literature may provide a reference, but the same percentages cannot be used, for example, for onion peel or avocado seed, because each residue or plant performs differently during extraction.

pH also plays a role, reinforcing the difficulty of standardizing processes. Added to this is reproducibility, which is already a challenge even with synthetic dyes, and becomes even more complex with natural dyes. Sometimes parameters, such as using a mordant in a particular proportion relative to the fiber weight, are sought, but applying them uniformly isn't always possible.

- Are there any problems with quality, fixation, toxicity, or durability?

Yes, there are toxicity issues, because even when using natural dyes, regulations establish limits for certain mordants or fixatives. Specific quantities can be used, but are not always clearly specified for all cases.

For example, in the case of alum, I have found literature indicating that up to 30% of the fiber weight can be used, while other sources indicate only 20%. This shows that there is no standardized criterion.

Something similar happens with copper sulfate: the GOTS regulation indicates that only up to 5% can be used, but this only applies to specific colors, not all. Therefore, toxicity issues still require greater precision and regulation.

Quality, hold, and durability?

Regarding quality, I've had to perform tests on fastness to rubbing, washing, and sunlight, and I've observed that many companies are untrained or struggle to achieve proper dyeing. For example, I've received poorly washed samples with residue, which directly affects the quality and results.

Problems are also evident in the fixation process, especially in sunlight, where resistance is inadequate. Although the sample sometimes does not stain the multi-fiber control in the washing test, the fixed color is almost completely removed. If, for example, the yellow color is of average intensity, it loses all its tone after washing.

I've even seen dyes that didn't pass a sunlight fastness test, yet still deteriorate rapidly in artificial light. Another case occurred with cotton: the dye didn't set well because the scouring process hadn't been performed beforehand. This demonstrates that dyeing cotton and alpaca are not the same, and experience is required to apply the methods correctly.

That's why research is valuable, but there needs to be greater collaboration between academia and companies. Academia provides the theoretical part, but companies have the practical experience and face the reality of the process. If both work together, better results can be achieved in natural dyeing.

- Are any necessary equipment or materials difficult to obtain locally?

Yes, now that we're working with universities, there is equipment that only certain institutions have; for example, some are available only at UNSA and others only at UCSM. Furthermore, several articles show that other methods of extracting dyes have been developed in Europe. So, yes, there are different types of equipment and techniques available.

4. Ecosystem and diffusion

- Are there any public institutions, NGOs, or innovation centers involved?

Yes, definitely. We are committed to helping entrepreneurs by providing assistance, training, consultations, and support, not just in dyeing. CITEtextil Camélidos Arequipa works extensively with natural and synthetic dyes and performs quality control tests. We also conduct alpaca fineness, strength, twist, and titration tests. It's worth noting that our laboratory is accredited.

For example, the rubbing and washing fastness tests are accredited, which means INACAL endorses the results. There are no other accredited laboratories in the south. Large companies like Incalpaca TPX SA, Michell & Cía SA, and Inca Tops SA don't have this type of laboratory. They send their samples abroad, as they must meet export parameters. With our laboratory's accreditation, we can offer that support directly from Arequipa.

- Are there collaboration networks between academia, businesses, or the government?

Yes, this year, we're working extensively with microentrepreneurs. CITEtextil Camélidos Arequipa has been serving as a bridge between academia and entrepreneurs because academia often lacks a close understanding of their problems.

In this way, both parties complement each other, and we at the CITEtextil Camélidos Arequipa facilitate this union. For example, several meetings have been held with universities such as UCSM, Universidad Católica San Pablo (UCSP), UTP, and UNSA. In these spaces, real problems are shared; for example, natural dyes fail to achieve the blue color. Academia can only understand these limitations through direct communication with the companies.

5. Recommendations

- What is needed to make these solutions viable for SMEs?

Research should be developed on a large scale for it to be viable. Excellent results can often be obtained in the laboratory, but the real test is when it works in a plant. If that's achieved, then the objective is achieved.

The problem is that, in practice, much of academic research remains on paper and is never applied to production. In other words, a problem is theoretically solved but not tested in the real world on the factory floor. For me, that's the great challenge.

- What experiences or cases would you highlight as examples to follow?

I conducted some research, although I can't say which industrial waste it was used with because I'm just going to present it. I achieved good results in that work, as I could apply and combine the knowledge I acquired, conducting tests at different temperatures and varying several parameters.

The results were positive in the tests for fastness to washing, rubbing, and sunlight, especially the latter. That experience motivated me to continue researching and looking for improvements in the process. If I can optimize the extraction method, I could achieve greater intensity in natural dyes, which is precisely the main limitation.

I have also observed dyeing with avocado seed, eucalyptus, and onion peel, where colors were achieved with greater intensity. Therefore, if the extraction is perfected, it is possible to achieve better results in intensity, since the fastness can now be adequately managed.

6. Closing

- In closing, is there any aspect we haven't addressed that you consider essential for this study?

Encouraging feedback from entrepreneurs is essential because it's also part of our work. This process would be much more enriching if we worked hand in hand with academia, as this would create better opportunities for everyone. When research is conducted, the primary beneficiaries are entrepreneurs, academic institutions, and ourselves. That's why it's key to continue strengthening communication between these three parties.

Another aspect I've noticed is the limited information available in Peru; generally, there's very little, and turning to foreign sources is necessary. In other economies, cotton and wool are studied extensively, while here we focus almost exclusively on alpaca, and even then, it's not valued as it should be. In the case of the vicuña, the situation is more complex, but imagine the impact of developing natural dyes for its fiber, beyond its original color; it would truly be a breakthrough.