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VALORIZATION OF *PRUNUS SPINOSA* EXTRACT AS SUSTAINABLE COLORING AGENTS IN TEXTILE FINISHING: A GREEN CHEMISTRY APPROACH

BY

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Abstract. In the context of the need to develop sustainable textile technologies, this research investigates the application of *Prunus spinosa* extracts as environmentally friendly coloring agents. The fruits and bark of this species are rich sources of bioactive compounds, including tannins, flavonoids, and *anthocyanins,* characterized by antioxidant, antimicrobial, and dyeing properties, thus providing a viable alternative to synthetic dyes.

Pigment extraction from *Prunus spinosa* fruits can be conducted through various methods such as maceration, boiling, and pressing. The chemical composition of the extracts can be characterized using advanced analytical techniques, including High-Performance Liquid Chromatography (HPLC), Proton Nuclear Magnetic Resonance (^{1}H-NMR), and Fourier Transform Infrared Spectroscopy (FTIR). Employing these extracts in environmentally friendly textile dyeing processes significantly contributes to the reduction of environmental pollution by eliminating the necessity of harmful chemical agents.

The stability and fixation properties of these natural dyes can be evaluated using spectroscopic analyses, wash, light, and rub fastness tests, as well as colorimetric measurements. Literature studies have indicated a high affinity of these natural dyes towards natural textile fibers, such as cotton and wool, ensuring strong adherence and enhanced color durability.

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In addition to ecological advantages, this method supports the development of a more sustainable textile industry by providing products with additional functional properties, such as ultraviolet (UV) protection and antimicrobial activity. Therefore, the valorization of *Prunus spinosa* extracts in textile dyeing aligns with green chemistry principles, promoting innovative and eco-friendly alternatives to conventional dyes.

This approach represents a significant step towards reducing the ecological impact of the textile industry by demonstrating the feasibility of utilizing natural resources in sustainable processes. Future studies will focus on extending the applicability of these natural dyes to synthetic fibers, optimizing extraction procedures, and maximizing pigment fixation efficiency.

Thus, the application of *Prunus spinosa* extracts as natural coloring agents not only offers a viable and environmentally friendly alternative to synthetic dyes, thereby reducing the negative environmental impact of the textile industry but also opens new perspectives for the development of functional textiles with antimicrobial and UV-protective properties, contributing to the transition towards more sustainable production processes aligned with circular economy and green chemistry principles.

Keywords: Natural dyes; *Prunus spinosa*; textile dyeing; green chemistry; sustainability.

1. Introduction

The contemporary textile industry is under increasing pressure to adopt sustainable practices in response to the significant environmental impact associated with conventional manufacturing processes. Textile finishing, a critical stage aimed at improving the quality and performance of fabrics, often involves intensive consumption of chemical substances and energy. In this context, the development of environmentally friendly technologies capable of reducing the ecological footprint of this sector has become a priority for ensuring its long-term sustainability (Kim, 2006; Tena and Asuero, 2022).

Green chemistry provides a systematic framework for designing chemical processes that minimize toxic risks and waste generation while maintaining efficiency and product quality (Anastas and Warner, 1998). Its application to textile finishing supports the implementation of innovative methods that optimize resource use and reduce health and environmental hazards (de la Guardia and Garrigues, 2012).

This study aims to explore the extent to which the principles of green chemistry can be implemented in textile dyeing using natural pigments extracted from *Prunus spinosa*, emphasizing their advantages over synthetic dyes and identifying the associated technological challenges and future perspectives (Anitha and Beda, 2024).

The objective of this research is to assess the current scientific literature on the application of green chemistry in sustainable textile finishing, with a focus on the potential of natural colorants derived from *Prunus spinosa*. While this species is known for its bioactive properties and traditional uses, its efficient integration into ecological textile processing remains insufficiently documented (Lellis *et al*., 2019; Malovrh *et al*., 2025). The study seeks to synthesize existing data, highlight recent advances, and identify future research directions in the field.

2. Presentation of the species *Prunus spinosa* and its significance

Prunus spinosa, commonly referred to as blackthorn or sloe, is a perennial shrub of the *Rosaceae* family, naturally distributed across temperate regions of Europe, Western Asia, and North Africa. This species has attracted growing scientific and industrial interest due to its complex phytochemical profile, being a rich source of *polyphenols, flavonoids, anthocyanins*–such as cyanidin-3-rutinoside and peonidin-3-rutinoside–and tannins, compounds recognized for their antioxidant, antimicrobial, and dyeing properties (Castañeda-Ovando *et al*., 2009; Islam *et al*., 2025; Malovrh *et al*., 2025).

Traditionally, *Prunus spinosa* fruits have been used both in herbal medicine, for their therapeutic effects, and in textile dyeing, owing to their natural pigment content and their high affinity for natural fibers such as wool and cotton (Lellis *et al*., 2019; Shahid *et al*., 2013).

In the context of green chemistry, this species has gained renewed attention for its multifunctional potential. Its pigments show good affinity toward protein and cellulosic fibres, and offer chromatic stability under light exposure and repeated washing, making it a promising resource for developing environmentally friendly dyeing processes (Islam *et al*., 2025; Zollinger, 2003).

Green Chemistry Principles

Green chemistry is grounded in twelve core principles established by Paul Anastas and John Warner in 1998. These principles provide a foundation for designing chemical processes that reduce environmental impact, promote safer chemical use, and ensure efficient resource utilization (Anastas and Warner, 1998).

Key principles include:

1. Waste prevention – prioritizing the avoidance of waste generation over post-treatment.
2. Atom economy – maximizing the incorporation of all atoms from starting materials into the final product.

3. Less hazardous synthesis – designing reactions to avoid toxic substances.

4. Designing safer chemicals – substances should fulfill their function with minimal toxicity (Anastas and Warner, 1998).

5. Safer solvents and auxiliaries – use of benign or no solvents and auxiliary substances.

6. Energy efficiency – conducting reactions at ambient temperature and pressure.

7. Renewable raw materials – using materials from renewable rather than depletable sources.

8. Avoiding unnecessary derivatization – minimizing steps that do not contribute to final product efficiency (Anastas and Warner, 1998).

9. Catalysis – preferring catalytic processes over stoichiometric ones.

10. Design for degradation – ensuring substances break down into non-harmful products post-use.

11. Real-time analysis – monitoring processes in real time to prevent hazardous by-products.

12. Inherently safer design – minimizing risks of chemical accidents.

The application of these principles in textile dyeing fosters a transformation toward sustainable chemical processes (Kim, 2006; Lellis *et al.*, 2019). The use of renewable plant-based raw materials for pigment production, such as *Prunus spinosa*, eliminates reliance on petroleum-based dyes and aligns with sustainable sourcing goals. Replacing toxic solvents with safer options like water, ethanol, or dilute organic acids reduces health and environmental risks (Gulrajani, 2001; Islam *et al.*, 2025). Moreover, low-temperature processing limits energy consumption and helps preserve the bioactivity of thermolabile pigments. The biodegradability of these natural dyes ensures their environmental compatibility, while replacing synthetic colorants with natural extracts supports cleaner production practices (Chengaiah *et al.*, 2010).

Challenges in Applying Green Chemistry Principles to Natural Dyeing

Although the use of natural pigments such as those derived from *Prunus spinosa* offers a promising and environmentally friendly alternative to synthetic dyes, the full implementation of green chemistry principles encounters several technical, economic, and methodological challenges (Islam *et al.*, 2025; Shahid *et al.*, 2013).

One of the main difficulties lies in the reduction of chemical derivatives, since extraction and dyeing processes often involve complex physicochemical steps where the complete elimination of auxiliary agents or intermediate compounds is difficult without compromising dyeing yield or quality. The use of catalysts, another key principle, is not typically applicable in this field, as natural dyeing processes do not involve catalytic chemical reactions in the traditional sense. As such, this principle remains underutilized in the current context.

Furthermore, real-time process monitoring, essential for pollution prevention, requires advanced instrumentation such as [1]HPLC or UV-Vis spectroscopy, which is often inaccessible in small-scale production environments. The lack of such monitoring can lead to uncontrolled formation of by-products or decreased process efficiency (Anastas and Warner, 1998; Tobiszewski, 2018; Płotka *et al*., 2013).

These limitations highlight the need for continued innovation and research aimed at adapting green chemistry principles to the specific conditions of natural dyeing workflows. Solutions may involve the development of accessible monitoring technologies, more effective extraction and fixation methods, or the formulation of standardized protocols tailored to natural dye systems.

Compliance with Green Chemistry Principles in natural dyeing

Textile dyed with natural pigments generally show a high degree of alignment with green chemistry principles, although the extent of compliance varies depending on the specific techniques and materials used. These principles can be grouped into three categories based on their level of implementation: fully respected, partially respected, and difficult to achieve.

Fully respected principles include, above all, waste prevention, as natural dyeing processes typically generate lower amounts of toxic residues and utilize optimized techniques that reduce material loss (Islam *et al*., 2025; Tena and Asuero, 2022).

The design of less hazardous chemical methods is ensured through the use of natural pigments and biomordants derived from renewable and safe sources, significantly lowering toxicity compared to synthetic dyes. The renewable nature of raw materials, such as *Prunus spinosa* extracts, also contributes to the sustainability of the process. Additionally, design for degradation is fulfilled, since natural dyes degrade naturally in the environment, avoiding the accumulation of persistent or polluting compounds (Gulrajani, 2001; Lellis *et al*., 2019).

Partially respected principles refer to several process-related aspects. The overall chemical yield is influenced by the fact that natural dyeing involves extraction and adsorption rather than conventional synthesis, which may result in variable efficiency depending on raw material quality and process conditions.

Regarding the use of safer solvents and auxiliaries, eco-friendly choices such as water, ethanol, and weak organic acids are increasingly adopted; however, some methods still rely on agents with potential environmental or health risks.

Energy efficiency is partially achieved, especially through low-temperature dyeing, but certain stages still require heat input, leading to increased consumption.

Moreover, despite the general safety of the process, complex interactions between pigments, fibers and auxiliaries may occur, requiring constant monitoring and adjustments (Kim, 2006; Samanta and Konar, 2011).

Principles that are difficult to implement include the reduction of chemical derivatives, as the elimination of all auxiliary substances is often unrealistic without compromising process performance.

The use of catalysis is generally not applicable to traditional natural dyeing, which typically lacks catalytic steps.

Likewise, real-time monitoring for pollution prevention remains challenging due to the cost and availability of advanced analytical equipment. Without such systems, continuous control and process optimization are limited (Lellis *et al*., 2019). In summary, while natural dyeing complies substantially with green chemistry principles and offers a favourable sustainability profile, several areas require further innovation and technological investment to ensure full alignment and long-term industrial scalability. Energy efficiency is partially achieved, especially through low-temperature dyeing, but certain steps still require heat input, which leads to increased consumption. Furthermore, despite the overall safety of the process, complex interactions between pigments and auxiliaries can occur, requiring constant monitoring and adjustments.

Among the principles that are difficult to implement is the reduction of chemical derivatives, as minimizing unnecessary derivatization is often unrealistic for natural dyeing processes. The use of catalysis is also generally not applicable, as natural dyeing usually does not have catalytic performance.

Real-time monitoring, essential for pollution prevention, remains a challenge due to the cost and limited availability of advanced analytical equipment. Without such systems, continuous control and optimization of processes are restricted (Bechtold and Mussak, 2009).

Natural Dye Extraction

The extraction of natural pigments is a crucial step in sustainable textile dyeing, directly influencing dye yield, colour stability, and the environmental impact of the process (Anitha and Beda 2024; Islam *et al.*, 2025). The choice of extraction method must be adapted to the characteristics of the plant material, the thermal sensitivity of the pigments, and the ecological and technological objectives pursued.

Common techniques include maceration, decoction, mechanical pressing, ultrasound-assisted extraction (UAE), microwave-assisted extraction (MAE), and supercritical CO_2 extraction (SFE-CO_2). Each method has specific advantages and limitations, and optimizing the process is essential to maximize pigment yield and minimize energy use and waste generation (Anitha and Beda, 2024; Kong *et al*., 2003).

Maceration involves prolonged contact between the plant material and a mild solvent at low or ambient temperatures. It is suitable for thermolabile compounds such as *anthocyanins*, preserving their integrity, but it requires extended time and typically yields less pigment (Gulrajani, 2001; Samanta and Konar, 2011).

Decoction, which involves boiling tougher plant parts (bark, seeds, roots), provides a rapid and concentrated extract. However, high temperatures can degrade sensitive compounds, compromising both intensity and stability (Shahid *et al*., 2013).

Mechanical pressing is primarily used for juicy plant materials such as fruits. It extracts pigment-rich juice through crushing and squeezing, without solvents. It is limited to materials with high moisture content and is not suitable for fibrous or dry matter (Anitha and Beda, 2024).

UAE uses high-frequency sound waves to induce cavitation, which disrupts cell walls and promotes pigment release. It is a fast and energy-efficient method that preserves compound stability (de la Guardia and Garrigues, 2012; Yabré *et al*., 2018).

MAE heats both the plant and solvent quickly and uniformly, enhancing mass transfer. It reduces processing time and energy consumption but requires strict temperature control to avoid pigment degradation (Chengaiah *et al*., 2010; Anitha and Beda, 2024).

SFE-CO uses carbon dioxide in its supercritical state as a clean and selective solvent, ideal for preserving thermosensitive compounds. Despite its ecological advantages, this method involves high costs and specialized equipment, limiting its industrial scalability (de la Guardia and Garrigues, 2012; Kong *et al*, 2003).

In the case of *Prunus spinosa*, mild methods such as acidified maceration or UAE/MAE offer the best balance between efficiency, selectivity, and compliance with green chemistry criteria. Thermal extraction investigations indicate that anthocyanins achieve maximal yields within the 60–90°C range (Table 1). Their functional relevance in textile systems (specifically UV attenuation and antimicrobial effects) has been substantiated by Kong (2003), who demonstrated the protective performance of anthocyanin-enriched extracts when applied to fabric substrates (Fig. 1). Extending these findings, the UV-protective and antimicrobial effects of *Prunus spinosa* extracts can be attributed to its polyphenolic composition, with anthocyanins, tannins, and flavonoids being primarily responsible. These observations are consistent with broader evidence concerning the structural characteristics and bioactivity of anthocyanins (Kong *et al*., 2003; Castañeda-Ovando *et al*., 2009).

Table 1

Comparison of extraction methods

Extraction method	Solvent	Temperature (°C)	Extraction Time	Pigment Yield	References
Water bath extraction	Acidified water	60–70	30–45 min.	Moderate	Tena and Asuero, 2022
Ultrasonic extraction	Ethanol–water 50–70%	40–50	10–20 min.	High	Rodríguez-Saona and Wrolstad, 2001
Microwave extraction	Acidified ethanol	60–80	5–10 min.	High	Castañeda-Ovando, *et al*., 2009
Soxhlet extraction	Ethanol	90	2–4 h	Low to moderate	Bechtold and Mussak, 2009; Bechtold *et al*., 2003

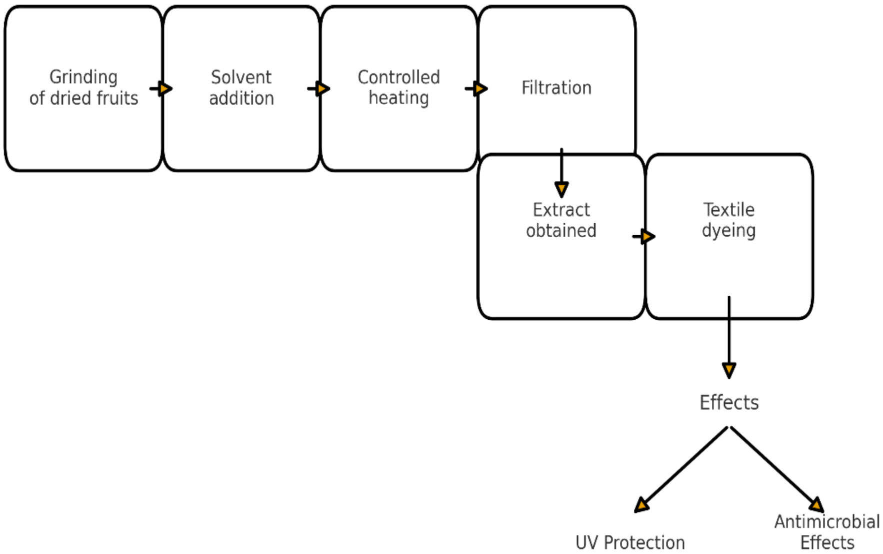

Fig. 1 − Simplified workflow for the extraction of *Prunus spinosa* pigments, textile dyeing and their functional properties.

Characterization of *Prunus spinosa* Extracts

The extract obtained from *Prunus spinosa* fruits contains a mixture of natural pigments with distinct chemical structures and functional roles in textile dyeing. The dominant class is *anthocyanin*s, water-soluble red-violet pigments sensitive to pH and light. Their structure is based on the *flavylium cation*, substituted with various hydroxyl, *methoxyl*, or *glycosidic* groups that influence hue and reactivity (Islam *et al*., 2025).

These compounds impart intense coloration but degrade under high pH, heat, or UV exposure, requiring precise control during extraction and application (Zollinger, 2003).

Tannins, reddish-brown *polyphenoli*c compounds, also occur in significant amounts. They act both as colorants and as natural mordants, promoting pigment fixation and enhancing resistance to washing and friction (Castañeda-Ovando *et al*., 2009; Kaur and Chopra, 2023).

Flavonoids, pale yellow pigments such as *flavonols* and *flavanols,* contribute to colour stabilization and oxidative protection of *anthocyanins.* Though less intense in colour, they provide synergetic chromatic effects and support long-term durability (Gulrajani, 2001; Lellis *et al*., 2019).

The extract's stability depends on critical parameters such as pH, temperature, and light. Acidified environments (e.g., with diluted acetic acid) stabilize the *flavylium* form, while extraction at 90–95°C yields optimal pigment without thermal degradation.

These properties recommend *Prunus spinosa* as a viable candidate for natural dyeing, particularly on natural fibers like cotton and wool (Shahid *et al*., 2013).

Complementary Analytical Methods

A rigorous characterization of natural extracts for textile applications requires multiple complementary techniques that offer detailed insights into their chemical composition, pigment stability, and performance.

High-performance liquid chromatography (HPLC) is an essential tool for separating and identifying the main chromophoric compounds, particularly *anthocyanins* and *flavonoid*s. It provides accurate data on concentration, purity, and molecular profile, enabling optimization of extraction conditions and quality control of the final pigment (Samanta and Konar, 2011; Yabré *et al*., 2018).

Ultraviolet–Visible (UV-Vis) spectroscopy is used to evaluate the absorption spectra of pigments under different conditions. It helps monitor the pigment's behaviour depending on pH, temperature, or light exposure and is essential in assessing chromatic stability (de la Guardia and Garrigues, 2012).

Fourier-transform infrared spectroscopy (FTIR) provides a molecular "fingerprint" of the extract by identifying specific functional groups such as hydroxyl, carbonyl, or aromatic structures. This technique confirms the presence of phenolic compounds and supports the analysis of interactions between pigment and fibre (Lellis *et al.*, 2019; Rodríguez-Saona and Wrolstad, 2001).

Nuclear magnetic resonance (NMR) offers structural insights at the molecular level, revealing the spatial configuration and bonding of atoms in *anthocyanins* and other colorant molecules. It is useful in elucidating mechanisms of pigment degradation or fixation.

Spectrometry, often coupled with chromatographic techniques ([1]HPLC-MS), allows precise identification and quantification of both major and minor compounds. This is crucial for the detailed chemical profiling of plant-based dyes, especially when working with complex extracts containing multiple pigment types (Kong *et al*., 2003; Kaur and Chopra, 2023).

In addition to these chemical analyses, fastness testing is carried out to evaluate the durability of dyed fabrics. Resistance to washing, rubbing, and light exposure is assessed using standardized procedures.

Finally, CIELab colorimetric provides objective quantification of colour tone and intensity. This system is essential for quality control and ensures repeatability and reproducibility in both laboratory and industrial dyeing processes (Welch *et al*., 2010).

By combining these complementary techniques, researchers can comprehensively evaluate natural dye extracts and ensure their suitability for sustainable and efficient textile finishing.

Natural Dyeing Techniques with *Prunus spinosa* Extracts

The application of natural pigments extracted from *Prunus spinosa* requires adapted dyeing methods to ensure adequate pigment fixation, color fastness, and compatibility with green chemistry principles. The main techniques used include the following (Kim, 2006; Lellis *et al*., 2019):

1. Direct dyeing involves applying the pigment extract directly onto the textile fibre without any prior treatment. While this method is technically simple and cost-effective, it often results in poor fixation, requiring the additional use of mordants to improve colour durability (Islam *et al*., 2025; Lellis *et al*., 2019).

2. Premordanting consists of treating the textile with a mordant before the dyeing process. This technique enhances pigment adherence by forming stable bonds between the dye and the fibre. It significantly improves color intensity and fastness, and it is commonly used when working with natural pigments with low affinity for certain fibres (Lellis *et al*., 2019; Gulrajani, 2001).

3. Simultaneous mordanting refers to the concurrent addition of both the mordant and the pigment extract to the dye bath, with the fibre immersed in the combined solution. Although this approach simplifies the dyeing process, it may lead to uneven color distribution, thus requiring careful process control (Lellis *et al*., 2019; Anitha and Beda, 2024).

4. Post-mordanting is performed after dyeing, applying a mordant treatment to the fabric to reinforce pigment fixation. This method allows for tonal adjustments and improved fastness properties, especially for resistance to washing and light (Lellis *et al*., 2019).

5. Cold dyeing, carried out at temperatures below 30°C, is suitable for thermosensitive pigments like *anthocyanins from Prunus spinosa*. It minimizes pigment degradation and energy consumption, aligning with green chemistry

goals. However, it generally requires longer processing times and strict environmental control (Chengaiah *et al*., 2010; Gulrajani, 2001; Anitha and Beda, 2024).

6. Hot dyeing involves immersing the fibre in a heated dye bath, typically between 70 and 95°C. This method promotes rapid and effective pigment penetration and fixation and is particularly recommended for protein or cellulose fibers and heat-stable pigments (Anitha and Beda, 2024).

7. Immersion dyeing consists of submerging the fabric in the pigment solution for a controlled period, ensuring uniform colour distribution across the textile surface. Due to its simplicity and effectiveness, immersion dyeing is widely used in laboratory and industrial processes (Lellis *et al*., 2019).

Each method must be chosen and adapted according to the nature of the fibre, the pigment characteristics, and the desired durability and uniformity of the final colour. The goal is to maximize both technical performance and environmental responsibility in natural dyeing processes.

Mordants and Biomordants

Mordants are chemical or natural agents used in textile dyeing to fix pigments onto fibers, ensuring strong adhesion and durable color. By forming stable chemical or physical complexes between the dye and the textile substrate, mordants influence not only color intensity and uniformity but also resistance to environmental factors such as washing, light, and friction (Cardon, 2007; Lellis *et al*., 2019).

In traditional dyeing methods, the most commonly used mordants are metallic salts–particularly aluminium, iron, copper, and chromium. Although effective, these compounds raise environmental concerns due to their toxicity, bioaccumulation, and the challenges they pose for wastewater treatment. As a result, they are incompatible with green chemistry principles, which promote the use of safer, biodegradable substances.

In this context, biomordants have emerged as viable eco-friendly alternatives. Derived from renewable plant-based sources, they are rich in phenolic compounds, tannins, and flavonoids that can bind with pigments and fibres in a manner similar to metallic mordants, but without harmful side effects. Biomordants fulfill key green chemistry criteria such as non-toxicity, biodegradability, and renewable sourcing (Negi, 2025; Lellis *et al.*, 2019).

Among the most widely studied and applied biomordants are natural tannins extracted from pomegranate peel (*Punica granatum*) and nettle leaves (*Urtica dioica*). These substances not only promote pigment fixation on natural fibers but also confer additional functional benefits, including antioxidant and antimicrobial properties (de la Guardia and Garrigues, 2012; Gulrajani, 2001).

The use of biomordants supports circular economy principles by valorizing natural by-products and reducing environmental pollution.

Additionally, they enhance the intensity and durability of natural colors, making them both ecologically and technically advantageous.

The adoption of biomordants in *Prunus spinosa*-based dyeing processes represents a significant step toward implementing green chemistry in the textile industry. It offers a sustainable, efficient, and non-toxic alternative to conventional mordants, while also contributing to product innovation and environmental protection (Negi, 2025; Lellis *et al*., 2019).

Integration of Green Chemistry in Extraction and Dyeing

The implementation of green chemistry principles in pigment extraction and textile dyeing with *Prunus spinosa* involves optimizing each stage of the process to minimize environmental impact and promote sustainable practices.

Eco-friendly extraction methods: The extraction of pigments from plant sources requires the careful adjustment of key parameters such as solvent type, temperature, extraction time, and pH. In the case of *Prunus spinosa*, gentle methods such as maceration in hydroalcoholic solutions or acidic infusions have proven effective in preserving anthocyanin stability. To comply with green chemistry principles, eco-friendly solvents such as ethanol or diluted acetic acid are recommended, while hazardous organic solvents are avoided (Kong *et al*., 2003; Yabré *et al*., 2018). Additionally, assisted extraction techniques such as ultrasound-assisted extraction (UAE) and microwave-assisted extraction (MAE) enhance pigment yield, reduce processing time, and lower energy consumption. The resulting pigments can be characterized using UV-Vis spectroscopy and HPLC-MS to identify active compounds and assess their stability under light, temperature, and pH variations (Giusti and Wrolstad, 2001; Anitha and Beda, 2024).

Application of extracts in textile dyeing: The pigments extracted from *Prunus spinosa* exhibit high affinity for natural fibers such as wool and cotton, providing intense violet-reddish shades characteristic of *anthocyanins.* Application can be done through conventional methods (e.g.: immersion, boiling) or modern techniques at reduced temperatures to minimize energy use (Chengaiah *et al*., 2010; Lellis *et al*., 2019).

Mordanting: An essential aspect of pigment fixation on textiles is the use of mordants. Instead of toxic metal salts (e.g., chromium or copper), recent studies promote the use of biomordants, natural substances such as tannins extracted from pomegranate peel or nettle leaves. These not only improve pigment adherence but also provide functional properties such as antioxidant and antimicrobial effects.

*Quality evaluation of dyeing:*To demonstrate the industrial applicability of natural colorants, rigorous evaluation of color fastness to washing, light, and rubbing is necessary. In the case of *Prunus spinosa* dyeing, laboratory tests have shown acceptable resistance, especially when biomordants are used. Instrumental measurements (CIELab, ΔE) have confirmed colour stability over time under controlled conditions (Cardon, 2007; Gulrajani, 2001).

The entire process, from extraction to pigment fixation, can be effectively aligned with several green chemistry principles. Hazardous substances are reduced or eliminated by avoiding toxic solvents and mordants, instead favoring plant-based alternatives (Lellis *et al.,* 2019; Yabré *et al.,* 2018). Low-temperature dyeing processes are promoted to minimize energy consumption, while water recycling and reuse through wastewater recovery systems help reduce both total water use and environmental contamination (de la Guardia and Garrigues, 2012; Anitha and Beda, 2024). Furthermore, optimizing extraction and fixation methods maximizes pigment yield and ensures effective adherence to textiles, and the careful choice of materials and techniques minimizes waste while enabling the valorization of by-products (Anastas and Warner, 1998; Yabré *et al.,* 2018). In this way, the valorization of *Prunus spinosa* extracts not only offers a sustainable alternative to synthetic dyes but also serves as a clear example of innovation in environmentally conscious textile production.

Industrial Applications and Challenges

Natural dyeing with plant-based pigments such as those derived from *Prunus spinosa* not only provides an environmentally friendly alternative to synthetic dyes but also offers long-term economic benefits by enabling less energy-intensive production methods.

Some eco-conscious fashion brand such as Stella McCartney, have already integrated plant-based extracts into their collections, demonstrating the viability of sustainable textiles at a commercial scale (Rodríguez-Saona and Wrolstad, 2001).

Several challenges must be addressed to enable large-scale industrial adoption. Raw material availability is constrained by the seasonal and regional variability of plant sources, affecting production continuity and supply chain reliability. Consistent color standardization remains difficult due to natural fluctuations in pigment concentration and composition. Furthermore, although natural dyes are promising, their durability and fastness often need optimization to meet the long-term performance expectations of the textile industry.

In addition, further research is needed to improve pigment formulations, enhance their compatibility with various types of textile fibers, whether natural, synthetic, or blended, and to develop industrial protocols that preserve both ecological and functional integrity. Overall, despite these challenges, the integration of natural pigments like those from *Prunus spinosa* represents a critical step toward the decarbonization and detoxification of the textile industry, aligning with circular economy goals and consumer demands for safer, greener products (Lellis *et al*., 2019; Shahid *et al*., 2013).

3. Conclusions

The use of *Prunus spinosa* extracts in textile dyeing clearly demonstrates the potential of green chemistry principles to be applied in an industry traditionally associated with high environmental impact. The natural pigments derived from this species provide competitive chromatic performance while enabling sustainable processes aligned with the circular economy.

Current scientific literature does not report textile dyeing studies using *Prunus spinosa* extracts. Most available publications focus on the chemical composition of anthocyanins and tannins and on analytical techniques used to characterize these compounds. These studies do not include standardized dyeing procedures, colorimetric measurements, ΔE values or fastness tests performed on textile fibers. This absence of experimental data limits the possibility of comparing performance indicators or evaluating reproducibility. For this reason, the present work synthesizes only the chemical, functional and analytical aspects documented in previous research, without extending the discussion to quantitative textile performance parameters that have not yet been investigated.

However, large-scale implementation requires rigorous standardization of methodologies, optimization of process parameters, and effective integration into existing industrial workflows (Anastas and Warner, 1998; Yabré *et al.*, 2018).

Green chemistry offers a solid foundation for transforming the textile sector toward eco-friendly practices, reducing the use of hazardous substances, replacing toxic solvents with biodegradable alternatives, and minimizing energy consumption.

By utilizing renewable raw materials and adopting environmentally conscious technologies, it becomes possible to create textile products with reduced ecological footprint, while also fostering technological innovation and contributing to the development of a circular economy in the industry.

Ultimately, sustained progress in the research and application of these green technologies will be decisive for building a responsible and future-ready textile industry, where aesthetics, functionality, and environmental safety coexist in harmony (Cardon, 2007; Kim, 2006).

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VALORIFICAREA EXTRACTULUI DE *PRUNUS SPINOSA* CA AGENT COLORANT SUSTENABIL ÎN FINISAREA TEXTILELOR: O ABORDARE DIN PERSPECTIVA CHIMIEI VERZI

(Rezumat)

În contextul actual al necesității dezvoltării unor tehnologii textile durabile, această cercetare investighează aplicabilitatea extractelor din *Prunus spinosa* ca agenți coloranți ecologici. Fructele și scoarța acestei specii constituie surse bogate de compuși bioactivi, precum taninuri, flavonoide și antociani, caracterizați prin proprietăți antioxidante, antimicrobiene și colorante, oferind astfel o alternativă viabilă la coloranții sintetici.

Pigmenții pot fi extrași din fructele de *Prunus spinosa* prin diverse metode, precum macerarea, fierberea și presarea. Compoziția chimică a extractelor poate fi caracterizată prin tehnici analitice avansate, inclusiv cromatografie lichidă de înaltă performanță (HPLC), rezonanță magnetică nucleară a protonului (^{1}H-NMR) și spectroscopie în infraroșu cu transformată Fourier (FTIR). Utilizarea acestor extracte în procese de vopsire ecologice contribuie semnificativ la reducerea poluării mediului, prin eliminarea necesității utilizării unor agenți chimici nocivi.

Stabilitatea și proprietățile de fixare ale acestor coloranți naturali pot fi evaluate prin analize spectroscopice, teste de rezistență la spălare, lumină și frecare, precum și prin măsurători colorimetrice. Studiile din literatura de specialitate au evidențiat o afinitate crescută a acestor pigmenți față de fibrele textile naturale, precum bumbacul și lâna, asigurând o aderență puternică și o durabilitate cromatică sporită.

Pe lângă avantajele ecologice, această metodă susține dezvoltarea unei industrii textile mai sustenabile, oferind produse cu proprietăți funcționale suplimentare, cum ar fi protecția împotriva radiațiilor ultraviolete (UV) și activitatea antimicrobiană. Prin urmare, valorificarea extractelor de *Prunus spinosa* în vopsirea textilelor este în deplină concordanță cu principiile chimiei verzi, promovând alternative inovatoare și prietenoase cu mediul la coloranții convenționali.

Această abordare reprezintă un pas semnificativ în reducerea impactului ecologic al industriei textile, demonstrând fezabilitatea utilizării resurselor naturale în procese sustenabile. Studiile viitoare vor urmări extinderea aplicabilității acestor coloranți naturali asupra fibrelor sintetice, optimizarea procedurilor de extracție și maximizarea eficienței de fixare a pigmenților.

Astfel, aplicarea extractelor de *Prunus spinosa* ca agenți coloranți naturali nu doar că oferă o alternativă viabilă și ecologică la coloranții sintetici, contribuind la reducerea impactului negativ asupra mediului, ci deschide și noi perspective în dezvoltarea textilelor funcționale cu proprietăți antimicrobiene și de protecție UV, susținând tranziția către procese de producție sustenabile, aliniate principiilor economiei circulare și chimiei verzi.