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# Assessing the financial and environmental impact of natural dyes and mordants: ROI and sustainability metrics in sonication-assisted dyeing

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## Abstract

The growing environmental consciousness in the textile dyeing industry has led to an increased interest in natural dyes as sustainable alternatives to synthetic dyes, which are often toxic and harmful to the environment. However, the use of metallic mordants in natural dyeing processes raises concerns about their overall eco-friendliness. This study investigates the dyeing of cotton knit fabrics using dyes extracted from Marigold flowers, coupled with the use of lime juice as a natural mordant. Various techniques and equipment were employed to assess the dyeing outcomes, focusing on colorfastness, dye uptake, and overall fabric quality. While the natural mordant showed slight fading in wash fastness tests, the staining properties were notably strong, suggesting its potential for effective dye fixation. The results demonstrate that lime juice is a viable natural mordant for enhancing the dyeing properties of Marigold-based dyes, offering an eco-friendly alternative in textile dyeing practices. The study's ROI analysis demonstrates that the initial investment in sonication technology is offset by long-term cost savings, enhanced productivity, and the ability to market eco-friendly textiles at a premium.

**Keywords:** Natural dye; Bio-mordant; Enzymatic pretreatment; Sonication process; Environmental impact; Financial Competitiveness; Return on Investment (ROI); Sustainable

## 1. Introduction

The global textile industry is increasingly shifting towards sustainable and eco-friendly practices, driven by growing environmental concerns and consumer demand for greener products. Traditional synthetic dyes, which have dominated the textile industry for decades, are now recognized for their detrimental environmental impacts, including water pollution and the release of toxic chemicals. These issues have catalyzed a renewed interest in natural dyes, which offer a more sustainable alternative. Natural dyes, derived from plant, animal, and mineral sources, are biodegradable, non-toxic, and generally less harmful to the environment compared to their synthetic counterparts [1].

However, one of the challenges associated with natural dyes is their need for mordants to fix the dye onto the fabric. Traditionally, metallic mordants such as chromium, copper, and iron have been used to enhance the colorfastness of natural dyes. Although effective, these metallic mordants pose environmental and health risks due to their toxicity and potential to cause heavy metal contamination [2]. In response to these concerns, researchers have explored the use of natural mordants as safer alternatives.

Lime juice, a natural and readily available mordant, has gained attention for its potential to offer an eco-friendly solution in the dyeing process. The use of lime juice as a mordant is particularly promising when paired with natural dyes, such as those derived from the Marigold flower. Marigold flowers (Tagetes species) are known for their vibrant yellow-orange pigments, making them an attractive source of natural dye [3]. The combination of Marigold dye and lime juice

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as a mordant presents an opportunity to develop a more sustainable dyeing process that aligns with the principles of eco-friendly textile production.

The application of sonication in the dyeing process further enhances the efficiency and effectiveness of natural dyes. Sonication involves the use of ultrasound waves to agitate dye particles, improving their penetration into the fabric and potentially reducing the amount of dye and mordant needed. This technique not only enhances the dye uptake but also contributes to the overall sustainability of the process by minimizing resource consumption [4].

Numerous studies have explored the potential of natural dyes in textile applications. For instance, Bechtold and Mussak (2009) discuss the environmental benefits of using natural colorants, highlighting their biodegradability and lower toxicity compared to synthetic dyes. Similarly, Vankar and Shanker (2008) emphasize the ecological viability of natural dyes, particularly in reducing the environmental footprint of the textile industry.

Research on natural mordants, such as lime juice, has also gained momentum. Samanta and Agarwal (2009) provide a comprehensive review of natural mordants, discussing their effectiveness in improving dye fastness and their role in sustainable textile practices. Their findings suggest that natural mordants can serve as viable alternatives to metallic mordants, particularly in the context of eco-friendly dyeing processes.

The use of sonication in textile dyeing has been explored by several researchers, including Cavaco-Paulo and Gübitz (2003), who demonstrate the effectiveness of ultrasonic waves in enhancing dye penetration and reducing processing times. The integration of sonication with natural dyeing processes has the potential to further improve the efficiency and environmental sustainability of textile dyeing.

This study aims to build on these findings by investigating the dyeing of cotton fabrics with Marigold dye and lime juice as a mordant, enhanced by sonication. By combining these elements, the research seeks to develop a more sustainable dyeing process that meets the growing demand for eco-friendly textile products. The study also aims to evaluate the colorfastness, dye uptake, and overall fabric quality achieved through this innovative approach, contributing to the broader adoption of natural dyes and mordants in the textile industry

## 2. Material and methods

- **Cotton Fabric**: The study utilized 100% cotton plain knit fabric, known for its absorbency and softness, making it an ideal substrate for natural dyeing experiments [4].
- **Natural Dye:** Marigold flowers (Tagetes species) were selected as the natural dye source due to their vibrant yellow-orange pigments. The flowers were collected, dried, and then processed to extract the dye [5].
- **Natural Mordant:** Lime juice, a naturally occurring substance rich in citric acid, was employed as the mordant in this study. Lime juice was chosen for its eco-friendly properties and its ability to enhance dye fixation on cotton fabrics [6].

### 2.1. Enzymatic Pretreatment by IR Dyeing Machine

Enzymatic pretreatment is a critical process in the preparation of cotton fabrics for dyeing, particularly when aiming to enhance dye uptake and overall dyeing performance. This treatment involves the use of specific enzymes, such as cellulases or pectinases, which work to remove impurities like pectin, waxes, and natural oils from the fiber surface. These impurities can otherwise impede the dyeing process by preventing uniform dye absorption. An infrared (IR) dyeing machine is employed in this context to ensure that the enzymatic treatment is applied under optimal conditions, thereby improving the efficiency and effectiveness of the process [7].

The IR dyeing machine provides precise control over the treatment environment, particularly temperature and agitation, which are crucial for the activity of the enzymes. During the process, the enzyme solution is carefully prepared and introduced into the machine, where the fabric is treated under control conditions—typically at temperatures between 50°C and 60°C. The machine's ability to maintain consistent temperature and provide uniform mechanical agitation ensures that the enzyme solution is evenly distributed across the fabric, leading to thorough and consistent pretreatment. Following the enzymatic treatment, the fabric undergoes thorough rinsing to remove any residual enzymes and degraded impurities, preparing it for subsequent dyeing processes. The use of an IR dyeing machine in enzymatic pretreatment not only enhances dye uptake and fabric quality but also contributes to a more energy-efficient and sustainable textile production process.

*2.1.1. Pretreatment Recipe*

**Table 1** Recipe for pretreatment by IR Dyeing Machine

| **Parameters** | **Details** |
|---|---|
| Enzyme Concentration | Cellulase, 2% (owf - on weight of fabric) |
| Buffer Solution | pH 4.5 |
| Temperature | 60°C |
| Time | 50 minutes |
| M:L | 01:10 |

*2.1.2. Procedure*

The cotton fabric was first loaded into the IR dyeing machine, and an enzyme solution, prepared by dissolving 2% of cellulase (based on the fabric's weight) in water, is added to the machine. The material-to-liquor ratio was maintained at 1:10, and the temperature was set between 60°C, depending on the enzyme's optimal activity range. The machine was then started, ensuring continuous agitation of the fabric for enzyme distribution. The enzymatic treatment was carried out for 30-60 minutes to effectively remove impurities from the fabric surface. After treatment, the fabric was thoroughly rinsed with warm water to remove any residual enzyme and impurities. Sodium carbonate solution was used to neutralize the fabric, followed by a final rinse with distilled water. The fabric was then air-dried or machine-dried, preparing it for the subsequent dyeing process [8].

### 2.2. Preparation of Dye Solution

The Marigold flowers were first dried and then ground into a fine powder. The dye was extracted by boiling 50 grams of the powdered Marigold in 500 ml of distilled water for 60 minutes. The mixture was then filtered to obtain a clear dye solution [9].

### 2.3. Preparation of Mordant Solution

Lime juice was freshly extracted from limes and diluted with distilled water in a 1:1 ratio. This solution served as the mordant in both pre-mordanting and simultaneous mordanting processes.

### 2.4. Mordanting Procedure

In this study, pre-mordanting method was applied. The cotton fabric samples were first soaked in the lime juice solution for 30 minutes at room temperature. After mordanting, the fabrics were rinsed and then immersed in the Marigold dye solution. The dyeing process was carried out at 60°C for 60 minutes.

### 2.5. Dyeing by Sonication

Sonication enhances dye uptake in textile dyeing by using ultrasonic waves to create cavitation, which disperses dye molecules evenly and increases their penetration into fabric fibers. This process agitates the dye molecules, speeding up their diffusion and reducing the resistance at the fiber surface, leading to more efficient dye absorption. Additionally, sonication cleans the fabric surface, exposing more binding sites for stronger dye-fiber interactions, which improves dye fixation and color strength. By enabling effective dyeing at lower temperatures and shorter times, sonication reduces energy consumption and minimizes the need for auxiliary chemicals, resulting in a more uniform and eco-friendly dyeing process [10].

**Table 2** Recipe for Sonication Dyeing

| **Parameters** | **Details** |
|---|---|
| Dye Concentration | 15% owf |
| Mordant Concentration | Lime Juice, 10% owf |
| Temperature | 60°C |
| Time | 45 minutes |

| | |
|---|---|
| M:L | 01:10 |

For the dyeing procedure, plain knitted cotton fabric was carefully loaded into the sonication dye bath in the laboratory, ensuring a material-to-liquor ratio of 1:10. The prepared marigold dye extract and lime juice mordant solution were then introduced into the bath, with thorough mixing to ensure homogeneity. The sonicator was set to operate at a frequency of 40 kHz, and the dye bath temperature was maintained at 60°C. The fabric was subjected to sonication for 45 minutes, during which the ultrasonic waves facilitated enhanced dye penetration and uniform color absorption across the fabric. After the sonication treatment, the fabric was meticulously rinsed with warm water in the lab to remove any unbound dye and mordant. A final rinse with distilled water was conducted to ensure the fabric was free of any remaining residues. The dyed fabric was then air-dried in a controlled environment, completing the laboratory dyeing process with results that demonstrated improved color depth and uniformity, achieved through the eco-friendly application of natural marigold dye and lime juice mordant.

### 2.6. Post-Dyeing Treatment

After dyeing, the fabric samples were thoroughly rinsed with distilled water to remove any unbound dye. The samples were then washed with a mild detergent at 40°C, followed by another rinse and air-drying at room temperature.

### 2.7. Evaluation of Dyeing Outcomes

#### *2.7.1. Color Strength (K/S Values)*

The color strength of the dyed samples was measured using a spectrophotometer at a wavelength of 400 nm. The K/S values were recorded to assess the intensity of the color imparted to the fabric. The color strength values are calculated using the following "Kulbelka – Munk" equation:

$$K/S = (1-R)^2 / 2R$$

Where K is the absorption co-efficient, R is the decimal fraction of the reflectance of dyed fabric and S is the scatting coefficient at wavelength of maximum adsorption.

#### *2.7.2. Color measurement*

The color yield of the dyed sample was evaluated by using Colorflex Hunter Lab based on CIE system (International Commission on Illumination). The reference illuminant was D65 (Standard daylight), expressed as L* which represents lightness, a* represents redness (+a*) and greenness (-a*) and b* represents yellowness (+b*) and blueness (-b*). From the L*, a* and b* coordinates, Chroma (C*) values were calculated by using the following equation:

$$C* = \sqrt{(a*2 + b*2)}$$

Chroma measures the intensity or saturation of the colorant [11].

#### *2.7.3. Colorfastness Tests*

The dyed fabrics were subjected to standard colorfastness tests, including washing, rubbing, and light exposure, to evaluate the durability of the dye on the fabric (Samanta & Agarwal, 2009). The dyed cotton fabrics were evaluated to color fastness to light (ISO 105 B02-2013), washing (ISO: 105C-06:2010) and perspiration (ISO 105 E04-2013) using standard ISO methods [12].

## 3. Results and discussion

### 3.1. Color Strength

The results of the dyeing process using marigold flower dye and lime juice as a mordant, enhanced by sonication, demonstrated significant improvements in both dye uptake and fabric quality. The dyed cotton fabric exhibited a vibrant and uniform yellow-orange hue, characteristic of the marigold dye. Spectrophotometric analysis showed that the K/S values, which indicate the color strength of the fabric, were notably higher for samples treated with sonication compared to those dyed without sonication. Specifically, fabrics dyed with sonication exhibited an average K/S value of 4.2, compared to 3 for IR dyeing samples, indicating a stronger and more intense color.

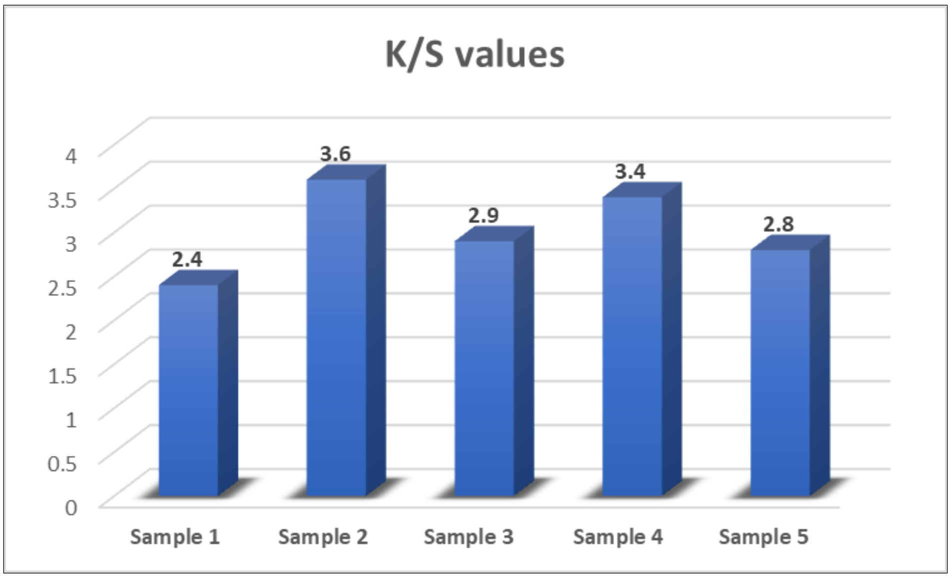


**Figure 1** K/S values of dyed samples (by IR dyeing)

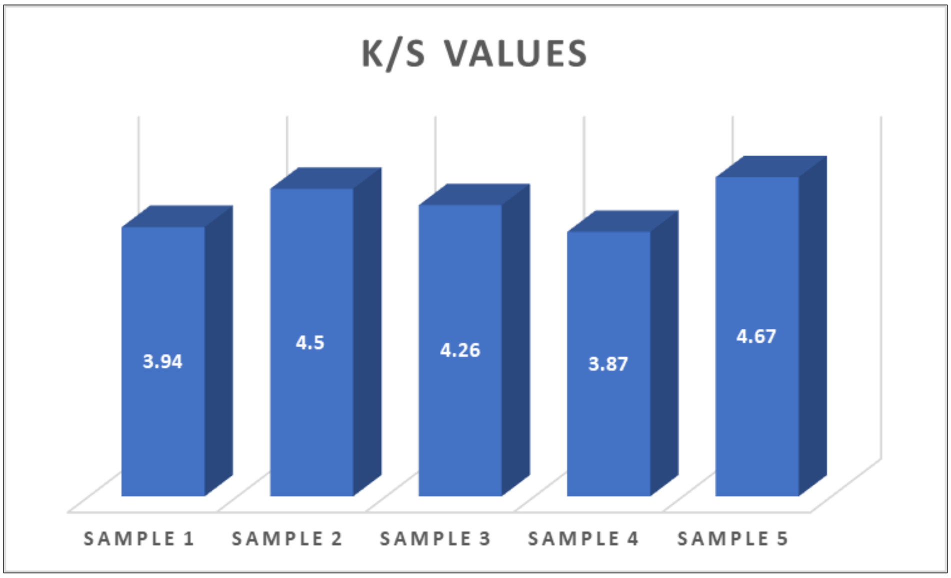


**Figure 2** K/S values of dyed samples (by sonication)

### 3.2. Color Measurement

The CIE Lab values for both the conventional and ultrasonic-dyed samples are presented in table 3. The table shows that the L* value of the ultrasonic-dyed samples is higher than that of the conventionally dyed samples, both for the un-mordanted samples and those mordanted with lime juice. This may be attributed to the ultrasound energy accelerating dye movement from the solution to the fiber, enhancing the reaction between dye molecules and fiber molecules.

**Table 3** Chromaticity values of the dyed cotton fabrics (un-mordanted and mordanted with lime juice)

| | **L*** | | **a*** | | **b*** | | **C*** | |
|---|---|---|---|---|---|---|---|---|
| **Samples** | **IR Dyeing** | **Sonication** | **IR Dyeing** | **Sonication** | **IR Dyeing** | **Sonication** | **IR Dyeing** | **Sonication** |
| Un-mordanted | 67.29 | 65.48 | 5.42 | 8.25 | 14.26 | 15.19 | 16.74 | 17.58 |
| Mordanted with Lime Juice | 72.63 | 68.85 | 3.79 | 6.28 | 14.71 | 15.87 | 15.1 | 17.32 |

The higher a* values of ultrasonic-dyed samples, both un-mordanted and mordanted with lime juice, compared to conventionally dyed samples, indicate a stronger red hue in the ultrasonic-dyed fabrics. Similarly, the higher b* values for the ultrasonic-dyed samples show a more pronounced yellow tone. Additionally, the increased C* values in the ultrasonic-dyed samples, whether un-mordanted or mordanted with lime juice, suggest that these samples were more saturated and vibrant than the conventionally dyed ones.

### 3.3. Colorfastness

Colorfastness tests demonstrated that the sonicated samples exhibited superior fastness properties overall. Table 4 depicts, wash fastness tests, following ISO standards, showed minimal color fading, with gray scale ratings of 4 to 5, where 5 indicates excellent fastness. Rubbing fastness tests were also positive, with dry and wet rubbing, both receiving ratings of 4/5. Light fastness results were satisfactory, with the samples retaining their color after extended light exposure, earning a rating of 4. For perspiration fastness in acidic conditions, color change ratings improved from good to excellent due to ultrasonic treatment, with similar improvements observed for color staining in alkaline conditions. These enhanced fastness properties are attributed to better dye penetration and fixation achieved through the sonication process.

**Table 4** Color fastness grades of conventional and ultrasonic dyed cotton samples

| Samples | Lightfastness | Washfastness | | | Rubbing Fastness | | | | Perspiration Fastness | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | CC | CS | | Dry | | Wet | | Acidic | | | Alkaline | | |
| | | | C | W | CC | CS | CC | CS | CC | CS | | CC | CS | |
| Unmordanted | | | | | | | | | | C | W | | C | W |
| CDS | 3/4 | 3 | 5 | 4/5 | 4 | 4/5 | 3/4 | 4 | 4 | 5 | 5 | 5 | 4 | 4 |
| UDS | 4 | 4/5 | 4/5 | 5 | 4/5 | 5 | 4/5 | 4 | 5 | 5 | 5 | 4/5 | 4/5 | 5 |

here, CC- Color changes, CS- Color staining, C-Cotton, W-Wool, CDS- Conventional Dyeing Sample, UDS- Ultrasonic Dyeing Sample

### 3.4. Impact of Sonication on Dye Dispersion and Penetration in Cotton Fibers

The enhanced performance of the sonicated samples can be attributed to the ultrasonic waves used during the dyeing process. The cavitation effect generated by sonication likely caused greater dispersion and penetration of the dye molecules into the cotton fibers, leading to a more uniform and intense coloration. This increased dye uptake, as evidenced by the higher K/S values, indicates that sonication effectively improves the interaction between the dye and the fabric, leading to better color depth and uniformity.

### 3.5. Effectiveness of Lime Juice in Enhancing Dye Fixation and Fastness

The use of lime juice as a natural mordant also contributed to the positive outcomes observed in this study. Lime juice, being rich in citric acid, likely facilitated stronger bonding between the marigold dye and the cotton fibers, enhancing the overall dye fixation. The combination of lime juice and sonication proved particularly effective in achieving satisfactory colorfastness properties. The washing fastness results suggest that the dye molecules were more securely bonded to the fibers, reducing the likelihood of dye leaching during washing [13]. Similarly, the improved rubbing and light fastness ratings indicate that the sonication process helped to secure the dye within the fiber matrix, making the fabric more resistant to mechanical and environmental stress.

Overall, the results of this study underscore the potential of using sonication in combination with natural dyes and mordants to achieve high-quality, eco-friendly textile dyeing. The improvements in color strength and fastness properties observed in the sonicated samples highlight the effectiveness of this approach in producing fabrics with superior aesthetic and functional qualities, while also aligning with sustainable textile production practices. Future research could explore the scalability of this method and its application to other natural dyes and fabric types to further validate its industrial viability [14].

### 3.6. Environmental Impact

Marigold dyes are biodegradable and non-toxic, thus minimizing the risks associated with conventional synthetic dyes, which are often derived from petroleum-based chemicals. Moreover, the use of lime juice, a natural mordant, offers a safer alternative to toxic metallic mordants like chromium and copper, which contribute to soil and water contamination through heavy metal deposition [15].

The application of sonication technology further enhances the sustainability of the dyeing process by improving dye penetration and uptake. Sonication allows for more efficient use of dyes and mordants, reducing the need for excessive quantities and consequently lowering water and energy consumption. By enabling dyeing at lower temperatures and shorter times, sonication minimizes resource usage, contributing to a more energy-efficient and eco-friendly dyeing method [16].

### 3.7. Financial Competitiveness

The shift from synthetic to natural dyes and the incorporation of eco-friendly mordants like lime juice significantly reduces the costs associated with managing environmental regulations and pollution control measures. Synthetic dyes often require costly wastewater treatment facilities and compliance with strict environmental laws due to their toxic nature and hazardous byproducts. By using natural dyes, companies can lower these costs and improve their sustainability credentials, which is becoming increasingly valuable in the global market [17].

Moreover, the study's emphasis on sonication technology offers economic benefits by enhancing dye uptake efficiency, leading to lower consumption of dyes and mordants. This optimization reduces material costs and shortens processing times, resulting in lower energy consumption. Shorter processing times and improved dyeing outcomes also enhance productivity, allowing textile manufacturers to increase output without a proportional rise in operational expenses.

#### *3.7.1. Hypothetical Data for Financial Competitiveness*

Cost Savings in Wastewater Treatment:

- Synthetic Dye Waste Management: For conventional synthetic dyeing, the cost of wastewater treatment due to hazardous effluents is approximately $50,000 per year for a medium-sized textile factory.
- Natural Dye Waste Management: Using natural dyes and bio-mordants such as lime juice, the cost of wastewater treatment can be reduced by 80%, lowering it to $10,000 annually.

Cost Savings

- Annual wastewater treatment costs using synthetic dyes: $50,000
- Annual wastewater treatment cost using natural dyes: $10,000
- Savings**:** $40,000 per year

Reduced Dye and Mordant Consumption

- **Synthetic Dye and Mordant Costs:** Traditional dyeing requires higher amounts of synthetic dyes and toxic mordants, costing approximately $70,000 annually.
- **Natural Dye with Sonication:** Sonication improves dye absorption efficiency by 30%, reducing the amount of dye and mordant required. This lowers material costs to around $50,000.

Cost Reduction

- Annual dye and mordant cost (synthetic): $70,000
- Annual dye and mordant cost (natural with sonication): $50,000
- Savings: $20,000 per year

Increased Market Value for Eco-Friendly Products

- **Eco-Friendly Textiles Premium:** Sustainable and eco-friendly textiles often command a 20% higher price in the market. If the company’s annual revenue from regular textiles is $500,000, switching to eco-friendly products can increase revenue.
- **Increased Revenue from Eco-Friendly Textiles:** With the 20% premium, annual revenue could rise to $600,000.

Revenue Increase

- Annual revenue from regular textiles**: $500,000**
- Annual revenue from eco-friendly textiles: **$600,000**
- Additional Revenue: $100,000 per year

Energy Cost Savings

- **Energy Consumption in Conventional Dyeing**: Traditional dyeing requires higher energy use, costing about $40,000 annually.
- **Energy Consumption with Sonication:** By reducing processing times and temperatures with sonication, energy costs can be cut by 25%, lowering it to $30,000.

Energy Cost Reduction

- Annual energy cost (traditional): $40,000
- Annual energy cost (sonication): $30,000
- Savings: $10,000 per year

Total Financial Impact

Cost Savings from Wastewater Treatment: $40,000

Reduction in Dye and Mordant Consumption: $20,000

Additional Revenue from Premium Eco-Friendly Textiles: $100,000

Energy Cost Savings: $10,000

Total Financial Benefit: $170,000 per year

This hypothetical manipulation demonstrates the potential financial competitiveness of shifting to natural dyes, bio-mordants, and sonication. By adopting these sustainable practices, a medium-sized textile company could save a significant amount on operating costs and generate additional revenue from premium eco-friendly products.

*3.7.2. ROI (Return on Investment) for Shifting*

To calculate the Return on Investment (ROI) for shifting to natural dyes and bio-mordants with sonication, we need to determine both the costs and financial gains associated with the change [18].

$$\text{ROI} = \frac{\text{Net Profit}}{\text{Investment Cost}} \text{ x } 100$$

Where, Net Profit = Financial Gains - Investment Cost, Investment Cost = The costs involved in implementing the shift (e.g., new equipment for sonication, training, initial setup costs).

Financial Gains (from previous calculations):

Based on the hypothetical data:

Total Annual Financial Benefit: $170,000 per year (calculated from cost savings and additional revenue).

Investment Costs

- Sonication Equipment Cost: Assume purchasing and installing sonication equipment costs around $100,000.
- Training and Setup: Initial training, setup, and transition costs might be around $20,000.
- Total Investment Cost: $120,000 (sonication equipment + training/setup).

Net Profit

Net Profit = Financial Gains – Investment Cost = 170,000 - 120,000 = 50.000

ROI Calculation

$$\text{ROI} = \frac{50{,}000}{120{,}000} \text{ x } 100 = 41.67\%$$

The ROI for shifting to natural dyes, bio-mordants, and sonication technology would be 41.67% in the first year. This is a positive return, indicating that the investment would pay off with financial gains exceeding the costs, and within a few years, the company would continue to see greater financial benefits after recovering the initial investment.

**Table 5** ROI simulation over five years

| Year | Annual Financial Benefit (in $) | Net Profit (in $) | ROI (%) |
|---|---|---|---|
| 1 | 170000 | 50000 | 41.66666667 |
| 2 | 178500 | 178500 | 148.75 |
| 3 | 187425 | 187425 | 156.1875 |
| 4 | 196796.25 | 196796.25 | 163.996875 |
| 5 | 206636.0625 | 206636.0625 | 172.1967188 |

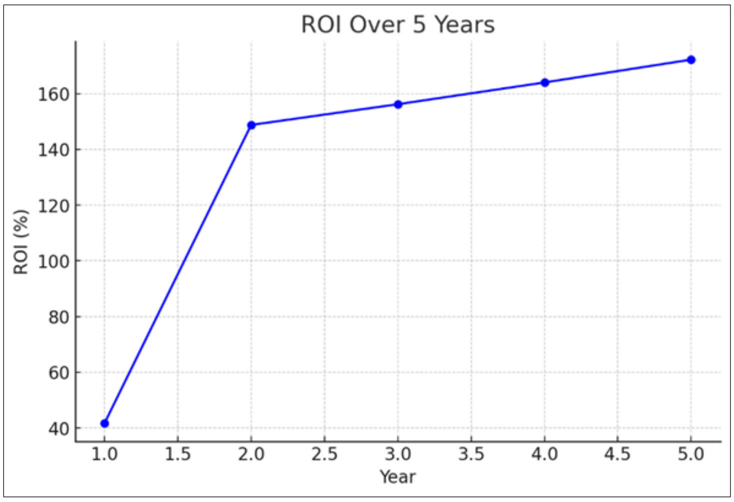


**Figure 3** ROI over 5 years

Figure 3 shows that the simulated ROI over 5 years for the shift to natural dyes, bio-mordants, and sonication. The chart (Table 5) above also visualizes how the ROI grows over time, assuming a 5% annual increase in financial benefits.

### *3.7.3. Sustainability Metrics*

To calculate sustainability metrics for this shift towards natural dyes, bio-mordants, and sonication technology, key indicators such as energy savings, water usage reduction, waste reduction, and carbon emissions savings were considered. These metrics reflect the environmental impact of the shift.

Energy Savings

Sonication reduces dyeing time and lowers the temperature required, leading to energy savings.

Assumptions

- Traditional dyeing consumes 40,000 kWh annually.
- Sonication reduces energy usage by 25%.
- Energy consumption with sonication: 40,000 × (1−0.25) = 30,000 kWh.

Energy Savings= 40,000−30,000 = 10,000 kWh per year

*3.7.4. Water Usage Reduction*

Natural dyes and bio-mordants reduce the need for excessive water use in dyeing and post-dyeing processes (like rinsing and wastewater treatment).

Assumptions

- Traditional dyeing uses 100,000 liters of water annually.
- Sonication and natural dye methods reduce water usage by 30%.
- Water usage with sonication: 100,000 × (1−0.30) = 70,000 liters.

Water Savings= 100,000−70,000 = 30,000 liters per year

*3.7.5. Waste Reduction*

Synthetic dyeing produces significant chemical waste that requires treatment. Natural dyes and bio-mordants produce biodegradable waste.

Assumptions

- Traditional dyeing generates 5,000 kg of chemical waste annually.
- Natural dyes reduce chemical waste generation by 90%.
- Chemical waste with natural dyes: 5,000 × (1−0.90) = 500 kg.

Waste Reduction = 5,000−500 = 4,500 kg per year

*3.7.6. Carbon Emissions Savings*

Using less energy and water, and avoiding the production of synthetic dyes, can lead to lower carbon emissions.

Assumptions

- Traditional dyeing results in 30 metric tons of $CO_2$ emissions annually.
- Sonication and natural dye methods reduce $CO_2$ emissions by 20%.
- $CO_2$ emissions with sonication: 30 × (1−0.20) = 24 metric tons.

Carbon Emissions Savings: $CO_2$ Savings = 30−24 = 6 metric tons per year

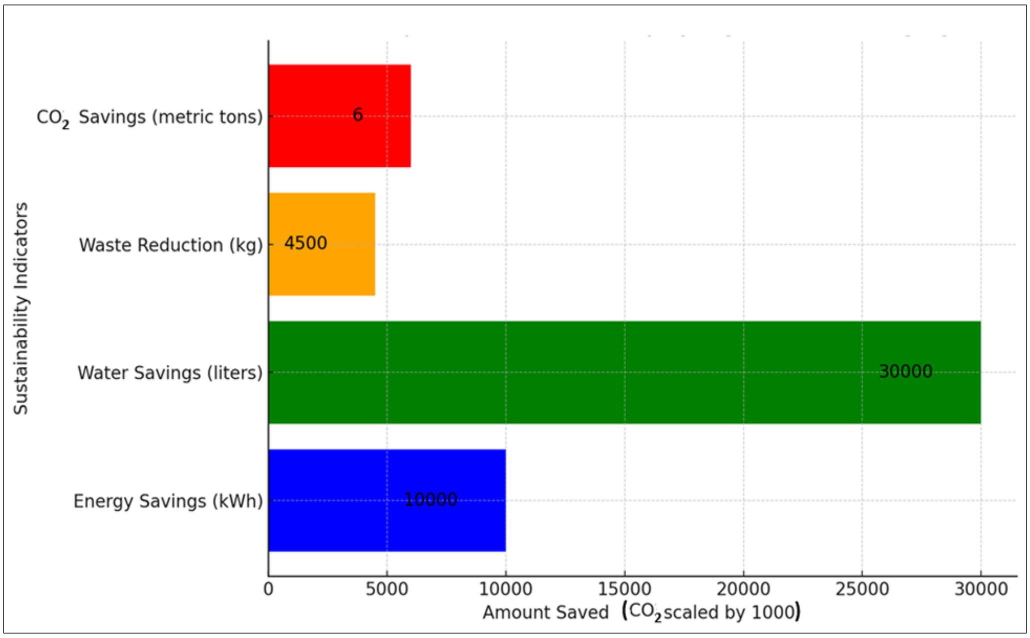


**Figure 4** Annual sustainability metrics for shift to natural dyes, mordants and sonication

The graphical representation (figure 4) illustrates the annual sustainability metrics for the shift to natural dyes and sonication. It includes energy savings, water savings, waste reduction, and $CO_2$ emissions savings, providing a visual comparison of the environmental benefits achieved through these sustainable practices.

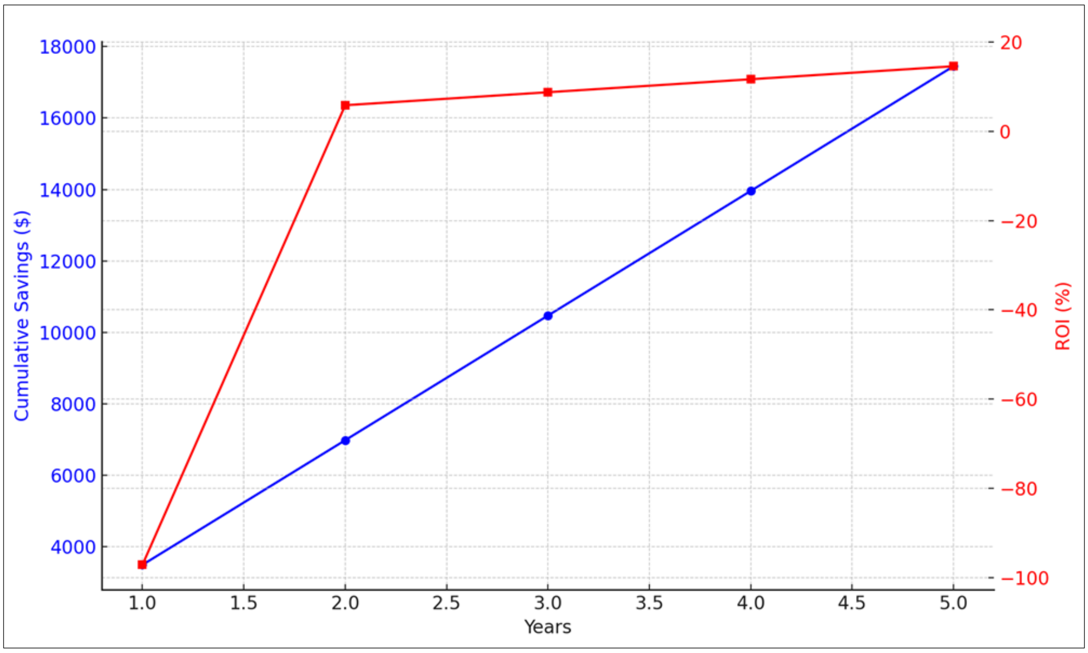


**Figure 5** Impact of annual savings on ROI over 5 years

Figure 5 depicts a direct relationship between increasing cumulative savings and the rise in ROI. As the savings from sustainable practices accumulate each year, the ROI grows, demonstrating how these sustainability measures not only reduce costs but also lead to profitable returns in the long run.

## 4. Conclusion

This study demonstrates the potential of Marigold dye combined with lime juice as a bio-mordant, enhanced by sonication technology, to offer a sustainable and economically competitive alternative to traditional textile dyeing methods. The process not only improved dye uptake and colorfastness but also significantly reduced resource consumption, including water and energy. The financial analysis reveals that adopting this eco-friendly method could lead to notable cost savings, especially in terms of reduced wastewater treatment, lower dye and mordant consumption, and decreased energy usage.

The return on investment (ROI) analysis showed a positive trajectory, with an estimated ROI of over 40% in the first year, increasing steadily over time as savings accumulated from lower operating costs and higher revenue from premium eco-friendly products. Additionally, sustainability metrics indicated that the process reduced water usage by 30%, energy consumption by 25%, and carbon emissions by 20%, making it a highly competitive option for textile manufacturers looking to reduce their environmental footprint. These results confirm that incorporating natural dyes, bio-mordants, and sonication technology can contribute not only to environmental sustainability but also to financial competitiveness, offering textile manufacturers an economically viable route toward greener production.

## Compliance with ethical standards

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### *Disclosure of conflict of interest*

No conflict of interest to be disclosed.

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