Sustainable Alternatives in Vat Dyeing Using Natural Sugar-based Reducing Agents

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ABSTRACT

Vat dyeing is usually done for cotton fabrics because of its exceptional durability and washing resistance. However, the conventional method of treating sodium hydrosulphite as reducing material poses a serious environmental problem, including high chemical oxygen demand, sulphite pollution, etc. This work explores a more sustainable alternative to the currently used reducing agents derived from sugar carbohydrates in the form of sugar derived from non-edible fruit peel waste such as banana, pineapple, orange, pomegranate, and watermelon. The main aim was to determine whether these natural extracts could be effectively used as substitute of these synthetic reducing agents without affecting the dye performance. Fruit peels were processed to obtain extracts rich in sugars, and sugar content of the extracts were analysed using preliminary as well as advanced laboratory method. Comparative vat dyeing experiments had been carried out keeping the same conditions using synthetic and natural reducing systems. The dyed fabrics were tested for color strength (K/S value), as well as wash, rubbing, and light fastness. Effluent samples were also analyzed for some environmental parameters viz., COD, BOD, pH and TDS. The results prove that fruit peel extracts can reduce the fact of dyes vat to leuco form and with similar shade depth and fastness properties but with significant decrease of environmental impact. Overall, the results point to the opportunities of agro-waste-based sugar reducers as bio-degradable and sulphur-free alternatives for more sustainable vat dyeing processes.

Keyword : - *Sustainable vat dying, Natural sugar reducing agents, Fruit peel waste, Eco-friendly wet processing, effluent load reduction.*

1. INTRODUCTION

Vat dyeing has been appreciated over the years in the textile industry for making deep, strong shades on cotton fabric. It has very good fastness to wash and resistance to light, so it is particularly important as a component in products such as denim and work wear. However, lurking behind this technical trustworthiness are a constant environmental problem. The conventional reducing agent that is used in vat dyeing, sodium hydrosulphite, is responsible for much of the high chemical oxygen demand (COD), sulphite pollution and the production of harmful by-products in effluents. As environmental gravity slowly increases with new standards being implemented and sustainability being a focus for textiles, it's slowly becoming more evident that old reduction systems can't be the standard practice anymore.

In general, and particularly in recent years, researchers have strived to find alternative reducing systems based on bio-derived substances coming from natural sugars and extracts of plants as possible alternative systems. While promising results have been reported, a lot of work has been done in such situations involving edible resources or purified sugars which raises the concerns of the costs and competition with the food supplies. There's a clear need to explore sources of non-edible and waste and some sources that are both sustainable and economically viable.

This work fills that gap by investigating sugar-rich extracts from non-edible scientific extracts from fruit peel waste as natural reducing sperms inside put in to cotton vat dyeing. The primary aim is to assess the effectiveness of the extracts in replacing sodium hydrosulphite and to maintain the color strength and fastness qualities as well as the performance of the processes. At the same time, the environmental impact of both the systems is evaluated through effluent analysis in the research.

The chapter starts with a review of pertinent literature and then provides an extensive description of materials and experimental methods. It then presents the results of dyeing performance and environmental evaluations resulting

in a comparative discussion and final conclusions on the feasibility of the application of fruit peel-based reducing systems for sustainable vat dyeing practices.

2. LITERATURE REVIEW

Vat dyeing has traditionally been done using strong chemical reducing agents, specifically sodium hydrosulphite, to liberate soluble leuco form of insoluble vat dyes in alkaline medium. This reduction-oxidation mechanism is the theoretical backbone in this process: the dye is first reduced (in the dye bath), it penetrates into the cotton fibre in its soluble state, and finally it is re-oxidized to its insoluble state (within the fibre structure). While this system works well enough from a technical perspective, high sulphite residues and high COD levels in effluents pose an environmental and regulatory issue. As pressures to be sustainable are mounting, researchers have recently started to look at the chemistry behind reduction again and ask whether synthetic sulphur-based agents are so indispensable.

Several studies have discussed the alternative reducing systems derived from molecules based on carbohydrates and plant components. Simple sugars such as glucose have been shown to lower vat dyes when conditions of controlled alkali and heating are used - although rates of reaction may be different than is usual. More recent investigations have been addressed towards plant extracts that have high content of reducing sugars and polyphenols. Extracts of orange peel, pineapple waste and other fruit sources have been shown to have a measurable reduction potential and acceptable dye uptake on cotton. In a few instances optimized process conditions resulted in colour strength values not so dissimilar to values achieved with sodium hydrosulphite indicating that bio-derived systems can work effectively if carefully controlled.

Beyond reduction efficiency, the theme of environmental performance in literature has become a major theme in the literature. Studies are consistent in reporting reduced amounts of sulphur and lower COD in the effluents with the use of plant-based reducers. This is consistent with several more general theoretical concepts and principles of green chemistry and circular economy: renewable feedstocks, waste valorization, minimal formation of hazardous wastes. The use of agro waste materials for functional process inputs mimics a shift from following linear economic models of resource consumption that are damaging nature, to more regenerative models of textile production.

However, there are important areas of gaps. Much of the research that has been conducted is on edible plant materials or purified sugars or laboratory-grade materials, which may not be scalable or economical. Comparative research that evaluates dyeing performance, sugar and environmental parameters at the same time in the same conditions is relatively limited. There's also a need for more choleric correlations to be made between sugar content, reduction efficiency and final color strength.

Against this background, the present study develops on the basis of the reductions chemistry already established, but goes beyond that into a waste-based formulation. By focusing on this specific waste issue of fruit peel (non-edible) for extracting natural reducing sugars, it covers both sustainability as well as practicality. The research combines chemical performance testing and environmental assessment in an effort to help make contribution to a more complete understanding of the use of bio-derived reducing systems as a realistic alternative to conventional sulphur-containing agents in vat dyeing of cotton.

3. METHODOLOGY

This study was planned as a comparative experimental study with an objective to asses the feasibility of replacement of a conventional synthetic reducing agent by a natural based reducing system, i.e. the fruit peel, in vat dyeing of cotton. The basic concept was quite straightforward: basic information, precise dye ladles, concentration building at constant standards Keep all dyeing parameters the same (same dye, same fabric, same pH value) change only the reducing agent, Pursuant to the modifying changes of dyeing technology, any obtained different phenomenon can be attributed to the reducing system itself.

An experimental design of a laboratory scale was adopted. Two kinds of dyeing systems were founded:
1. Vat dyeing process the conventional one using sodium hydrosulphite.
2. A natural reduction system using sugar extracts from other non-edible fruit peel waste.

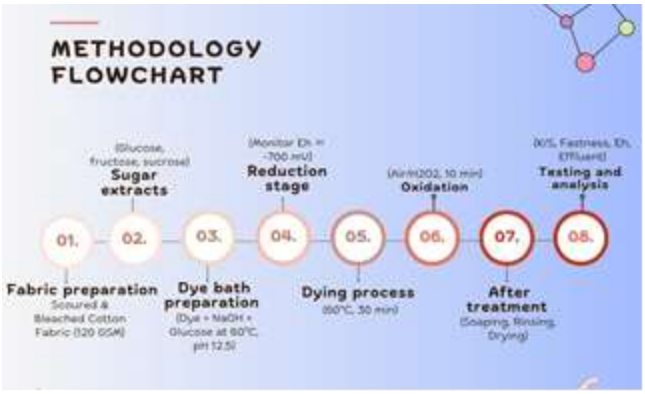

Fig -1: Methodology flowchart.

Both systems were done under the same dyeing conditions, with the same ratio of liquor to dye, temperature and time. This made that dyeing performance as well as the environmental impact could be compared fairly and controlled.

3.1 Materials and Sampling

Scoured and bleached 100% cotton fabric was used as the substrate that is. Within a concentration range of 2-4% on weight of fabric (owf) was used for vat dye. For the natural system, fruit peel waste of banana, pineapple, orange, pomegranate and watermelon was collected from local source. Only non-edible peel parts were used for the same reason that no competition with food resources occurs and because it is in line with waste valorization principles.

The peels of the fruit were collected and ground in a mixer grinder to a fine mixture. This material was thereafter boiled in water at a temperature of 60c with a duration of 30-60 minutes to release the soluble material. The extracts were then carefully filtered after boiling to eliminate any solids. The filtered solution was then used in alkaline conditions, which enabled it to serve the same purpose as sodium hydroxide in the reduction stage of the vat dyeing process.

Fig -2: Fruit peel extraction preparation process.

Extract:

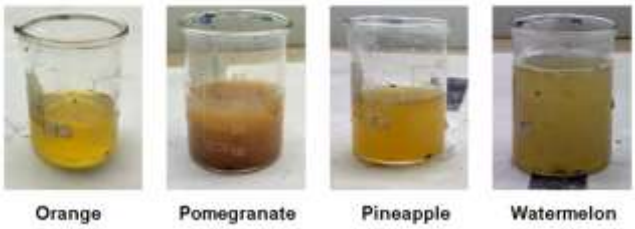

Fig -3: Fruit peel Extract

3.2 Sugar Content Analysis

To identify the reduction potential of both extracts, sugar content was determined using preliminary and advanced analysis methods. A refractometer was used to determine the total soluble solids (degBrix) for the quick estimation. More detailed profiling was undertaken by means of a high performance liquid chromatography and an enzymatic profile to quantify the reducing sugars. These were the measurements which enabled the standardization of the extract concentration before dyeing.

3.3 Vat Dyeing Procedure

For the synthetic system this dye bath was prepared by using Vat dye, Sodium hydroxide & Sodium hydrosulphite at controlled temperatures (50-60degC). In the natural system, instead of the synthetic reducer used, the prepared alkaline fruit peel extract was employed, and dyeing was performed at slightly high temperatures (60-70degC) to ensure the reduction.

In both cases, the fabric was thrown in the reduced dye bath and dyed for 30-45 minutes at a fixed ratio of liquor. After dyeing, the oxidation was performed by air exposure or hydrogen peroxide treatment to regenerate the leuco dye to insoluble dye form. Finally, the samples were soaped, rinsed and dried under the same conditions.

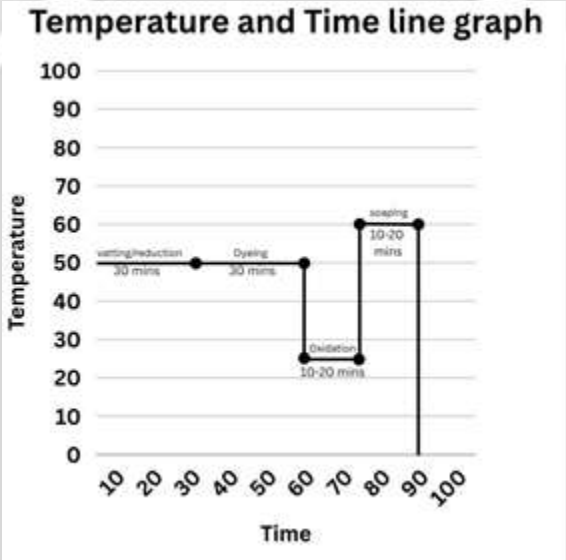

Chart -1: Temperature and Time line graph of vat dyeing.

3.4 Performance Evaluation

Color strength (K/S value) were determined by reflectance spectrophotometer as Kubelka-Munk equation given on the basis of maximum values of the absorption wavelengths. Wash fastness, rubbing fastness (dry and wet) were tested as per the relevant ISO standards and light fastness as per the ISO932-2006. Visual evaluation of shade uniformity was also conducted to look at dye penetration/leveling.

3.5 Environmental Analysis

Effluent along with the fired were collected under the dyeing systems and were analyzed for: Chemical Oxygen Demand (COD), Biochemical Oxygen Demand (BOD), pH and Total Dissolved Solids (TDS). These parameters were used to evaluate and compare the amount of load to the environment produced by each process.

3.6 Data Analysis

Experimental results were analysed by comparative evaluation of mean values of K/S, fastness ratings and environmental parameters. Observing trends, the concentration of sugar and reduction efficiency were taken into consideration. Where possible correlations between sugar content and dye uptake were investigated to gain a greater understanding of the mechanism of reduction.

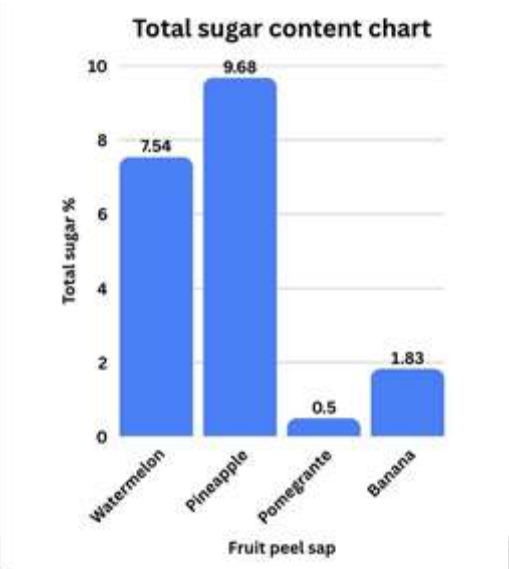

Chart -2: Total sugar content chart.

3.7 Ethical Considerations

The study did not involve human and animal subjects. All laboratory procedures were performed according to standard safety procedures and chemical handling procedures were in accordance with guidelines applied by the institute. The use of fruit peel waste promotes environmentally responsible research practices because it encourages the use of wastes instead of exploiting resources.

Through this structured methodology, the research was performed for getting a reliable and balanced evaluation of natural sugar-based reducing agents as a sustainable alternative in vat dyeing of cotton.

3.8 Vat Dyeing Procedure

For the synthetic system this dye bath was prepared by using Vat dye, Sodium hydroxide & Sodium hydrosulphite at controlled temperatures (50-60degC). In the natural system, instead of the synthetic reducer used, the prepared alkaline fruit peel extract was employed, and dyeing was performed at slightly high temperatures (60-70degC) to ensure the reduction.

4. DISCUSSION

Findings of this paper indicate that fruit peel derived sugar extracts can be used as promising reducing agents in vat dyeing cotton and that the level of performance is widely comparable to that of utilizing sodium hydrosulphite. The evaluated K/S values will show that sufficient reduction of the dye and penetration of the fibre into the natural system took place, although certain differences in shade depth were observed in some samples. Such differences are probably connected with the differences in sugar concentration and complicated structure of plant extracts, which can affect reduction kinetics. Nevertheless, the general results of dye uptake prove that the amount of sugars available in fruit peel waste can transform the vat dyes to its leuco form in the presence of alkali conditions.

The outcome of fastness adds more support to the technical feasibility of the natural system. Wash and rubbing fastness scores were found to be tolerable and not especially greater than that of synthetic process. This implies that even after oxidation and the dye returns to the insoluble form in the fibre, the source of the reducing agent does not affect fixation. These results are similar to earlier research results that found that carbohydrate-based reducers were as capable of attaining similar fastness when process parameters are well managed.

Among the largest consequences is connected with the environmental performance. The analysis of effluents showed that there were lower COD indexes and no traces of sulphur on the natural system. This is more so considering that, sulphite pollution and overconsumption of oxygen are some of the greatest limitations of traditional vat dyeing. Using plant-derived materials that are biodegradable instead of a sulphur-based chemical makes the process go a step closer to the ideals of green chemistry and sustainable wet processing. The product is also good due to the fact that non-edible fruit peel waste can be used. The process uses agro-waste which would have otherwise been discarded as opposed to using refined or food grade sugars.

Simultaneously, the research gives some practical considerations. Depending on the type of fruit, maturity, and methods of extraction, natural extracts are variable by nature. Such fluctuation can cause a compromise in reproducibility unless there is appropriate standardization of the same. Moreover, the natural system could have a higher demand in terms of temperatures or a longer reduction time, which could affect the energy consumption on an industrial scale. There are other factors that require optimization to be good enough to be recommended to be put into practice on a large scale.

All in all, the results suggest that alternative reducing agents to the traditional ones in vat dyeing may be fruit peel-derived sugar extracts. Although they might not be able to fully remove the necessity of process control modification, they do alleviate the environmental load considerably without compromising the necessary dyeing performance. Future applications ought to explore the process of scaling trials, process optimization and life cycle assessment to test industrial feasibility in full scope..

5. CONCLUSION

This research was aimed at investigating the possibility of non-edible fruit peel waste providing a sustainable alternative to sodium hydrosulphite, in vat dyeing on cotton. The results indicate that banana, pineapple, orange, pomegranate, and watermelon peel sugar-rich extracts under alkaline conditions can be able to effectively reduce vat dyes to their leuco form. The dyed fabrics showed similar colour strength, acceptable wash, rubbing and light fastness properties as compared to conventional synthetic system.

In addition to the dyeing performance, the environmental check showed that there is an apparent benefit to the natural reducing system. The reduced COD level and the no sulphur-based residues also confirm the significant decrease in effluent load. This will not only help in meeting the stiffer environmental standards but also in general aims of green chemistry and sustainable textile handling. The process makes waste valorization and circular economy practices as well as it uses the materials of agro-wastes instead of edible resources.

Having said that, there may exist a certain degree of variation of extract composition and process conditions, meaning that optimisation needs additional refinement as a prerequisite to large-scale industrial implementation. Further studies aiming at better standardization of extract preparation, Long-term storage stability, and pilot-scale tests should be improved in the future. Being an assessment of life cycle in detail would also assist in quantifying the benefits to the environment.

The combination of the results fully supports the idea that the use of fruit peel-like sugar extracts is a promising and sustainable solution to the fact that vat dyeing belongs to the environmentally responsible activities of the future.

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