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Sustainable Development of UV-Protective Farmer Workwear Using Natural Indigo and Agro-Waste Derived Dyes

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Abstract: ***Agricultural workers are routinely exposed to prolonged solar radiation, making ultraviolet (UV) protection an important requirement in workwear design. At the same time, conventional textile dyeing contributes substantially to environmental pollution due to the use of synthetic dyes and chemical auxiliaries. This study explores the development of sustainable farmer workwear using 100% cotton fabric dyed with natural indigo and agro-waste dye sources, namely onion peel and pomegranate peel. Alum was used as an eco-friendly mordant for the agro-waste dyed samples, while natural indigo dyeing was carried out through a chemical-free fermentation vat prepared with lime and henna. The dyed fabrics were evaluated for UV protection and color fastness to washing, perspiration, and rubbing. The UV protection results showed that indigo-dyed fabric exhibited the highest UV protection efficiency (88.00%), followed by onion peel (78.80%), pomegranate peel (65.50%), and the onion-pomegranate blend (58.02%). Color fastness results revealed superior overall performance for indigo-dyed fabric, with ratings largely between 4 and 5, indicating slight to no change. The study demonstrates that natural indigo and selected agro-waste dyes can be effectively used to produce functional and eco-friendly textiles for agricultural workers. Among the tested samples, natural indigo emerged as the most suitable dye source for protective farmer garments due to its superior UV resistance and better fastness behavior. These findings support the integration of sustainable dyeing methods into protective rural clothing development.***

Keywords: onion peel dye, pomegranate peel dye, UV protection finishes, sustainable textiles, agro-waste valorization

I. INTRODUCTION

Agriculture is still considered a critical source of livelihood in developing countries like India where a large proportion of the population is engaged in manual and field working [16]. These are farmers who often work long hours under direct sunlight and are therefore forgeedly subject to the harmful impact of ultraviolet (UV) rays with the same exquisiteness [27]. Extensive UV exposure puts persons at risk of sunburn, pigmentary changes, premature cutaneous aging, and in the worst scenario, cutaneous neoplasms [16].. In spite of these verifiable threats, the wearable of this population group is mostly heavily determined by functionality and affordability and not the functionality and performance in terms of protection, which explains a desperate demand of working clothes that could provide both thermal and effective protection and protection against the sun during the extended periods of farm work [11]. Also corresponding to this occupational exigency is the environmental cost of traditional processing of textiles. The process of the synthetic dyeing is inherently connected to the release of dangerous chemistries to the aqueatic and land-based environments, creating ecological disequilibrium and provoking subsequent dangers to human health. To address such worries, natural dyes have to a larger extent become the focal point of sustainable textile studies due to their environmentally friendly nature, which means biodegradability and a less toxic profile, than artificial dyes. In addition, the recycling of agro-waste materials into chromogenic sources increases the valorization of waste and encourages the management of the circularity of resources. Onion and pomegranate peels that are regularly thrown out as domestic or commercial wastes are robust reservoirs of bioactive chromophores like flavonoids and tannins compounds that are capable of simultaneously imparting UV absorption characteristics to textile materials [11,17].Natural indigo is also another salient dyeing sustainable approach. Contrasting with many of the plant-derived dyes that work by simple adsorption, the indigo is processed by a vat dyeing process that comprises chemical reduction and repeated oxidisation to form a durable blue color and possibly give the process superior protection against UV-rays due to its greater shade depth [7].

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As a result, the current study, which evaluates the performance of natural indigo in comparison with agro-waste dyes on cotton cloth to the application in agricultural workwear, integrates the traditional knowledge of natural dyeing with the current paradigms of functional textile engineering and sustainable design, thus, enabling the creation of a practical solution in the field of apparel to the fieldworkers.

II. MATERIALS AND METHODS

The medium-weight and 100% cotton fabric was used as an investigation sample because its selection was based on the proven appropriateness of the item in work-wearing, as it inherently has the characteristics of breathability, the ability to absorb sweat, and the overall benefit to the wearers. Natural dye substrates were indigo powder found in Indigofera tinctoria (hence positions), onion peel and pomegranate peel which were dried and added into the indigo vat preparation. The mordant used with the agro waste dyed specimen was alum and lime was used to provide the appropriate alkaline environment to reduce indigo.The cotton fabric was scoured with warm water and a dilute detergent before dyeing to remove the oils, dust and starchy residues thus increasing the fiber absorbency and allowing the dye to be uniformly absorbed. In the case of the onion and pomegranate peel dyes separate and aqueous extracts were made, by ratio of 1:20 of the material to the liquor keeping the mass at 80oC temperature to 60 minutes and filtration to produce transparent liquors of the dye. The concentration of alum used at the pretreatment step was between 10 -15 per cent of the weight of the fabric at 60 -80 o C between 30-45 minutes before the dyeing step. Then the mordanted textiles were dipped in the extracts as respective at 80o C to 90o C within 45 to 60 minutes. Onion and pomegranate extracts were also incorporated in a blended sample through equal part proportions. The natural indigo vat made was under the protocol of fermentation vat and was made using indigo powder lime, warm water and henna powder as a natural reducing agent. This was left to ferment until the yellow-green color appeared which is an indication of reduced leuco indigo formation. After pretreatment, the cotton fabric was immersed into the vat between 5-10minutes after which it was left in the air to oxidize, the color of the cotton fabric during this process changed to blue as compared to greenish-yellow. There were several dipping cycles to obtain more intensive tonal variations .Opposite to the agro-waste dyes, indigo dyeing did not require further wave of mordanting since the dyeing was achieved by oxidizing the dyeing matter in a fiber matrix. The colored fabric was then used in planning and manufacturing of farmer working clothing and clothes such as a male full sleeves shirt, a female protective apron, and a protective covering of the arms. A functional test was performed on the basis of ultraviolet protection and colour fastness. The parameters of ultraviolet protection tried were under UV-Vis spectrophotometry in accordance with the internationally recognised fabric UV protection parameters as mentioned in the report. There were also colour fastness tests, which included the wash, perspiration and rubbing tests .

III. RESULTS AND DISCUSSION

A. UV Protection Performance

The results of the ultraviolet protection test. The highest UV protection rating was of 88.00 making that of the natural indigo followed by onion peel with 78.80, pomegranate peel with 65.50 and the blend of the two (onion-pomegranate) with 58.02. These results show that any organically-dyed cloth gave a measurable amount of UV protection; however, the indigo-dyed cotton was more protective than other considered dyestuffs. This chromatic richness of indigo and the inherent property of the vat dyes to generate deeply within the fiber bed, can be attributed to the superior status of vat dyes. Darker color increases UV absorption, and this in turn reduces dermal transmittance. Onion peel also demonstrated a good performance, which could also be explained by quercetin and other flavonoids which are known to possess UV absorbing properties . Pomegranate peel which is rich in tannins and phenols provided moderate protection but the decant onion pomegranate did not provide the best efficacy of the sampled samples . These results suggest that blending did not increase the elastic functionality in the current experimental set-ups and might lead to a weakening of the proper concentration or the interactive power of the UV absorbing components.

Sample	Dye Source	Type of Source	Mordant / Reducing System	Dyeing Method	UV Protection (%)	Fastness Performance	Key Functional Observation
S1	Natural Indigo	Plant-based natural vat dye	Lime + henna fermentation vat; no	Vat dyeing with dipping	88	Very good to excellent (mostly 4–5)	Highest UV protection and best overall durability; most

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			mordant required	and oxidation cycles			suitable for farmer workwear
S2	Onion Peel	Agro-waste natural dye	Alum	Aqueous extraction and hot dyeing	78.8	Moderate to good (mostly 3–4)	Good UV protection due to flavonoids such as quercetin; promising sustainable alternative
S3	Pomegranate Peel	Agro-waste natural dye	Alum	Aqueous extraction and hot dyeing	65.5	Moderate (around 3–4)	Moderate UV protection; tannin-rich source with functional textile potential
S4	Onion Peel + Pomegranate Peel Blend	Agro-waste blended dye	Alum	Mixed extract dyeing	58.02	Moderate	Lowest UV protection among all samples; blending did not improve functional performance in this study

Table 1. Result Of Agro- Waste Dye And Indigo Dye.

B. Color Fastness Performance

Indigo has also been established to be the most promising dye system in this inquiry by the color fastness data further cementing. Indigo-stained cotton recorded as fast with a 4 to 5 score in most of the parameters at alkaline and acidic conditions, indicating insignificant color change and slight staining of the fabric during laundry sweating, as well as rubbing. Such a level of strength is especially positive towards work wear where repetition of usage, exposure to sweat and abrasion on the surfaces are expected. Onion peeled fabric exhibited fair durability with the ratings of the fabric mostly falling between the range of 3 to 4 particularly with regard to color change and rubbing fastness. Pomegranate peel showed slightly higher performance in some facets of performance as compared to onion (especially the wet rubbing area) but not better than indigo on the whole. The pomegranate-onion amalgamation was intermediate in nature, which there was not the greatest durability, but rather acceptable . These findings indicate that agro-waste dyes become more practical with alum mordanting; nevertheless, the obtained fastness remains not the same as in the case with the natural indigo specimen.

C. Implications of Sustainability and functional.

Functionally, the findings in this paper support the feasibility of naturally dyed cotton fabrics as protective way of dressing to the agricultural workers. Practical exigency Since full-sleeve shirts, aprons, and arm cocoons needed to offer maximum dermal protection in the field, the incorporation of these elements fulfills practical exigency. Considering that the fabrics employed were made up 100-percent cotton, the end result is a garment which has to be kept to its indescribable comfort assets, such as being able to breathe and to take up moisture, which are key attributes in hot climate reefs. In the sustainability perspective, there are two relevant pathways that the research outlines . To start with, the transformation of onion and pomegranate peels into the functional textile colorants is one of the examples of an effective transformation of the low-value organic waste, which supports the premises of the circular economy. Second, an implementation of a natural indigo fermentation system eliminates synthetic reducing agents which used in dyeing processes induce dependency on chemicals, thus reducing such dependency in the dyeing processes.

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The integrated strategy will demonstrate how the provisions of conventional dye techniques and innovation, which is based on wastes, could provide a model of creating safer and more ecologically friendly textiles.

IV. CONCLUSION

This study has reached the development of sustainable agricultural working workwear on the basis of natural indigo and agro-waste dyes on cotton substrates and benchmarked their ultraviolet (UV) protection and color fastness. Every coloured sample had an apparent amount of UV protection, which supports the hope of natural dyes to be useful in practical textiles. However, natural indigo appeared unquestionably the best source of dyes combining the highest value of UV protection of 88.00% with superior color fastness. Onion peel which was one of the agro-waste varieties offered visual benefits like property protection through UV filtering, whereas pomegranate peel and the blended dye portrayed moderate results.. The discoveries suggest that the use of natural indigo-dyed cotton is highly appropriate in producing protective wear (in farming) especially where durability and protection against UV radiations is significant. Agro-waste dyes also do not lose their value due to their sustainability, proximity, and the ability to convert waste to usable final products. Together, this research paper introduces a strong model on how to combine the eco-friendly dyeing processes, workplace safety, and countryside textile innovation. Future research can continue this work by including UPF classification, longitudinal studies of laundering, wear and trial of wearer and optimizing shade depths and mordant mixings to gain greater performance measures.

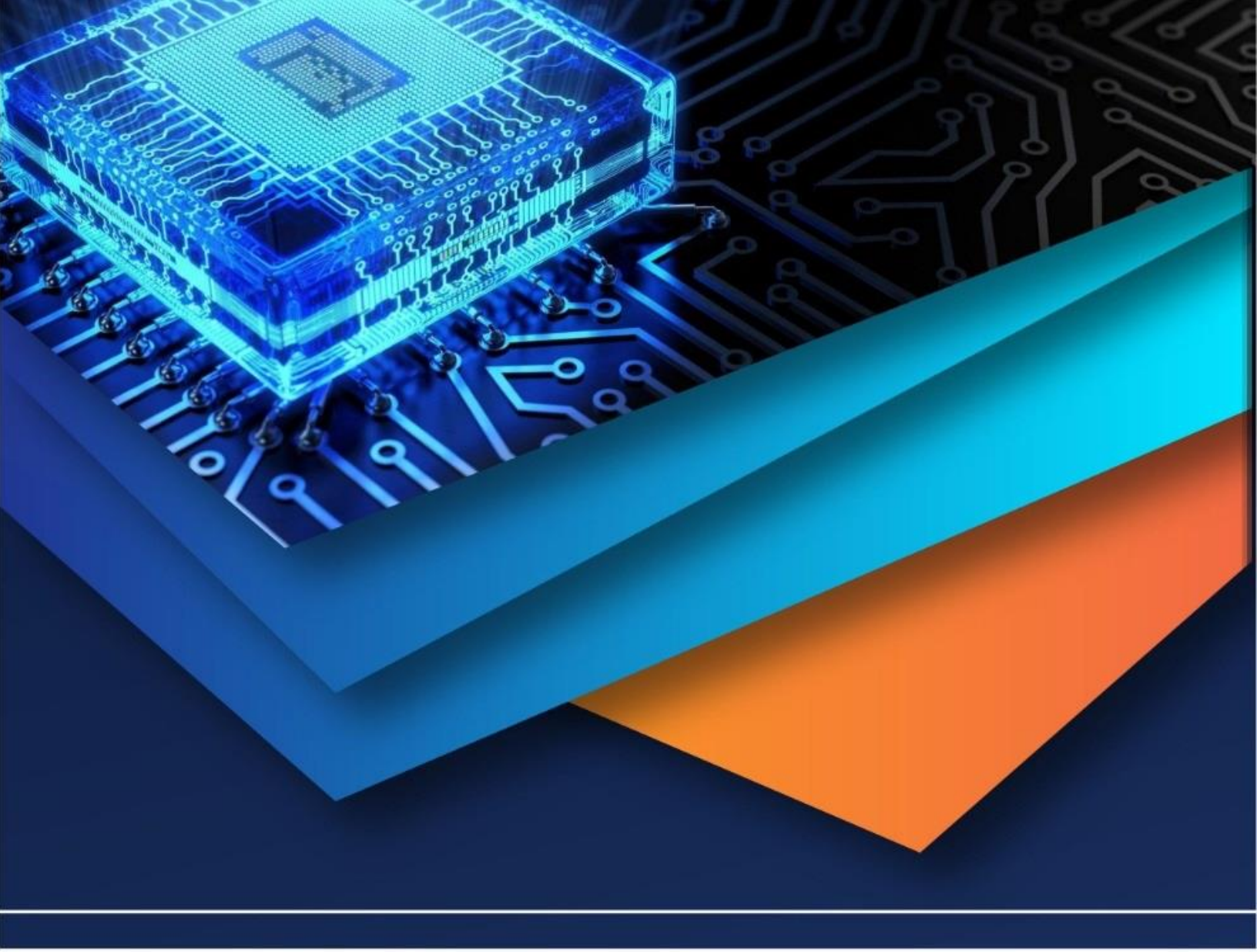
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