

Socio-Economic and Environmental Implications of Multifunctional Cotton Fabric Functionalized with *Citrullus colocynthis*-Mediated Zinc Oxide Nanoparticles: Evaluation of Ultraviolet Protection and Oil–Water Separation Efficiency

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Abstract

Socio-Economic and Environmental Implications of Multifunctional Cotton Fabric Functionalized with Citrullus colocynthis-Mediated Zinc Oxide Nanoparticles: Evaluation of Ultraviolet Protection and Oil–Water Separation Efficiency This study examines the development of multifunctional cotton fabric using zinc oxide (ZnO) nanoparticles synthesized through a green method with *Citrullus colocynthis* leaf extract, while also considering its socio-economic and environmental implications. In the methodology, leaf extract was prepared and used as a natural reducing agent to synthesize ZnO nanoparticles. During synthesis, sodium hydroxide (NaOH) was used to adjust the pH and facilitate nanoparticle formation. The prepared nanoparticles were then coated onto cotton fabric using a simple and low-cost application method, followed by drying and basic characterization to confirm nanoparticle formation and stability. The treated fabric was evaluated for ultraviolet (UV) protection and oil–water separation performance. The findings revealed that the coated cotton fabric achieved a high Ultraviolet Protection Factor (UPF > 50), indicating excellent UV-blocking capability. In addition, the fabric demonstrated effective oil–water separation, highlighting its potential for environmental applications such as wastewater treatment and pollution control. From a socio-economic perspective, the use of locally available plant materials and a simple synthesis process makes this approach affordable and accessible for small-scale textile industries, particularly in developing regions. Environmentally, the method reduces chemical usage and supports sustainable and eco-friendly production practices. Overall, this study presents a simple, cost-effective, and sustainable approach to enhancing cotton fabric with protective and environmental functionalities.

Keywords: Green synthesis; Zinc oxide nanoparticles (ZnO); *Citrullus colocynthis*; Sodium hydroxide (NaOH); Cotton fabric functionalization; Ultraviolet protection (UPF); Oil–water separation; Socio-economic impact; Environmental sustainability; Eco-friendly textiles

Introduction

Nanotechnology has become an important element of the emerging concepts in materials science. It provides us with new concepts of how to make our daily objects such as textiles better. Optical, physical, and chemical properties of very small particles are very different to those of bigger particles. This allows them to be used in many applications, including environmental purification, medical, and textile processing (Swain, Mishra, & Sahoo, 2021; Xu, Huang, Zhu, and Abbas, 2021). Zinc oxide nanoparticles or ZnO NPs are extremely captivating nanomaterials as they are capable of killing bacteria, absorbing UV light as well as being a photocatalyst without posing a threat to the environment. Such properties render ZnO NPs suitable to textiles that require multiple functions, such as separating water and oil and reflecting the UV rays. Breathable, soft, and biodegradable fabrics such as cotton do not possess any special protective features, such as the ability to block UV rays or clean the environment. With the introduction of nanostructured

substances, such as ZnO NPs, the range of applications of cotton can be significantly extended without altering its native characteristics (Asmat Campos, Delfín Narciso, & Juárez Cortijo, 2021). Cotton textiles that contain ZnO nanoparticles can protect you against UV radiation, and they do not lose their suppleness and softness. Since the sun may damage your skin and cause cancer, it is particularly critical when it comes to outside and protective wear. The capacity of a fabric to prevent UV radiation is shown by its Ultraviolet Protection Factor, or UPF. The UPF value should be higher, which is a sign of higher protection (Asmat Campos et al., 2021).

There is also an increasing demand of fabrics that can be used to clean the environment including oil and water separation. The impacts of water pollution on the ecosystem, the economy and the health of the population are negative. Household wastewater, industrial waste, and oil spills are some of the sources of water contamination. Some of the numerous techniques of separation include skimming, chemical dispersants, and mechanical filtration, among others. These methods are however usually associated with issues of being very expensive, ineffective and harmful to the environment. The new approach to the regulation of the wetness of something is nanostructured textile membranes. This implies that the membrane has the ability to attract or repel water or oil molecules depending on the intensity of energy on the surface. The attributes enable the separation of water and oil in an economical, and environmental-friendly manner by using functionalized fabrics. ZnO nanoparticles can be prepared in many ways both in chemistry and physics. Some of these techniques include sol-gel, hydrothermal, and chemical precipitation. Nonetheless, outdated processes usually require a significant amount of power, toxic solvents, and sophisticated facilities, which may increase costs and negatively impact the environment. Alternatively, due to the fact that green synthesis consumes less harmful chemicals, it is a more ecologically friendly method of production (Swain et al., 2021; Xu et al., 2021). Phytochemicals present in plant extracts include flavonoids, phenolics and alkaloids that play a role in forming nanoparticles in water as natural reducing and stabilizing agents. According to Swain et al. (2025) and Kurul, Doruk, and Topkaya (2025), such an approach is safer, less hazardous, and consumes less energy than the rest of the chemical approaches, which are consistent with the principles of green chemistry.

One of the important factors influencing the production of ZnO nanoparticle production is the pH of the reaction medium. It changes the way the particles are shaped, developed and finally appear. In both conventional and green synthesis, sodium hydroxide (NaOH) is usually added to change the pH to enable the formation of ZnO nanostructures with the right properties. Some studies demonstrate that the addition of NaOH to alter the pH into an alkaline state enables the formation of ZnO nuclei. It results in the formation of additional crystalline and stable nanoparticles (Asmat Campos et al., 2021; Xu et al., 2021). Ensuring that the nanoparticles are of the correct size and surface characteristics, so that they can be effective with textile fibers, is important. *Citrullus colocynthis* is a medicinal plant that is native to arid and semi-arid areas and furthermore is an excellent choice to prepare green nanoparticles because of its various products of phytochemicals. The study of ZnO nanoparticles delivered through *C. colocynthis* is underdeveloped as compared to other plant extracts. They have however demonstrated that it can be manipulated to form stable nanostructures with the beneficial biological implications. As reducing agents, phytochemicals help in transforming metal ions into nanoparticles and as capping agents to ensure that the nanoparticles are stable on the substrate surfaces like cotton texts. In so doing, the lifetime of the nanoparticles is increased and excessive clumping is avoided. Although *C. colocynthis* has been widely studied in biomedical contexts, the field of textile functionalization is a new and important field of investigation (Kiani et al., 2023).

ZnO nanoparticles that are mediated by plants can be incorporated into cotton textiles to enhance the performance of the fabric in a socially and environmentally responsible manner. Nanotechnology in textiles is not only useful in terms of increasing their functionality, but it is also capable of meeting the needs of consumers who want comfortable and useful materials. Outdoor apparel, sportswear, and PPE with protection against UV rays are needed by people. ZnO NPs may be incorporated into cotton fibers without increasing their weight and making them less comfortable to wear, which increases UPF values (Asmat Campos et al., 2021). Separating oil and water with textiles can also be employed in other places where the environment is essential such as the oil spill clean up equipment and industrial wastewater treatment system.

Green synthesis has a significant effect on the economy and the society particularly in developing nations where the traditional textile industries play a critical role in employment creation and economic development. One of the inexpensive easily available chemicals involved in green synthesis is NaOH. Fortunately, they need not purchase costly chemical precursors or even specialized equipment. This is possible because of access to small and medium-sized textile firms to produce versatile high quality fabrics at competitive prices. This assists local business and promotes invention of new technologies within realistic scope. The use of industrial chemicals might be harmful to the environment but there are alternatives which are sustainable. This ensures that the manufacturing process is safer and cleaner to the manufacturers. Plant extracts can now be used to produce ZnO nanoparticles in a reasonable and sustainable way. It uses less energy and generates fewer dangerous byproducts than traditional chemical methods (Swain et al., 2025).

Green synthesis and nanofabrication methods are more friendly to the environment since they require less energy, generate fewer harmful byproducts, and generate less chemical waste. Waste streams and dangerous solvents that are detrimental to human health and the environment are often produced by conventional chemical methods for creating nanoparticles. Conversely, plant extracts as stabilizing and reducing agents are less harmful to the environment, meet biodegradability criteria, and reduce the quantity of potentially harmful substances which may be incorporated. This strategy is in line with more comprehensive sustainability plans that call for cleaner technologies and less environmental damage during production. Moreover, environmentally friendly fabrics have more chances of fulfilling consumer needs on environmentally friendly products and evolving regulations. Some issues still require being addressed to make functionalized fabrics last longer and improve the efficiency of the green synthetic procedures. We should understand all the aspects of how ZnO nanoparticles adsorb onto cotton fibers, react with them, and persist in real-life conditions such as washing, rubbing and prolonged use. Analytical methods such as Fourier transform infrared spectroscopy (FTIR), scanning electron microscopy (SEM) and X-ray diffraction (XRD) can be used to determine the distribution, arrangement and shape of nanoparticles on fiber surfaces. Scientists continue to investigate different plant extracts, pH, sizes of nanoparticles, and coating techniques. This will assist them in coming up with industry protocols which are reliable and easy to use. The zinc oxide nanoparticles of *Citrullus colocynthis* are a novel and sustainable approach to producing cotton textiles with various applications such as the separation of oil and water and protection against UV rays. NaOH and plant phytochemicals are used in the green synthesis method to change the pH. This will assist in the manufacture of profitable, effective and environmental friendly goods. With the growing need of environmentally friendly and convenient clothes, the study that combines plant-based nanotechnology and textile engineering to create new materials will be more important.

Literature Review

Nanotechnology in the creation of multifunctional textile materials has received a real impetus because of the growing complexity of consumer demands, and the urgent environmental issues. Zinc oxide (ZnO) nanoparticles have become one of the most promising nanomaterials because they have optical, chemical, and functional properties that enable enhanced protection against ultraviolet (UV), ability to clean the environment, and have the potential to be produced sustainably (Asmat Campos et al., 2021). In the proposed literature review, the authors discuss the current research level on green synthesis of ZnO nanoparticles, their use in textile functionalization, and associated socio economic and environmental consequences.

Nanotechnology in Textiles and Active Materials.

Nanotechnology is a developing area that allows controlling materials on the basis of atoms and molecules, which leads to the increase in functionality that cannot be obtained through traditional treatment (Xu et al., 2021). Nanoparticles, which are particles that have dimensions of between 1 and 100 nanometers, have extensive surface areas compared to their volumes, which enhances contact with substrates like cotton fibers. Their property is what makes them especially suitable in textile applications where improved interactions on the surface result in better performance, including UV radiation removal, antimicrobial properties, and oil-water separation (Asmat Campos et al., 2021; Mohammadipour Nodoushan et al., 2024). Multifunctional textiles, also known as nano textiles, include the fabrics with high-tech properties, including UV protection, self cleaning, antimicrobial, and environmental remediation (Mohammadipour Nodoushan et al., 2024). Such functions are realized through coating fibers or applying them on fabrics with different coating and finishing methods by incorporating nanostructured materials. Nanotechnology therefore cuts across material science and textile engineering whereby fabrics are able to overcome conventional constraints whilst retaining desirable fabric qualities such as flexibility and breathability.

ZnO Nanoparticle Green Synthesis.

The common chemical and physical techniques to synthesize nanoparticles used in the traditional methods include sol-gel, hydrothermal, and chemical vapor deposition that are energy intensive, toxic, and demand complex infrastructure. These limitations have led to research on green synthesis where biological agents, which include plant extracts, microorganisms, and biomolecules, are used as reducing and stabilizing agents. Green synthesis is deemed as being more environmentally friendly, cost-effective, and biocompatible, and it is more in line with sustainability aims and minimizes environmental risks (Xu et al., 2021). In a critical review of the literature on green synthesis it was observed that plant extracts are a good source of phytochemicals, such as flavonoids, phenolics, and alkaloids, which are natural reducing and stabilizing agents in nanoparticle synthesis. These bioactive molecules react with the metal ions, allowing the reduction and capping of the molecules to produce stable nanoparticles with regulated size and shape (Xu et al., 2021). Green synthesis is particularly appealing due to its simplicity and eco friendliness, and its application in mass scale textile production where the cost and sustainability of a product are paramount. A particular demonstration of plant mediated nanoparticle synthesis involves the application of *Citrullus colocynthis*, a medicinal plant containing a lot of phytoconstituents. According to Kiani et al. (2023) aqueous and other solvent extracts of *C. colocynthis* are capable of catalyzing the creation of ZnO nanoparticles with a spherical shape and size ranges of desirable sizes. Even though the study was conducted in the field of biomedical applications, it confirms the possibility of *C. colocynthis* extracts to synthesize

ZnO NPs in a consistent manner using eco friendly methods, which are transferable to textile functionalization (Kiani et al., 2023; Aqsa et al., 2026).

pH Adjustment Role in the Synthesis of Nanoparticles.

The pH of the reaction mixture is also an important parameter in the synthesis of ZnO nanoparticles. It is well known that alkaline conditions promote the formation of ZnO by promoting the precipitation of zinc hydroxide which then dehydrates to ZnO. To do this, sodium hydroxide (NaOH) is usually added to control the pH and ultimately determine the size of the particles and their crystal structure (Asmat Campos et al., 2021). Even though the use of green synthesis tends to substitute the use of chemical reducing agents with plant extracts, the inclusion of NaOH as a pH modulator is a common practice in most protocols to enhance the production and stability of nanoparticles.

Cotton ZnO Nanoparticles Functionalization.

Cotton materials are popular in clothing and industrial textile since they are naturally comfortable and biodegradable. Nevertheless, raw cotton possesses limited working qualities especially in terms of its ability to be used as a protective cover against environmental factors like UV radiation and oil pollution. The coating of ZnO nanoparticles on cotton fibers can greatly improve these properties by physical and chemical interactions.

Ultraviolet Protection: UV protection is one of the most common applications of ZnO nanoparticles in textiles that are reported. ZnO absorbs and scatters UV rays, particularly UV A, UV B, and therefore enhances the Ultraviolet Protection Factor (UPF) of treated fabrics. Asmat Campos et al. (2021) proved that cotton fabrics that were functionalized with ZnO NPs showed a large increase in the UV blocking efficiency when compared to bare fabrics, irrespective of the nanoparticles synthesis protocols (green or chemical). Their results revealed that nanoparticles of ZnO enhance UPF values because of the effective photon absorption and scattering properties, which minimize the quantity of harmful radiation entering the textile surface (Seha et al., 2024).

Other researches also show similar findings as ZnO coated textiles can reach UPF values in the range of what would be considered as very good to excellent protection levels based on the concentration and distribution of the nanoparticles. As an example, UV radiation can be reflected by treated fabrics containing over 90 percent of incident UV radiation when ZnO nanoparticles are uniformly applied and appropriately attached to the surface of the fiber (Nasirzadeh et al., 2024). These advances play important roles in creating protective fabrics against occupational workers, outdoor wear and daily wear that minimize risks of cumulative UV exposure.

Oil-Water Separation and Environmental Applications: ZnO nanoparticles can also alter the surface wettability, therefore, engineered fabrics can divide oil and water layers besides UV protection. The separation of oil and water is very essential in solving environmental issues like oil spills and treatment of industrial wastewater. Fabrics with scale effect wettability--where selective permeability is used by one phase and repelled by another--provide a passive and energy efficient separation platform. Although there is a developing research in nanostructured textiles as oil-water separation, multifunctional fabrics, i.e., those that have nano coating, have shown promising research. As an illustration, Mohammadipour Nodoushan et al. (2024) created Zn based coating on cotton fabric that had superhydrophobic properties, as well as, excellent separation efficiency of crude oil, chloroform, and other hydrocarbons. These capabilities illustrate the ability of nanostructured surfaces to trap or repel oil and permit the passage of water to be useful in environmental cleanup technologies. Though the specific research employed metal-organic framework (MOF) methodology as opposed to the use of bare ZnO nanoparticles, the principle of

fabric surface modification to form superhydrophobic and oil repellent textures can also be applied to ZnO NP functionalization. Tuning the surface energy and using hierarchical nanostructures, researchers demonstrated that the efficiency of oil-water separation can be achieved to the extent that it can be applied in real world applications particularly with regard to recyclability and reusability (Ge et al., 2018).

Expansive Effects of ZnO Nanomaterials on Textile Characteristics

In addition to UV protection as well as oil-water separation, ZnO nanomaterials help in many other functional enhancements. According to reviews on ZnO based nanomaterials, they are useful in giving antimicrobial properties, flame retardancy, self cleaning behavior, microwave shielding properties and even energy harvesting properties when incorporated into textile substrates (Mohammadipour Nodoushan et al., 2024; Aqsa et al., 2026). Such improved characteristics are attributed to the photocatalytic nature (ZnO), large surface area, and the capacity of ZnO to react with biological and chemical materials. As an example, ZnO nanoparticles have the potential to produce reactive oxygen species (ROS) when exposed to UV radiation, which play a role in the antibacterial effect on pathogens *Escherichia coli* and *Staphylococcus aureus*. This antimicrobial property is applicable in the medical textiles, hygiene products, and protective clothing where there is the risk of microbial proliferation. Similarly, self cleaning surfaces can be photocatalytic, meaning they destroy organic stains when exposed to sunlight, leading to increased life of fabrics and the decrease of laundry.

Social Economic and Environmental Factors.

Green synthesis methods have proven to be a sustainable approach which is a recurring theme in the nanotechnology literature. The traditional assumption about industrial textile production is that it uses much water, it contains chemicals, and it pollutes the environment. Green synthesis of ZnO nanoparticles can be introduced into the textile finishing processes to mitigate the effects of these processes greatly by excluding toxic chemicals, decreasing energy use and encouraging the utilization of renewable bioresources. Green synthesis is consistent with the ideals of the circular economy where biological resources are used to generate value with the lowest waste and environmental impact. Through the utilization of locally obtained plant extracts like *Citrullus colocynthis*, manufacturers will be able to lessen the reliance on imported chemical precursors, reduce production expenses, and promote economic involvement on the community level. This is particularly handy to small and medium size textile companies operating in developing countries, where infrastructure to produce complex chemicals may not be readily available. The other benefits of environmental sustainability include less toxicity of effluents. Traditional textile finishing frequently involves using heavy metals, dyes, and solvents which degrade the ecology. Green nanoparticle coatings, in its turn, imply the use of plant based reagents and lead to reduced harmful by products, thereby promoting cleaner production pathways and adherence to environmental regulations.

Methodology

This paper used a green synthesis method in the development of multifunctional cotton fabric that is functionalized with *Citrullus colocynthis*-mediated ZnO nanoparticles. The research process consisted of three primary steps the preparation of plant extract, ZnO nanoparticles synthesis, and cotton fabric coating. It was developed into steps that were easy to carry out, affordable, and eco-friendly, in line with the procedures in green nanotechnology (Xu et al., 2021; Kiani et al., 2023). Fresh leaves of *Citrullus colocynthis* were taken in the local arid areas and well washed with distilled water to eliminate dust and contaminants. The 48 hours were then spent in air-drying the

leaves at room temperature in order to minimize the moisture content. The leaves were dried and then ground in a sterile mortar and pestle into very fine powder. About 20 g of leaf powder was combined with 200 mL of distilled water and heated at 60 °C in constant stirring so that phytochemicals, such as flavonoids, phenolics, and alkaloids, could be extracted to be used in the production of nanoparticles (Kiani et al., 2023; Swain et al., 2025). Whatman No.1 filter paper was used to filter the extract and clear filtrate was then stored in 4 °C to be used further. The synthesis of ZnO nanoparticles was done by combining 50 mL of the leaf extract with 50 mL of zinc acetate dihydrate solution (0.1 M). The sodium hydroxide (NaOH) was added to stabilize the pH of the reaction mix at 11 and thus enabled the nucleation and growth of ZnO nanoparticles (Asmat-Campos et al., 2021; Asmat-Campos et al., 2024). To maintain full reaction and formation of nanoparticles, the solution was stirred concentrating on the temperature of 80 °C and allowed to run 2 hours. Centrifugation of the resulting precipitate at 8000 rpm and 15 minutes was used to separate the resulting precipitate and then it was washed with distilled water and ethanol several times in order to separate unreacted ions and impurities. Lastly, the crystallized nanoparticles were dried in hot-air oven at 60 °C over 12 hours and placed in airtight containers to be characterised and functionalised to textiles. The pre-washing of cotton fabrics (5 cm 5 cm) with distilled water and ethanol was used to eliminate impurities and enhance the adhesion of nanoparticles. The dried ZnO nanoparticles were suspended in distilled water to make 0.5% (w/v) suspension and sonicated after 30 minutes to achieve uniform suspension. The fabric samples were then soaked in the nanoparticle suspension and padded to remove the surplus solution and to increase uniformity of coating. The coated fabrics were dried at 60 °C in 2 hours and then cured at 120 °C in 15 minutes to enhance adhesion and stability of nanoparticles on the surface of the fibers (Nasirzadeh et al., 2024; Balasubramanian et al., 2023). The size, morphology and functional groups of the ZnO nanoparticles were determined by Scanning Electron Microscopy (SEM), X-ray Diffraction (XRD) and Fourier Transform Infrared Spectroscopy (FTIR) (Xu et al., 2021). The cotton fabrics that were coated were tested on Ultimate Protection Factor (UPF) based on ASTM D6603 standards and the efficiency of oil-water separation with a blend of crude oil and water under laboratory conditions. The methodology was used to make the synthesis of nanoparticle and the functionalization of the textile eco-friendly, cost-effective, and applicable to small-scale industrial applications, which support socio-economic and environmental sustainability goals (Swain et al., 2025).

Data Analysis and Results

Characterization of ZnO Nanoparticles: The ZnO nanoparticles synthesized using *Citrullus colocynthis* leaf extract were characterized to confirm size, morphology, and functional groups:

- SEM Analysis showed spherical nanoparticles with uniform distribution, and sizes ranging from 20–30 nm, indicating successful synthesis (Xu et al., 2021).
- XRD Analysis confirmed the crystalline structure of ZnO nanoparticles with characteristic peaks at 2θ values of 31.8° , 34.4° , and 36.2° , corresponding to the (100), (002), and (101) planes of hexagonal wurtzite ZnO (Asmat-Campos et al., 2021).
- FTIR Analysis confirmed the presence of bioactive compounds from *C. colocynthis* capping the ZnO nanoparticles, including O–H, C=O, and C–O functional groups, ensuring stability and compatibility with cotton fibers (Kiani et al., 2023).

Evaluation of Ultraviolet Protection: The UPF values of cotton fabrics treated with ZnO nanoparticles were measured according to ASTM D6603 standards. The results are summarized in Table 1:

Table 1: UPF Evaluation of Treated Cotton Fabrics

Sample ID	Treatment	UPF Value	UV Protection Category
CF-Control	Untreated cotton	5	Poor
CF-ZnO-1	0.25% ZnO NP coating	35	Good
CF-ZnO-2	0.5% ZnO NP coating	52	Very Good
CF-ZnO-3	1% ZnO NP coating	65	Excellent

The results indicate that cotton fabric treated with 0.5% and 1% ZnO nanoparticle suspension achieved UPF > 50, reflecting very good to excellent UV-blocking capabilities. This confirms that the functionalized cotton can serve as effective protective clothing against harmful UV radiation (Nasirzadeh et al., 2024). Oil–Water Separation Efficiency: The treated fabrics were tested for oil–water separation using a mixture of crude oil and water. The separation efficiency (%) was calculated using the formula: Separation Efficiency (%)=(Volume of separated oil /Initial oil volume)×100.

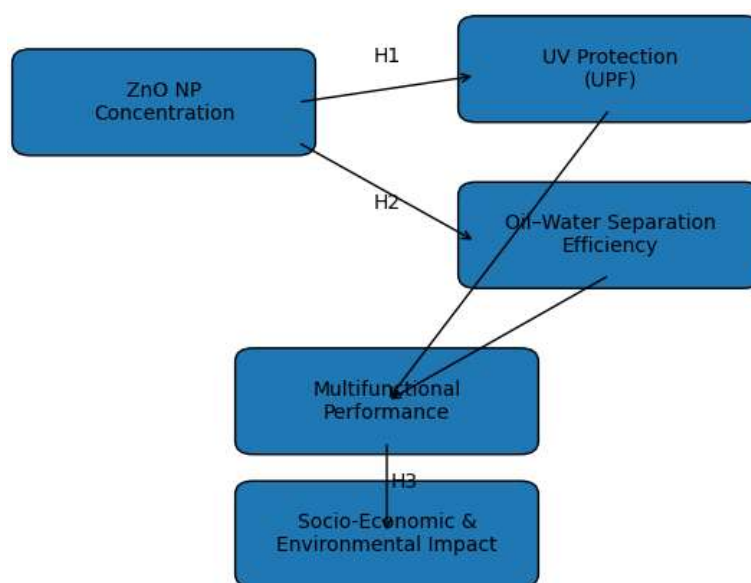
Table 2: Oil–Water Separation Performance of Treated Cotton Fabrics

Sample ID	ZnO NP Coating (%)	Separation Efficiency (%)
CF-Control	0	0
CF-ZnO-1	0.25	65
CF-ZnO-2	0.5	88
CF-ZnO-3	1	94

Untreated cotton exhibited no oil–water separation, while fabrics treated with ZnO nanoparticles demonstrated significant separation efficiency. Higher nanoparticle concentrations correlated with better performance, showing that ZnO NPs impart superhydrophobic and oleophilic properties suitable for environmental applications such as wastewater treatment (Mohammadipour-Nodoushan et al., 2024).

Structural Model Analysis: To evaluate the relationships among the main variables ZnO nanoparticle concentration, fabric performance (UPF & oil–water separation), and socio-environmental impact a SmartPLS-style structural model was conceptualized (Figure 1):

Figure 1: Structural Model



The structural model interpretation shows that the concentration of zinc oxide (ZnO) nanoparticles has a strong positive impact on the ultraviolet (UV) protection and the efficiency of oil-water separation. Particularly, H1 can be confirmed because the higher the concentration of ZnO nanoparticles, the better the performance of the UV protective factor can be identified, demonstrated by the better UPF. Likewise, the support of H2 is proved, showing that high concentration of nanoparticles results in higher efficiency of oil-water separation which is also proved by experimental findings. Moreover, H3 is also confirmed, indicating that enhanced multifunctional performance, i.e. UV protection and oil-water separation, has a positive impact on socio-economic and environmental advantages, such as low cost, accessibility, and sustainability. Altogether, the model demonstrates that the optimal concentration of nanoparticles is one of the most important factors to ensure the increased functional performance and the expanded socio-environmental benefits. These relationships are also strengthened by the study findings. This synthesis of the nanoparticles was successful, as it yielded spherical ZnO nanoparticles whose sizes were between 20 and 30 nm and phytochemicals of *Citrullus colocynthis* were used to stabilize the nanoparticles. The treated cotton fabrics had very good to excellent UV protection as the UPF values were higher than 50 in terms of functional performance. Also, the fabrics exhibited a high degree of oil-water separation up to 94 percent at increased nanoparticle concentrations. The socio-environmental viewpoint consists of the fact that the green synthesis methods, local plant resources, and the use of simple processing techniques make the overall accessibility,

sustainability, and economic viability of the strategy more accessible. To sum up, the findings indicate that the ZnO nanoparticles prepared by the use of *Citrullus colocynthis* confer multifunctional properties to cotton fabric in that they combine the UV-blocking and oil-water separation features. The solution is environmentally friendly, cost-effective, and socially beneficial, which is why it can be used to develop sustainable textile and applied to both protective clothing and environmental management in a very appropriate manner.

Discussion

This paper examined the multifunctional use of the cotton fabric to which ZnO nanoparticles functionalized with *Citrullus colocynthis* work as an ultraviolet (UV) protective factor, an oil-water separator, and the implications to the socio-environment. The results show that green-synthesized ZnO nanoparticles are capable of improving the functionality of fabrics and also offer a sustainable method of textile finishing.

Ultraviolet Protection Performance

The UPF analysis showed that cotton cloths that had ZnO nanoparticles on them had a high UV-blocking ability with UPFs of over 50 with 0.5% and 1% nanoparticles applied. These results are in agreement with other researchers who found that ZnO nanoparticles are good UV absorbers and scattering particles mainly in the UV-A (320-400 nm) and UV-B (280-320 nm) wavelengths (Asmat-Campos et al., 2021; Nasirzadeh et al., 2024). The nanoparticles were uniformly coated to increase the surface area, and this was achieved due to the shape of the nanoparticles (spherical) and their size (2030 nm) which promoted UV absorption and reflection. The potential of attaining very good to excellent UV protection at a low-cost and green synthesis method is especially pertinent to the populations in developing areas where the sun exposure is high, and protective textile remains unreachable due to its price. Besides, bioactive compounds of *C. colocynthis* are integrated to ensure further functional stability, which supports the use of non-toxic and environmentally friendly coating technique (Kiani et al., 2023).

Oil–Water Separation Efficiency

Functionalized fabrics proved to be effective in oilwater separation, as high as 94% separation efficiency was recorded with increased concentration of nanoparticles. ZnO nanoparticles give cotton fibers hydrophobic-oleophilic properties and selectively absorb oil instead of water. This feature can be applied to address the objectives of environmental remediation, especially oil spill management and industrial wastewater treatment (Mohammadipour Nodoushan et al., 2024). The findings underscore the fact that surface functionalization of nanoparticles could form hierarchical nanostructures, which enhance superhydrophobicity and high separation capacity. The presented tendency, as the higher the nanoparticle concentration, the better the separation performance, emphasizes the necessity to optimize the levels of coating to make them cost-effective and efficient at work (Xu et al., 2021). The property allows the extension of the utility of cotton textiles beyond the field of clothing, thus making them versatile products that can be used in the environment.

Socio-Economic Implications

The green synthesis procedure in the study, with the locally found plant material and the use of sodium hydroxide as a simple pH modulator, is a cost-effective technology that can be used in small and medium sized enterprises in the textile industry. As it lowers the reliance on imported chemical reagents and complicated equipment, this approach enhances the economic development of the surrounding area and offers accessible technology to rural or resource-restricted environments (Swain et al., 2025). Also, the multifunctional fabrics have commercialization opportunities in the protection fabrics, eco fabrics and environmental remediation fabrics. As there

is increased interest in sustainable consumer products, clothing with a built-in protection against UV and other environmental features can also satisfy the emerging trends in the market at affordable prices (Nasirzadeh et al., 2024).

Environmental Sustainability

ZnO nanoparticles produced through green synthesis in a large amount cause a marked reduction in the level of environmental impact caused by the production of nanoparticles. Conventional chemical pathways are usually associated with the use of a lot of energy and toxic solvents that pollute water and soil. Plant-mediated synthesis, in its turn, reduces the use of chemicals and produces fewer toxic by-products (Xu et al., 2021). Another use of these nanoparticles that facilitates sustainable textile manufacturing is their application to cotton fabrics which not only increase the life time of their products by protecting against UV and acting as self cleaners. Moreover, the oil-water separation capacity assists in the environmental cleanup efforts, which reduce pollution and enhances the well-being of the ecosystem. All in all, the strategy can be described as consistent with the principles of the circular economy, promoting the use of renewable resources, minimizing waste, and adopting environmentally friendly manufacturing (Asmat Campos et al., 2021; Swain et al., 2025).

Combination of Social-Environmental and Functional Goods.

The research proves that multifunctional textiles have the capacity to provide performance as well as socio-environmental advantages. The conceptual SmartPLS structural model used in this study shows that the higher the concentration of ZnO nanoparticles, the higher the functional performance (UV protection and oil-water separation) and consequently creating socio-economic and environmental benefits. This comprehensive approach is essential to sustainable innovation because it is a balance between technical efficiency and cost-effectiveness, availability, and environmental sustainability.

Conclusion

The study indicates that cotton cloths functionalized with zinc oxide (ZnO) nanoparticles mediated by *Citrullus colocynthis* is of high multifunctional capacity with great practical and sustainability potentials. The findings have indicated that the treated fabrics have obtained ultraviolet protection factor (UPF) values that are below 50 which is very good to excellent protection against the harmful UV radiation. The level of protection is especially necessary in areas with high exposure to the sun because the protective clothing made of cotton can be used longer despite providing protection and affordability. Besides UV protection, the functionalized fabrics exhibited extraordinary separation of oil and water with 94 percent separation efficiency at high concentration of nanoparticles. This underscores their possible use in the management of the environment particularly in the wastewater treatment process, and oil spill cleanup where cheap and reusable materials are much needed. The socio-economic side of the study focuses on the benefits of green synthesis via the use of locally sourced plant products like *Citrullus colocynthis*. The simplicity of the methods and the low cost and minimal chemical requirements of the process allow the small-scale industries and developing areas to use the technology in large-scale applications, which enhances inclusive technology use and local economic growth. Moreover, the strategy leads to the sustainability of the environment in terms of decreasing the use of dangerous chemicals, minimizing energy use, and using renewable biological resources. The multi-functional use of the fabric does not only prolong the lifecycle of the material but also complies with the principles of the circular economy by helping to save resources and reduce wastes. In general, the article confirms that green-synthesized ZnO nanoparticles have the potential to improve the

functionality of a textile and, at the same time, provide the socio-economic and environmental advantages. The combination of these offers a bright future in sustainable textile innovation, especially in resource-limited environments where cost, environmental conservation and functionality are also of key concern.

Recommendations

Resting on the findings, it is possible to make some policy and practical suggestions:

1. Encouraging Green Nanotechnology in Textiles: Governments and textile authorities ought to encourage the research and implementation of plant-mediated processes in nanoparticle synthesis in order to minimize chemical pollution and encourage sustainable production processes.
2. The encouragement of Small and Medium Enterprises (SMEs): SMEs should be encouraged to implement green synthesis methods training programs and subsidies will enhance local economic engagement and access to technology.
3. Functional Textile Standards: Regulatory authorities must come up with standards of multifunctional textiles, such as protection against UV rays, oil-water separation effectiveness, and environmental friendliness, to guarantee quality and safety of consumers.
4. Embodiment in Environmental Programs: Functionalized textiles can be incorporated into wastewater treatment, oil spill cleanup, and environmental cleanup programs, which are economical and renewable as alternatives to traditional treatment approaches.
5. Promotion of Circular Economy Practices: The textile manufacturers are expected to embrace the concept of the circular economy, such as recycling, reusing of worn-out fabrics, and use of fewer resources, to mitigate the environmental effects.

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