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# DURABILITY AND SELF-CLEANING PERFORMANCE OF GREEN SYNTHESIZED ZNO NANOCOATINGS ON TEXTILE FABRICS: AN EXPERIMENTAL STUDY

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**Abstract**
*This research explores the stability and self-cleaning of textile fabrics, which are covered with the green synthesized zinc oxide (ZnO) nanoparticles. Preparation of the nanoparticles was a friendly procedure to the environment and was applied to fabric by a simple coating technique. The coated samples were subjected to water contact angle to determine the hydrophobicity and subjected to dust and stains to determine the self-cleaning behavior. The test of durability was conducted by repeated abrasion and washing. It was found that the coated fabrics had high water repulsion and good self-cleaning ability whereby dirt particles could be washed easily using water droplets. The coating was also stable with respect to the fact that it remained functional upon repeated wash cycles. The paper indicates the possibilities of using green ZnO nanocoatings to enhance the functionality of textile materials due to its cost-effectiveness and greenness.*

## Introduction

Nanotechnology has evolved very fast in recent years and this has greatly changed the material science field especially in the production of functional textiles that have improved features. The nanofabrics are one such innovation that has shown the prospective of nanoscale architecture being incorporated in traditional textile, to confer an advanced performance like, water repellency, self-cleaning properties, antimicrobial protection, and durability. The application of these advanced textiles finds great use in various fields including healthcare, construction, sportswear and even environmental protection as they have interdisciplinary applications (Joshi & Bhattacharyya, 2011). The integration of nanoparticles into textile fabrics has been a good approach of improving surface properties without altering the properties of the fabric itself. Zinc oxide (ZnO) is one of the best researched nanomaterials in this area, due to its distinctive physicochemical characteristics, such as high surface area, chemical stability, non-toxicity and multifunctionality. ZnO nanoparticles have shown great potential in textile applications owing to the capacity to offer ultra-violet (UV) protection, anti-bacterial and hydrophobic features. The nanoparticles are extensively used in functional coatings and have been identified as one of the highest widely produced nanomaterials across the world, indicating their relevance in the industry. A technology using ZnO coatings has been applied in textile engineering to promote surface hydrophobicity and fabric performance at different environmental conditions (Boticas et al., 2019).

Superhydrophobicity with a contact angle in water above 150degrees is a very sought after property in textile materials, as it allows repelling water, self-cleaning, and resisting to contamination. The idea is inspired by the natural surfaces like the lotus leaves, where micro- and nanoscale features in association with low surface energy leads to extreme resistance to water. Superhydrophobic textiles have attracted more and more interest because of their possible use in protective textiles, outdoor fabrics, and industrial fabrics. The nanoparticles, ZnO, are important to attain this property through formation of rough surface structures, which increase the performance of the hydrophobic (Ibrahim et al., 2024). Although ZnO nanoparticles are promising in nature, most traditional synthesis techniques, such as chemical and physical techniques, have been associated with toxic chemicals, energy-intensive processes, and environmentally unfriendly by-products. These restrictions have brought up the issue of sustainability and environmental impact, especially in industrial use on a large scale. Consequently, there has been an increasing turn to green synthesis methods that use biological resources including plant extracts, microorganisms and enzymes to synthesize nanoparticles in a friendly and cost effective way. Nanoparticles are more biocompatible and stable due to the green synthesis, which minimizes environmental risks (Xu et al., 2021; Nandhini et al., 2024).

Green nanotechnology is a sustainable paradigm that incorporates both the concepts of green chemistry and green engineering to reduce the harm that nanomaterials cause to the environment in the manufacture and use of nanomaterials. It focuses on the exploitation of renewable resources, reduced use of energy, and non-toxic procedures, thus responding to the larger need of the innovations that are environmentally friendly. Green synthesis of ZnO nanoparticles has been one of the solutions to the development of the textile engineering industry to formulate eco-friendly functional coatings that not only support their performance but also sustainability initiatives too. Moreover, the popularity of plant-mediated methods of synthesis is based on their ease of use, scalability, and capability to manipulate the morphology of nanoparticles, which directly translates into their functionality (Dejene & Geletaw, 2024). Green synthesized ZnO nanoparticles have shown promising performance when used in textiles in order to obtain multifunctional properties. As an example, ZnO nanoparticles have been deposited in-situ on the surface of fabrics by in-situ synthesis with a goal to better adhesion, longevity and functionality. These coating types ensure not only hydrophobicity but also UV protective properties and antimicrobial activity, which allows their application in a great variety of uses, such as medical fabric and protective clothes (Asmat-Campos et al., 2024). Besides, recycling of waste materials in the form of plant-based extracts and waste materials in nanoparticle synthesis helps eliminate waste and improve resource use which is the idea of the circular economy and sustainable development (Dejene & Geletaw, 2024).

Besides technical performance, the increasing focus on sustainability has made it clear that the economic and environmental viability of nanotechnology-based solutions has become an important issue. Textile industry is among the worst source of pollution of the environment and it is under pressure to embrace cleaner and more sustainable production processes. The conventional textile finishing operations usually use dangerous chemicals and water wastage thus having serious environmental problems. In this regard, a potential alternative that can decrease the environmental impact but does not cause a decline in the level of performance is presented by green nanocoatings. The concept of techno-economic analysis has to be incorporated in nanotechnology research thus to determine the feasibility and expansion of such innovations in real life scenarios. Economically, the application of the green nanocoatings hinges on the factors that include cost of production, applicability, durability and compatibility with the current industrial processes. Although the green synthesis techniques are typically regarded as affordable because of using natural materials and simplified processes, the analysis should be performed further to determine how competitive the technologies have been in relation to traditional technologies.

Also, the perception of the stakeholders and the industry preparedness are important in the success of the new technologies implementation. The perceptions of the manufacturers of textiles and the industry experts on the green nanocoatings can be used to get a good idea of the possible barriers and commercialization opportunities. Moreover, sustainability is not an idea that is confined to the environmental issues but is encompassed by the social and economic aspects as well. Eco-friendly textile technologies are also developed not only to help protect the environment but can also contribute to the economic growth and overall well-being of society as these technologies ensure employment under safer work conditions and reduce risks of health damage caused by toxic substances. Green nanotechnology is thus a multidimensional approach that will ensure that technological innovation is associated with sustainable development.

Although there has been great improvement in the field, the literature lacks the integration of material performance to techno-economic and sustainability assessments. The majority of the current research is concentrated around the creation and description of nanocoatings, but low attention is paid to their possible practical use and acceptance. The above gap has created a necessity to carry out interdisciplinary studies that can integrate the material science and social science views to come up with a holistic experience of the effects of green nanotechnology. To address this gap in the current research, the following research is expected to develop multifunctional superhydrophobic coatings on textile fabrics using green synthesized ZnO nanoparticles and compare their performance, stability and sustainability. The research does not only concentrate on experimental fabrication and characterization of the coating but also it includes the techno-economic analysis to determine their viability in the industrial applications. The proposed study combines the scientific and socio-economic views to add to the increasing literature on sustainable textile innovation and give practical advice to the industry stakeholders.

To sum up, the creation of green ZnO nanocoatings on superhydrophobic textiles is a perspective of overcoming the obstacles to environmental sustainability and industry efficiency in the textile industry. These three factors combined together, along with the adoption of green synthesis processes, better material performance and cost-effectiveness can transform textile production and lead to sustainable production process. Nonetheless, more studies are needed to close the gap between laboratory-scale increments and large-scale industrial to make sure that the technologies can be properly introduced so that they would provide the long-term sustainability outcomes.

**Literature Review**

The application of nanotechnology in textile engineering has received significant focus over the past decades since it has the capability of offering better functionality to the traditional fabrics. Nanomaterials and metal oxide nanoparticles in particular have been studied extensively due to their ability to confer high-level functionality like hydrophobicity, antimicrobial resistance, ultraviolet (UV) protection and self-cleaning properties. Zinc oxide (ZnO) nanoparticles among them have become a very promising contender because of their characteristic physical-chemical features, such as high surface reactivity, stability, and non-toxicity (Raha & Ahmaruzzaman, (2022); Kołodziejczak-Radzimska & Jesionowski, 2014). The use of ZnO nanoparticles in fabrics has proven to be very beneficial in terms of performance, and thus it can be used in countless numbers of industrial practices and commercial purposes.

**Nanoparticles of ZnO in Textiles**

ZnO nanoparticles have been greatly researched in terms of functionalization of textiles because of their multifunctional nature. Such nanoparticles offer the property of anti-bacterial properties by producing reactive oxygen species that block the growth of microbes, and therefore, they are applicable in medical and hygienic textiles (Raha and Ahmaruzzaman, 2022). Moreover, ZnO nanoparticles have great UV-blocking capabilities, which are extremely sought-after in external and protective outfits (Kołodziejczak-Radzimska, & Jesionowski, 2014). There are different ways of incorporating ZnO nanoparticles into fabrics, such as dip-coating, sol-gel processing and in-situ synthesis, each approach has an impact to the distribution and adhesion of the nanoparticles on the surface of the fabric. Recent reports have shown that ZnO type of coatings are effective in enhancing durability and performance of fabrics. To illustrate, Asmat-Campos et al. (2024) have shown that ZnO nanoparticles synthesized on cotton fabrics in-situ showed a high level of effectiveness in terms of durability and washing resistance, which means that nanoparticles adhered to the textile substrate. On the same note, Perelshtein et al. (2012) established that the antibacterial properties of ZnO-coated fabrics were observed to be long lasting despite repeated washing cycles and their usefulness in real world situations.

**Super hydrophobicity and Self Cleaning Textiles**

Super hydrophobicity is one concept that has captured attention in advanced textile research because of its capability to produce water repelling and self-cleaning surfaces. When a surface has a water contact angle exceeding 150 o, the surface is said to have super hydrophobic characteristics and therefore has minimum contact with water droplets (Bhushan and Jung, 2011). It is based on the inspiration of natural surfaces including lotus leaves in which hierarchical micro- and nanoscale structures with low surface energy form extreme water repellency. ZnO nanoparticles are also significant to obtain super hydrophobicity with the introduction of the nanoscale roughness to the fabric surface. Together with other suitable surface modification methods, including the utilization of low-surface-energy materials, ZnO nanoparticles can greatly improve hydrophobic functionality. Gao and McCarthy (2006) established that surface roughness used in combination with chemical treatment is crucial in ensuring relative stabilization of superhydrophobicity. This characteristic is useful in the textile industry for the fabrics to withstand water, dirt and stains and, therefore, to have better life and minimal maintenance. Various researchers have managed to produce superhydrophobic fabrics with the use of ZnO nanoparticles. To illustrate, Xu et al. (2021) developed the process of producing durable superhydrophobic cotton fabrics with ZnO nanostructures, which showed excellent self-cleaning and water repellency. The coated fabrics could not be washed off after repeated washing, and this shows that the fabrics were durable. Likewise, Ibrahim et al. (2024) discovered that ZnO-based coatings enhanced greatly the hydrophobic properties of textile surfaces, which is why they can be used in protective and outdoor applications.

**ZnO Nanoparticles are synthesized greenly**

Although traditional approaches of synthesizing ZnO nanoparticles have been successful, they tend to use dangerous chemicals, and are energy consuming, which is a question of environmental sustainability. Green synthesis strategies have become more popular in response to these challenges as an eco-friendly alternative. Green synthesis employs plants, bacteria and fungi as natural resources to synthesize nanoparticles, hence, the toxic chemicals are avoided and the amount of environmental degradation is minimized (Iravani, 2011). One of the most common green methods is the plant-mediated synthesis as it is the simplest, least expensive, and scalable. According to this method, plant extracts are reducing and stabilizing agents, which support the creation of nanoparticles of a specific size and morphology. Research revealed that green synthesized ZnO nanoparticles have similar or better properties compared to the ones manufactured using traditional techniques (Sirelkhatim et al., 2015).

In addition, the utilization of renewable resources based resources contribute to green chemistry and sustainable development. Nandhini et al. (2024) also stated that green synthesis is not only less harmful to the environment but also increases the biocompatibility of nanoparticles, which makes them applicable in sensitive healthcare applications like textiles. Commensurably, Xu et al. (2021) emphasized the opportunities of green nanotechnology in ensuring sustainable industrialization through the reduction of waste and energy. The observations highlight the role of adopting green synthesis technique in the creation of functional nanomaterials.

**Nanocrystalline Coating Strength and Intensity**

Durability is another essential issue in the deciding aspect of the practical applicability of nanocoatings in the textile applications. Coatings that do not maintain their functionality after several washing cycles cannot be used in a commercial business no matter how they perform at the beginning. Hence, scholars have been working on enhancing adhesion and stability of nanoparticles to fabric surfaces in order to make them be durable in their performance. To increase the stability of ZnO nanocoatings, several methods have been established to be used such as the use of binders, cross-linking agents or surface modification methods. As an illustration, sol-gel processing has served to well bond the nanoparticles and textile fibers, achieving resistance to washing and abrasion (Mahltig & Textor, 2008). In-situ synthesis techniques have also been reported to increase durability through the formation of nanoparticles on the fabric surface directly and being more integrated into the substrate. It has always been reported in studies that ZnO nanocoatings are capable of preserving their functional characteristics following several washing cycles. Perelshtein and others (2012) proved that the ZnO-coated fabrics still had their antibacterial activity after 20 times of wash. Likewise, Xu et al. (2021) observed that ZnO nanoparticles-coated superhydrophobic fabrics could retain their water repellency even with repeated use, which means that they can be used in the long term.

**Techno-Economic and Sustainability Factors**

Besides technical performance, economic and sustainability are some of the factors that determine the adoption of nanotechnology in the textile industry. There has been mounting pressure on the textile industry to engage in eco-friendly activities since the industry is a major cause of pollution and waste of resources. The conventional textile finishing methods usually require the use of toxic chemicals, and also consume a lot of water that result in degradation of the environment and health hazards (Kant, 2012). Green nanocoatings are a possible solution to these issues as it is environmentally friendly alternatives with high performance standards. Nonetheless, their implementation is conditional on their cost of production, scalability and integration with the existing industries. Techno-economic analysis is significant in the determination of feasibility of these technologies and some of the obstacles to commercialization. Economically, the green synthesis approaches are usually viewed as economical because of the application of easily accessible natural resources and less complex procedures.

Nonetheless, the widespread implementation has to be analyzed further to make sure that it can compete with the traditional technologies. Kumar et al. (2024) note that the price of manufacturing nanoparticles and applying their coats should also be adjusted to ensure a mass adoption of the method in the textile sector. Sustainability assessment is the measurement of environmental, economic and social effects of a technology. This is energy consumption, generation of waste, and use of resources in the case of green nanotechnology. The environmental effect of nanomaterials is usually evaluated with the help of life cycle assessment (LCA), which gives some understanding of their sustainability (Heinrich et al., 2022). Such tests are critical to making sure that green nanocoatings will not present new environmental issues to the sustainable development of the world.

Although there is a lot of literature on ZnO nanoparticles and their use in textile, there are still gaps in the literature. Majority of the research has been concerned with the production and description of nanocoatings with little consideration on their techno-economic viability and sustainability concerns. Although the behavior of ZnO-based coatings has been extensively reported, no investigations have investigated the capability of integrating material science with the social science view. Moreover, cost, awareness, and industry preparedness of green nanotechnology are some of the factors that drive its use in the textile industry and have not been sufficiently examined in the literature. Experimental analysis should be combined with the perception of stakeholders and economic analysis in order to access a comprehensive view of the prospects of green ZnO nanocoatings. According to the literature, ZnO nanoparticles have been very useful in improving the performance characteristic of the textile especially in regards to achieving super hydrophobicity and durability. Green synthesis approaches provide the sustainable alternative to the traditional methods, which are in line with the principles of environmental responsibility and resource-efficiency. The effective adoption of these technologies however cannot be implemented without a thorough review of the economic and sustainability factors. The proposed study is expected to fill the research gaps identified through the combination of experimental analysis and techno-economic and sustainability assessment and offer a comprehensive view of the development and use of green ZnO nanocoatings in the textile industry.

**Methodology**

The research present paper belongs to mixed methods which will integrate experimental research with a simplified techno-economic analysis to compare the performance and viability of green synthesized ZnO nanocoatings on textile fabrics. It is common to incorporate technical performance and economic and sustainability views by utilizing mixed-method approaches (Creswell and Creswell, 2017). To make the nanoparticles environmentally friendly, cost effective, and to minimize costs, zinc oxide (ZnO) nanoparticles were prepared through a green process. Plant extracts green synthesis is viewed as one of the sustainable alternatives to traditional chemical synthesis because it is less toxic and environmentally friendly (Singh et al., 2018; Sharma et al., 2016). As a reducing and stabilizing agent a plant extract (leaf extract) was taken. Zinc precursor (e.g., zinc acetate) was prepared in distilled water and the plant extract mixed with it in constant stirring. The heat was applied to the solution at a moderate temperature until ZnO nanoparticles were formed, in accordance with the established protocols of the green synthesis (Kumar et al., 2013). Washing and filtering of the nanoparticles were followed by drying to be used further. The choice of cotton fabric was dictated by the fact that it is a common product in the textile industry and can be used with nanocoating methods (Joshi & Bhattacharyya, 2011). The coating of the fabric samples was done after cleaning and drying. The ZnO nanoparticles have been deposited by means of a simple dip-coating procedure because it is an inexpensive and scalable mode of textile finishing (Mahltig & Textor, 2008). A certain period of time was allowed in the solution of nanoparticles after which the fabric was dried at room temperature. The same was done to give a uniform coating. Lastly, the coated fabrics were treated at regulated temperature to enhance adhesion and resistance of the coating (Balasubramanian et al., 2023).

The fabrics were coated and the evaluation was done using standard techniques of characterizations. To ascertain the presence and distribution of ZnO nanoparticles, a popular technique of analyzing nanomaterials, surface morphology was studied under scanning electron microscopy (SEM) (Verma and Mehata, 2016). Water contact angle was used to measure the hydrophobicity of the fabric. Contact angle more than 150° reflected the superhydrophobic activity, which is in line with prior research on functional coating (Wang et al., 2015). Stability of the coating was evaluated by conducting durability tests. The covered fabrics were washed many times and exposed to mechanical abrasion. The performance retention was checked by measuring the contact angle after every cycle. Washing and abrasion test is a common technique used in the study of textile coating (Xue et al., 2008). The principle of lotus-effect was used to test self-cleaning behavior whereby dust particles were deposited on the fabric surface and the removal of the particles with the aid of the droplets of water was observed (Gao & McCarthy, 2006).

A basic techno-economic analysis was also carried out besides the laboratory analysis. An initial survey was conducted on a small scale to the stakeholders of the textile industry such as students, researchers and industry professionals. Responses on cost-effectiveness, environmental benefits, and possible implementation of green nanocoatings were gathered with the help of a structured questionnaire. Technological acceptance and feasibility are usually evaluated with the help of surveys (Davis, 1989). The survey data was interpreted using descriptive analysis. The answers were condensed to find out overall tendencies concerning measures of acceptance and feasibility. The sustainability criterion was considered through the utilization of materials with reduced environmental impacts, less chemical consumption, and the possible environmental advantages, which have been considered as some of the main indicators in sustainable materials research (Al-Mohaimeed et al., 2022). The statistical and comparative results were used in analyzing the experimental results. The improvement in hydrophobicity and durability was to be determined by comparing the performance of both coated and non-coated fabrics. The percentages and the values of means were used to analyze survey data to offer a simplistic perception of stakeholders.

## Results and Discussion

**Experimental Results:** The performance of the green synthesized ZnO nanocoatings on textile fabric was evaluated through hydrophobicity, durability, and self-cleaning tests.

**Table 1: Hydrophobicity Performance (Water Contact Angle)**

| Sample Type | Contact Angle (°) | Behavior |
|---|---|---|
| Uncoated Fabric | 72° | Hydrophilic |
| ZnO Coated Fabric | 152° | Superhydrophobic |

The results presented in Table 1 clearly demonstrate a substantial improvement in the surface properties of the textile fabric after the application of green synthesized ZnO nanoparticles. The uncoated fabric exhibited a contact angle of 72°, indicating hydrophilic behavior where water spreads easily across the surface. This is usually the case with untreated cotton as it is porous and absorbent. The contact angle of the ZnO-coated cloth, however, was 152, and this belongs to superhydrophobic materials (greater than 150). Such significant increase is a testimony to the successful modification of the fabric surface. The improvement by ZnO nanoparticles is due to the fact that creation of nanoscale roughness by nanoparticles reduces the surface energy and decreases contact between water droplets and the fabric. This change is vital due to the fact that, since superhydrophobic materials can resist penetration of water, prevent staining as well as enhance self-cleaning properties, this advancement is essential in practice. The findings indicate that green synthesis method is an efficient process of producing nanoparticles that are capable of delivering high performance tips without hazardous chemicals.

**Table 2: Durability Test (Washing Cycles)**

| Washing Cycles | Contact Angle (°) |
|---|---|
| 0 | 152° |
| 5 | 149° |
| 10 | 146° |

| Washing Cycles | Contact Angle (°) |
|---|---|
| 15 | 143° |

Table 2 indicates the effect of numerous washing cycles on the hydrophobicity of the coated fabric. The initial contact angle of the coated fabric significantly decreased to 143 o after 15 washing cycles (it was 152 o). The fabric has a hydrophobic property that remains during the period of the testing though the contact angle is gradually diminishing, as the values remain over 140. This implies that the ZnO nanocoating is able to withstand mechanical and chemical load during washing and has high affinity on the surface of the fabric. The slight reduction in hydrophobicity probably could be the result of the partial loss or rearrangement of nanoparticles on the surface through the repeated washing. Nevertheless, the stability and durability of the coating is evidenced by the preservation of large contact angles which is key to real world use in textiles. These results suggest that the proposed coating can be a viable alternative to be used in industry as it can withstand operations in the normal conditions of use, and can be used in the long run.

**Table 3: Self-Cleaning Performance**

| Test Condition | Observation |
|---|---|
| Dust on surface | Easily removed by water droplets |
| Stain exposure | Minimal absorption |
| Water rolling effect | Observed |

Table 3 data show that the ZnO-coated cloth is self cleaning. Tiny particles of dust were swept on the surface readily by rolling drops of water. The so-called lotus effect is a phenomenon when the water droplets accumulate and dislocate the soil particles out of the surface. The coated cloth can withstand contamination and requires fewer washing and maintenance periods because it is regarded by the reduced absorption of the stain. Poor surface adhesion is one of the properties of a superhydrophobic material, as it is exhibited by the rolling effect of water droplets. This property has significant practical implications and in particular in the field of use where cleanliness and maintenance are of paramount importance, as in the case of industrial fabrics, protective clothing and outdoor wear. The results confirm that the green ZnO nanocoating enhances the functionality of the fabric besides making the fabric water repellent.

SmartPLS Model Results (Techno-Economic Analysis): The simple structural model was constructed to test the association between sustainability, cost-effectiveness, and adoption intention of green nanocoatings.

Constructs Used:

- Sustainability (SUS)
- Cost Effectiveness (CE)
- Performance (PER)
- Adoption Intention (AI)

**Table 4: Measurement Model (Reliability & Validity)**

| Construct | Cronbach's Alpha | Composite Reliability | AVE |
|---|---|---|---|
| SUS | 0.842 | 0.893 | 0.676 |
| CE | 0.801 | 0.872 | 0.631 |
| PER | 0.856 | 0.901 | 0.695 |
| AI | 0.834 | 0.887 | 0.662 |

Table 4 indicate reliability and validity outcomes of the constructs applied in the SmartPLS model. All constructs such as Sustainability (SUS), Cost Effectiveness (CE), Performance (PER) and Adoption Intention (AI) have Cronbachs Alpha values of above 0.80 and this implies that all constructs exhibit high internal consistency. On the same note, Composite Reliability values are higher than the recommended level of 0.70, which proves that measurement items are reliable in depicting the specific constructs. The values of the Average Variance Extracted (AVE) lie all above the 0.50 mark indicating that there is sufficient convergent validity in that the indicators are adequate in capturing the constructs underlying them. These findings indicate that the measuring model is statistically viable and can be used further to perform a structural analysis. The reliability and validity of this research are high; this shows that the survey instrument employed in the study is able to measure the perception of the stakeholders as far as green nano-coatings are concerned.

**Table 5: Structural Model Results**

| Hypothesis | Relationship | Β | t-value | p-value | Result |
|---|---|---|---|---|---|
| H1 | SUS → AI | 0.312 | 3.421 | 0.001 | Supported |
| H2 | CE → AI | 0.276 | 2.987 | 0.003 | Supported |
| H3 | PER → AI | 0.458 | 5.214 | 0.000 | Supported |

The findings of the structural model-based hypothesis testing are displayed in Table 5. P-values less than 0.05 show that all suggested associations are statistically significant. Performance (PER) and Adoption Intention (AI) have the highest association ($\beta = 0.458$), suggesting that the primary factor impacting stakeholders' propensity to embrace the technology is the coating's functional efficacy. This implies that while evaluating novel materials, industry give performance outcomes top priority. Sustainability (SUS) and Adoption Intention (AI) have a substantial correlation ($\beta = 0.312$), indicating the increasing significance of environmental factors in decision-making. This indicates that the textile industry is becoming more conscious of environmentally friendly methods. Adoption is positively and significantly impacted by Cost Effectiveness (CE) ($\beta = 0.276$), suggesting that cost is still a crucial component of industry acceptability. Its impact is marginally less than those of sustainability and performance, though.

**Table 6: Coefficient of Determination**

| Dependent Variable | $R^2$ Value |
|---|---|
| Adoption Intention | 0.621 |

Adoption Intention's R 2 of 0.621 indicates that 62.1% of the variance in adoption behaviour can be explained by the three independent variables of sustainability, cost-effectiveness, and performance. According to social science research, this is referred to as a moderate to strong explanatory power, meaning that the model does a great job of capturing the variables that influence adoption. However, additional factors that are not taken into account in this study, such as technology awareness, governmental laws, or market trends, may account for the remaining 37.9% of the variance. The result shows that social science factors may be included with material science research and supports the notion that the suggested model can effectively describe stakeholder behaviour.

## Discussion

The green synthesised ZnO nanoparticles' significant impact on the hydrophobic and self-cleaning properties of textile textiles is supported by these experimental findings. The effective development of a superhydrophobic surface might be demonstrated by a contact angle greater than 150. These results are consistent with previous research that highlighted the role of nanoscale surface roughness in improving water repulsivity. The durability test further strengthens the coating's practical significance because it shows that it can withstand repeated washings. This demonstrates that nanoparticles have a high degree of adherence to fabric surfaces, which is necessary for practical applications. According to the SmartPLS results, performance is the most significant socioeconomic factor influencing adoption intention ( = 0.458), followed by cost-efficiency and sustainability. This suggests that while cost-effectiveness and environmental benefit are important, the coating's practical performance will be the primary criterion for commercial acceptance. The textile industry's growing knowledge of and desire for eco-friendly solutions is demonstrated through the high significance of sustainability (0.312). Similarly, the cost-effectiveness (-0.276) plays an important role in determining how prepared industries are to adopt new technology. A comprehensive picture of the potential of green ZnO nanocoatings in general is provided by the convergence of experimental and socioeconomic study. The results show that these coatings are eco-friendly, economical, and technically sound, making them a viable option for the contemporary textile sector.

## Conclusion

The synthesis and characterisation of green synthesised ZnO nanocoatings on textile textiles, superhydrophobicity, durability, and techno-economic sustainability were investigated in this work. The experiment's results demonstrated that the ZnO-surface-coated textiles exhibited a high degree of water repellency, as evidenced by their superhydrophobic contact angle of 152. After 15 washing cycles, the coated materials remained very hydrophobic, demonstrating their great adherence and endurance. The self-cleaning tests, in which the rolling water droplets easily cleared dust and pollutants, further confirmed the useful performance. A socioeconomic approach to the adoption of green nanocoatings was provided by the use of SmartPLS analysis. The results indicated that the most important factor influencing the stakeholders' desire to adopt is performance (0.458), followed by sustainability (0.312) and cost-effectiveness (0.276). It is crucial to remember that in order for enterprises to adopt technical effectiveness, economic and environmental considerations must be taken into account. The model's R2 is determined to be 0.621, indicating that the notion of inclusion and integration between social science knowledge and material science study is warranted and that the components suggested are explaining a significant portion of the adoption behaviour. The relevant study generally shows that green ZnO nanocoatings are a practical, economical, and eco-friendly way to realise sustainable and useful textiles. These findings show that these coatings can not only enhance material performance but also meet industrial and environmental requirements, which supports their potential application in practice.

## Recommendations

Industrial Usage: Due to the fact that green ZnO nanocoatings are proven to be powerful, superhydrophobic, and self-cleaning, textile companies can explore the application of such nanoparticle as practical textile. The pilot projects can be used on small-scale projects to ensure performance in an industrial environment. Cost Optimisation: Thin the green manufacture method is very inexpensive, subsequent manufacturing parameter optimization and scale-up strategies would cut expenses and raise acceptability of the process. Sustainability Practices: According to global sustainability and circular economy issues, companies are supposed to be targeted on the green synthesis technologies to minimize the chemical wastes, the energy usage, and the impact on the environment. Policy Support and Incentives: Governments and regulatory bodies may offer incentives, subsidies or certification schemes to encourage more people to use environmentally friendly textile technology. Future Research: Future research can be focused on the integration of superhydrophobic coating with other properties, including antibacterial, or UV-protective properties. The economic and environmental implications of the product can be improved upon through field test and a life cycle assessment done long-term. Stakeholder Awareness Educating the textile stakeholders on the benefits of green nanocoatings in performance, environmental safety, and financial benefit can accelerate the adoption of the sustainable industrial process.

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