Journal of Textiles, Coloration and Polymer Science

https://jtcps.journals.ekb.eg/

Egyptian Society for Textile Science and Technology
الجمعية المصرية لعلوم وتكنولوجيا النسيج

Innovative Self-Cleaning Technologies: Transforming Textiles into Sustainable and Multifunctional Materials

Heba Ghazal * and Yasmeen Hamdi Eldeeb

Textile Printing, Dyeing and Finishing Department, Faculty of Applied Arts, Benha University, Benha, Egypt

Abstract

In textiles, there are lots of developments to make self-cleaning coatings that are effective and sustainable, this is to save effort, energy and water used to clean clothes. In general, we are talking here about the fact that this technology can be applied in many ways, such as the critical state technology of carbon dioxide, the photocatalyst technology and other technologies, taking advantage of the types of preparation methods that can be obtained in addition to self-cleaning, such as resistance to combustion. All this is done on different fabrics such as cotton, polyester, wool, etc., which gave impressive results and self-cleaning and flame-resistant fabrics were obtained.

Keywords: Self-cleaning, Lotus Effect, Contact angle, photo catalysis, Nano composite, supercritical carbon dioxide.

Introduction

There are various innovations available in the world today. From nature, one of them: is self-cleaning technology. Many examples include the wing of butterflies and plant leaves like cabbage and lotus. This technology gained much attention. Fabrication of self-cleaning super hydrophobic surfaces have recently gained a Great deal of attention. Up to now, various methods have been employed to Prepare super hydrophobic films such as layer-by-layer assembly, [1, 2] dip-coating, chemical vapor deposition, spray coating, electro spinning and etching. [3, 4] Generally, super hydrophobic coatings may be required on various substrates such as glass, metals, paper, textile etc. [5, 6]

In textiles, there are lots of developments to make self-cleaning coatings that are effective and sustainable. This technology also provides a wide variety of applications, different benefits, including minimized operating costs, removal of tedious manual effort, and time-saving, Expended on the job of washing. [7, 8]

Self- cleaning textiles mean the textile surface which can be cleaned itself without using any laundering action. It can normally be categorized as hydrophobic or hydrophilic. The first includes the coating of a hydrophobic film on fabric to eliminate water droplets that contain pollutants. [9, 10] The surfaces of hydrophobic and super hydrophobic have a tightly arranged structure. [11, 12] The hydrophilic technique is not strictly dependent on water flowing to remove pollutants. [13] Instead, photo catalytic oxidation is utilized; enabling photo degraded organic pollutants materials to be extracted all across the water surface. [14-21]

This article is a review that talks about self-cleaning technology and how to apply it using different techniques on different fabrics.

Self-Cleaning Properties of Cellulosic Fabrics

Mechanism of self- cleaning: Types of Coatings: It can normally be categorized as hydrophobic or Hydrophilic. Hydrophobic and super hydrophobic coatings (Lotus Effect): That hydrophobic coating's self-cleansing effect comes from large contact angles with water; the water forming near-sphere droplets on these surfaces quickly roll away and with them moves dust and soil. Hydrophilic coatings: In comparison to hydrophobic, scientists are searching for hydrophilic surfaces useful for self-cleaning applications in the presence of water. The dampness is elevated and the contact angle is about 0. So, rather than droplets, water lays on the surface. The surface is washed along with the photo catalysis and the surface is then filled with water to extract the dirt molleculations. [22]

1. The Lotus effect: Lotus is considered a special plant in Hinduism, botanically called

* Corresponding author: Heba Ghazal, E-mail: drheba_ghazal@yahoo.com
Received date: 05 February 2025, **Revise Date**: 02 April 2025, **Accept Date**: 27 April 2025
DOI: 10.21608/jtcps.2025.358321.1417

"Nelumbo nucifera". Lotus is also the national flora of India and is considered a sign of pureness Nano sized wax papillae upon this top part of each epidermal cell give the lotus (Nelumbo nucifera) leaf and flower their water-repellent surface. As the reason, raindrops create a high contact angle through the papillae and rolling off, bringing stains and dust with them but keeping the surface clean. Such a self-cleaning effect, called the lotus impact, has given a chance to produce super hydrophobic surfaces for various items. Their surfaces are highly hydrophobic.

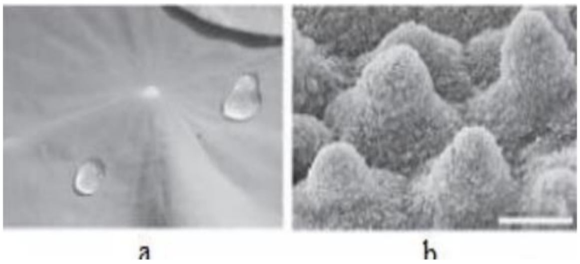

Figure 1: Hydrophobic structure of lotus leaf (a), electron microscope image of Nano and microstructure protrusions in lotus leaf (b)

2. Contact angle: Usually, the level of surface wettability is evaluated by measuring the static contact angle of a drop of water in contact with the surface. As seen in Figure 2, the angle between the surface and the curvature of the droplet that is in contact with the surface is considered as the contact angle (CA). A contact angle of more than 90 degrees indicates that the surface is hydro phobic; a contact angle of less than 30 degrees indicates that it is hydrophilic, and an angle of more than 150 degrees indicates that the surface is super hydrophobic. It is worth mentioning that although the use of materials such as fluorocarbon compounds they are not classified in the group of self-cleaning surfaces

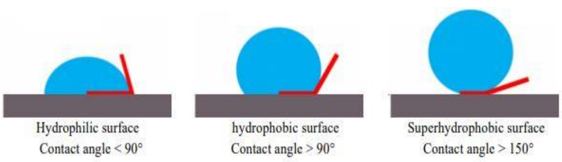

Figure 2: Measurement of stable contact angle in hydrophilic, hydrophobic and super hydrophobic surfaces

3. Photo catalytic coatings: Subsequently, photo catalysts can break down mutual organic matters in the air like odor molecules, bacteria, and viruses. A photo catalytic semiconductor technique has shown great potential as a low price, environmentally friendly, and sustainable curing. [16-19, 23-29]

Method for photo catalysis

In the availability of catalysts, photosynthesis is speeded up. Through using light from the sun, this mechanism breaks down the dirt molecules. The organic Pollutants can be transformed into air and water using photo catalytic reactions. [30] When a photo catalyst is emitted by light, usually ultraviolet light, the photo catalytic process starts. Electrons at the photo catalyst surface are stimulated with a power similar to or greater than the band gap and leaving the valence band to go to the conduction band. The negative electrons charged (e-) in the conduction band stimulated pair in the surface, with the positively charged holes (H+) in the valence band. The produced pairs can be reunions and bind with other materials, which the photo catalyst absorbs. [22, 31] The couples activate redox reactions onto the surface. The negatively charged ions and the oxygen combine into racial superoxide anions (O_2^-), while hydroxyl radicals (OH^-) are produced by positively charged holes and water. [30] So many shaped highly activated oxygen molecules can ultimately oxidize organic compounds to carbon dioxide (CO_2) and water (H_2O). The photo catalytic activity could then break down organic material, including particles of odorants, viruses, and bacteria in the air. [32]

Titanium dioxide: Titanium dioxide (TiO2) is a photo catalytic semiconductor and has proven to be an ideal catalyst for the visual degradation of dyes and other organic contaminants. Due to its different benefits, including non-toxicity, availability, cost efficiency, chemical constancy, and beneficial physical and chemical properties, are widely applied. [22] There are three crystalline phases in which titanium dioxide is present; rutile, anatase, and brookite. [33] In the case of pigments as sun blockers and paintings, the rutile between these three types is more reliable than the two others. The anatase has an open crystal-based structure, it is highly photo catalytic and often seemed to be the most active and the simplest to manufacture in semiconductor photochemistry. [34] In terms of heat, anatase and brookite will be rutile. There are band holes for either the anatase or the rutile. Their photoactive existence ensures the existence of radical species on their surfaces in the presence of sun and water. [14, 16, 20, 33, 35-40]

TiO_2 has become a product for industrial self-cleaning surfaces, including kitchen and bath ceramic tiles and garments, indoor air filters, and window glass. [22, 41] If the particle size of TiO_2 decreases to Nano, the photo catalytic behavior increases. Titanium (TiO_2) nanoparticles with a cellulose or cotton surface have been merged, producing an occurrence of self-cleaning. In the latest items known as intelligent textiles, the manufacture of cotton textiles with a life cycle of between 25–50 washings or higher is a goal pursued by the textiles industry. So many experiments have shown that cotton textiles can be coated by TiO_2 using various pretreatment methods and techniques, such as RF-plasma, MW-plasma, UV radiation, dip-pad-dry-cure, and dip-coating. [33]

Zinc oxide: Zinc oxide is another semi-conductive element that seems to be an alternative to TiO2 (ZnO). Due to its non-toxic nature, cheap, and strong photochemical reactivity, the use of ZnO as degrading content for environmental contaminants has been widely discussed. ZnO was often mentioned to be more effective than TiO2. ZnO in powder form has mainly been used to Degrade dyes found in effluent photo catalysis. Even so, after degradation, the ZnO powder has a recovery issue because some ZnO powder is lost when solutions have been drained. ZnO particles should especially be added to the material because it has the highest surface area to fix the issue. Such textiles with practical ZnO can be used for effluent and self-cleaning applications [21]. Zinc Oxide (ZnO) and doped Iron zinc Oxide (2% Fe-ZnO) has been given great importance due to the physiological, chemical, and optic properties of the components that make them ideal for diversified catalytically purposes, photo catalysis, sensors, ultra-violet (UV) photo detectors, etc. [42] Different nanoparticles synthesis methods, including the sol-gel and hydrothermal processes, SILAR, CVDs, etc., have previously been published. [26, 43-45] However, sol-gel is favored for greater photo catalytic action than all other methods. Similarly, this synthesized approach offers an economical resolution of agricultural wastewater cleaning. [46, 47] There were quite a few attempts for the functionalization of ZnO textiles for self-cleaning. [33]

Self-Cleaning on Fabric: All has been done to create finished fabrics with several results once nanoparticles in textiles were introduced. This was primarily because fabrics of textiles consider one of the best surfaces for nanotechnology, and cotton fibers, commonly referred to as cotton fibers, have a wide area. The strong fixation of nanoparticles to fabric surfaces is an important part of the Nano technological operation in the textile industry. This means that the durability of the required characteristics is improved and nanoparticles are minimally lost to the atmosphere. An optimum chemical integration among nanomaterial's and even the textile surface must be obtained to ensure the application of nanoparticles. For this reason, A technique that utilizes covalent linkers is a widely used one. [34] The method of dip-pad-dry-curing also creates linkages among Nanomaterial's and a textile. The authors tested the influence of Nano TiO2 chemical treatment on the characteristics of cotton fabric. The cotton material was prepared by the pad-dry-cure process using nano TiO2particles. [48] Functionalization of wool fabrics utilizing sol-gel low temp process with TiO2and TiO2/SiO2 Nano composite. [49]

Self-cleaning textiles perform by using photo catalysts such as titanium dioxide and zinc oxide to introduce a photo catalytic response in the material. The textile that is covered with a thin layer of titanium dioxide molecule, this semiconductor, exposed to the sun, radiation with an energy equivalent or greater than the photo catalyst wavelength, stimulates electrons to the conductive band. Throughout the crystalline structure, only the excited electrons interact with oxygen atoms in the air, producing free-radical oxygen. Such oxygen atoms are powerful oxidants that can destroy most carbonic substances via the oxidation process. This process breaks down the organic materials (i.e., toxins and microscopic creatures) into substances such as carbon dioxide and water. [32]

In addition to high separation and the structural effects of the amorphous silica compound, the cotton fabric TiO2-SiO2 treated exhibited an excellent photo catalytic activity above TIO2 cotton alone. [50, 51] Experts have confirmed that cotton textiles can be linked to TiO2 via chemical holes. A coating process was easy and non-toxic surfactants had been used. TiO2 cotton textiles have a steadily self-cleaning effect and caused any chromophore (s) of wine to be slightly removed by daylight, which shows a stable long-term efficiency. [22]

Experts also defined that the degree of self-cleaning in cross-linked textiles is higher than in non-cross-linked cured substances. This results in a higher amount and more reliable distribution of titanium components over cotton surfaces in the cross-linking process than in the non-crosslink process. These higher levels of self-cleaning are done. [52]

In different industries, the idea of self-cleaning provides several benefits. Self-cleansing fabric, in particular, that, due to times, materials, energy reduction, and thus cost-effectiveness in manufacturing, has a huge potential for improving products and the textile industry, health industry. Besides, this technology encompasses environmental characteristics as cleaning activities are effectively reduced, a substantial volume of water and energy are conserved, as well as time and laundering costs are saved. [53]

4. Denim Fabric with Flame retardant, hydrophilic and self-cleaning properties conferring by in-situ synthesis of silica nanoparticles: Recently most published papers were concentrated on various finishing on textiles such as synthesis of nanoparticles on cotton fabric, industrial washing of denim garment and changing the color of fabrics. The color psychology is a critical issue for the consumers because of the importance of the

color in choosing of a product by the costumers. Therefore, color change can be a useful way to attract the costumers for buying a cloth. The hydrophilic or hydrophobic nature of fabric can be strongly affected on the textile finishing, dyeing and printing. Hence, most researchers worked on various methods to enhance the hydrophobicity of fabrics. treated the cotton fabrics by DC air plasma and cellulose to improve the hydrophobicity, wettability, and dye-ability without substantial fiber deterioration. In this study, sodium silicate solution was used in an alkaline solution of Keliab as a friendly compound to synthesize silica NPs on the denim fabric. Also, the synthesis was performed in two different alkaline solutions and the results compared. The better thermal behavior of denim fabrics with minimum effect on the handle and low color difference were explored. Besides, the hydrophilic, photo catalytic, and mechanical properties of the treated samples were investigate. [54-57]

In summary, S. Rosmarinus (Keliab) ash, as a source of alkali, can be used for in situ synthesis of silica NPs on denim fabric. This can be achieved by means of diluted sodium silicate solution under alkaline conditions. The FESEM images revealed the rod-shaped silica NPs by Keliab solution and spherical-shaped NPs by ethanol in alkaline conditions with the average size of 78.9 and 311.43 nm, respectively. FTIR spectra confirmed formation of the Si–O stretching at 1000 cm-1 on the treated fabric. The breakages in cellulosic chains due to alkaline treatment at high temperature along with ionic linkages of cellulose with SiO2 caused to the higher tensile strength and bending rigidity. The silica NPs on the fabrics made absorption of water faster and improved the hydrophilic properties. Besides, the silica NPs on the fabric surface significantly decreased the burning length and increased the residue of fabric at 500 C providing the consumer protection. The handle of the fabrics turns to rigid, harsh, and hard, nevertheless the fabric air permeability improved. Overall, the applied synthesis method is environmentally friendly and low cost that can be applied on cellulose fabric to produce multifunctional properties such as flame retardant and self-cleaning. The final denim fabric can be used in various situations such as apparel manufacturing, protective clothing for humans and pets, mobile cases, insulation textiles, and bags and shoes industry. It can also be exploited in home textiles including curtains, furniture, seat covers, mattresses, and sleepwear. [58, 59]

5. Self-cleaning and super hydrophilic wool by TiO2/SiO2 Nano composite: In this investigation, wool fabrics were treated with colloids ofTiO2/SiO2 through a low temperature sol–gel method using the dip-pad-dry-cure process. This study was set out to investigate the synergistic role of silica in enhancing the functionality of TiO2on wool fabric, and to elucidate the impacts of silica addition on self-cleaning and hydrophobicity of wool fabrics. Wool fabrics were stained with coffee and exposed to UV to assess the self-cleaning property. The water absorption behavior of treated samples was analyzed based on the water droplet contact angle. [60] Preparing the sols: Titanium sol was prepared by vigorous stirring of TTIP, acetic acid, distilled water and hydrochloric acid mixture for 2 h at 60°C. Silica sol was prepared through hydrolysis and condensation of TEOS in water and in the presence of hydrochloric acid (pH = 3). This mixture was stirred for 2 h and then kept overnight for 16 h.TiO2/SiO2 composite sols were prepared through mixing the TiO2and SiO2 sols together based on three different Ti/Si molar percentage ratios of 70:30, 50:50 and 30:70 and stirring for 1 h. [61, 62] Scouring **:** Scouring was performed to remove the surface impurities of wool fabrics, in a bath containing 2 g/L of colorless nonionic detergent (Kieralon F-OL-B) with a liquid to fabric ratio of 50:1 at 40 ◦C for 20 min. Then the samples were rinsed thoroughly with water. TiO2/SiO2 treatment: Prepared sols were applied to the surface of wool fabrics using the dip-pad-dry-cure process. The excessive uptake of sols was removed from the fabrics by an automatic horizontal padding machine with a nip pressure of 2.75 kg cm−2 and rotating speed of 7.5 rpm. The fabrics were dried in an oven at 80°C for 5 min and subsequently cured at 120°C for 2 min.Self-cleaning test on fabrics: Functionalized wool fabrics were stained with 20 of 12 g/L coffee solution and exposed to UV radiation with an intensity of0.98 mWcm^{-2}. The self-cleaning property was evaluated based on the color removal of coffee stains on fabrics. [63] Solid extraction: Immediately after adding sodium carbonate solution into theTiO2/SiO2 sols, the suspended nanoparticles formed a precipitate at the bottom of the beaker. The precipitate was separated from the liquid phase through centrifugation. The pH of nanoparticles was lowered to neutral through washing with distilled water and subsequent centrifugation. The extraction process was finalized through drying the product at 70°C for 12 h. [64]

Esfandiar Pakdel and “et al: Self-cleaning function and hydrophobicity of wool fabrics were successfully improved through the integration of silica in the TiO_2/SiO_2 Nano composites. Increasing the concentration of silica, the TiO_2/SiO_2 Nano composite showed more capability in decomposing the stains. This was confirmed through monitoring the discoloring rate of coffee stains on pristine and treated wool samples. Providing a higher surface area in the vicinity of TiO_2 and also increasing the surface acidity of the photo catalyst, silica could enhance the functionality of the self-cleaning coating layer on wool fabric. After applying TiO_2/SiO_2 50:50 and 30:70 onto a wool fabric, a super hydrophilic surface was obtained even in the absence of UV irradiation. Establishing Ti—O—Si and Si—O—Si linkages in the synthesized Nano composite was demonstrated using the FTIR pattern. Furthermore, the presence of anatase crystalline structure in synthesized nanoparticles was confirmed using the XRD patterns. SEM images showed a relatively even layer of TiO_2 and TiO_2/SiO_2 nanoparticles on the surface of wool. Further work is still required to examine other important aspects of the treated wool fabric, such as durability in washing and abrasion.

6. Stain proofing finishing of polyester fabric in supercritical carbon dioxide

Supercritical fluid Carbon dioxide: A supercritical fluid is a substance at a temperature and pressure above its critical temperature and pressure. The critical point represents the highest temperature and pressure at which the substance can exist as a vapor and liquid in equilibrium. It has the unique ability to diffuse through solids like a gas, and dissolve materials like a liquid. Additionally, it can readily change in density upon minor changes in temperature or pressure. These properties make it suitable as a substitute for organic solvents. Carbon dioxide usually behaves as a gas in air or as a solid called dry ice when frozen. Above its critical temperature and pressure, it behaves like a supercritical fluid and can adopt properties midway between a gas and a liquid. [65] Procedures of the one-step process for tri-proofing finishing of polyester in SCF-CO_2: A one-step tri-proofing finishing of polyester in SCF-CO_2 was carried out on a supercritical multi-functional treatment machine constructed by the waterless coloration team from Soochow University of China. The employed supercritical multi-functional machine was comprised with a pressurizing, a high-pressure finishing, a separation and recycling subsystems, etc., as shown in Fig. Moreover, as shown in Fig, predetermined dosages of the tri-proofing finishing agent of TG-5574 and AOT were sufficiently dissolved in a solution including 10.0 mL of absolute ethanol and 40.0 mL of deionized water, and well stirred to obtain a working solution, and then it was loaded into the high-pressure finishing unit. Moreover, 6.0 g polyester fabric was also set in a mesh sarong and fixed in the high-pressure finishing unit. Since all preparations were already made, the supercritical finishing treatment unit was sealed, and carbon dioxide was injected by the pressurization pump. [66] Then a one-step tri-proofing finishing process was initiated with the circulation pump working after the system temperature and pressure being raised to predetermined conditions according to an individual experiment request. When a predetermined finishing duration was fulfilled, the separation and recycling subsystems were employed to recover the residual working solution and most of carbon dioxide gas to a balance between the high-pressure finishing unit and the separators. Thereafter, a continuous rise of the system temperature to 150.0 ◦C was also performed for a further short treatment of the polyester sample for 5.0 min, and then the system was fully depressurized to recover the remaining carbon dioxide. Finally, the tri-proofing finished sample was taken out as the system pressure was in equilibrium with atmospheric pressure. [67, 68]

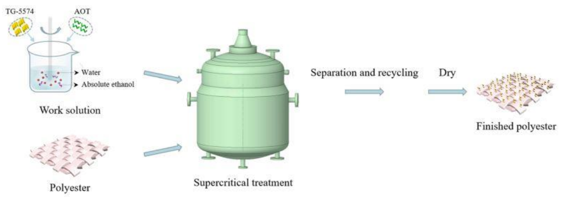

Fig. Schematic diagram for the procedure of the supercritical tri-proofing finishing of polyester substrate in a one-step manner.

Li-Yuan Guan and “et al **:** In this work, a supercritical one-step method or process for the triproofing or namely the stain proofing finishing of polyester with apparent characteristics of green and eco-friendly was successfully developed and validated. The achieved results show that the finishing agent concentration in work solution, system temperature, pressure as well as duration could impact important and various effects on triproofing performances. A water-proofing and a soil-proofing performance at 4-grade or above, and an oil-proofing performance at 5–6 grade for the finished polyester fabric under one of the recommended conditions of 100℃× 20 MPa × 90 min was achieved, respectively. Furthermore, a mechanism for tri-proofing finishing in an eco-friendly way with the developed supercritical one-step process was successfully derived, and the supercritical tri-proofing finishing was also verified by SEM and FT-IR analysis. Additionally, a good or comparable air permeability performance with less variation (lower than 1.3 %) was also achieved for the supercritical finished substrate in comparison with the control one. The 50-time repetitive washings showed no evident effect on the water- and soil-proofing performances, and a relative high oil-proofing performance at or over 5-grade was also achieved even some slight decrease accompanied as prolonging the repetitive washings under appropriate supercritical finishing conditions. All the results further demonstrate that the developed supercritical tri-proofing finishing method in a one-step manner affords a new strategy and possibility to manufacture some multifunctional polyester products in practice, involving social, economic benefits and eco-friendly characteristics for clean finishing in textile industry.

Conclusions

The development of self-cleaning textiles presents a significant advancement in material science, offering environmentally friendly, cost-effective, and innovative solutions for various industries. This review highlights the integration of hydrophobic and hydrophilic coatings, nanotechnology, and advanced fabrication techniques to create textiles with self-cleaning properties. These textiles not only enhance durability and reduce maintenance costs but also contribute to environmental sustainability by minimizing water and energy usage. Applications of self-cleaning textiles extend to apparel, home furnishings, and protective gear, demonstrating their versatility. Techniques such as the use of titanium dioxide (TiO_2) and zinc oxide (ZnO) nanoparticles, silica composites, and supercritical carbon dioxide processing have shown promise in achieving multi functionality, including flame resistance, UV protection, and improved hydrophilicity or hydrophobicity. Future research should focus on optimizing these technologies for scalability, enhancing the durability of coatings under real-world conditions, and expanding their applicability across different fabric types. By doing so, the textile industry can further harness the potential of self-cleaning technologies to meet the growing demand for sustainable and high-performance materials.

Funds

No fund

Conflict of Interest

The authors declared no competing interests in the publication of this article

Acknowledgment

The authors are gratefully grateful to acknowledge the Faculty of Applied Arts, Benha University.

References

1. Han, J.T., Zheng, Y., Cho, J.H., Xu, X. and Cho, K. Stable superhydrophobic organic− inorganic hybrid films by electrostatic self-assembly, *The Journal of Physical Chemistry B*, **109**(44) 20773-20778 (2005).

2. Amigoni, S., Taffin de Givenchy, E., Dufay, M. and Guittard, F. Covalent layer-by-layer assembled superhydrophobic organic− inorganic hybrid films, *Langmuir*, **25**(18) 11073-11077 (2009).

3. Zhi, J. and Zhang, L.-Z. Durable superhydrophobic surface with highly antireflective and self-cleaning properties for the glass covers of solar cells, *Applied Surface Science*, **454** 239-248 (2018).

4. Mahadik, S.A., Kavale, M.S., Mukherjee, S. and Rao, A.V. Transparent superhydrophobic silica coatings on glass by sol–gel method, *Applied surface science*, **257**(2) 333-339 (2010).

5. Hozumi, A., Cheng, D.F. and Yagihashi, M. Hydrophobic/superhydrophobic oxidized metal surfaces showing negligible contact angle hysteresis, *Journal of colloid and interface science*, **353**(2) 582-587 (2011).

6. Liu, X., Wang, Y., Chen, Z., Ben, K. and Guan, Z. A self-modification approach toward transparent superhydrophobic glass for rainproofing and superhydrophobic fiberglass mesh for oil water separation, *Applied Surface Science*, **360** 789-797 (2016).

7. Latthe, S.S. and Rao, A.V. Superhydrophobic sio2 micro-particle coatings by spray method, *Surface and Coatings Technology*, **207** 489-492 (2012).

8. Li, J., Yan, L., Ouyang, Q., Zha, F., Jing, Z., Li, X. and Lei, Z. Facile fabrication of translucent superamphiphobic coating on paper to prevent liquid pollution, *Chemical Engineering Journal*, **246** 238-243 (2014).

9. Ma, M., Hill, R.M., Lowery, J.L., Fridrikh, S.V. and Rutledge, G.C. Electrospun poly (styrene-block-dimethylsiloxane) block copolymer fibers exhibiting superhydrophobicity, *Langmuir*, **21**(12) 5549-5554 (2005).

10. Han, D. and Steckl, A.J. Superhydrophobic and oleophobic fibers by coaxial electrospinning, *Langmuir*, **25**(16) 9454-9462 (2009).

11. Chu, F. and Wu, X. Fabrication and condensation characteristics of metallic superhydrophobic surface with hierarchical micro-nano structures, *Applied Surface Science*, **371** 322-328 (2016).

12. Zhang, Y., Wu, J., Yu, X. and Wu, H. Low-cost one-step fabrication of superhydrophobic surface on al alloy, *Applied Surface Science*, **257**(18) 7928-7931 (2011).

13. Ebert, D. and Bhushan, B. Transparent, superhydrophobic, and wear-resistant coatings on glass and polymer substrates using sio2, ZnO, and ito nanoparticles, *Langmuir*, **28**(31) 11391-11399 (2012).

14. Diaa, M. and Hassabo, A.G. Self-cleaning properties of cellulosic fabrics (a review), *Biointerf. Res. Appl. Chem.*, **12**(2) 1847 - 1855 (2022).

15. Attia, E.F., Helal, T.W., Fahmy, L.M., Wahib, M.A., Saad, M.M., Abd El-Salam, S., Maamoun,

D., Mahmoud, S.A., Hassabo, A.G. and Khattab, T.A. Antibacterial, self-cleaning, UV protection and water repellent finishing of polyester fabric for children wheelchair, *J. Text. Color. Polym. Sci.*, **20**(2) 181-188 (2023).

16. Mahmoud, M., Sherif, N., Fathallah, A.I., Maamoun, D., Abdelrahman, M.S., Hassabo, A.G. and Khattab, T.A. Antimicrobial and self-cleaning finishing of cotton fabric using titanium dioxide nanoparticles, *J. Text. Color. Polym. Sci.*, **20**(2) 197-202 (2023).

17. Tarek, D., Mohmoud, A., Essam, Z., Sayed, R., Maher, A., Maamoun, D., Abdel Salam, S.H., Mohamed, H., Hassabo, A.G. and Khattab, T.A. Development of wrinkle free and self-cleaning finishing of cotton and polyester fabrics, *J. Text. Color. Polym. Sci.*, **20**(2) 175-180 (2023).

18. Adel, M., Mohamed, M., Mourad, M., Shafik, M., Fathallah, A., Maamoun, D., Abdelrahman, M.S., Hassabo, A.G. and Khattab, T.A. Enhancing the self-cleaning properties of polyester fabric with rtv – silicone rubber, *J. Text. Color. Polym. Sci.*, **21**(1) 91-95 (2024).

19. S., S., A., S., A., S., S., A., Maamoun, D., Hassabo, A.G., Mahmoud, S.A. and Khattab, T.A. Self-cleaning finishing of polyester fabrics using znonps, *J. Text. Color. Polym. Sci.*, **21**(1) 103-107 (2024).

20. Roshdy, Y.A., El-Shamy, M.N., Mohamed, H.A., Gaafar, Z.S. and Hassabo, A.G. Self-cleaning cotton textiles enhanced with nanotechnology, *J. Text. Color. Polym. Sci.*, **22**(1) 349-354 (2025).

21. Meng, H., Wang, S., Xi, J., Tang, Z. and Jiang, L. Facile means of preparing superamphiphobic surfaces on common engineering metals, *The Journal of Physical Chemistry C*, **112**(30) 11454-11458 (2008).

22. Saad, S.R., Mahmed, N., Abdullah, M.M.A.B. and Sandu, A.V. Self-cleaning technology in fabric: A review, IOP conference series: materials science and engineering, IOP Publishing, p. 012028 (2016).

23. Chaudhari, S.B., Mandot, A.A. and Patel, B.H. Effect of nano TiO2 pretreatment on functional properties of cotton fabric, *International Journal of Engineering Research and Development*, **1**(9) 24-29 (2012).

24. Rehan, M., Elshemy, N.S., Haggag, K., Montaser, A. and Ibrahim, G.E. Phytochemicals and volatile compounds of peanut red skin extract: Simultaneous coloration and in situ synthesis of silver nanoparticles for multifunctional viscose fibers, *Cellulose*, **27** 9893-9912 (2020).

25. Ibrahim, N.A., Nada, A.A., Eid, B.M., Al-Moghazy, M., Hassabo, A.G. and Abou-Zeid, N.Y. Nano-structured metal oxides: Synthesis, characterization and application for multifunctional cotton fabric, *Adv. Nat. Sci.: Nanosci. Nanotechnol.*, **9**(3) 035014 (2018).

26. Zayed, M., Othman, H., Ghazal, H. and Hassabo, A.G. Psidium guajava leave extract as reducing agent for synthesis of zinc oxide nanoparticles and its application to impart multifunctional properties for cellulosic fabrics, *Biointerf. Res. Appl. Chem.*, **11**(5) 13535 - 13556 (2021).

27. Zayed, M., Ghazal, H., Othman, H.A. and Hassabo, A.G. Synthesis of different nanometals using citrus sinensis peel (orange peel) waste extraction for valuable functionalization of cotton fabric, *Chem. Pap.*, **76**(2) 639-660 (2022).

28. Zayed, M., Othman, H., Ghazal, H. and Hassabo, A.G. A valuable observation on natural plants extracts for valuable functionalization of cotton fabric (an overview), *Egy. J. Chem.*, **65**(4) 499 – 524 (2022).

29. Hassabo, A.G., znatii, a., muhammad, m., mostafa, s. and Saad, M.A.O. Pectin as organic framework for znonps to enhance the functionality of textile printed fabrics, *J. Text. Color. Polym. Sci.*, **21**(Special Issue) 23-32 (2024).

30. Kumar, B. Self-cleaning finish on cotton textile using sol-gel derived TiO2 nano finish, *IOSR Journal of Polymer and Textile Engineering*, **2**(1) 1-5 (2015).

31. Anwar, Y. and Alghamdi, K.M. Imparting antibacterial, antifungal and catalytic properties to cotton cloth surface via green route, *Polymer Testing*, **81** 106258 (2020).

32. Samal, S.S., Jeyaraman, P. and Vishwakarma, V. Sonochemical coating of ag-TiO2 nanoparticles on textile fabrics for stain repellency and self-cleaning- the indian scenario: A review, *Journal of Minerals and Materials Characterization and Engineering*, **9**(6) 519-525 (2010).

33. Karimi, L., Mirjalili, M., Yazdanshenas, M.E. and Nazari, A. Effect of nano TiO2 on self-cleaning property of cross-linking cotton fabric with succinic acid under UV irradiation, *Photochemistry and Photobiology*, **86**(5) 1030-1037 (2010).

34. Asokan, A., Ramachandran, T., Ramaswamy, R., Koushik, C. and Muthusamy, M. Preparation and characterization of zinc oxide nanoparticles and a study of the anti-microbial property of cotton fabric treated with the particles, *Journal of Textile and Apparel, Technology and Management*, **6**(4) (2010).

35. El-Zawahry, M.M., Abdelghaffar, F., Abdelghaffar, R.A. and Hassabo, A.G. Equilibrium and kinetic models on the adsorption of reactive black 5 from aqueous solution using eichhornia crassipes/chitosan composite, *Carbohydrate Polymers*, **136** 507-515 (2016).

36. Kamel, M.Y. and Hassabo, A.G. Anti-microbial finishing for natural textile fabrics, *J. Text. Color. Polym. Sci.*, **18**(2) 83-95 (2021).

37. Mohamed, A.L., El-Naggar, M.E. and Hassabo, A.G. Preparation of hybrid nano-particles to enhance the electrical conductivity and performance properties of cotton fabrics, *Journal of Materials Research and Technology*, **12** 542-554 (2021).

38. Hassabo, A.G., Ragab, M.M. and Othman, H.A. Ultraviolet protection of cellulosic fabric, *J. Text. Color. Polym. Sci.*, **19**(1) 51-61 (2022).

39. Mohamed, A.L., El-Zawahry, M., Hassabo, A.G. and Abd El-Aziz, E. Encapsulated lemon oil and metal nanoparticles in biopolymer for multifunctional finishing of cotton and wool fabrics, *Indust. Crop. Prod.*, **204** 117373 (2023).

40. Hassabo, A.G., Khaleed, N., Shaker, S., Abd El-Salam, N.A., Mohamed, N.A., Gouda, N.Z. and Othman, H. Impact of various treatments on printing wool techniques, *J. Text. Color. Polym. Sci.*, **21**(1) 75-86 (2024).

41. Parkin, I.P. and Palgrave, R.G. Self-cleaning coatings, *Journal of Materials Chemistry*, **15**(17) 1689-1695 (2005).

42. Isai, K.A. and Shrivastava, V.S. Photocatalytic degradation of methylene blue using ZnO and 2%fe–ZnO semiconductor nanomaterials synthesized by sol–gel method: A comparative study, *SN Applied Sciences*, **1**(10) 1247 (2019).

43. Zayed, M., Ghazal, H., Othman, H. and Hassabo, A.G. Psidium guajava leave extract for improving ultraviolet protection and antibacterial properties of cellulosic fabrics, *Biointerf. Res. Appl. Chem.*, **12**(3) 3811 - 3835 (2022).

44. El-Zawahry, M.M., Hassabo, A.G., Abdelghaffar, F., Abdelghaffar, R.A. and Hakeim, O.A. Preparation and use of aqueous solutions magnetic chitosan / nanocellulose aerogels for the sorption of reactive black 5, *Biointerf. Res. Appl. Chem.*, **11**(4) 12380 - 12402 (2021).

45. Joshi, N.C., Malik, S. and Gururani, P. Utilization of polypyrrole/ZnO nanocomposite in the adsorptive removal of cu 2+, pb 2+ and cd 2+ ions from wastewater, *Letters in Applied NanoBioScience*, **10**(3) 2339-2351 (2021).

46. Jurablu, S., Farahmandjou, M. and Firoozabadi, T. Sol-gel synthesis of zinc oxide (ZnO) nanoparticles: Study of structural and optical properties, *Journal of Sciences, Islamic Republic of Iran*, **26**(3) 281-285 (2015).

47. Protasova, L.N., Rebrov, E.V., Choy, K.L., Pung, S.Y., Engels, V., Cabaj, M., Wheatley, A.E.H. and Schouten, J.C. ZnO based nanowires grown by chemical vapour deposition for selective hydrogenation of acetylene alcohols, *Catalysis Science & Technology*, **1**(5) 768-777 (2011).

48. Vodišek, N., Šuligoj, A., Korte, D. and Lavrenčič Štangar, U. Transparent photocatalytic thin films on flexible polymer substrates, *Materials*, **11**(10) 1945 (2018).

49. Pakdel, E., Daoud, W.A. and Wang, X. Self-cleaning and superhydrophilic wool by TiO2/sio2 nanocomposite, *Applied Surface Science*, **275** 397-402 (2013).

50. Yuranova, T., Mosteo, R., Bandara, J., Laub, D. and Kiwi, J. Self-cleaning cotton textiles surfaces modified by photoactive sio2/TiO2 coating, *Journal of Molecular Catalysis A: Chemical*, **244**(1) 160-167 (2006).

51. El-Naggar, M.E., Hassabo, A.G., Mohamed, A.L. and Shaheen, T.I. Surface modification of sio2 coated ZnO nanoparticles for multifunctional cotton fabrics, *Journal of Colloid and Interface Science*, **498** 413-422 (2017).

52. Mirjalili, M. and Karimi, L. Photocatalytic degradation of synthesized colorant stains on cotton fabric coated with nano TiO2, *Journal of Fiber Bioengineering and Informatics*, **3**(4) 208-215 (2011).

53. Diaa, M. and Hassabo, A.G. Self-cleaning properties of cellulosic fabrics (a review), *Biointerf. Res. Appl. Chem*, **12**(2) 1847-1855 (2022).

54. Aksit, A., Onar, N., Kutlu, B., Sergin, E. and Yakin, I. Synergistic effect of phosphorus, nitrogen and silicon on flame retardancy properties of cotton fabric treated by sol-gel process, *International Journal of Clothing Science and Technology*, **28**(3) 319-327 (2016).

55. Al-Oweini, R. and El-Rassy, H. Synthesis and characterization by ftir spectroscopy of silica aerogels prepared using several si(or)4 and r″si(or′)3 precursors, *Journal of Molecular Structure*, **919**(1) 140-145 (2009).

56. Aladpoosh, R., Montazer, M. and Samadi, N. In situ green synthesis of silver nanoparticles on cotton fabric using seidlitzia rosmarinus ashes, *Cellulose*, **21**(5) 3755-3766 (2014).

57. Alongi, J. and Malucelli, G. State of the art and perspectives on sol–gel derived hybrid architectures for flame retardancy of textiles, *Journal of Materials Chemistry*, **22**(41) 21805-21809 (2012).

58. Thompson, R., Summers, S., Rampey-Dobbs, R. and Wheeler, T. Color pressure garments versus traditional beige pressure garments: Perceptions from the public, *The Journal of burn care & rehabilitation*, **13**(5) 590-596 (1992).

59. Torvi, D.A., Douglas Dale, J. and Faulkner, B. Influence of air gaps on bench-top test results of flame resistant fabrics, *Journal of Fire Protection Engineering*, **10**(1) 1-12 (1999).

60. Montazer, M. and Pakdel, E. Functionality of nano titanium dioxide on textiles with future aspects: Focus on wool, *Journal of Photochemistry and Photobiology C: Photochemistry Reviews*, **12**(4) 293-303 (2011).

61. Tung, W.S. and Daoud, W.A. Self-cleaning fibers via nanotechnology: A virtual reality, *Journal of Materials Chemistry*, **21**(22) 7858-7869 (2011).

62. Chen, D., Tan, L., Liu, H., Hu, J., Li, Y. and Tang, F. Fabricating superhydrophilic wool fabrics, *Langmuir*, **26**(7) 4675-4679 (2010).

63. Guan, K. Relationship between photocatalytic activity, hydrophilicity and self-cleaning effect of TiO2/sio2 films, *Surface and Coatings Technology*, **191**(2-3) 155-160 (2005).

64. Wang, X., Cao, G. and Xu, W. Improving the hydrophilic properties of wool fabrics via corona discharge and hydrogen peroxide treatment, *Journal of applied polymer science*, **112**(4) 1959-1966 (2009).

65. Shahid, M. and Adivarekar, R. Advances in functional finishing of textiles, Springer, (2020).

66. Eren, H.A., Avinc, O. and Eren, S. Supercritical carbon dioxide for textile applications and recent developments, *IOP Conference Series: Materials Science and Engineering*, **254**(8) 082011 (2017).

67. Liu, S.-Q., Chen, Z.-Y., Sun, J.-P. and Long, J.-J. Ecofriendly pretreatment of grey cotton fabric with enzymes in supercritical carbon dioxide fluid, *Journal of Cleaner Production*, **120** 85-94 (2016).

68. Hart, A., Anumudu, C., Onyeaka, H. and Miri, T. Application of supercritical fluid carbon dioxide in improving food shelf-life and safety by inactivating spores: A review, *Journal of Food Science and Technology*, **59**(2) 417-428 (2022).