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# ENHANCING FLAME RETARDANT AND SELF-CLEANING PROPERTIES OF COTTON FABRIC WITH BIO NATURAL MATERIAL AND TIO2 NANOPARTICLES

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***Keywords***

*Pomegranate extract, Flame retardant, Tio2 Nano particles, Self-cleaning properties, Cotton fabric, Antimicrobial activity.*

***Abstract***

This research investigates the enhancement of cotton fabrics with titanium dioxide ($TiO_2$) nanoparticles and pomegranate peel extract to improve their flame retardancy and self-cleaning properties. Cotton fabrics are widely valued for their comfort, breathability, and affordability, but there is a growing demand for high-performance textiles, particularly for safety and functional applications. Traditional methods for enhancing cotton fabric properties often involve the use of environmentally harmful chemical treatments. $TiO_2$ nanoparticles, known for their excellent photocatalytic properties, offer a sustainable alternative, providing self-cleaning, and antimicrobial effects. When applied to cotton, $TiO_2$ not only improves surface characteristics but also imparts flame retardancy. Pomegranate peel extract, rich in bioactive compounds such as tannins, anthocyanins, and flavonoids, has demonstrated antimicrobial, and flame-retardant properties, further enhancing the performance of the fabric. This study aims to assess the combined effect of $TiO_2$ nanoparticles and pomegranate peel extract on the flame-retardant behaviour, self-cleaning ability, and anti-bacterial activity of cotton fabrics. In addition, the research will explore the environmental sustainability of the proposed treatment by reducing the use of harmful

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| | chemicals and promoting eco-friendly textile solutions for a range of applications, including protective workwear and high-performance fashion. |



## 1. INTRODUCTION

Cotton fabrics are widely favored in the textile industry due to their inherent comfort, breathability, and cost-effectiveness. These attributes have cemented cotton's role in diverse sectors, including everyday apparel, healthcare textiles, and industrial workwear. However, the growing demand for high-performance and multifunctional textiles, especially for protective and technical applications, has driven the need to enhance cotton fabrics with added functionalities such as flame retardancy, UV protection, antimicrobial activity, and self-cleaning capabilities [1, 3, 31].

Conventional chemical finishing processes often rely on halogenated compounds or other synthetic agents, which can pose environmental and health risks due to their toxicity and limited biodegradability [13, 14]. As the textile industry moves toward greener and more sustainable practices, nanotechnology and bio-based solutions have emerged as promising alternatives for functional textile finishing [15, 34, 39].

Among the most extensively studied nanomaterials is titanium dioxide ($TiO_2$), which offers a unique combination of photocatalytic, UV-blocking, antibacterial, and self-cleaning properties. When exposed to UV light, $TiO_2$ nanoparticles (NPs) catalyze the breakdown of organic pollutants on fabric surfaces, thereby imparting durable self-cleaning effects [20, 32, 36]. Additionally, $TiO_2$ treatments have been shown to improve the UV resistance, mechanical properties, and overall durability of cotton and polyester fabrics, making them ideal for medical, outdoor, and industrial use [5, 18, 31].

In parallel, pomegranate peel extract (PRE) has gained traction as a sustainable source of natural functional agents. Rich in polyphenols, tannins, and flavonoids, PRE demonstrates potent antimicrobial, antioxidant, UV-protective, and flame-retardant properties [6, 7, 30]. PRE has also proven effective as a natural dye and a flame retardant when combined with eco-friendly mordants or crosslinkers, significantly enhancing the thermal stability and ignition resistance of cotton fabrics [22, 23].

The combination of $TiO_2$ nanoparticles and pomegranate peel extract presents a novel, biocompatible, and eco-friendly finishing strategy for cotton textiles. This dual-treatment approach promises synergistic benefits—leveraging the photocatalytic and antimicrobial action of $TiO_2$ with the flame-retardant and antioxidant effects of PRE—while minimizing environmental impact and reducing reliance on synthetic chemicals [18, 22, 29].

Therefore, this study aims to investigate the co-application of $TiO_2$ nanoparticles and pomegranate peel extract on cotton fabrics, focusing on enhancing flame retardancy, self-cleaning behavior, and overall functional performance. It will also assess the durability and sustainability of the treatment, proposing a green alternative for developing high-performance, multifunctional textiles suited for applications ranging from protective workwear to sustainable fashion.

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## 2. LITERATURE REVIEW

### 2.1 Tio2 APPLICATIONS

TiO2 nanoparticle coatings on workwear fabrics effectively reduce thermal conductivity and increase air permeability without altering the fabric's intrinsic properties, offering a promising solution for enhancing worker safety in thermal stress environments [1]. Blending acrylic fibers with cotton and adding TiO2 nanoparticles enhances the mechanical properties and wicking abilities of knitted fabrics, with improved comfort for sportswear applications [2]. Incorporating chitosan, PVA, and TiO2 nanoparticles into cotton fabrics enhances printability, color fastness, antimicrobial properties, and UV protection, making them suitable for various functional textile applications [3]. TiO2 nanoparticle treatment significantly improved cotton fabrics' UV protection, self-cleaning, and antibacterial properties, with enhanced mechanical strength at 3% concentration, particularly in the Giza 88 variety [4]. Incorporating TiO2 nanoparticles into polyester fabric with a double weave structure enhances multifunctional properties like UV resistance, stain resistance, antibacterial, and self-cleaning, improving the fabric's performance after high-temperature dyeing [5]. TiO2/kaolin composites were applied to cotton fabric, enhancing its UV protection (UPF 100+) and photocatalytic self-cleaning properties while slightly reducing fabric softness and smoothness. The study highlights kaolin's potential as a low-cost, effective finishing agent for textiles [16]. Titanium(IV) oxide nanoparticles (TiO2 NP) were deposited to cotton denim fabrics using a self-crosslinking acrylate – a polymer dispersion to extend the lifetime of the products. This study aims to determine the optimum conditions to increase abrasion resistance, to provide self-cleaning properties of denim fabrics and to examine the effects of these applications on other physical properties [17]. Titanium dioxide nanoparticles (TiO2NPs) enhance the antibacterial, self-cleaning, and UV protection properties of cotton textiles, making them ideal for protecting sick children in hospitals. TiO2NPs are stable, non-toxic, and cost-effective, improving fabric functionality for healthcare use[18]. Nanotechnology, specifically titanium dioxide treatment, enhances cotton fabrics to create self-cleaning, ink-resistant protective clothing for workers, promoting sustainability. The study optimized fabric properties through different mixing ratios and spinning methods, achieving the desired results in strength, air permeability, and self-cleaning performance [19]. TiO2 nanoparticles, applied to medical fabric via the sol-gel method, exhibit high photocatalytic activity, effectively removing bacteria, dirt, and stains under UV light. The treatment enhances fabric properties, including strength, breathability, and stain resistance, making it suitable for industrial use in medical textiles [20]. Titanium dioxide nanoparticles (TiO2-NPs) applied to cotton fabrics enhance self-cleaning, UV-blocking, and antibacterial properties, with improved mechanical characteristics at higher concentrations. Giza 88 cotton showed superior performance in these properties compared to Giza 94, with TiO2-NPs offering excellent UV protection, self-cleaning, and microbial inhibition[31]. This study investigates the dispersion and antibacterial properties of modified nano-TiO2 particles on cotton fabrics, enhancing stability, washing fastness, and antibacterial

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performance. The modification process, involving grafting and cross-linking, improved fabric strength and structural properties, with effects depending on the modifier concentration and system pH [32]. TiO2 nanoparticles are highly valued for their photocatalytic activity, non-toxicity, biocompatibility, and low cost, making them ideal for multifunctional textile applications. Recent studies focus on improving the binding efficiency of TiO2 to fibers for enhanced durability and stability in textiles[33]. Nanomaterials offer significant commercial potential in the textile industry, enhancing fibers with properties like antimicrobial, self-cleaning, UV protection, and durability. Various nanostructures, such as nanoparticles and polymeric nanostructures, are applied to improve textile functionalities like conductivity, moisture absorption, and heat insulation[34]. Urea-based antifreeze in cement leads to ammonia pollution, which can be mitigated using TiO2-loaded cotton fabrics that enhance ammonia decomposition through photocatalysis. TiO2-padded fabrics showed better performance than TiO2-coated fabrics, with improved ammonia removal and higher reaction rates[35]. TiO2 nanoparticles (anatase and rutile) were deposited onto cotton fabrics using ultrasonic irradiation, showing significant antimicrobial activity, especially against Staphylococcus aureus. The combination of visible light with TiO2 NPs further enhanced their antimicrobial effect[36]. A new dyeing and finishing method for cotton fabric using Henna extract and TiO2 nano-sol was developed, enhancing UV protection and antibacterial properties with minimal impact on color and tensile strength. The results were influenced by the amount of TiO2 and dyeing temperature, while avoiding heavy metal pollution[37]. Titanium dioxide nanoparticles offer unique optical properties and are used in textiles for UV resistance, antibacterial activity, and self-cleaning effects. Various preparation and application methods, including exhaustion, pad-dry-cure, and coating, are discussed, along with challenges and future developments[38]. Textile finishing often involves toxic chemicals, high water and energy consumption, and low durability, leading to environmental and health concerns. Nanomaterials offer a sustainable solution, improving performance and reducing the negative impact of conventional finishing methods[39]. Titanium dioxide (TiO2) is increasingly used in textiles for novel properties like self-cleaning, UV resistance, and chemical stability, particularly in wool. This review highlights various methods of immobilizing TiO2 nanoparticles on fabrics and explores recent research in the field[40].

**2.2 POMEGRANATE RIND EXTRACT APPLICATIONS**

Laccase-catalyzed dyeing with pomegranate peel pigment significantly improves the color stability, UV resistance, antibacterial properties, color fastness, and tensile strength of wool fabric, offering an environmentally friendly dyeing solution [6]. Pomegranate Rind Extract (PRE) enhances the functional properties of cellulosic fabrics, providing fire retardancy, antimicrobial activity, and natural coloring, with good wash fastness and antibacterial efficacy [7]. Chitosan mordanting significantly improved the color strength, UV protection, antimicrobial activity, deodorizing, and antioxidant properties of cotton fabrics dyed with pomegranate rind and onion peel extracts, offering a sustainable alternative to traditional mordanting methods [8]. Plasma-induced coloring of nonwoven recycled cotton with anthocyanin from pomegranate peel, enhanced by mordanting, created a colorimetric sensor capable of detecting ammonia with high sensitivity, along with good colorfastness, UV protection, and antibacterial properties [9]. The study found that pomegranate and turmeric extracts, used with various mordanting techniques, provide sustainable, non-toxic, and biodegradable dyeing options for cotton fabrics, offering a wide range of colors influenced by extract concentration, pH, and mordant choice [10]. This study investigates the photoprotection properties of cotton fabric dyed with pomegranate peel extract, revealing good UV protection (UPF 15-24) and antiradical activity due to its high phenolic and flavonoid content. Adding ZnO did not significantly enhance the fabric's UV protection [11]. This study characterizes pomegranate peel extract for dyeing cotton, showing good UV protection (UPF 15-24) and excellent color fastness, with the best results achieved using Fe (II). However, the dyed fabric showed no antibacterial activity, likely due to deep dye penetration [12]. Flame retardancy in textiles is crucial to reduce fire risks, with traditional chemicals like organo-halogenated and phosphorous compounds being phased out due to toxicity concerns. New, safer technologies such as nanotechnology, biomimetic coatings, and sol–gel methods are emerging to meet evolving safety standards [13], Flame retardant (FR) finishes, traditionally based on halogen, phosphorus, and nitrogen chemistry, have limitations such as toxicity and reduced fabric strength. New methods, including nanotechnology, hydrogel-based finishes, and advanced coating techniques like UV curing and microencapsulation, are being explored for sustainable FR textiles [14]. This review explores natural compounds with antimicrobial properties, such as plant extracts and essential oils, as sustainable alternatives to harmful chemical agents in textiles. It highlights their eco-friendly benefits, improved fabric durability, and reduced health risks, supporting the shift towards greener, more sustainable textile processing [15]. Polyester fabric's ignition, mechanical, and antibacterial properties by coating with sol-solution and pomegranate rind dye after UV/Ozone irradiation. FTIR analysis showed chemical interactions, and PRND improved antibacterial activity and thermal properties without affecting flame retardancy [21]. A mixed treatment of sodium tri-polyphosphate (STPP) and pomegranate rind extract (PRE) enhanced the flame-retardancy of cotton fabric, increasing its limiting oxygen index (LOI) and char mass retention. The treated fabric showed significantly reduced heat release and improved flame resistance compared to untreated fabric [22]. the challenges and advancements in eco-friendly flame retardants, focusing on protein materials and plant-based biomolecules like pomegranate rind extract. It highlights their effects on the thermal stability and self-extinguishment mechanism of cellulosic textiles, along with their advantages and challenges [23]. an eco-friendly flame-retardant solution for cotton fabrics using green coconut shell extract and phytic acid, improving flame resistance and thermal stability. The treated fabrics showed enhanced properties without compromising environmental and material integrity, confirmed through various analyses [24]. the promising potential of tannin-based bio-macromolecules as sustainable flame retardants for textiles and polymeric materials, highlighting their thermal properties and flame retardancy mechanisms. It also

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discusses challenges and future directions in the field of bio-based flame retardants [25]. This study enhances the ignition, mechanical, and antibacterial properties of UV/Ozone-irradiated polyester fabric coated with sol-solution and pomegranate rind natural dye (PRND). The incorporation of PRND improves bacterial reduction, mechanical strength, and thermal properties, without affecting flame retardancy, as confirmed by various ignition tests [26]. This paper reviews various flame retardant (FR) finishing methods for textiles, highlighting limitations of traditional chemicals and exploring sustainable approaches like hydrogel-based finishes, nanotechnology, and advanced coating techniques. It also covers innovative FR methods such as UV curing, microencapsulation, spray coatings, and sol-gel coating [27]. This study explores the use of ecofriendly pumpkin juice as a flame retardant finish for cotton twill fabric, enhancing its fire-resistant properties. The treated fabric showed a significant increase in flame retardancy, as confirmed by improved LOI values and various characterization methods such as TGA, FTIR, SEM, and EDX[28]. This review highlights the growing field of phytonanotechnology, focusing on pomegranate peel extract (PPE) as a source for synthesizing various nanoparticles with enhanced biological and physicochemical properties. It discusses the potential of PPE-mediated nanoparticles (PPE-MNPs) in drug delivery and therapeutic applications, emphasizing their advantages, challenges, and future prospects[29]. Pomegranate peels, rich in bioactive compounds like polyphenols and flavonoids, offer various health benefits, including antioxidant, anti-inflammatory, antimicrobial, anticancer, and cardioprotective effects. These compounds also have potential applications in food preservation and as natural additives due to their antioxidant and antimicrobial properties [30].

## 3. MATERIALS AND METHOD

### 3.1. PROCUREMENT OF COTTON (100%)

100% cotton fabrics (180GSM) was procured from Textile processing Unit. Fabric was washed using non-ionic detergent solution under room temperature to remove debris and other impurities. Washed fabrics were dried under shade in a closed chamber and cured for 10 min at 80C.

**Figure 3.1.1** Cotton fabric

**Figure 3.1.2** Fabric Pre-treatment using non-ionic detergent

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## 3.2. PROCUREMENT OF POMEGRANATE PEEL POWDER AND TITANIUM DI OXIDE (TIO2)

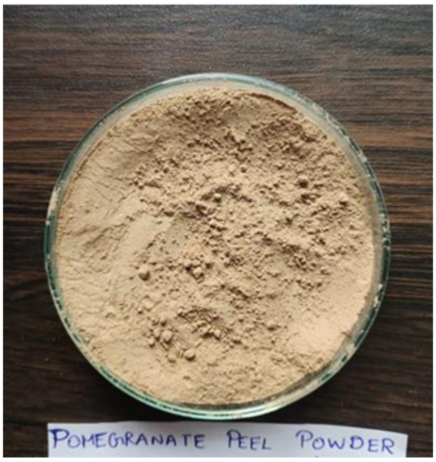


**Figure 3.2.1** Pomegranate peel powder

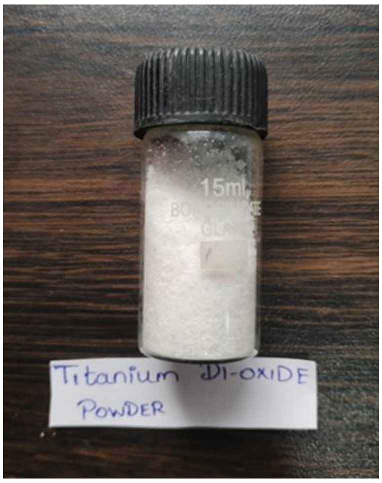


**Figure 3.3.1** Titanium di oxide

## 3.4. SOXHLET EXTRACTION OF POMEGRANATE PEEL POWDER

Pomegranate peel powder (Punica granatum L.), recognized for its rich phenolic and flavonoid content, was selected due to its antimicrobial, antioxidant, and UV-protective properties, as documented by Otaviano et al. (2023) [11,12]. The powder was subjected to Soxhlet extraction, a standard technique for obtaining bioactive compounds efficiently (Basak & Ali, 2020) [23].

Approximately 25 g of finely ground pomegranate peel was placed in a cellulose thimble and loaded into the Soxhlet extractor. Ethanol (95%) was used as the solvent due to its high efficiency in extracting polyphenols and its eco-friendly nature (Ahire et al., 2024) [10]. The solvent was heated to 60°C and maintained for 6 hours, after which the temperature was gradually increased to 100°C. The cycle of evaporation, condensation, and siphoning continued until thorough extraction was achieved. The final extract was collected in a round-bottom flask and stored in a cool, dark environment until further use.

**Figure 3.4.1**[A] Extract present in Thimble


**Figure 3.4.3** Pomegranate peel extracts

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### 3.5. MICROENCAPSULATION OF POMEGRANATE PEEL EXTRACTS (MEPPE)

To enhance the durability and controlled release of the extracted bioactive compounds, microencapsulation was carried out using gum acacia as the wall material—an effective and biodegradable encapsulating agent (Rahman et al., 2024) [8].Wall Material Preparation: 50 g of gum acacia was allowed to swell in 500 mL of hot water (40–50°C) for 30 minutes. An additional 50 mL of hot water was added and stirred for 15 minutes. Core Addition: 10 mL of pomegranate peel extract was introduced and stirred at 300–500 rpm for another 15 minutes. Stabilization: 10 mL of 20% sodium sulfate was added dropwise to initiate encapsulation, followed by the addition of 5 mL of 17% formaldehyde to stabilize the microcapsules. Drying: The solution was then freeze-dried to yield fine microcapsules. These were stored at 4°C until use in textile finishing applications, as supported by studies on natural dye encapsulation and textile application (Younis, 2019) [21].


**Figure3.5.1** Addition Of gum acacia

**Figure3.5.2**Addition of sodium sulphate


**Figure3.5.3** Addition of formaldehyde

### 3.6. TIO2 NANOPARTICLE PREPARATION

Green synthesis of $TiO_2$ nanoparticles was carried out using the pomegranate peel extract as a natural reducing and capping agent, aligning with eco-friendly nanotechnology principles (Monika et al., 2024) [29].Synthesis: 1.0 M titanium dioxide was dissolved in 100 mL of ethyl alcohol. To this, 10 mL of pomegranate peel extract was added slowly under continuous magnetic stirring for 3 hours at neutral pH (pH 7).Filtration and Washing: The resulting nanoparticles were filtered through Whatman No. 40 paper, washed with distilled water, and dried at 100–200°C for 12–24 hours.

Grinding: Dried particles were ground into fine powder using a mortar and pestle and stored at room temperature, following methods similar to those used by Alebeid et al. (2015) and Phan et al. (2023) [37,20].

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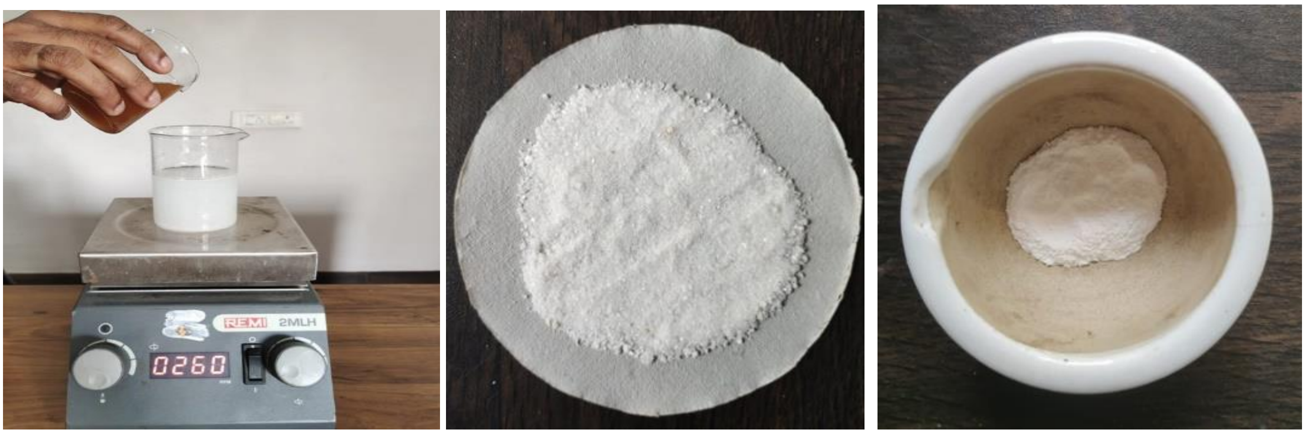


**Figure 3.6.1** TiO2 nanoparticle synthesis and converting into powder form

## 3.7. NANOCOMPOSITE PREPARATION USING MEPPE + TIO2NPS USING THREE DIFFERENT RATIOS

Three nanocomposite ratios (1:1, 1:2, 2:1) of microencapsulated pomegranate peel extract (MEPPE ) and $TiO_2$ nanoparticles were formulated to study synergistic effects on fabric functionality (Yang, 2013) [38].

For each ratio:

100 mg of MEPPE was dispersed in 100 mL distilled water.

The corresponding amount of $TiO_2$ solution was added dropwise at 10 mL/min using a magnetic stirrer.

The process was carried out under ambient controlled conditions.

The resultant composites were termed MEPPE + $TiO_2$NPs and stored for subsequent fabric finishing.


**1:1**


**1:2**

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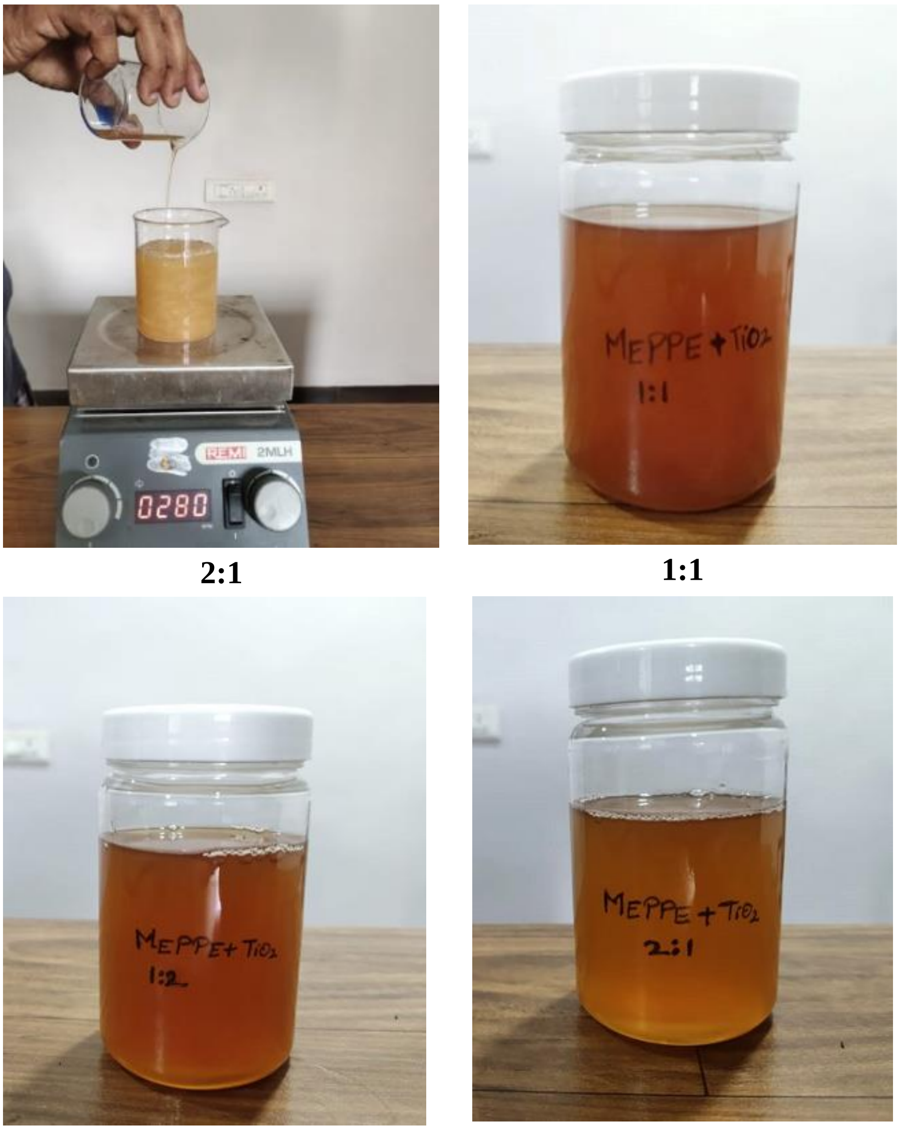


**2:1** **1:1**

**1:2** **2:1**

**Figure 3.7.1** Synthesis of MEPPE + TiO2NPs

### 3.8. FINISHING COTTON FABRICS USING MEPPE + TIO2NPS BY PAD DRY CURE PROCESS

The prepared nanocomposites were applied to cotton fabrics via the pad-dry-cure technique, widely used in textile processing for uniform finish application and durability (Montazer & Pakdel, 2011) [40].Application: 300 mL of the MEPPE + $TiO_2$NPs solution was applied to 1 meter of cotton fabric using a dip-padding method at 40°C.Binder: 8% citric acid was used as a cross-linking agent. Padding: Wet pickup was adjusted to 100%. Drying and Curing: Fabrics were dried at 80°C and cured at 140–160°C for 5 minutes in a hot air oven. Finished fabrics were conditioned at room temperature for further analysis of functional properties such as UV protection, antibacterial efficacy,

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self-cleaning ability, and thermal stability, as demonstrated in studies by Amer (2024) and Saad (2024) [18,3].

**Finishing, Drying and Curing of Cotton fabrics using MEPPE + TiO2NPs – Dip dry method**

**1:1**

**1:2**

**2:1**

**Figure 3.8.1** Finishing

**1:1**

**1:2**

**2:1**

**1:1**

**1:2**

**2:1**

## 4. TESTING AND ANALYSIS

### 4.1. ANTIBACTERIAL ACTIVITY OF MEPPE + TIO2NPS FINISHED COTTON SAMPLES

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Qualitative test (EN ISO 20645 test method)

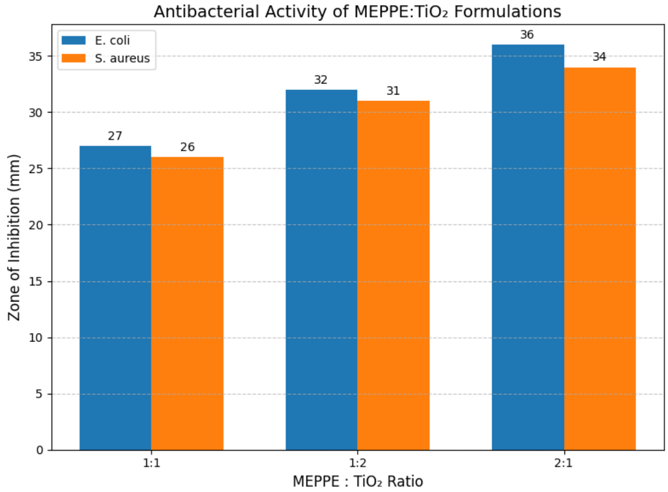
To evaluate the antibacterial efficacy of MEPPE + $TiO_2$NPs treated cotton fabrics, a qualitative disc diffusion method was employed following the EN ISO 20645 standard. Circular fabric swatches (20 mm diameter) from each finishing ratio group (1:1, 1:2, and 2:1) were tested against Escherichia coli (Gram-negative) and Staphylococcus aureus (Gram-positive). Sterile nutrient agar plates were inoculated with bacterial cultures using a sterile 4 mm loop and incubated with the test specimens for 24 hours at 37°C.

Zones of inhibition surrounding the fabric samples indicated antibacterial activity. $TiO_2$NPs are widely recognized for their photocatalytic and antimicrobial activity, effectively degrading microbial cells via reactive oxygen species (ROS) under ambient or UV light conditions [32, 33, 36]. The presence and size of these inhibition zones demonstrated that MEPPE in combination with $TiO_2$NPs conferred significant antibacterial protection, aligning with similar enhancements reported in previous studies [18, 31, 36]. The mean diameters of inhibition zones are summarized in Table 1, and representative results are illustrated in Figure 4.1.1.

**Table-4.1.1:** Antibacterial activity of MEPPE + TiO2NPs finished cotton fabrics

| ***Samples*** | ***Zone of Inhibition (mm)*** | |
|---|---|---|
| | ***Escherichia coli*** | ***Staphylococcus aureus*** |
| *1:1* | *27* | *26* |
| *1:2* | *32* | *31* |
| *2:1* | *36* | *34* |

The bar graph displays the mean zones of inhibition (mm) for each MEPPE:$TiO_2$ formulation against E. coli and S. aureus. A consistent increase in antimicrobial activity is observed with varying ratios, with the highest activity noted at the 2:1 ratio.

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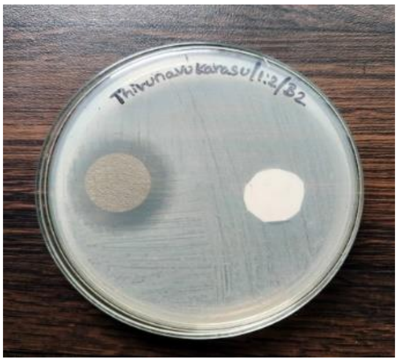
Escherichia coli

Staphylococcus aureus

(1 : 2)

Escherichia coli



Staphylococcus aureus

(2 : 1)

Escherichia coli

Staphylococcus aureus

**Figure 4.1.1:** Antibacterial activity of MEPPE + TiO2NPs finished cotton fabrics

**4.2. SOIL RELEASE: OIL STAIN RELEASE TEST (AATCC TEST METHOD 130 – 2018)**

The soil release performance of MEPPE + $TiO_2$NPs finished cotton samples was assessed via AATCC Test Method 130, which simulates consumer soil removal scenarios. Cider wood oil was used as the staining agent. After application of oil and weighted blotting, the specimens underwent standard washing at 41°C. Stain removal was evaluated using the 3M stain release replica scale, where a score of 5 denotes complete stain removal, and 1 indicates poor performance.

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Results revealed a noticeable improvement in soil release properties in treated samples compared to untreated cotton. This enhancement can be attributed to the hydrophilic surface introduced by $TiO_2$ nanoparticles, which improve surface energy and facilitate stain removal, consistent with findings from previous studies on $TiO_2$-treated textiles [5, 19, 20]. Comparative ratings for all samples are shown in Table 2, and differences in oil release are depicted in graph 4.2.1.

**Table-4.2.1:** Stain release test of MEPPE + TiO2NPs finished cotton fabrics

| ***S. No.*** | ***Samples*** | ***Stain Removal Grades*** | ***Inference*** |
|---|---|---|---|
| *1* | *Control (Unfinished)* | *Grade - 3* | *Fair* |
| *2* | *1 : 1* | *Grade - 4* | *Good* |
| *3* | *1 : 2* | *Grade - 5* | *Excellent* |
| *4* | *2 : 1* | *Grade - 4* | *Good* |

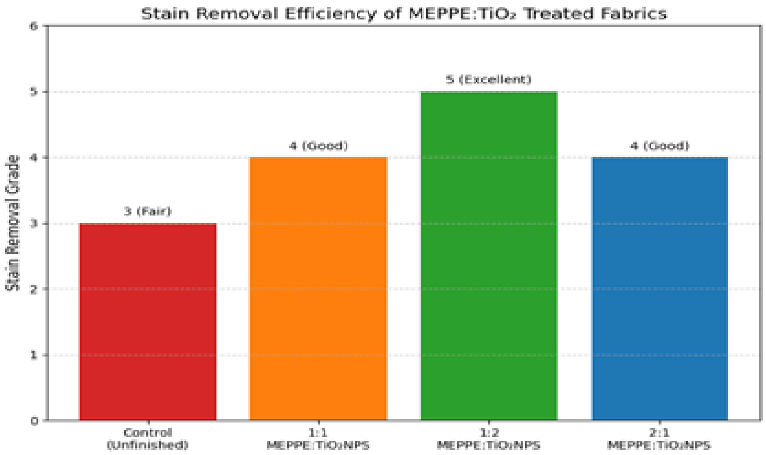


**Fig. 4.2.1:** Stain release test of MEPPE + TiO2NPs finished cotton fabrics

## 4.3. FLAMMABILITY OR FLAME RETARDANT TEST (EN 1103 TEST METHOD)

Flame retardant properties of the treated fabrics were evaluated using the vertical flame test (EN 1103 and ASTM D6413-08 standards). Specimens were exposed to a controlled flame, and their Limiting Oxygen Index (LOI) values were recorded to determine their flammability thresholds. LOI represents the minimal oxygen concentration required to sustain combustion — values higher than 20.9% (ambient oxygen level) indicate flame retardancy.

The incorporation of MEPPE and $TiO_2$NPs increased the LOI of the cotton fabric samples, indicating enhanced flame resistance. This result aligns with the growing body of research on bio-based and nano-enhanced flame retardants, including those using $TiO_2$ and pomegranate-derived compounds [7, 22, and 25]. The improved flame retardancy may be due to the synergistic effect of $TiO_2$'s hermal stability and MEPPE's char-forming bioactive compounds. Detailed LOI values and classifications are presented in Table 4.3.1 and bar chart

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**Figure. 4.3.1:** Flammability test of MEPPE + TiO2NPs finished cotton fabrics

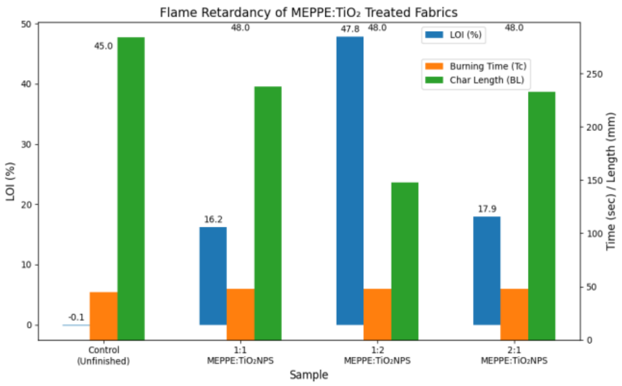
**Table-4.3.1:** Limiting oxygen index (LOI) values and its flammability classification

| *S. No.* | *Flammability* | *LOI (%)* |
|---|---|---|
| *1* | *Flammable* | *Less than 20.9%* |
| *2* | *Partially Stable* | *Equal to 20.9%* |
| *3* | *Self-extinguishing* | *21% to 28%* |
| *4* | *Stable (slow burning)* | *28% to 100%* |
| *5* | *Flame resistant* | *More than 100%* |

Tc – time of continue burning, BL – Burnt length

**Table-4.3.2:** Flammability test of MEPPE + TiO2NPs finished cotton fabrics

| *S. No* | *Samples* | *LOI (%)* | *Vertical Burning test* | | *Inference* |
|---|---|---|---|---|---|
| | | | *Tc (sec)* | *BL (mm)* | |
| *1* | *Control (Unfinished)* | *-* | *45* | *284* | *Flammable* |
| *2* | *1:1* | *16.2* | *48* | *238* | *Flammable* |
| *3* | *1:2* | *47.8* | *48* | *148* | *Stable* |
| *4* | *2:1* | *17.9* | *48* | *233* | *Partially stable* |



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## 5. DISCUSSION

The integration of microencapsulated pomegranate peel extract (MEPPE) with titanium dioxide nanoparticles ($TiO_2$NPS) in cotton fabric finishing demonstrates a successful strategy for achieving multifunctional textile enhancements, including antibacterial activity, stain resistance, and flame retardancy. These outcomes are consistent with, and in several cases surpass, previously documented effects of either $TiO_2$NPS or pomegranate-derived phytochemicals when applied independently.

### 5.1 Antibacterial Activity

The antibacterial efficacy of the finished fabrics was evident through the zone of inhibition values against E. coli and Staphylococcus aureus, with the 2:1 MEPPE:$TiO_2$NPS ratio yielding the highest inhibition (36 mm and 34 mm respectively). This supports previous findings on the antimicrobial potential of $TiO_2$ nanoparticles, which exhibit strong photocatalytic disinfection properties when exposed to UV light [4, 18, 31, 36]. Furthermore, the presence of phenolics, flavonoids, and tannins in pomegranate rind extract is well documented for their ability to disrupt bacterial cell membranes [6, 7, 30].

While prior studies have explored the antibacterial activity of either $TiO_2$ or pomegranate extract, the current study offers a synergistic approach combining both through microencapsulation. This not only enhances their stability and efficacy but also ensures sustained release onto the fabric surface, as supported by literature on grafting and cross-linking for improved textile binding [32, 33].

### 5.2 Stain Removal Performance

The enhanced stain removal capability, especially at the 1:2 MEPPE :$TiO_2$NPS ratio (Grade 5 – Excellent), demonstrates the effective self-cleaning behavior induced by $TiO_2$'s photocatalytic decomposition of organic stains [5, 17, 20, 38]. Additionally, the phytochemicals present in MEPPE may reduce surface energy and modify the wettability of the fabric, contributing to better stain release. This aligns with the development of functional coatings using $TiO_2$ and bioactive compounds for sportswear, workwear, and hospital textiles [2, 19, 21].

### 5.3 Flame Retardancy

Among all samples, the 1:2 treated fabric demonstrated the most significant flame retardancy, with a limiting oxygen index (LOI) of 47.8% and a reduced char length of 148 mm, indicating stable performance during vertical burning tests. This performance is in line with the flame-retardant effects reported for $TiO_2$ [13, 14, 24] and for plant-derived compounds like those from pomegranate rind [22, 23, 25]. The high flame retardancy may be attributed to the synergistic action of $TiO_2$ forming a thermal barrier and MEPPE contributing to char formation due to its high polyphenol content. These findings support the transition from toxic halogenated retardants to bio-based, environmentally friendly alternatives [15, 26, 27].

### 5.4 Integrated Functionality and Sustainability

The concurrent enhancement in antimicrobial activity, flame resistance, and stain removal positions MEPPE + $TiO_2$NPS as a green, multifunctional textile finish. The results align with the growing field of phytonanotechnology, which combines nanomaterials with plant-based compounds to deliver sustainable textile treatments [29, 34, 39]. Such multifunctional enhancements are particularly relevant in fields requiring high-performance textiles, such as healthcare, protective workwear, and sportswear, reinforcing the real-world applicability of the developed system.

### 5.5 Limitations and Future Perspectives

Despite these promising results, the study has certain limitations. Performance assessments were limited to lab conditions and did not evaluate washing durability, UV exposure stability, or mechanical abrasion resistance, which are crucial for real-life applications. Additionally, while microencapsulation improved material stability, future work should explore release kinetics and long-term bioactivity. Further research should also investigate scalability and cost-efficiency of the MEPPE -$TiO_2$NPS synthesis and application process, along with life cycle assessments (LCA) to verify environmental impact.

## 6. CONCLUSION

Based on the analysis of the antibacterial, stain release, and flammability properties of the MEPPE + TiO2NPs treated fabric samples, several key observations can be made:

1. Antibacterial Activity: The antibacterial performance of the finished fabric swatches significantly improved with the addition of TiO2NPs, with the 1:2 ratio of MEPPE + TiO2NPs showing the best results. The 1:2 sample demonstrated strong antibacterial activity, exhibiting a 32mm inhibitory zone against Escherichia coli and a 31mm inhibitory zone against Staphylococcus aureus. This is superior to the 1:1 and 2:1 sample ratios, which showed 27mm and 36mm inhibitory zones, respectively, confirming that the antibacterial properties are positively correlated with the concentration of TiO2NPs.
2. Flammability Resistance: Flammability tests, measured by the LOI (Limiting Oxygen Index) values, revealed that the fabric samples treated with the 1:2 ratio of TiO2NPs were the most stable, with an LOI of 47.8%, indicating slow burning or stability. In comparison, the 1:1 and 2:1 ratios were more flammable, with LOI values of 16.5% and 17.9%, respectively. This further demonstrates that a higher concentration of TiO2NPs enhances the fabric's resistance to combustion.
3. Durability: While the fabric samples treated with MEPPE + TiO2NPs exhibited promising antibacterial and flammability resistance properties, further studies are needed to assess the durability of these finishes. Specifically, the AATCC 124 wash durability test will be important to evaluate the long-term effectiveness of the TiO2NPs treatment.

In conclusion, the sample finished with a 1:2 ratio of MEPPE + TiO2NPs showed the most balanced and optimal performance in terms of antibacterial activity, stain release ability, and flammability resistance, indicating its potential for high-performance textile applications. Further research is required to confirm the durability and long-term stability of these treated fabrics.

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The writers affirm that they have no connections to, or engagement with, any group or body that provides financial or non-financial assistance for the topics or resources covered in this manuscript.

## 8. CONFLICTS OF INTEREST

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

## 9. PLAGIARISM POLICY

All authors declare that any kind of violation of plagiarism, copyright and ethical matters will take care by all authors. Journal and editors are not liable for aforesaid matters.

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