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USES OF TITANIUM DIOXIDE IN TEXTILE PRODUCTS

TİTANYUM DİOKSİTİN TEKSTİL ÜRÜNLERİNDE KULLANIMI

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ABSTRACT

This review study investigates the functional applications of titanium dioxide (TiO_2) in textile products. TiO_2 is a widely used metal oxide compound in the textile industry due to its high thermal stability, photocatalytic activity, and low toxicity. The study particularly focuses on various application areas of TiO_2. One of these is flame-retardant finishing processes, where the incorporation of TiO_2 can reduce the flame propagation rate in textile materials, thereby improving fire resistance. Another significant application is in functional textiles that emit far-infrared (FIR) radiation. Through the addition of ceramic-based materials like TiO_2, textile surfaces can emit FIR waves, which are known to offer health benefits such as improved blood circulation. Additionally, TiO_2 nanoparticles act as strong ultraviolet (UV) filters, protecting fabrics against harmful UV radiation and providing a high level of UV protection. Moreover, the applications of TiO_2 in nanofiber production, photocatalytic treatment of textile wastewater, bleaching of textile fibers, and the development of self-cleaning surfaces are also examined. The photocatalytic properties of TiO_2 enable the decomposition of organic contaminants and dyes under light exposure, imparting self-cleaning capabilities to fabrics and contributing to the removal of dye pollutants from textile wastewater. This study aims to provide a comprehensive overview of these applications by compiling and synthesizing findings from previously published research through an extensive literature review.

Keywords: Smart textiles, uv protection, fır textiles, flame retardancy, photocatalytic.

ÖZET

Bu derleme çalışmasında, titanyum dioksitin (TiO_2) tekstil ürünlerine kazandırdığı işlevsel uygulamalar araştırılmıştır. TiO_2, yüksek termal kararlılığı, fotokatalitik aktivitesi ve düşük toksisitesi sayesinde tekstil endüstrisinde yaygın olarak kullanılan bir metal oksit bileşiğidir. Çalışmada özellikle TiO_2'nin farklı kullanım alanları ele alınmıştır: Bunlardan ilki alev geciktirici terbiye işlemleridir. TiO_2 ilavesi, tekstil materyallerinde alev yayılım hızını azaltarak yanmazlık performansını iyileştirebilmektedir. Bir diğer önemli uygulama, uzak kızılötesi (FIR) ışıma yapabilen fonksiyonel tekstillerdir. TiO_2 gibi seramik katkılar sayesinde tekstil yüzeyleri FIR dalgaları yayabilir; bu da kan dolaşımını iyileştirme gibi sağlık açısından faydalar sunmaktadır. Ayrıca, TiO_2 nanopartikülleri güçlü bir ultraviyole (UV) filtresi olarak işlev görüp kumaşları zararlı UV ışınlarına karşı korumakta ve bu sayede yüksek düzeyde UV koruması elde edilmesini sağlamaktadır.
Bunlara ek olarak, TiO_2'nin nanolif üretiminde kullanımı, tekstil atıksularının fotokatalitik arıtımı, tekstil liflerinin ağartılması ve kendi kendine temizlenebilen yüzeylerin oluşturulması gibi alanlardaki uygulamaları da incelenmiştir. TiO_2'nin fotokatalitik özelliği, organik kirleri ve boyarmaddeleri ışık altında parçalayarak kumaşlara kendi kendini temizleme özelliği kazandırmakta ve tekstil kaynaklı atıksulardaki boyar madde kirliliklerinin giderilmesine imkân vermektedir. Bu çalışma, literatür taraması yoluyla, yayınlanan araştırmaları derleyerek TiO_2'nin tekstil sektöründeki tüm bu kullanım alanlarına dair kapsamlı bir bakış sunmayı amaçlamıştır. Çalışmanın metodolojisi kapsamında kapsamlı bir literatür taraması yapılmış ve elde edilen bulgular sentezlenerek sunulmuştur.

Anahtar Kelimeler: Akıllı tekstiller, uv koruma, fır tekstilleri, alev geciktirici, fotokatalitik

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INTRODUCTION

"Nano" comes from the Greek word "nanos" or "nannos" meaning small, old man, or dwarf. "Nano" is used for physical quantities on the scale of one billionth of a reference unit. It is therefore used in measurement concepts such as nanometer (length), nanosecond (time), nanogram (weight), and nanofarad (charge). Nanotechnology is a multi-disciplinary field. It consists of various technological and scientific disciplines. It has many application areas such as health, pharmaceutical industry, textile, space, electronics, automotive, food, and chemistry. Nanotechnology is used in medicine for drug development, diagnosis and treatment, prevention of traumatic wounds, and control of pain (Eroğlu, 2021). TiO_2 particles are widely used in textile research and are usually nano-sized (Radetić, 2013; Ciğeroğlu & Basyigit, 2024).

Titanium dioxide (TiO_2), renowned for its physicochemical stability and photocatalytic properties, stands out as one of the extensively manufactured and utilised nanoparticles globally and across Europe, finding applications in a diverse range of products (Ferreira et al., 2020). Nano TiO_2 is also one of the most attractive nanomaterials for functionalization of textiles due to its unique structural, physicochemical, optical and electrical properties, non-toxicity, and low cost (Rashid et al., 2021). TiO_2 nanoparticles find application in the textile sector for their UV-protection, photocatalytic, antibacterial, anti-dirt, anti-odor, and FIR properties. Titanium dioxide (TiO_2) is found in paints, plastics, papers, cosmetics, sunscreens, toothpaste, and various food products, where it is used as a whitening and brightening agent. Incorporating TiO_2 on fabric surfaces enables the creation of materials with superhydrophobic, UV-protective, self-cleaning, and flame-retardant characteristics (Ferreira et al., 2020; Yüce, 2022). Titanium dioxide (TiO_2) exists in nature in three main crystal forms: anatase, rutile, and brookite. Each phase is characterised by different crystal structures and properties. Anatase, which has a tetragonal structure, is generally preferred in photocatalytic applications. Thanks to its high surface area and suitable band gap, it is especially effective in solar cells and environmental treatment systems. Anatase transforms into the rutile phase at approximately 500-600°C. The rutile phase is also tetragonal and is the most thermodynamically stable TiO_2 phase. It is widely used in pigment and ceramic applications due to its high refractive index and density. Rutile maintains its stability even at high temperatures and is therefore favoured in high temperature applications. Brookite, which has an orthorhombic crystal structure, is a rare TiO_2 polymorph in nature. Although it exhibits photocatalytic properties, it is less used in industrial applications due to its stability and synthesis difficulties. Brookite transforms into the rutile phase above about 750°C. These different phases of TiO_2 show various physical and chemical properties due to differences in their crystal structures (Hanaor et al., 2012; Titanium dioxide, 2025).

In this study, the usage areas of titanium in the textile industry were examined. Firstly, the flame-retardant effect of titanium was mentioned. Then, far infrared ray (FIR) emitting properties, its use in textile products as a whitening agent, its use in nanofibres, its use in wastewater treatment, its self-cleaning properties, and finally its UV protective properties are mentioned respectively.

USE OF TIO_2 IN FLAME RETARDANT TREATMENT

Today, the increase in industrialization, the increase in mass settlements, and the development of technology have increased the risks of fire, thus making the use of flame-retardant textiles inevitable. Therefore, the use of flame-retardant fabrics in home textiles, automotive textiles, upholstery fabrics, etc., and fabrics that do not emit toxic gases when burned has gained importance. Although the main objective in obtaining a flame-retardant product is to prevent burning, the product should be environmentally friendly, have a strong impact, and have a long retention time. Apart from these, non-toxicity and low cost are among the features expected from a flame-retardant product (Ömeroğulları & Kut, 2012). New environmental, health, and fire regulations are now phasing out halogenated flame retardants (Paul, 2014).

The flammability of fabrics varies according to the type of fibre. For example, cellulosic fibres show very high flammability, while based on melamine synthetic fibres have a natural flame retardant (FR) structure. In general, natural fibres, such as cotton, linen, and silk, are easily combustible fibre types. Regardless of the type of fibres, the flame spread rate of fabrics also depends on the density and structure of the fabric; lightweight and loose fabrics are more prone to catch fire quickly. Most synthetic fibres, such as nylon, acrylic, and polyester, can be resistant to ignition. However, synthetic fabrics melt once ignited and their danger can increase because the high burning rate combined with the melting of the fabric can cause even more serious burns (Lam et al., 2011; Weil&Levchik, 2008).

Especially in cotton/polyester blended fabrics, the difficulty of extinguishing these fabrics increases due to the melting of polyester and the rapid burning of cotton (Carosio et al., 2014).
In a study, it was observed that TiO_2 particles had a significant effect on reducing the flame spread rate on cotton fabrics and also improved the tensile and tear strength of the fabrics (Lam et al., 2011). In the study by Moafi et al., cotton fabrics were treated with sol solution containing TiO_2. It was observed that the obtained fabrics were successful as flame retardant (Moafi et al., 2011).

Titanium and hexafluoro zirconate salts are used to improve the flame-retardant properties of wool textiles. These substances are applied to fabrics by the impregnation method in an acidic environment (Mazumder & Islam, 2021). Also, in another study, wool fabric treated with 1,2,3,4-butanetetracarboxylic acid (BTCA), phytic acid (PA), and TiO_2 nanoparticles exhibited good flame retardancy and much lower smoke formation (Cheng et al., 2018).
The mechanism by which TiO_2 imparts flame retardant properties to textile products is explained by the theories given below.

Increasing Char Formation: TiO_2 promotes the formation of a stable, protective char layer on the material surface during combustion. This char layer acts as a thermal barrier, reducing heat transfer and slowing down the combustion process. At the same time, TiO_2 catalyses the formation of cross-linked structures in polymers, making coal more resistant to thermal degradation (Lam et al., 2011; Li et al., 2015).

Heat Shielding and Radiative Cooling: TiO_2 has a high refractive index, meaning it reflects and scatters heat and infrared radiation. This property helps lower the surface temperature of materials, reducing the risk of further ignition (Ke et al., 2025; Infrared Reflecting Titanium Dioxide, 2025).

Oxygen Reduction in the Burning Zone: TiO_2 can release oxygen at high temperatures, which can participate in oxidation reactions. However, in some cases, it can also promote barrier effects that limit the diffusion of oxygen to the burning surface, reducing flammability (Bakulin et al., 2021).

TiO_2 nanoparticles can be applied to textile products by applying different methods. The main ones are padding method (Wiener et al., 2017; Yang, 2013), spray coating (Ortelli et al., 2020), exhaustion (Li et al., 2018), coating (Yüce, 2022; Radetic, 2013), incorporation into fibre spinning (Esen et al., 2006), in-situ synthesis (Sadr&Montazer, 2014), and plasma treatment methods (Nasadil&Benešovský, 2008).

As a result, TiO_2 inorganic particles are finding applications for the purpose of providing flame retardancy. However, inorganic nanocomposites such as TiO_2 alone are not sufficient as flame retardants. They do not pass important flame retardancy tests and may need additional conventional flame retardants as auxiliary additives to increase their effectiveness (Neisius et al., 2014).

THE USE OF TIO_2 IN THE EMISSION OF FAR INFRARED RAYS (FIR)

The term infrared radiation (IR) encompasses electromagnetic waves with a wide range of wavelengths, ranging from visible light to terahertz frequencies. Infrared radiation can be analysed in three different regions. These are near infrared (NIR), mid infrared (MIR), and far infrared (FIR) radiation. Far infrared rays (FIR) include rays with wavelengths between 5.6-1000 microns and are invisible to the human eye. Of the sunlight, 47% is infrared, 46% is visible light, and 7% is ultraviolet radiation (Kızılötesi, 2025). Many studies have reported that FIR radiation in the 4-14 μm wavelength range is beneficial for human health (Vatansever & Hamblin, 2012; Dyer, 2011; Shih et al., 2015). The benefits of these rays are summarized below.

- ✓ It increases the amount of oxygen in the blood,
- ✓ Rejuvenates muscle tissues and skin,
- ✓ Provides tissue regeneration and rapid healing,
- ✓ Improves nervous system function,
- ✓ Reduces lipids in skin tissue,
- ✓ Improves metabolism,
- ✓ Increases blood circulation,
- ✓ Increases oxygen delivery and nutrition to soft tissue,
- ✓ Helps to remove accumulated toxins,
- ✓ Relaxes muscles and improves sleep quality (Dyer, 2011; Lou&Lin, 2011; Qin et al., 2024).

There has been a growing interest in far infrared (FIR) textiles, which have demonstrated health benefits. Giving FIR properties to textile products can be realized by using bioceramic additives. All ceramics have the ability to emit IR radiation depending on their temperature (Vatansever & Hamblin, 2012). Bioceramic materials can emit far infrared rays (Dyer, 2011; Cian et al., 2015; Stamatoski & Fidoski, 2017). These ceramic additives (particles) are micro or nano sized. Some compounds used to impart FIR properties to fabrics or textile products are as follows: TiO_2 (Song el al., 2021; Yüce et al., 2022), SiO_2 (Chung & Lee, 2014; Yüce et al., 2022), Al_2O_3 (Kim, 2022; Wei et al., 2020), MgO (Singh & Panwar, 2022; Shim et al., 2009), CeO_2 (Jie et al., 2014; Xue et al., 2010), ZrC (Li et al., 2019), Ge (Chung & Lee, 2014; Sankauskaitė et al., 2020).

Ceramics increase thermal insulation by reflecting FIR radiation emitted from the body back to the body surface. FIR radiation emitted from the human body comes to these ceramic particles, which act as "absorbers" and then reflect the FIR radiation back to the body (Cian et al., 2015). Researchers have concluded that ceramic particles absorb FIR rays emitted by the human body and retain heat, thereby reducing the temperature difference between the body and the garment. As a result, textiles containing ceramics help retain body heat more effectively (Sankauskaitė et al., 2020).

TiO_2 can emit FIR rays in the wavelength range of 8-10 μm with a value of 0.941 ε (Lee et al., 2011). Therefore, the use of TiO_2 is common in the production of FIR-enabled textiles. When the mechanism of TiO_2 enhancing FIR emission is analysed, the high refractive index of TiO_2 ($n \approx 2.5$) provides an advantage in absorbing and re-emitting infrared radiation and improves FIR emissivity in textiles (Refractive index.info; Yao et al., 2009). TiO_2 can help maintain temperature and increase thermal comfort by converting absorbed light into heat energy (Xia et al., 2024). In addition, nano-TiO_2 particles can be incorporated into fibres or coatings to increase the surface area for FIR radiation absorption and emission (He et al., 2023; Yüce, 2022).

Titanium dioxide particles can be added to fabrics by various methods. One of these methods is realized by feeding TiO_2 particles in masterbatch form to the spinnerets during synthetic fibre extraction (Kim, 2022). The properties obtained with this method are more permanent. Another method is the addition of particles into the coating paste and coating or lamination of the prepared paste on the fabric surface (Yüce et al., 2022; Shim et al., 2009). Nanofibres containing TiO_2 can also be produced by the electrospinning method. In the study by Song et al., nanofibres were obtained by the electrospinning method using TiO_2 and SiO_2 nanoparticles (Song et al., 2021).

UTILISATION OF TIO_2 IN NANOFIBRES

Nanostructured textiles generally consider surfaces with fibre diameters smaller than 100 nm. At the same time, nanofibres with diameters between 100-500 nm are also of great technological importance and these fibres are often used in nanofibre research when innovative fibre spinning techniques are needed. Nanofibres in the diameter range of 20 - 500 nm are 10-500 times finer than standard spinnable fibres, and the latest technological productions should be preferred as fibre spinning techniques (Salem, 2007). Nano fibres produced by using the electrospinning method are used in many application areas such as chemical and biological protective materials, gas sensing materials, moisture sensing, photo-sensing materials, solar clothing, wound dressings, tissue scaffolds, drug delivery, and solar cells (Ghosal et al., 2019; Someswararao et al., 2018).

TiO_2 has three crystal phases. These are: anatase, rutile, and brookite. These structures affect the physicochemical properties and application areas of TiO_2 differently. Controlling the crystal structure, whether anatase, rutile, or brookite, allows fine-tuning. For example, anatase is generally better for photocatalysis, while rutile is more stable for pigments. This control enables TiO_2 to fulfil specific needs, such as increasing solar cell efficiency or improving water purification. Therefore, the control of the crystal structure at the nanoscale is very important for the application of TiO_2. In particular, the morphology of the crystal phase and nanofibres is affected by the calcination temperature (Eddy et al., 2023; Luttrell et al., 2014; Nuansing et al., 2006; Li & Xia, 2003).

Recently, TiO_2-based nanofibres produced by electrospinning have attracted great interest due to their wide potential applications. The electrospinning process is based on placing the polymer solution in the feeding unit and creating an electrical field between the metal needle tip and the collector surface. The physical, chemical, and morphological properties of nanofibres in the electrospinning method are affected by solution (viscosity, conductivity, molecular weight, etc.), environment (humidity, temperature, etc.), and production (electrical power, flow rate, needle tip, etc.) parameters (Nuansing et al., 2006; Duygulu, 2020).

Nano titanium dioxide (TiO_2), which has attractive properties such as biocompatibility, biodegradability, and non-toxicity, has been studied in various nanofibre applications (Gupta et al., 2013; Costa et al., 2016; Hong et al., 2009; Song et al., 2008). In the study by Gupta et al, titanium precursor was electrosprayed simultaneously during the preparation of poly(lactic acid) (PLA) electrospun fibres. The resulting hybrid nanofibre structure showed a 70% reduction in bacterial growth (Gupta et al., 2013). Costa et al. also produced poly(lactic acid) (PLA)/titanium dioxide anatase (TiO_2) nanocomposite fibres by the solution blow spinning (SBS) technique. It was stated that the SBS method was effective in nanofibre applications, and the presence of TiO_2 increased the biodegradation behaviour. This is an important parameter in biodegradable membrane production (Costa et al., 2016).

TiO_2 nanofibres have been investigated as photoanode materials for the application of dye-sensitised solar cells (DSSCs). Dye-sensitised solar cells (DSSCs) are a type of thin-film solar cell that uses a photosensitive dye to convert sunlight into electricity. Unlike conventional silicon-based solar cells, DSSCs rely on a process that mimics photosynthesis, making them a promising low-cost alternative for solar energy harvesting. However, photoanode materials based on 1D-TiO_2 nanostructures have been improved due to their low dye adsorption in relation to surface morphology. For this purpose, Li et al. worked on the design of dye-sensitised solar cells. Acidification and oxygen plasma treatments were applied to improve the dye adsorption and conversion efficiency of dye-sensitised solar cells (DSSCs) based on TiO_2 nanofibres obtained by electrospun. An increase of 17% in energy conversion efficiency was observed as a result of acidification and O_2 plasma treatment of nanofibre structures (Li et al., 2013; Koyama et al., 2009).

UTILISATION OF TIO_2 IN TEXTILE WASTEWATER TREATMENT

Textile finishing involves various processes (sizing, alkali treatment, bleaching, washing, desizing, rinsing, mercerizing, dyeing, etc.) that generate large quantities of wastewater (Holkar et al., 2016; Pekakis et al., 2006). Textile wastewater contains high biological oxygen demand (BOD), chemical oxygen demand (COD), nitrogen, colour, acidity, high suspended solids, high dissolved solids, surfactant, dyestuffs, heavy metals, and other soluble substances due to the use of various types of chemicals. The most typical characteristic of textile effluents is that they have strong colours due to residual dyes. In addition, textile dyes account for just over half of the world's organic colourant production (Al-Mamun et al., 2019). Another characteristic of textile finishing wastewaters is that they are resistant to waste removal due to the presence of compounds such as dyes, surfactants, and sizing agents, high salinity, high temperature, and variable pH (Yaseen & Scholz, 2019). Given the complex and bio-resistant character of textile wastes, their effective treatment and especially their decolorization often requires a combination of various physical, chemical, and biological technologies. Among these techniques, those of practical interest are: adsorption on activated carbon, coagulation and flocculation followed by sedimentation or dissolved air flotation, reductive cleavage of dyes containing azo or other reducible groups, oxidative chlorine and ozone degradation, electrochemical oxidation and aerobic and anaerobic biological treatment (Periyasamy, 2024; Li et.al, 2022; Christian et al., 2023; Pekakis, 2006).

Photocatalytic degradation of organic compounds in aqueous media with TiO_2 has been studied since the mid-1960s. Since then, research on the use of TiO_2 for photo-oxidation of organic compounds, removal of inorganic compounds and (toxic and valuable) metal ions, and disinfection of water has been of considerable interest (Horikoshi & Serpone, 2020). Furthermore, heterogeneous semiconductor photocatalysis using TiO_2 as a photocatalyst is of great interest for water and wastewater treatment (Lazar et al., 2012; Choi et al., 2007).

Some doping processes have been applied to improve the properties of TiO_2 for use in wastewater treatment. Doping agents used to improve the performance of photocatalytic materials (especially semiconductors such as TiO_2 and ZnO) are applied to increase light absorption, lower the band gap, and reduce recombination rates. Some of these doping chemicals are Fe^{3+} (Iron), Cu^{2+} (Copper), Cr^{3+} (Chromium), Ni^{2+} (Nickel), Co^{2+} (Cobalt), Nd^{3+} (Neodymium), Ce^{3+} (Cerium), Eu^{3+} (Europium), La^{3+} (Lantanium), Silver (Ag^{+}), etc (Dharma et al., 2022; Amaechi et al., 2019; Zaleska, 2008). One of the widely used of these doping chemicals is neodymium. Neodymium is one of the rare earth elements and is often used for doping in photocatalytic materials. When neodymium is doped into semiconductor materials such as TiO_2 and ZnO, it is used to improve optical properties, lower the band gap, and increase photocatalytic activity. This improves their effectiveness in the treatment of wastewater (Lal et al., 2024).

Lal et al. studied the effect of neodymium doped TiO2 and ZnO in the treatment of wastewater. In the study, the photocatalytic activity of both nanostructures was tested on textile wastewater by measuring biological oxygen demand (BOD) and chemical oxygen demand (COD). The maximum degradation rates under UV and solar

irradiation were 96% and 89% for Nd-TiO2 and Nd-ZnO, respectively (Lal et al., 2024). Pekakis et al. investigated the main factors affecting the photocatalytic treatment of a real textile dyehouse wastewater. Among these factors, the photocatalytic efficiency of different crystalline forms of TiO_2, the effect of catalyst concentration, the pH of the solution, and the effects of hydrogen peroxide addition were emphasized. The possibility of recycling the photocatalyst was also evaluated within the scope of the study. The results showed that TiO_2-mediated photocatalysis with UV-A irradiation can decolorize and sufficiently purify textile wastewater consisting of reactive dyes, inorganic compounds, and other organic auxiliary chemicals. The strength of the treatment varied with TiO_2 concentration, pH value, amount of oxygen dissolved, and presence of extra hydroxyl. The importance of catalyst recycling and reuse was also emphasized from an economic point of view (Pekakis et al., 2006). In a study conducted by Ambaye and Hagos, the decolorization of real textile dye (Azo dye, Reactive Black 5) wastewater was investigated using TiO_2 and H_2O_2. As a result of the study, the photocatalytic pre-treatment of textile wastewater altered the composition of its components and enhanced subsequent biological degradation, indicating its potential application in textile wastewater treatment plants. Additionally, it was stated that the TiO_2/H_2O_2/UV process, along with the optimization of microbial consortium and culture conditions, is a promising technology for textile wastewater treatment not only for colour removal but also for dye mineralization (Ambaye&Hagos, 2020).

USE OF TIO_2 IN THE BLEACHING OF TEXTILE PRODUCTS

Textile bleaching is a process applied to remove the natural colour of fibres or to make the fabric white. This process is usually done to prepare the fabric for dyeing. Photocatalysis is a photochemical method of converting UV irradiation energy into chemical energy, forming radicals and similar unstable chemical structures. Titanium dioxide shows photocatalytic properties under UV light and raw cotton products can be bleached by photooxidation formation under UV light using TiO_2. It can be said that bleaching of cotton products with TiO_2 is a more environmentally friendly method than conventional methods (Eren & Özenç, 2023; Gedik, 2020). TiO_2 is also added to the extruder during fibre extrusion to impart opacity to polyester fibres (Karasu, 2020). TiO_2 is also used as a whitening agent in toothpastes (Monteiro et al., 2020).

Although bleaching with TiO_2 is not yet widely used in industry, research shows that it offers a more efficient and less environmentally damaging process, especially for cotton fabrics. In the photocatalytic bleaching process, TiO_2 is applied to the fabric, and under UV light, it generates active oxygen species that break down natural colours and impurities, resulting in a whiter and brighter fabric (Eren & Özenç, 2023; Basyigit & Ciğeroğlu, 2024). Research suggests that this method could reduce the use of chemicals, like H_2O_2, that can damage the fabric and decrease energy consumption, which is a significant advantage for sustainability. For example, some studies show that better whiteness can be achieved at lower temperatures compared to traditional methods. (Basyigit & Ciğeroğlu, 2024; Bleach Clean-up in Textile Production, 2014). The photocatalytic approach adapts to sustainability trends by reducing chemical and energy use. However, the presence of titanium dioxide nanoparticles in soil poses potential ecological risks, such as TiO_2 nanoparticles discharged into the environment and accumulation in sewage sludge from the washing of textiles, and requires further investigation (Solymos et al., 2024).

Eren and Özenç studied the bleaching of cotton fabrics by the photocatalytic effect. In the study, bleaching of cotton fabrics was carried out with TiO_2 particles at room temperature using UV rays. It was observed that TiO_2 alone caused an increase in whiteness values, while the combination of TiO_2 and H_2O_2 led to higher whiteness values under UV irradiation. It was also observed that the whiteness levels of all TiO_2 added samples were higher than the raw fabric. Furthermore, the whiteness of TiO_2-containing fabrics was compared after treatment with UV light and after treatment without UV light. It was observed that the whiteness index of the samples treated with UV light was higher (Eren & Özenç, 2023).

Montazer and Morshedi investigated the photo-bleaching of wool. They used nano TiO_2 and utilised daylight as a light source. It was reported that wool fabric bleached by photobleaching achieved better whiteness values than bleached with hydrogen peroxide. In addition, other advantages of loading nano TiO_2 on woolen fabrics include self-cleaning, UV protection, antibacterial, and anti-felting properties (Montazer & Morshedi, 2014).
In another study by Montazer and Morshedi, scouring and bleaching of raw cellulosic fabrics using the photocatalytic activity of TiO_2 was studied. Desized cotton fabrics coated with TiO_2 were treated with UV-A and daylight. It was observed that the hydrophilicity and whiteness values of cotton fabrics increased with increasing TiO_2 concentration (Montazer & Morshedi, 2012).

SELF-CLEANING ACTION OF TIO_2

The self-cleaning effect breaks down dirt and facilitates the cleaning of surfaces, and is used in coatings for buildings and fabrics. The previously mentioned bleaching effect focuses on colour. TiO_2 is also used in dental care for the whitening effect of toothpastes. Both effects mainly utilise the photocatalytic properties of TiO_2. TiO_2 is a non-toxic chemical and has reasonable stability with well-positioned valence. It has also been reported to exhibit self-cleaning, photocatalytic effects, and has the ability to modify surfaces when exposed to UV radiation (Eren & Özenç, 2023; Gedik, 2020). Nano-sized anatase TiO_2 has been widely used as an effective photocatalyst for the photodegradation of organic pollutants in various phases due to its thermostability, cheapness, non-toxicity, strong oxidising power, and long-term photostability (Moafi et al., 2011).

Many companies produce glass and building materials with TiO_2-based coatings that have self-cleaning properties. At the same time, it is desirable that textile products that cannot be washed, such as bus seats, train upholstery, chair fabrics, childcare centres, etc., have self-cleaning and deodorizing properties. For this purpose, the self-cleaning feature can be realized by coating an inorganic chemical such as TiO_2 in anatase form, which exhibits high photocatalytic properties, on the surface of fabrics. During the first stage of the process, when exposed to UV irradiation, an electron is generated within the conduction band, creating a hole in the valence band. In the second stage, the resulting electron and hole interact with adsorbed pollutants to form unstable radicals that decompose into carbon dioxide and water (Prorokova et al., 2017; Park et al., 2013). To put it another way, in the first stage, when TiO_2 is exposed to ultraviolet (UV) light, photons with energy equal to or greater than its bandgap (~3.2 eV for anatase) excite electrons from the valence band to the conduction band, creating electron-hole pairs. In the second stage, these highly reactive species interact with adsorbed organic pollutants, water molecules, and oxygen, generating hydroxyl radicals (OH) and superoxide anions (O_2^-), which break down contaminants into harmless byproducts such as carbon dioxide and water (Photocatalysis, 2025; Titanium dioxide, 2025).

Compared to other photocatalysts like Zinc oxide (ZnO) and Tungsten (VI) Oxide (WO_3), anatase-phase TiO_2 is preferred due to its strong oxidation ability, chemical stability, and non-toxicity (Damkale et al., 2021; Hernández et al., 2015; Baia et al., 2016). However, its photocatalytic activity is primarily activated under UV light, limiting its efficiency under natural sunlight. To address this, researchers have explored doping TiO_2 with elements such as nitrogen, carbon, or transition metals to extend its activation into the visible light spectrum, enhancing its practical applications (Etacheri et al., 2015).

This self-cleaning technology has significant implications for textiles used in healthcare, outdoor environments, and protective clothing. Fabrics coated with TiO_2 can degrade stains, bacteria, and pollutants, reducing the need for frequent washing and improving hygiene. However, challenges such as the durability of coatings, adhesion to fibres, and potential loss of photocatalytic efficiency over time remain areas of active research. Future advancements in nanotechnology and material engineering may further optimize the stability and effectiveness of TiO_2-based self-cleaning fabrics (Padmanabhan & John, 2020; Tudu et al., 2020). One of these challenges is the difficulty of TiO_2 coating on polyester. We can summarize these challenges as follows: The nanostructured coating needs to be firmly bonded to the surface of PES fibres. Since the number of carboxyl and hydroxyl functional groups in poly(ethylene terephthalate)-based fibres is low, high adhesion cannot be achieved, so TiO_2 cannot be firmly bonded to the fibre surface. At the same time, since the surface of PES fibres is smooth, it is difficult for TiO_2 to adhere to the fibre surface. Another challenge is that in order to impart high photocatalytic properties to the fibres, a significant amount of TiO_2 has to be applied. This will negatively affect the hand of the fabrics (Prorokova et al., 2017; Radetić, 2013). In a study conducted to overcome these adverse conditions, polyester fibres were coated with nano TiO_2. Some of the fabrics were pre-activated, and some were not pre-activated. Pre-activation increases the amount of extra active functional groups on the fibre surface and increases the surface roughness, providing suitable conditions to increase the adhesion of TiO_2-based coatings. In the study, pre-activation processes were carried out with NaOH or plasma. It was observed that TiO_2 nanoparticles remained on the surface of the pre-activated PES fabrics without settling in the inter-fibre space. This significantly increased the photochemical activity of the modified fabric (Prorokova et al., 2017). In a study by Yuranove et al., RF-plasma, MW plasma, and UV-irradation pretreatments were applied to polyester and wool-polyamide fabrics for better binding of TiO_2 particles. At the same time, TiO_2 particles were also bonded to cotton products. According to the results, photochemical decolourisation/cleaning of wine and coffee stains in the presence of TiO_2 particles was successful in normal daylight (Yuranova et al., 2007).

USE OF TIO_2 IN PROTECTION AGAINST UV RADIATION

Ultraviolet (UV) is an electromagnetic radiation with a wavelength shorter than visible light but longer than X-rays. It comes to Earth from sunlight and makes up about 7% of the total electromagnetic radiation emitted from the Sun (Kızılötesi, 2025). If not protected from these rays, it can cause effects ranging from simple tanning to advanced skin cancer. Sunscreen creams, clothing, and shade structures can provide protection against the harmful effects of UV rays (Saravanan, 2007). In addition, ultraviolet rays are analysed in three wavelength ranges as UVA (320-400 nm), UVB (290-320 nm), and UVC (100-290 nm). UVC range rays, having an energy of about 4.43-12.4 eV, can cause more serious harm than UVB and UVA (Gautam et al., 2016).

For this reason, it is preferable that textiles have UV protection, especially in summer. UV protection textiles are designed to provide protection against harmful ultraviolet radiation and offer reliable defence for both clothing and shading applications. These specialized fabrics offer various advantages over traditional sun protection methods. The Ultraviolet Protection Factor (UPF) indicates the level of protection offered by UV protective clothing. The most essential feature required from these fabrics is having a high UPF. UV-protected fabrics can achieve Ultraviolet Protection Factor (UPF) values of up to 50+, which is considered excellent protection (Sun-Protective Clothing). Some textile products can even reach a UPF value of 80, allowing users to stay in the sun up to 80 times longer than their skin's natural protection time (Textiles - optimum protection from harmful UV rays - Hohenstein). At the same time, UV radiation is one of the main causes of degradation of fibres, and therefore textile materials, as it stimulates some parts of the polymer molecule and creates a loss of integrity over time (Saravanan, 2007; Mishra & Butola, 2019). UV rays also cause deterioration of food packaging and can cause a reduction in the storage life of food products. For this reason, storage products in the food industry are required to block UV rays (Gautam et al., 2016). The UV protection factors of fabrics can be increased through various properties or treatments. The following summarizes some of the ways in which fabrics can have high UPF ratings:

- **Tightly woven or knitted:** Fabrics with a dense weave naturally block more UV rays (Dubrovski and Golob, 2009).

- **Content of Fabric:** Synthetic fibres like polyester and nylon tend to offer higher UV resistance than natural fibres (Islam et al., 2019; Eltuğral, 2021).

- **Chemical Treatments:** Some fabrics are treated with UV-absorbing chemicals to enhance their protective properties (Seentrakoon et al., 2013; Kara et al., 2024).

- **Dyes and Finishes:** Certain fabric dyes and special finishes can absorb or reflect UV radiation, improving the UPF rating (Dubrovski and Golob, 2009).

It has been reported that inorganic fillers are added to polymer matrices to block UV rays (Gautam et al., 2016). Among additives for UV protection of textiles, inorganic TiO_2 is an important compound due to its excellent blocking properties against UVA and UVB radiation (Rashid et al., 2021). The UV protective properties of TiO_2 are attributed to both its chemical and physical properties, and the working principle of the protection mechanism is still under discussion. In fact, TiO_2 has been found to absorb UV radiation regardless of particle size due to its semiconducting properties. On the other hand, TiO_2 is assumed to impart UV protection through reflection and/or scattering of UV radiation due to its high refractive index (Gautam et al., 2016; Mishra & Butola, 2019).

Titanium dioxide (TiO2) is effective in providing UV protection due to its ability to absorb UV radiation and convert it into less harmful energy. When TiO_2 nanoparticles are added to fabric, they give it an Ultraviolet Protection Factor (UPF) (Rabiei et al., 2022). While standard summer clothing has a UPF of around 6, protective textiles usually have 50+. This means that if 50 units of UV fall on the fabric, only one unit will pass through to the skin. This makes it common to use TiO_2 to provide UV protection in summer and sportswear (Ferreira et al., 2020). In particular, the band gap of amorphous TiO_2, in which atoms are arranged irregularly, is higher than the band gap of crystalline TiO_2. This promises higher protection against UV harmful rays, especially in the UVC region (Gautam et al., 2016).

In a study by Seentrakoon et al., composite surfaces were prepared with natural rubber and TiO_2 particles, and UV protection of these surfaces was evaluated. In this study, the importance of carbonyl absorption peaks at 1715 cm^{-1} wavelength measured in ATR-FTIR spectrum to evaluate UV protection was emphasised. Carbonyl peaks formed in

the wavelength range of 1715 cm^{-1} increased as a result of exposure of the sample to UV radiation. As a result of the study, the positive effect of TiO_2 presence on UV protection was mentioned (Seentrakoon et al., 2013).

The study by Kara et al. involved the treatment of cotton fabrics with various concentrations of nano-TiO_2 and ZnO in both uniform and hybrid forms. It is intended to evaluate multifunctional properties including UV protection, self-cleaning, wettability, and photocatalytic activity. It was observed that UPF values of cotton fabrics coated with TiO_2 increased, UVA and UVB transmittance decreased. It was observed that the protection factor increased with the increase in the amount of TiO_2 on the fabrics (Kara et al., 2024).

CONCLUSION

Since TiO_2 has semiconductor, white pigment, physicochemical stability and photocatalytic properties, its use in textile products and other applications of textiles (waste treatment) is of great interest. In this study, photocatalytic self-cleaning, UV protection, flame retardancy, and far infrared radiation emission properties resulting from the application of TiO_2 on textile surfaces, as well as the treatment of textile wastewater, are discussed.

TiO_2 inorganic particles do not pass important fire tests, and therefore auxiliary additives are needed to increase their effectiveness. Since TiO_2 emits far infrared rays at high emissivity values, it has also been used to impart FIR properties to textile products. As a result of the photocatalytic properties of TiO_2 under UV light, it can bleach textile products. TiO_2 can also be added to the extruder during fibre extrusion to impart opacity to polyester fibres. TiO_2 nanofibres have been used in photoanode materials in solar cells (DSSCs) and have been observed to increase energy efficiency. Self-cleaning of fabrics is important in some uses (non-washable uses). For this reason, it has been observed that TiO_2 can self-clean and photochemical colour removal by taking advantage of its photocatalytic properties. UV protection of clothing is especially important in summer. For this reason, TiO_2 has gained importance in UV protective textiles as it absorbs UV rays and at the same time scatters these rays due to its high refractive index. In addition, it has been reported that TiO_2 is effective in the treatment of textile wastes, especially in the decolourisation of wastewater containing dyes, and is effective in reducing the chemical oxygen demand (COD).

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