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Textile Finishing Using Polymer Nanocomposites for Radiation Shielding, Flame Retardancy and Mechanical Strength

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Review

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ABSTRACT

The uses of nanotechnologies in textiles are strategic and allow textiles to become multifunctional. There is an ever-increasing demand for new functionalities, like flame retardancy, radiation shielding, improved mechanical strength etc., for highly specific applications. There is no industrial supply for the above-mentioned functionalities. Keeping in view of this background, surface treatment becomes one of the most important methods to create new textile properties. Polymer nanocomposites based on coatings for textiles have a huge potential for innovative modifications of surface properties like flame retardancy, radiation shielding and improved mechanical properties, which can be applied with a comparatively low technical effort and at moderate temperatures. This review compiles recent research on polymer nanocomposites for functional finishing of textiles to understand the theoretical and experimental tools on polymer nanocomposites and their applications in textiles.

KEYWORDS

Textile finishing, Polymer nanocomposites, Radiation shielding, Flame retardancy, Mechanical strength

INTRODUCTION

Functionalization of textiles is very important in view of improving their properties. The first commercial application of nanofinishing materials is found in textiles in the form of nanoparticles through finishing processes. But these finishes do not withstand subsequent washing due to poor fixing of these nanoparticles on the textile surface. Polymer nanocomposites are materials with high potential for developing a new class of coating system for textiles to overcome the above problem. Polymer nanocomposites are polymers usually filled with less than 10% of nanometre sized inorganic particles. They are superior in properties when compared to the conventional polymer composites [1-4]. The current research on textiles is focused on exploitation of the unique characteristics of polymer nanocomposites in textile industry. There are many synthetic methods followed to prepare polymer nanocomposites [5-7]. But the common theme of these approaches is intermingling the nanometre scale inorganic particles with properties not available from either of the pure component materials integrated in nanocomposites.

Multifunctional finishing of textiles

The uses of nanotechnologies in textiles are strategic and allow textiles to become multifunctional. The application of polymer nanocomposite coatings on textiles imparts various functionalities, like UV protection, antibacterial properties, flame retardancy, antistatic properties and radiation shielding. The addition of nanoparticles to the hydrophobic/hydrophilic functional polymers will improve the properties of the polymer with the additional incorporation of the functional properties of nanoparticles. Hydrophilic finishes on textiles are very important to impart absorbency in the applications of sportswear. The inorganic UV blockers are non-toxic compared to the organic UV blockers and they are chemically stable at a high temperature and exposure to UV. TiO_2 , SiO_2 , ZnO and Al_2O_3 are the certain inorganic oxides used as UV blockers [8,9]. In another work, zinc oxide nanoparticles were prepared by a wet chemical method and ZnO -PMMA nanocomposites were prepared by dispersing the ZnO nanoparticles in the solution of poly (methyl methacrylate) (PMMA) and applied on polyamide fabrics by padding. The results also showed that the impregnation of fabrics with ZnO -PMMA nanofinishings also enhanced the protection of polyamide fabrics against the UV radiation [10]. For imparting antibacterial properties, nanosilver, titanium dioxide and zinc oxide are used [11-14]. Textiles treated with nano TiO_2 could provide effective protection against bacteria and discoloration or stains due to the photo catalysis effect [15,16]. Nano ZnO has photo catalytic properties when illuminated by light and it imparts antibacterial properties to textiles [17-19].

Raza et al. studied the fabrication of chitosan/zinc oxide nanocomposites (CZNCs) by using a facile preparation method. The nanocomposite-coated cotton fabric exhibited durable antibacterial, UV-blocking and textile properties with a fair whiteness index [20].

Ulfqar et al. developed an antibacterial viscose fabric via a clean, easy and reproducible approach. Silver nanoparticles (SNPs) were prepared using chitosan both as a reducing and as well as a stabilizing agent to promote a green synthesis of SNPs. The developed treated viscose fabric showed good antibacterial properties, with fair textile characteristics. This is the first report on *in situ* fabrication and the impregnation of SNPs using chitosan as both a reducing and a stabilizing agent on a regenerated cellulose fabric like viscose [21].

Xiaoning et al. produced a knit polyester fabric simultaneously with remarkable electrical conductivity, water-repelling and photocatalytic activity properties through the aid of chitosan and polyaniline nanocomposite polymer. A facile fabrication of multifunctional knit polyester fabric was based on chitosan and polyaniline polymer nanocomposite [22]. For almost two decades, the nanofinishing of cellulose textile material while using copper and copper oxide nanoparticles has been in the focus of science and textile industries [23].

Textile surfaces need to be pre-treated making certain functional groups available for bonding with the polymer nanocomposite finishing. Hydroxylamine treatment and plasma discharges are the treatments used for the fabric surface pre-treatment of [24,25]. Studies on plasma treatment of cotton and linen, wool and synthetic fibres proved that this treatment improves the whiteness degree, removal of waxes and sizing agents, absorption and fixation of dyes and finishing agents, increases the durability of functional effects and is able to provide certain functional groups available to bind with polymer nanocomposites [26-30].

Multi-functional finishing of cotton fabrics by plasma with nano $\text{TiO}_2/\text{SiO}_2$ via pad dry method was studied by Palaskar et al. and it was observed that the textile surface modification by the plasma treatment reduced the concentration of chemicals by 20-25%, thereby reducing environmental pollution and proving to be cost effective in comparison to the conventional finishing technique [31]. Research work has been carried out on atmospheric pressure dielectric barrier discharge plasma treatment for fabric surface activation to facilitate deposition of nano silicon oxide and nano-titanium dioxide onto cotton fabric. It has been found

that the flame retardancy, UPF, antibacterial activity, wash fastness and thermal stability of the treated samples were improved compared to the untreated samples [32].

APPLICATION OF POLYMER NANOCOMPOSITES FOR DESIRED FUNCTIONAL PROPERTIES IN TEXTILES

Out of the many possible applications of polymer nanocomposites for functional properties other than surface properties (Figure1) some of the most successful ones are antimicrobial, UV protection, flame retardancy, radiation shielding and improvement of mechanical properties of textiles. Our earlier review paper on polymer nanocomposite-based multifunctional coatings on textile, covered various properties like UV resistance, hydrophilicity, hydrophobicity and antimicrobial properties [33]. Focus of this review will be on the application of polymer nanocomposite finishings on textiles to impart fire retardancy, enhanced mechanical properties and radiation shielding properties.

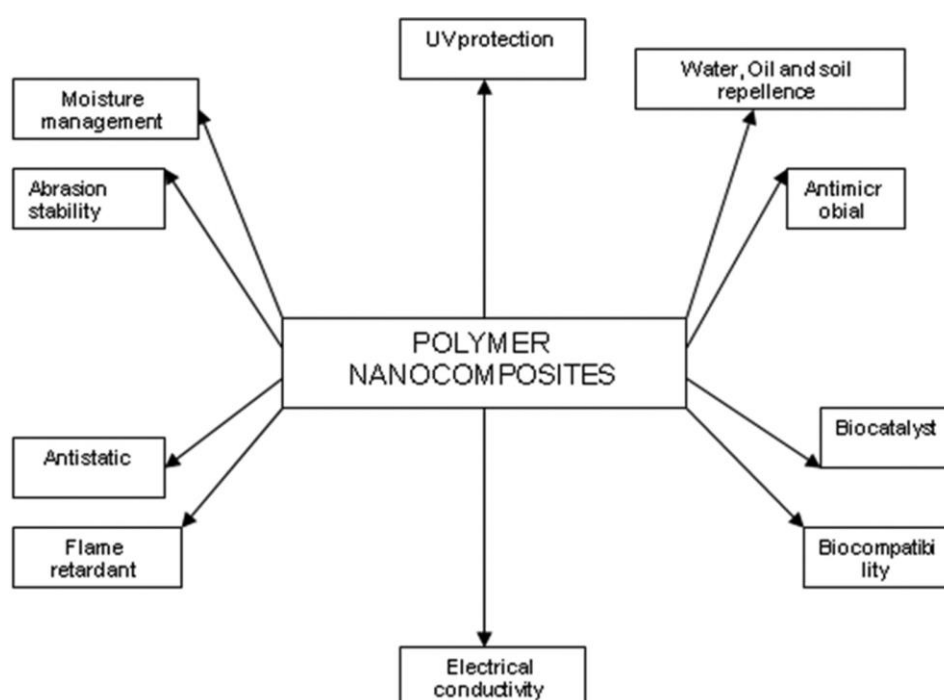
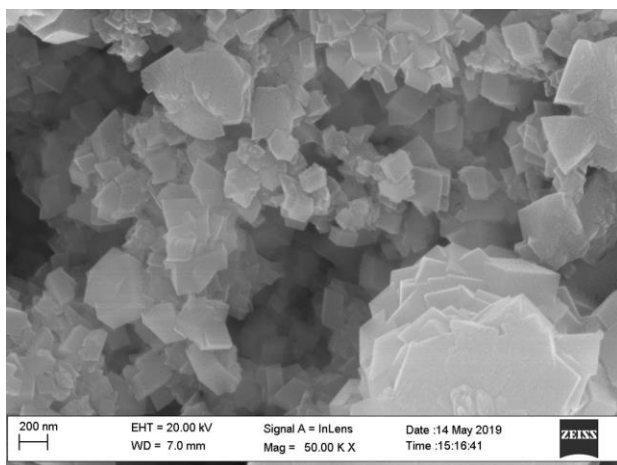
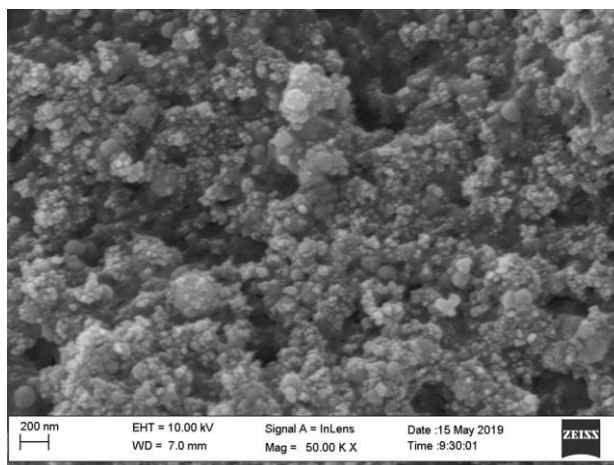
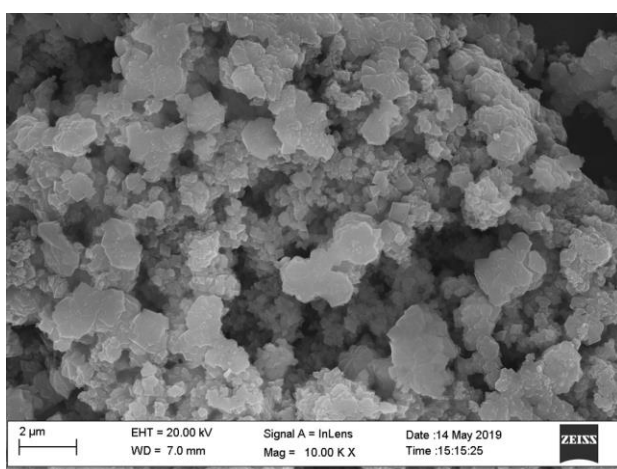
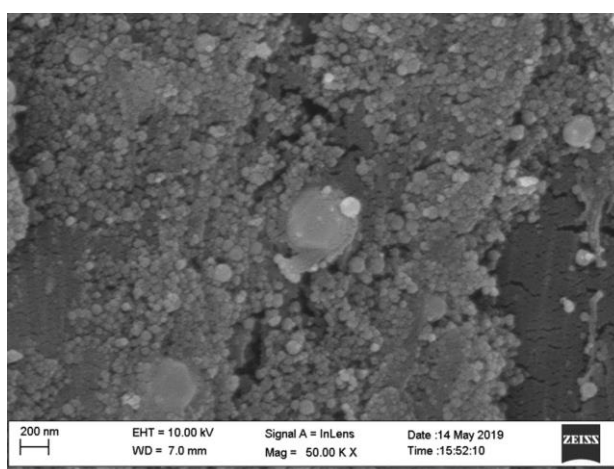


Figure 1. Some possibilities of textile functionalization using PNC

Dispersion of nanoparticles to get a homogeneous solution is very difficult, since there is a strong tendency of the nanoparticles to aggregate. However, in polymer nanocomposites the polymers inhibit the aggregation and significantly increase the stability of the composite making their application in many fields easier. Sorna Gowri et al. [34] synthesized a new copolymer epoxy poly (dimethyl acrylamide) to disperse the SiO_2 nanoparticles and developed a new method for the dispersion of nanoparticles. The results showed that the nanoparticles are well dispersed in epoxy poly (dimethyl acrylamide) as evidenced by the SEM analysis. Our recent unpublished results on polyvinyl alcohol-based polymer nanocomposites show that it is a good functional polymer system, which can be used for the dispersion of many inorganic nanoparticles (Figures 2, 3, 4, 5) since it is compatible with a number of inorganic nanoparticles.

Figure 2. SEM image of PVA film with Al_2O_3 Figure 3. SEM image of PVA film with SiO_2 Figure 4. SEM image of PVA film with TiO_2 Figure 5. SEM image of PVA film with Fe_2O_3

There are two principal ways for the application of polymer nanocomposites on textiles. One is melt spinning of PA-6 yarns, which can be knitted or woven [7]. Another approach is coating the textile surface by polymer nanocomposites formulations. Application of these polymer nanocomposites coatings can be done by simple techniques such as pad application dip coating, spray coating, or exhaust process. One interesting method of polymer nanocomposite synthesis is in situ polymerization in which polymer nanocomposites are developed from nanoparticles.

Application of Polymer Nanocomposites as Flame Retardants in Textiles

To inhibit or suppress the combustion of fabrics, flame retardants are applied to fabrics. Many flame-retardant approaches have been developed and are used today by the textile industry [35]. If typical flame retardant finish is applied to the fabric, it adversely affects the fabric properties, such as drape and hand [36]. Also, some of the flame-retardant additives release toxic products during combustion, which is of concern regarding the environment [37].

Polymer nanocomposites are a new class of organic/inorganic hybrid material showing impressive performance for fire retardant application. Polymer-layered silicate nanocomposites are being investigated widely for their flame retardant effect. It is found that the addition of 2-5 wt% of layered silicates like montmorillonite (MMT) reduce the peak heat release rate (PHRR) during the burning of polymers by about 50-60% [38-44]. While the addition of conventional flame retardants deteriorates the mechanical properties of

polymers in most cases, tensile strength and the modulus of nano components with above 5 wt% of nano-fillers are enhanced by 30-40% when compared with neat polymers [45-48]. Kadiravan et al. investigated the flame-retardant properties of nylon 6/organically modified montmorillonite (DMMT) fibres and fabrics, and they found that with a higher concentration level of 8-10% DMMT, the fabrics burned without any dripping [49]. The flame spread rate was reduced by 30-40% compared to the nylon 6 films and the peak heat-release rate of nylon 6 was reduced by 65-67% with this content.

Devaux et al. studied the addition of two kinds of additives to PU in order to provide flame retardancy to the coated textile structure, namely montmorillonite clay and polyhedral oligomeric silsesquioxanes (POSS) [50]. Polypropylene (PP) is one of the most widely used thermoplastic polymers for application in textiles and plastics. This is attributed to its low density, low cost, easy processing, high tensile strength and excellent chemical stability [51-54]. Consequently, similar to other polymeric materials, the properties such as flame retardancy, UV resistance, crystallization behaviour, strength, hygienic behaviour and electrical resistance of PP fibres have been modified by compounding them with very small amounts of nanoparticles. Some examples of these attempts are observed in products like PP/silver [55], PP/SiO₂ [53,56-59], PP/Ba Fe [60-62], PP/TiO₂ [63,64]. Nilufer et al. produced slow burning or flame-retardant polypropylene filaments for carpet pile yarns by incorporating SiO₂ nanoparticles into polypropylene [65]. The oxygen index test was used in their studies to evaluate the flammability of polymers, because this test is a useful method to get single numerical value of relative flammability of polymeric fibres. Materials between the thresholds 20.95% < LOI < 28% can be considered as slow burning materials in the oxygen index test. It has been found that filaments containing 1 and 3% of SiO₂ nanoparticles reach the limit value of slow burning materials in the oxygen index test, thus obtaining a fire-resistant filament for the carpet pile yarn.

Gillain et al. reported the burning behaviour of knitted fabrics produced from PP fibres comprising of several dispersed nanoclays and compatibilizing copolymers in the presence of ammonium polyphosphate (APP) as a model conventional fire retardant with regard to flammability when present alone [66]. Polylactic acid (PLA) is a biodegradable polymer which can be spun to produce textile fibres. In order to disperse the clay in PLA, two techniques are used: the solution-intercalation process [67,68] and the melt-blending process [69-73]. The interaction between the carbonyl functions of PLA chains and hydroxyl functions of alkyl ammonium surfactants surface-covering MMT nano platelets seem to improve the dispersion of this organoclay in a PLA matrix contrary to the other kinds of MMT without hydroxyl functions on the surfactants. [67,69-72]. An original way to obtain a good dispersion of clay in PLA matrix is the in-situ coordination-insertion polymerization [74]. The PLA nanocomposites are characterized by an increase of the crystallization rate but also by a decrease of the activity to crystallize, so by a lower melting enthalpy compared to pristine PLA [67,70,74]. But the clay does not seem to influence the glass transition temperature of second order of PLA [67,70,74]. An improvement of the thermal stability of PLA can be obtained, especially when MMT Cloisite is used [67,75]. The above studies show that the flame retardancy of neat polymers like poly urethane, polypropylene and PLA, can be improved by the addition of inert nanoparticles to the polymer system.

In 2002, for the first time, Bourbigot et al. described the use of a polymer matrix to produce a nanocomposite multifilament yarn [76]. The matrix they used was a polyamide 6 polymer (PA6) reinforced with commercial MMT Cloisite 30B (C30B). The flammability of a knitted structure made with PA6 and PA6/C30B yarns was compared using a cone calorimeter and a strong decrease of the heat release was observed in the last case. A method to produce PLA organoclay nanocomposites was proposed by Samuel et al. [77]. They prepared PLA organoclay nanocomposites by melt-blending and particularly by twin-screw co-rotating extrusion. It was shown that C30B increases the crystallization rate and improves the thermal stability, especially for PLA/4%C30B.

These polymer nanocomposite-coated textile fabrics showed excellent fire-retardant property evaluated by 45° flame test as per ASTM D1230-94 [78]. The flame-retardant cotton fabric was also developed by electrospinning polyamide/boric acid nanocomposites [79]. A one-pot approach based on coatings of sodium carboxymethylcellulose (CMC)/montmorillonite (MTM) polymer nanocomposites of bio-inspired brick-wall nanostructure on textiles was demonstrated by Paramita Das et al. Fire retardancy tests of these textile coatings elucidated the increasing fire barrier and the retardancy properties with the increasing coating thickness [80].

Yu-Chui Li et al. demonstrated a layer-by-layer assembly of branched polyethylenimine (BPEI) and sodium montmorillonite (MMT) clay nanocomposite coatings on cotton fabrics for imparting flame retardant properties. The treatments showed that all coated fabrics reduced the total heat releasing capacity of the fabric. These coatings are expected to be useful on a variety of substrates, like foam, fibre etc., as flame retardants [81]. In a research work, cotton fabric was coated with polypyrrole–zinc oxide–carbon nanotube (PPY-ZnO-CNT) composites prepared by an in situ chemical polymerization method. The composite-coated cotton was found to have better flame retardant properties than the uncoated cotton [82]. A polymer nanocomposite was developed from carbon nanotubes and different phosphorous flame retardants, like ammonium phosphate, or melamine phosphate resin. The fabrics were coated by these composites. The fabric flammability tests were carried out and it was found that the coatings effectively reduced flammability and improved the thermal stability of the fabric. It has been observed that there was a synergistic effect between carbon nanotubes and phosphorous compounds [83]. A facile coating method for imparting flame retardancy to a silk fabric was developed, which involved montmorillonite (MMT) and graphene oxide (GO) hydrosol being added to polyvinyl alcohol, which was then coated onto the silk fabric by a simple coating machine. The analysis of the coated silk fabric showed excellent flame retardancy, thermal stability and smoke suspension properties [84]. Ihor et al. studied the effect of styrene acrylate and urethane polymer coatings filled with titanium dioxide on the thermophysical properties of a cotton fabric surface and found that the presence of polymer nanocomposite coating leads to the formation of coke residue on the fabric under the influence of the flame, which allows the fabric surface structure to be preserved after ignition [85]. The above results show that treating various fabrics, like cotton, nylon and silk, by various polymer nanocomposite finishings, dramatically improves their fire resistance.

Influence of Polymer Nanocomposites Finishes on Mechanical Properties of Textiles

The application of polymer nanocomposites may affect fabric properties, like strength and bending rigidity. The addition of certain nanoparticles to neat polymers imparts improved mechanical strength to polymer nanocomposites and these polymer nanocomposites, applied as finishings on textiles, influence the mechanical strength of textiles. Polypropylene (PP)/organic-layered silica nanocomposites are attractive systems which impart improved mechanical properties, while simultaneously increasing dimensional stability, stiffness, strength and impact resistance [86-88]. By preparing PP nanocomposites in situ, with in situ formation of silicate nanoparticles by using an interlayer silicate modified by n-alkyl primary amine and PP-g-MA compatibilizer, an improved exfoliation of uniformly dispersed anisotropic nanoparticles was achieved [89]. The exfoliation of organoclay affords the in situ nano filler, which behaves as clay building bricks, to be uniformly dispersed into the PP matrix. The storage modulus was found to be three times that of the pure PP [88]. The improved mechanical properties of PP nanocomposites were attained by using SiO₂-g-PS nanoparticles, obtained by the modification of SiO₂ through the irradiation-grafting polymerization of styrene [90]. The elastic modulus of the syndiotactic polypropylene (SPP) nanocomposites, based on organophilic layered

silicates and grafted PP as compatibilizer, was higher over a wider temperature range than that of the unfilled SPP [91]. Zita Mlynarcikova et al. studied the influence of the spinning process on the properties and morphology of the SPP nanocomposite fibres [92]. From the mechanical and morphological study of the above nanocomposites, it has been found that the filler and the compatibilizer highly influenced the spinning process. In their work, the extruded sPP nanocomposite fibres were drawn on a vertical elongation device (at 708°C). The values obtained from the measurement of the tensile strength of the fibres of both the non-filled sPP and the sPP nanocomposite fibres showed that the non-filled sPP fibres have relatively high tensile strength values in comparison with the iPP nanocomposite fibres at the same drawing ratio. It is known that porous materials are better assimilated by living organisms, considering their similar structure to that of hard tissues [93]. Therefore, it is important that the precursor fibres for biomedical applications should be characterized by an increased porosity [94]. On the other hand, typical, highly porous precursor fibres are characterized by having an inadequate level of tensile strength. It is also known that the tensile strength of carbon fibres directly depends on the strength of the precursor fibres [95]. Therefore, in the case of manufacturing PAN fibres dedicated for the production of carbon fibres for medical applications, it is important to select process parameters in such ways that the fibres obtained would have a relatively high porosity and, at the same time, tensile strength that would allow for carrying out the carbonization process without any problems. The tensile strength of textile fibres also significantly depends on the type and the amounts of nano additives added to the fibre matrix which in turn influences the interactions with the polymer matrix [96-98]. If carbon nanotubes are added to the fibre matrix, an increase in the fibre tensile strength is observed depending on the nanotube type and amount [99,100]. T. Mikolajczyk et al. examined how the addition of silver nanoparticles to polyacrylonitrile spinning solutions influences their rheological properties as well as the structure and properties of the fibres produced [101]. Consequently, tensile strength properties were only a little lower than those of the fibres without silver nanoparticles, although there was a significant increase in porosity.

Ceyhan Celik et al. studied the mechanical and electrical properties of the polymer blend of a tactic polystyrene and poly(phenylene ether) containing 5.0 wt% of graphite nanoparticles [102]. It was observed that the lack of bonding between the polymer and the nanoparticles resulted in reduced extrinsic mechanical properties. Both the tensile strength and elongation of the fibre were 20-25% less than those of the neat fibres. The modulus of the oriented fibre was unchanged by the addition of the graphite nanoparticles. The dip coating of the nanocomposite solution of organosilanes was done on textiles and it has been found that these super hydrophobic coatings showed good mechanical properties in terms of abrasion, scratch resistance and adhesion on the textiles. In addition to these properties, the coatings improved the tensile strength and elongation at break of the textiles [103].

Yadav et al. prepared ZnO nanoparticles and applied them on cotton fabrics using acrylic polymer as a matrix [104]. Along with the UV-blocking property, they studied and evaluated the friction and the mechanical properties of the treated fabrics. The friction was significantly lower in the case of nano ZnO-coated fabric than in bulk ZnO-coated fabric, due to the nano size and distribution. CNT-polyacrylate composites and CNT polybutacrylate composites were applied onto cotton fabrics using a simple surface coating method. The coated cotton textiles exhibited enhanced mechanical properties, flame retardancy, improved UV blocking and super hydrophobic properties [105].

A novel polyester fabric, with enhanced mechanical properties and photo-, bio- and magneto-activated by the in situ synthesis of TiO₂/Fe₃O₄/Ag nanocomposites, which were coated onto the fabric surface, was developed by Tina et al. It has been shown that the tensile strength properties of the treated sample were enhanced when compared to the untreated fabric. The bending rigidity of the treated sample was reduced

by 76% in comparison to the untreated fabric, indicating a softer handle of the fabric [106]. The cotton fabric was finished with the PPMACC-AGE/MMT composite prepared by the polymer intercalation method. The tensile strength of the treated fabric was superior to that of the untreated fabric. It has been observed that the presence of montmorillonite in the composite was responsible for the improvement of thermal and flammability properties of the treated fabric [107].

In another research work, polymer nanocomposites were prepared from mixers of resin / clay, with various percentages of clay, and applied onto cotton fabrics. The mechanical properties were enhanced by the coatings and the maximum clay percentage to enhance the mechanical performance was from 4% to 5% [108]. The tensile strength of the woven fabric coated with the MWCNTPP polymer composite showed optimum increase in tensile strength at 2 wt% of MWCNT added to the composite. The tensile strength of knitted fabric is higher in the wale direction than along the course direction [109].

Preetam et al. [110] prepared cotton fabric coated with graphite nano platelets filled polyaniline-gum Arabic nanocomposites and analysed the mechanical properties of the coated fabric. It has been observed that fabric coated with 3wt% Gnp/PANI-GA nanocomposites showed enhanced tensile strength of 145 N in the weft direction. The effect of polymer nanocomposite finishings on various types of textiles is indicated in Table 1.

Table 1. Effect of the polymer nanocomposite finishing on mechanical properties of some of the textile samples

S.No.	Textile sample	Nanofiller	Polymer	Impact on the mechanical properties of textiles	Reference
1.	Cotton	Zinc Oxide	Acrylic polymer	The nano-ZnO coating was found to reduce the tensile strength of the fabric in the warp direction, with no significant change in the weft direction. The strain reduced significantly in both warp and weft directions.	(Yadav et al. 2006) 104
2.	Cotton	CNT	Polybutacrylate	The tensile strength improvement of the CNTs-coated cotton fabrics along the warp direction, indicating that after being coated with the CNTs both the loading capability and flexibility (displacement) have been improved.	(Liu et al. 2008) 105
3.	Cotton	MMT	PPMACC-AGE	The breaking strength of the fabrics finished with PDMDAAC-AGE/ MMT was superior to those of the unfinished fabric and the fabric finished with PDMDAACAGE. The bending length of finished fabrics was slightly higher than that of unfinished fabrics.	(Gao et al.2016) 107
4.	Cotton	Clay	PU & PAC	The mechanical performance of the fabric is globally increased versus the amount of clay in the two used resins. The maximum clay percentage to enhance the mechanical performance of a fabric is between 4% and 5%.	(Elamin et al. 2015) 108
5.	Woven fabric	MWCNT	Polypropylene	The maximum tensile strength along the weft direction of conductive woven fabrics is present when 2 wt% MWCNT is added. When the MWCNT content exceeds 2 wt% the tensile strength along the weft direction decreases, the agglomerated MWCNT forms stress concentration sites, thereby decreasing the tensile strength of conductive woven fabrics at higher concentration of 3 wt% of MWCNT.	(Zheng-lan et al. 2017) 109
6.	Cotton	Graphite nanoplatelets	Polyamide-gum Arabic	In another study the authors carried out In-situ polymerization to prepare GnP (Graphene nanoparticles) filled polyaniline-gum arabic (GnP/PANI-GA) nanocomposites. It has been observed that cotton fabric coated with 3 wt% GnP/PANI-GA nanocomposite showed enriched tensile strength of (145 N) in weft direction	(Preetam et al. 2019) 110

Polymer Nanocomposites for Radiation Shielding Fabrics

X-Ray Shielding Textiles

Lead-based material is generally used as a radiation-shielding material but due to its toxicity and severe health concerns its use poses, it is advisable to avoid these materials for such applications. Recently, X-ray protective materials based on lightweight nanoparticles have been gaining in importance. Nanoparticles can be successfully included in polymer matrices of X-ray and gamma ray shielding materials. Polymer nanocomposites proved to be an alternate solution for lead-based materials due to the properties like light weight, cost-effectiveness and a high potential for significantly attenuating X-rays. To shield from the high energy radiation, high density of the polymer is the main criteria. The following Table 2 gives density and theoretical value of linear attenuation coefficient of some commercially available polymers.

Table 2. Polymers and their density and linear attenuation coefficient at 276 keV [111]

S.No.	Polymer	Density (in g/cc)	Linear attenuation coefficient (cm ⁻¹)
1.	Polyamide (Nylon 6) (PA-6)	1.13	0.1362
2.	Polyacrylonitrile (PAN)	1.18	0.1370
3.	Polyvinylidene chloride (PVDC)	1.63	0.1819
4.	Polyaniline (PANI)	1.36	0.1576
5.	Polyethylene terephthalate (PET)	1.38	0.1581
6.	Polyphenylenesulfide (PPS)	1.35	0.1550
7.	Polypyrrole (PPy)	1.48	0.1701
8.	Polytetrafluoroethylene (PTFE)	2.20	0.2330

The radiation-barrier effects of polymer nanocomposites are attributable to the increased number of particles dispersed per unit of mass and also to the size effects at the nanometric dimension. Therefore, the use of polymer nanocomposites as a finishing on textiles with the purpose of radiation protection may have important advantages in terms of effective radiation shielding, lightweight and to replace the toxic lead and lead composites. A lot of work has been carried out on the use of polymer nanocomposites for X-ray and gamma ray shielding applications [112-114]. PDMS nanocomposites containing different weight (%) of bismuth oxide were studied by Nambiar et al. for the radiation attenuating properties, and they concluded that PDMS composites can be used as protective coatings [115]. To avoid lead aprons, Huda Ahmad et al. explored the suitability of bismuth oxide coating on textiles as an alternative to lead. It is evident from their study that bismuth oxide in a suitable resin matrix can be coated onto fabrics and that it is an effective method of providing flexible, wearable and lead-free aprons [116].

Aprons made of lead are being widely used to protect X-ray technicians and patients from harmful radiations, with lead oxide being widely used as a protective material since the beginning of making protective aprons, but the weight and toxicity of lead are important limitations [116,117]. In all these aprons, nylon/polyester fabrics are used as the casing for lead sheets [118]. There are some examples of radiation shielding materials without lead as well as those lighter than lead-based materials that are available. [119-122]. Polymer nanocomposites used for fabricating radiation shielding fabrics have been tested by many researchers [123,124]. An exploratory research was carried out at CSIR-AMPRI, Bhopal to develop X-ray shielding cotton fabrics based on the MWCNT (multi wall carbon nanotubes) nanocomposites. The cotton fabric was treated with plasma and the MWCNT coating in sodium dodecyl sulfate (SDS) was applied by dip

coating. The SDS-treated MWCNT and the coated fabric were studied under SEM (Figures 6(a), 6(b), 7(a) and 7(b)). As seen from Figure 6(a), the raw MWCNTs are in the form of agglomerated bundles and have a more fibre-like structure. These bundles were broken down into separate tubes and became shorter due to the sonication during the SDS (surfactant) treatment (Figure 6 (b)), since the treatment of MWCNTs with surfactants shortens the length of the MWCNTs.

The FE (field emission)-SEM microscopy image of the MWCNT-coated fabric at different magnifications shows a microfibril structure. The FE-SEM figures show the pores of cotton fabric without the coating, being the pore walls formed from fibre bundles, and thus feature an interstice structure as shown in Figure 7(a). Figures 7(a) and 7(b) show that the MWCNT coating can effectively fill the pores and enwrap the walls of the pores i.e., the interstices of fibre bundles, thereby forming a shielding layer on the cotton fabric. Studies on evaluation of these MWCNT-coated cotton fabrics for X-ray shielding are in progress.

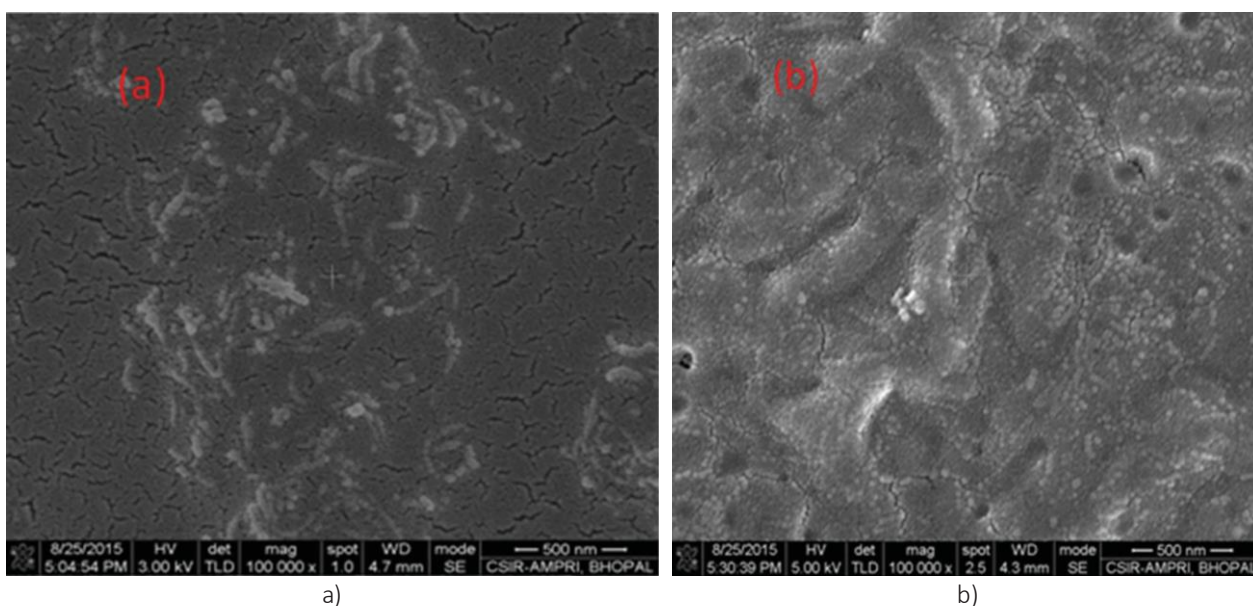


Figure 6. (a) SEM image of untreated MWCNT and (b) SEM image of MWCNT treated with SDS

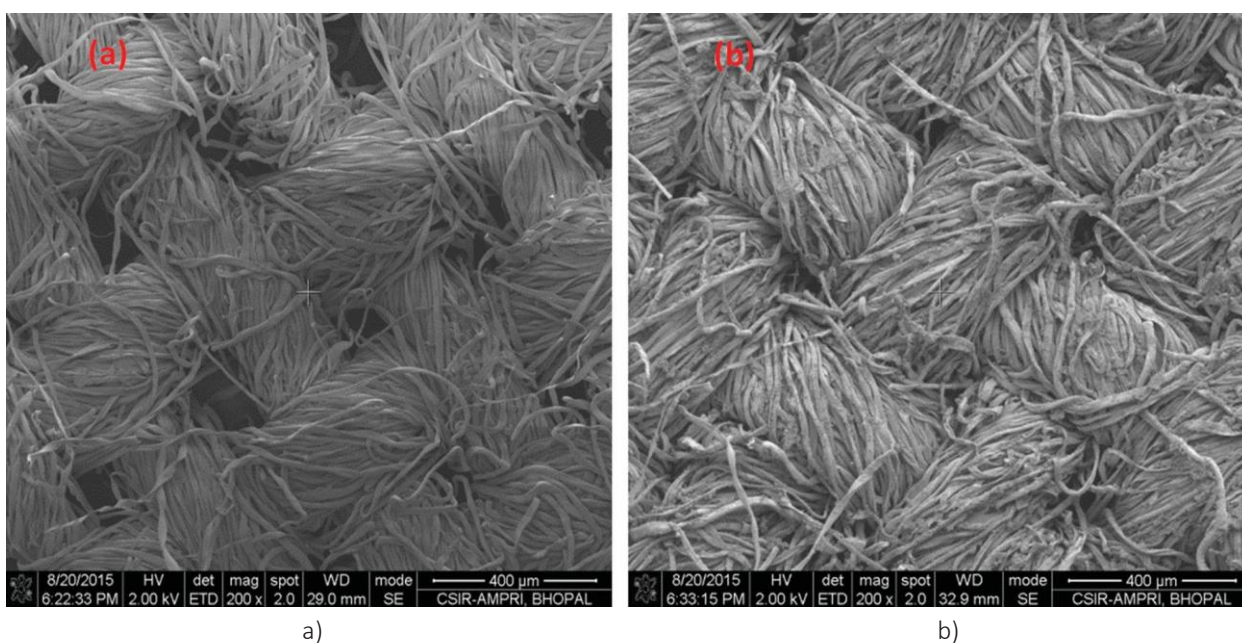


Figure 7. (a) Uncoated cotton fabric (b) MWCNT-coated cotton fabric

EMI/Microwave Shielding Fabrics

In recent years there has been a demand for using treated textiles for electromagnetic shielding applications. Textiles can be used for EMI shielding in protective garments [125,126]. EM shielding depends on electrical conductivity of the material, but textile materials are insulators and they can be made conductive by being treated with electrically conductive materials [127-130]. Shalu et al. synthesized the electrically conductive polypropylene (PP) and jute nonwoven fabrics by a chemical oxidative polymerization process [131]. The surface resistivity of PPy-coated PP nonwoven fabric was found to be superior to that of the jute nonwoven fabric.

Carbon nanotubes are potential materials for EMI shielding due to their electrical properties, high surface area, lightweight and mechanical properties. Carbon nanotubes have cylindrical nanostructure and they are allotropes of carbon. The cylindrical carbon molecules have unique electrical, thermal and mechanical properties, which are valuable for nanotechnology and other fields of material science and technology. Due to the simplicity of process and ease of handling, coating the textile surface with polymer nanocomposites is a suitable method among various textile treatment methods [132-134].

Electrically conductive polymer composites have received much attention recently compared to the conventional metal-based EMI shielding materials [135]. They are corrosion resistant, flexible and easy to process due to their lightweight. Carbon nanotubes are one of the effective candidates for EMI shielding as the filler in polymer composites [136,137]. Nargis and Ismail have investigated cotton fabrics coated with polyamide 6 (PA6)/multiwalled carbon nanotubes with varying amount of MWCNT for electromagnetic shielding properties and the effects of MWCNT loading on electrical resistivity, shielding effectiveness, shielding mechanism and also electromagnetic interference. They found that the highest electromagnetic shielding effectiveness value was obtained at 20wt%MWCNT [138].

Durable electromagnetic interference-shielding cotton fabric was prepared by Lihua Zou et al. with Nafion-MWCNT coatings. It has been shown that, in addition to the satisfactory shielding ability, the treated fabric exhibited good durability and superhydrophobicity [139]. Personal protective garments with high performance in EMI-shielding properties were prepared by Mingwei et al. via layer-by-layer self-assembly approach. In this work poly(sodium 4-styrene sulphonate) PSS was used as a polyanion and chitosan was adopted as a polycation with graphene added by solution mixing. The resultant fabric exhibited EMI-shielding ability with the maximum SE value of 30.04 dB [140].

In a study by Sundaramoorthy et al. different conducting and non-conducting fabrics were taken for an analysis of the EMI-shielding ability. It was found that the surface resistivity can be used to predict the EMI shielding ability of the fabric due to a strong inverse relationship between these parameters [141]. Tellakula et al. carried out the fabrication of impedance-graded composites containing polyurethane, carbon nanotubes, carbon fibres, and micro balloons. Polypyrrole (PPy) fabrics with different surface resistances were used along with these composites, and experiments were carried out to find the effect of the PPy fabric. It was found that both the surface resistance of the fabric and its location in the composite are critical for the reflection property of the electromagnetic absorber [142].

A methodology and a material for the production of flexible, lightweight and porous conductive fabric for EMI shielding was reported by Renata et al. These novel shielding fabrics were fabricated by coating with the carbon-nanotube composite consisting of polymers and metal nanoparticles. The EMI shielding of the fabric was 95-99.99% (40 dB) and CNT was found to be the most effective shielding material [143]. It has been shown by Mazeyar Gashtiet al. that nano zircon can be used in various polymer nanocomposites and textile coatings to increase the EM reflection properties. In this work, nano ZrO₂ particles were stabilized

on wool surface by using citric acid as a cross-linking agent and sodium hypo phosphate (SHP) as a catalyst under the UV radiation. The results indicated that stabilized nano zirconia enhanced the flame retardancy and electromagnetic reflection of wool [144].

It has been reported that the fabric preforms made from multiwalled carbon nanotubes and carbon fibres, which were reinforced in epoxy resin to make composites, produced significant electromagnetic shielding effectiveness of -51.1 dB for CF-MWCNT/epoxy composites with the thickness of 2 mm [145]. Mazeyar Gashti et al. developed a method for the production of polypyrrole-based nanocomposites which can be applied as high electromagnetic shielding on textiles. In this method polypyrrole was prepared by a one-step UV-inducing polymerization by using AgNO₃ as a catalyst for the oxidation of pyrrole monomers [146]. A simple and convenient approach for the fabrication of EMI-shielding textiles was developed by Lihua et al. In their work polyaniline-coated (PANI) carbon nanotube (CNTs) coating has been deposited onto a commercial fabric. The coated fabric had an exception EMI SE of 23.0dB. Simultaneously, the polymer nanocomposite-coated fabric exhibited a high adsorption ratio of the incident electromagnetic energy with distinguished EMI-shielding performance [147].

In a recent research work, phase separated PEDDT-PSS, ornamented with reduced graphene oxide (rGo) nano sheets, was deposited on the newly fabricated ultra-lightweight superhydrophobic merino wool/nylon (W-N) composite textile by a dipping and drying method. The coated textile showed electromagnetic shielding efficiency of 73.8dB (in the X-band) and the hydrophobicity of the coating lead to an excellent EMI-protective cloth, combined with an excellent performance under high mechanical or chemical tolerance [148]. Recently Shivam et al. reported zinc oxide and reduced graphene oxide-coated cotton fabric for the application of EMI shielding in the X-band (8.2-12.4GHz). The coated cotton achieved highest total EMI-shielding effectiveness of -99.999%. Such high EMI shielding is attributed to highly dielectric ZnO nanoparticles, highly conductive rGo sheets and the core shell structure of the coated cotton fabric [149].

Mengwei et al. reported a facile approach with excellent EMI-shielding performance using polyurethane and a filler consisting of 80% of CNT and 20% of graphene nanoparticles applied onto the textile by a dipping method. The electromagnetic interference shielding effectiveness (EMISE) of the coated textile could achieve 35dB with the thickness of 0.35mm and the reflectivity of ca.41.4% [150]. The comparison of the above results show that the EM properties and the EM absorption properties of polymer nanocomposites are increased with the increase in percentage by weight (wt%) of nanofiller materials like CNT, carbon fibres and graphene oxide.

Polypyrrole PPY/Al₂O₃ nanocomposites were prepared by the polymerization of pyrrole by using iron trichloride (FeCl₃) as an oxidant in the presence of Al₂O₃ nanoparticles. The obtained nanocomposites absorbed more than 53% of the incident microwave radiation after passing through a thick composite-coated textile [151]. Research work has been carried out to load amine functionalized multiwalled carbon nanotubes (NH₂-MWCNT) onto the polyester-fabric surface to obtain microwave shielding fabrics. The best microwave shielding properties were obtained from the fabric treated with plasma, which was then coated with 10% of NH₂-MWCNT in the presence of acrylic acid [152].

CONCLUSION

Polymer nanocomposites are a promising material with a potential for various applications in the textile industry, with regard to imparting various functional properties to textiles. In this review we have discussed radiation shielding, flame retardancy and enhanced mechanical properties of the textiles treated with polymer nanocomposites. It is evident from the earlier extensive research work that polymer nanocompos-

ites are a new class of organic/inorganic hybrid material showing impressive performance for fire retardant application. Earlier research studies also show it is possible to improve some of the mechanical properties such as tensile strength and stiffness of the textiles by the application of certain polymer nanocomposite finishings. Recent research works on radiation shielding textiles suggest carbon nanotubes are a good candidate for imparting radiation-shielding property to the polymer nanocomposite finishing.

Polymer nanocomposite finishings open up a new area of textile finishing by which a wide range of technical textiles can be produced. Multifunctional textiles finished with polymer nanocomposites, which are manufactured by environmentally friendly processes, are highly efficient. Textile products finished with polymer nanocomposites have wide applications in the handloom industry, the manufacturing industry and textile industries. Keeping in view the industrial application of polymer nanocomposites the further research work must be carried out to develop simple techniques which can be easily adopted by the industries.

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Conflicts of Interest

The authors declare no conflict of interest.

REFERENCES

- [1] Pinnavaia J, Beall GW. (Ed). Polymer-clay nanocomposites, Chichester, West Sussex, England: John Wiley & Sons Ltd; 2001. 1-345.
- [2] Vaia RA, Krishnamoorti R. (Ed). Polymer Nanocomposites: Introduction in Polymer Nanocomposites, Washington DC, USA: ACS Symposium series; 2001. 1-5.
- [3] Krishnamoorthy R, Richard Vaia A. (Ed). Polymer Nanocomposites: Synthesis Characterization and Modelling, Washington DC, USA: ACS Symposium Series; 2001. 1-256.
- [4] Carrado KA. Synthetic Organo and Polymer – Clays: Preparation, characterization and materials application. *Applied Clay Science*. 2000; 17:1-23.
- [5] Alexandre M, Dubois P. Polymer – layered silicate nanocomposites: preparation properties and uses of a new class of materials. *Material Science Engineering*. 2000; 28:1-63.
- [6] Stoppa M, Chiolerio A. Wearable Electronics and Smart Textiles: A Critical Review. *Sensors*. 2014; 14(7):11957-11992. 10.3390/s140711957
- [7] Bourbigot S, Devaux E, Flambard X. Flammability of Polyamide – 6 / clay hybrid nanocomposites textiles. *Polymer Degradation and Stability*. 2002; 75:397–402.
- [8] Sherman J. Nano particulate TiO₂ coatings and processes for the production and use thereof, Pat.No. 736738 (2003).
- [9] Yang HY, Zhu SK, Pan N. Studying the mechanism of TiO₂ as UV blocking additive for fibers and fabrics by an improved scheme. *Journal of Applied Polymer Science*. 2003; 92:3201–3210.
- [10] Sorna Gowri V, Luis A, Teresa A, Noemia C, Antonio PS, et al. Functional finishing of polyamide fabrics using ZnO–PMMA nanocomposites. *Journal of Material Science*. 2010; 45:2427-2435.
- [11] Yeo SY, Lee HJ, Jeong SH. Preparation of nanocomposite fibers for permanent antimicrobial effect. *Journal of Material Science*. 2003; 38:2143–2147.

- [12] Lee, HJ, Yeo SY, Jeong SH. Antibacterial effect of nanosized silver colloid solution on textile fabrics, *Journal of Material Science*. 2003; 38:2199–2204.
- [13] Yeo SY, Jeong SH. Preparation and characterization of polypropylene/ silver nano composites. *Fibers and Polymers*. 2003; 52:1053–1057.
- [14] Daoud WA, Xin JH. Nucleation and growth of anatase crystallites on cotton fabrics at low temperatures. *Journal of American Ceramic Society*. 2004; 87:953–955.
- [15] Bozzi A, Yusanova KJ. Self-cleaning of wool – polyamide and polyester textiles by TiO₂ rutile modifications under day light irradiation at ambient temperature. *Journal of Photochemistry and Photobiology*. 2005; 172:27-34.
- [16] Cui SY, Zu YD, Hui HQ, Zhang JY. Study on antibacterial properties of nano ceramics. *Journal of Hebei University of Science and Technology*. 2003; 24:19–22.
- [17] Chen RQ. Nanometric materials and health care textiles. *Dyestuff Industry*. 2002; 39:24-28.
- [18] Wang RH, Xin JH, Yang Y, Liu HF, Xu LM, Hu JH. The characteristic and photo catalytic activities of silver doped ZnO nano crystallites. *Applied Surface Science*. 2004; 227:312–317.
- [19] Yasuhide Y, Masahiko N, Kenji S. Composite material carrying zinc oxide fine particles adhered thereto and method for preparing same. Pat.No. 0791681, (1997).
- [20] Arazaz A, Anwar F, Ahmad S, Aslam M. Fabrication of ZnO incorporated chitosan nanocomposites for enhanced functional properties of cellulosic fabric. *Materials Research Express*. 2016; 3:115001.
- [21] Ulfiqar AR, Umaira B, Unsa N, Somayyaha M, Shahina R, Muhammad UA, et al. Chitosan mediated formation and impregnation of silver nanoparticles on viscose fabric in single bath for antibacterial performance. *Fibers and Polymers*. 2019; 20:1360–1367.
- [22] Xiaoning TB, Mingwei T, Lijun Q, Shifeng Z, Xiaoqing G, Guangting H, et al. A facile fabrication of multifunctional knit polyester fabric based on chitosan and polyaniline polymer nanocomposite. *Applied Surface Science*. 2014; 317:505-510.
- [23] Radetic M, Markovic D. Nano-finishing of cellulose textile materials with copper and copper oxide nanoparticles. *Cellulose*. 2019; 26:8971–8991.
- [24] Susie JM, Jonathan PC, Anita JH, Katie C, Jolon MD, Warren GB. Covalent modification of the wool fiber surface: The attachment and durability of model surface treatments. *Textile Research Journal*. 2008; 78:1087-1097.
- [25] Neomia C, Souto AP, Nogueira C. Reactive pad batch dyeing in corona discharged fabrics, *Journal of Natural Fibers*. 2007; 4:51-65.
- [26] Alay S, Goktepe F, Souto A P, Carneiro N, Fernandes F, Dias P. Improvement of durable properties of surgical textiles using plasma treatment. *Proceedings of 6th World Textile Conference AUTEX*; 26-27 June 2007; Tampere, Finlandia.
- [27] Oliveira F, Carneiro N, Souto AP. Reactive dyeing of Polyamide 6.6 by plasmatic modification. *CIRAT III*; 12-16 Novembro 2008; Sousse, Tunísia.
- [28] Carneiro N, Souto AP, Silva F, Marimba A, Tena B, Ferreir H, et al. Dyeability of corona treated fabrics. *Coloration Technology Society of Dyes and Colourist*. 2001; 117:298-302.
- [29] Mohammed MH, Dirk H, Giu SF, Axel S, Manfred H. Plasma deposition of permanent superhydrophilic a-C: H: N films on textiles plasma process. *Polymers*. 2007; 4:471-481.
- [30] Kull KR, Steen ML, Fisher FR. Surface modification with nitrogen-containing plasmas to produce hydrophilic, low-fouling membranes. *Journal of Membrane Science*. 2005; 246:203-215.

- [31] Palaskar S, Desai AN, Shukla SR. Development of multifunctional cotton fabric using atmospheric pressure plasma and nano-finishing. *Journal of Textile Institute*. 2016; 107:405-412. 10.1080/00405000.2015.1034932
- [32] Palaskar S, Desai AN, Shukla SR. Plasma induced nano-finish for multifunctional properties on cotton fabric. *Indian Journal of Fibre and Textile Research* . 2016; 41:325-330.
- [33] Sorna Gowri V, Luís A, Teresa A, Noémia, Pedro S, Fátima E. Polymer nanocomposites for multifunctional finishing of textiles – a review. *Textile Research Journal*. 2010; 18(13):1290-1306.
- [34] Sorna Gowri V, Luis A, Teresa A, Noemia C, Antonio PS, Maria FE. Novel copolymer for SiO₂ nanoparticles dispersion. *Journal of Applied Polymer Science*. 2012; 124:1553-1561.
- [35] Lewuir M, Weil ED. Mechanism and modes of action in flame retardancy of polymers, in fire retardant materials, Horrocks AR, Price D (Eds). Woodhead, Cambridge, England: Chapter. 2., 2000; 31-68.
- [36] Subbulakhshmi N, Kasturiya N, Bajal HP, Agarwal AK. Production of flame retardant Nylon 6 and 6-6. *Journal of Macromolecular Chemistry and Physics*. 2000; 40:85-104.
- [37] Horrock A R, Textiles. In: Horrocks A R and Price D (ed). *Fire retardant materials*, Woodhead Publishing Limited; Cambridge; chapter 4, 2001; 128-181.
- [38] Zhao C, Qui H, Gong F, Feng M, Zhang S, Yang M. Mechanical thermal and flammability properties of polyethylene /clay nanocomposites. *Polymer Degradation and Stability*. 2005; 87:183-189.
- [39] Su S, Jiang D, Wilkie C A. Poly (Methyl Methacrylate), poly propylene and polyethylene nanocomposites formation by melt blending using novel polymerically modified clays. *Polymer Degradation and Stability*. 2004; 83:321-331.
- [40] Kashiwagi T, Harris Jr RH, Zhang X, Briber RM, Cipriano BH, Raghavan SR, et al. Flame Retardant Mechanism of Polyamide 6. *Polymer*. 2004; 45:881-891.
- [41] Morgan AB, Kashiwagi T, Harris Jr RH, Chyall LJ, Gilman JW. Flammability of polystyrene layered silicates (clay) nanocomposites: carbonaceous char formation. *Fire Materials*. 2002; 26:247-253.
- [42] Song L, Hu Y, Tan Y, Zhang R, Chen Z, Fau W. Study on the properties of flame retardant polyurethane/ organoclay nanocomposites. *Polymer Degradation and Stability*. 2005; 87:111-116.
- [43] Chuang TH, Guo W, Cheng KC, Chen SW, Wang HT, Yen YY. Thermal properties and flammability of ethylene – vinyl acetate copolymer/ montmorillonite/ polyethylene nanocomposites flame retardant. *Journal of Polymer Research*. 2004; 11:169-174.
- [44] Inan G, Patr PK, Kuin YK, Warner SB. In-situ polymerized fire-resistant Nylon 6 / Clay nanocomposites; *Material Research Society Symposium Proceedings*: 2003; 788:L8.46.
- [45] Liu L, Qi Z, Zh X. Studies on Nylon 6/ Clay Nanocomposites by Melt Intercalation Process. *Journal of Applied Polymer Science*. 1999; 71:1133-1138.
- [46] Agag, T, Koga T, Takeichi T. Studies on thermal and mechanical properties of polyimide- clay nanocomposites. *Polymer*. 2001; 42:3399-3408.
- [47] Paul DR, Cho JW. Nylon 6 nanocomposites by melt compounding. *Polymer*. 2001; 42:1083- 1094.
- [48] Alexandre M, Dubois P. Polymer- Layered silicates nanocomposites: preparation, properties and uses of a new class of materials. *Material Science Engineering*. 2000; 28:1-63.
- [49] Kadhiraavan S, Sarang D, Nicholas A, Dembsey Qinguo F, Prabri Patra K. Condensed phase flame retardation in nylon 6 layered silicate nanocomposites. *Polymer and Engineering Science*. 2008; 48:662-675.
- [50] Devaux E, Rochery M, Bourbigot S. Polymethane / Clay and Polyurethane / POSS Nanocomposites as flame retardant coating for polyester and cotton fabrics. *Fire Materials*. 2002; 26:149-154.

- [51] Jeong SH, Yeo SY, Yi SC. The effect of filler particle size on the antibacterial properties of compound polymer / silver fibers. *Journal of Material Science*. 2005; 40:5407-5411.
- [52] Qian G, LAN T. In *Handbook of polypropylene and polyethylene composites*. Hanstun GK (ed)., Marcel Dekkar, New York, Basel: Chapter 20. 2003; 707-728.
- [53] Huang I, Zhan R, Lu Y. Mechanical properties and crystallization behaviour of polypropylene/nano-SiO₂ composites. *Journal of Reinforced Plastics and Composites*. 2006; 25:1001-1012.
- [54] Zhang S, Horrocks AR. A review of flame retardant polypropylene fibers. *Progress in Polymer Science*. 2003; 28:1517-1538.
- [55] Yeo S, Lee H J, Jeong SH. Preparation of nanocomposites fibers for permanent antibacterial effect. *Journal of Material Science*. 2003; 38:2143-2143.
- [56] Rottstegge J, Qiao YK, Zhang X, Zhou Y, Xu D, Hau CC, et al. Polymer nanocomposites powders and melt spun fibers filled with silica nanoparticles. *Journal of Applied Polymer Science*. 2007; 103: 218-227.
- [57] Asciglu B, Adamiu S. Nanoengineered fire resistant composite fibers. Auburn University Annual Research forum, Auburn. 2003.
- [58] Rong MZ, Zhang MQ, Zheng YX, Zeng HM, Friedrich K. Improvement of tensile properties of nano – SiO₂ / PP composite in relation to percolation mechanism. *Polymer*. 2001; 42:3301-3304.
- [59] Bikiaris DN, Papageorgiou GZ, Pavlidou E, Vouroutzis N, Palatzoglou P, Karajannidis GP. Preparation by melt mixing and characterization of isotactic Polypropylene/SiO₂ nanocomposites containing untreated and surface treated nanoparticles. *Journal of Applied Polymer Science*. 2006; 100: 2684–2696.
- [60] Marcin R, Janusz Z. Magnetic textile elements. *Fibers and Textiles in Eastern Europe*. 2006; 14:49-53.
- [61] Yu B, Qi L, Ye J, Sun H. The research of radar absorbing property of bicomponent fibers with infrared camouflage. *Journal of Polymer Research*. 2007; 14:107-113.
- [62] Ghasemi A, Hossienpour A, Morisaka A, Saatchi A, Salehi M. Electromagnetic properties and microwave absorbing characteristics of doped barium hexa ferrite. *Journal of Magnetism and Magnetic Materials*. 2006; 302:429-435.
- [63] Yang H, Zhu S, Pan N. Studying the mechanism of titanium dioxide as ultraviolet blocking additive for films and fabrics by an improved scheme. *Journal of Applied Polymer Science*. 2004; 92:3201-3210.
- [64] Burniston N, Bygott C, Stratton. Nanotechnology meets titanium oxide. *Surface Coatings International Part A*. 2004; 87:179-184.
- [65] Nilufer E, Aysum A, Cireli U, Erdogan H. Flame retardancy behavior and structural properties of polypropylene/ nanoSiO₂ composites textile filament. *Journal of Applied Polymer Science*. 2009; 111:2085-2091.
- [66] Gillain S, Baljinder K, Kandola A, Richard H, Shonate N, Donquqr M. Polypropylene fibers containing dispersed clays having improved performance part: characteristics of fibers and fabrics from PP-nanoclay blends. *Polymers for Advanced Technologies*. 2008; 19:658-670.
- [67] Krikorian V, Pochan DJ. Poly (Lacticacid) layered silicate nanocomposites: fabrication characterization and properties. *Chemistry of Materials*. 2003; 15:4317-4324.
- [68] Wu T, Chiang MF. Fabrication and characterization of biodegradable poly(lactic acid)/layered silicate nanocomposites. *Polymer Engineering and Science*. 2005; 45:1615-1621.
- [69] Paul MA, Alexandre M, Degée P, Henricc RA, Dubois P. New nanocomposites materials based on plasticized poly(lactide) and organo modified montmorillonites: thermal and morphological study. *Polymer*. 2003; 44:443-450.

- [70] Pluta M, Galeski A, Paul MA, Dubois P. Polylactide / Montmorillonite nanocomposites and micro composites prepared by melt blending: structure and some physical properties. *Journal of Applied Polymer Science*. 2002; 86:1497-1506.
- [71] Nam PH, Fujimori A, Masuko T. The dispersion behavior of clay particles in poly (lactide)/ organo – modified montmorillonite hybrid systems. *Journal of Applied Polymer Science*. 2004; 93:2711-2720.
- [72] Di Y, Lannace S, Di Maio E, Nicolais L. Nanocomposites by melt intercalation based on polycaprolactone and organoclay. *Journal of Polymer Science Part B Polymer Physics*. 2005; 43:689-698.
- [73] Pluta M. Morphology and properties of polylactide modified by thermal treatment filling with layered silicates and plastisization. *Polymer*. 2004; 45:8239-8251.
- [74] Paul MA, Alexandre M, Degee P, Calberg C, Jerome R, Dubois P. Exfoliated polylactide /clay nanocomposites by in situ coordination – insertion polymerization. *Macromolecular Rapid Communications*. 2003; 24:561–566.
- [75] Paul MA, Delcourt C, Alexandre M, Degee P, Monteverde F, Rulmint A, et al. Plastizised polylactide/ organo clay nanocomposites in situ intercalative polymerization. *Macromolecular Chemistry and Physics*. 2005; 206:484-498.
- [76] Bourbigot S, Devaux E, Flambar X. Flammability of polyamide – 6 /clay hybrid nanocomposites textiles. *Polymer Degradation and Stability*. 2002; 75:397-402.
- [77] Samual S, Fatma M, Manuela F, Eric D, Pierre B, Serge B, et al. (Plasticised) polylactide / clay nanocomposites textiles: thermal, mechanical, shrinkage and fire properties. *Journal of Materials Science*. 2007; 42:5105-5117.
- [78] Mandot A, Patel PN, Chaudari B, Patel BH. Preparation of flame retardant polymer nanocomposites textiles. *Chemical Fibers International*. 2016; 66(4):190-191.
- [79] Selvakumar N, Azhagurajan A, Natarajan TS, Mohideen M, Abdul K. Flame-retardant fabric systems based on electrospun polyamide/boric acid nanocomposite fibbers. *Journal of Applied Polymer Science*. 2012; 126(2):614-619.
- [80] Das P, Thomas H, Moeller M. Large-scale, thick, self-assembled, nacre-mimetic brick-walls as fire barrier coatings on textiles. *Scientific Reports*. 2017; 7:39910.
- [81] Yu-Chin L, Jessica S, Sarah M , Chris D, Brian C, Se-Chin C, et al. Flame Retardant behavior of polyelectrolyte–clay thin film assemblies on cotton fabric. *American Chemical Society Nano*. 2010; 4(6):3325-3337.
- [82] Kumaran BY, Halliah GP. Study on flame retardant and UV protection properties of cotton fabric functionalized with ppy-ZnO-CNT nanocomposites. *RSC Advances*. 2015; 49062-49069.
- [83] Wesolek D, Gieparda W. Single and multiwalled carbon nanotubes with phosphorus based flame retardants for textiles. *Journal of Nanomaterials*. 2014; (9):1-6.
- [84] Ji YM, Cao YY, Chen G Q, Xing TL. Flame retardancy and ultraviolet resistance of silk fabric coated by graphene oxide. *Thermal Science*. 2017; 21:61-61. 10.2298/TSCI160615061J
- [85] Ihor H, Irina K, Tatyana A, Yulia S, Sergey M, Oliya S, et al. Effect of styrene acrylate and urethane polymer coating filled with titanium dioxide on thermo physical properties of fabric surface. *Fibers and Textiles*. 2020; 4:26-31.
- [86] Liang JZ. Toughening and reinforcing in rigid inorganic particulate filled poly (propylene) a review. *Journal of Applied Polymer Science*. 2002; 83:1547-1555.
- [87] Kaempfer D, Thomann R, Mulhaupt R. Melt compounding of syndiotactic polypropylene nanocomposites containing organophilic layered silicates and in situ formed core / shell nanoparticles. *Polymer*. 2002; 43:2909-2916.

- [88] Ma J, Qi Z, Hu Y. Synthesis and characterization of polypropylene / clay nanocomposites. *Journal of Applied Polymer Science*. 2001; 82:3611-3617.
- [89] Tang Y, Hu Y, Wang S. Gui Z, Chen Z, Fan W. Novel preparation of poly (propylene) – layered silicate nanocomposites. *Journal of Applied Polymer Science*. 2003; 89:2586-2588.
- [90] Zhang MQ, Rong MZ, Zeng HM, Schmit S, Wetzel B, Friedrich K. Atomic force microscopy study on structure and properties of irradiation grafted silica particles in polypropylene based nanocomposites. *Journal of Applied Polymer Science*. 2001; 80:2218–2227.
- [91] Gorraasi G, Tortora M, Vittoria V, Kaempfer D, Mulhaupt R. Transport properties of organic vapours in nanocomposites of organophilic layered silicate and syndiotactic polypropylene. *Polymer*. 2003; 44:3679-3685.
- [92] Miynarcikova Z, Kaempfer D, Thomann R, Mulhaup ,R, Borsig E, Marcincin A. Syndiotactic poly(propylene)/ organo clay nanocomposite fibers: influence of the nano-filler and the compatibilizer on the fiber properties. *Polymer Advanced Technologies*. 2005; 16:362–369.
- [93] Jones JR, Lee PD, Hench LL. Hierarchical porous materials for tissue engineering. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences*. 2006; 364(1838):263-81. 10.1098/rsta.2005.1689
- [94] Mikolajczyk T, Szparaga G, Bogun M, Blazewicz S. Effect of spinning conditions on the mechanical properties of polyacrylonitrile fibers modified with carbon nanotubes. *Journal of Applied Polymer Science*. 2010; 115:3628-3635.
- [95] Mikotajczyk T. Scientific Bulletin of Technical University of Lodz, 781, Scientific Theses Z 243, Technical University of Lodz, Lodz, Poland. 1997
- [96] Mikolajczyk T, Rabiej S, Olejnik M. Analysis of the effect of the amount and type of montmorillonite in the supermolecular structure, porosity and properties of polyimidoamide fibers. *Journal of Applied Polymer Science*. 2007; 105:1937–1946.
- [97] Mikolajczyk T, Rabiej S, Olejnik M, Urbaniak W. Strength properties of polyimideamide nanocomposites fibers in terms of their porous and supramolecular structure. *Journal of Applied Polymer Science*. 2007; 104:339-344.
- [98] Mikolajczyk T, Bogun M, Rabeij S. Comparative analysis of the structural parameters and strength properties of polyacrylonitrile fibers containing ceramic nano additives. *Journal of Applied Polymer Science*. 2007; 105:2346–2350.
- [99] Chae HG, Sree Kumar TV, Uchida T, Kumar S. A comparison of reinforced efficiency of various types of carbon nanotubes in polyacrylonitrile fiber. *Polymer*. 2005; 46: 10925-10935.
- [100] SreeKumar TV, Liu T, Min BG, Guo H, Kumar S, Hauge R H, et al. SWNT/PAN composite fibers. *Advanced Materials*. 2004; 16:58-61.
- [101] Mikotajczyk T, Szparaga G, Janowska G. Influence of silver nano-additive amount on the supramolecular structure, porosity, and properties of polyacrylonitrile precursor fibers. *Polymers for Advanced Technologies*. 2009; 9995-9999.
- [102] Ceyhan C, Steven B. Warber. Analysis of the Structure and Properties of Expanded Graphite Filled Poly (Phenyl Ether) A tactic Polystyrene Nanocomposites. *Journal of Applied Polymer Science*. 2007; 103:645-652.
- [103] Junping Z, Bucheng L, Lei W , Aiqin W. Facile preparation of durable and robust superhydrophobic textiles by dip coating in nanocomposite solution of organosilanes. *Chemical Communications* 2013; 49:11509-11511

- [104] Yadav A, Virendra P, Kathe AA, Sheela R, Deepti Y, Sundramoorthy C, et al. Functional finishing in cotton fabrics using zinc oxide nanoparticles. *Bulletin of Material Science*. 2006; 29:641-645.
- [105] Liu Y, Wang X, Qi K, Xin, J. Functionalization of cotton with carbon nanotubes. *Journal of Materials Chemistry*. 2008; 18. 10.1039/b801849a
- [106] Tina H, Majid M. Photo-, bio-, and magneto-active colored polyester fabric with hydrophobic/hydrophilic and enhanced mechanical properties through synthesis of $\text{TiO}_2/\text{Fe}_3\text{O}_4/\text{Ag}$ nanocomposite. *Industrial and Engineering Chemistry*. 2013; 53:1119-1229.
- [107] Gao D, Rui L, Bin L, Jianzhong M, Fen T, Jing Z. Flammability, thermal and physical-mechanical properties of cationic polymer/montmorillonite composite on cotton fabric. *Composites. B. Engineering*. 2016; 329-337.
- [108] Elamin A, Abid K, Dhouib S, Sakli F. Morphological and mechanical properties of nanoclay coated fabrics. *American Journal of Nano Research and Applications*. 2015; 3:17-24.
- [109] Zheng-lan L, Ching-Wen L, Yi-Jun P, Chien-Teng H, Chen-Hung H, Chien-Lin H, et al. Conductive fabrics made of Polypropylene multiwall carbon nanotubes coated yarn: Mechanical properties and electromagnetic interference shielding effectiveness. *Composite Science and Technology*. 2017; 141:74-82.
- [110] Preetam B, Chetan M, Anil KS. Satyendra M. Enriched mechanical, UV shielding and flame retarding properties of cotton fabric coated with graphite nanoplatelets filled polyaniline -gum arabic nanocomposites. *Cellulose*. 2019; 26:8135-8151.
- [111] Kaçala MR, Akman F, Sayyed MI. Evaluation of gamma-ray and neutron attenuation properties of some polymers. *Nuclear Engineering and Technology*. 2019; 51:818-824.
- [112] Friedman MW, Singh MS. Radiation transmission measurements for demron fabric. Lawrence Livermore National Laboratory. <https://e-reports-ext.llnl.gov/pdf/246496.pdf/>
- [113] Pérez-Moreno J, Asselberghs I, Zhao Y, Song K, Nakanishi H, Okada S, et al. Record-High intrinsic hyperpolarizabilities for polymeric electro-optic modulators nanophotonics and macrophotonics for space environments. E. W. Taylor and D. A. Cardimona Ed., *Proc. SPIE*, 6713. SPIE, Bellingham: 2007; 671303-1-14
- [114] El Haber F, Froyer G. Transparent polymers embedding nanoparticles for X-rays attenuation. *Chemical Technology and Metallurgy*. 2008; 43:283-290.
- [115] Nambiar S, Osei E K, Yeow J T W. Polymer nanocomposite-based shielding against diagnostic X-rays. *Journal of Applied Polymer Science*. 2013; 127:4939–4946. 10.1002/app.3798
- [116] Huda AM, Arun V, Pradip D, Lijing W. Bismuth oxide-coated fabrics for X-ray shielding. *Textile Research Journal*. 2015; 86(6):649-658. 10.1177/0040517515592809
- [117] X-ray protective apron Filed Jan. 13, 1949 INI/EN TOR M ORP/S I. UB OW A TTORNEV Patented 17, 1950 2,494,664 X-RAY protective Apron, Morris Lubow, Long Beach, N. Y., assignor to Wolf X-Ray Products, Inc., 1949; New York, N.Y.
- [118] Xenolite – X ray cleanable fabric. Available from: <https://www.xenolitexray.com/products/customize-your-apron/fabric>
- [119] Edward WT. Organics polymers and nanotechnology for radiation hardening and shielding applications. *Proc. SPIE 6713. Nanophotonics and Macrophotonics for Space Environments*. 2007; 671307.
- [120] El Haber F, Froyer G. Transparent polymers embedding nanoparticles for X-rays attenuation. *Journal of Chemical Technology and Biotechnology*. 2008; 43(3):283-290.

- [121] Scuderi GJ, Brusovanik GV, Campbell DR, Henry RP, Kwon B, Vaccaro AR. Evaluation of non-lead-based protective radiological material in spinal surgery. *Spine Journal*. 2006; 6(5):577-582.
- [122] Botelho MZ, Künzel R, Okuno E, Levenhagen RS, Basegio T, Bergmann CP. February X-ray transmission through nanostructured and microstructured CuO materials. *Applied Radiation and Isotopes*. 2011; 527-530.
- [123] Nambiar S, Osei E, Yeow J. MO-F-BRA-01: Polymer composite-based shielding of diagnostic X-rays. *Medical Physics*. 2011; 38(6):3720-3720. <https://doi.org/10.1118/1.3612996>
- [124] Harish V, Nagaiah N, Prabhu TN, Varughese KT. Preparation and characterization of leadmonoxide filled unsaturated polyester based polymer composites for gamma radiation shielding applications. *Journal of Applied Polymer Science*. 2009; 112(3):1503-1508.
- [125] Bonaldi RR, Siores E, Shah T. Characterization of electromagnetic shielding fabrics obtained from carbon nanotube composite coatings. *Synthetic Metals*. 2014; 187:1-8.
- [126] Huseyin GO, Omer GS, Oznur S, Sinem B. Electromagnetic shielding characteristics of woven fabrics made of hybrid yarns containing metal wire. *Fibers and Polymers*. 2012; 13(1):63-67.
- [127] Fatma ZE, Ismail U. Electromagnetic shielding effectiveness of polyester fabrics with polyaniline deposition. *Textile Research Journal*. 2014; 84(9):903-912
- [128] Dhawana SK, Singha N, Venkatachalam S. Shielding effectiveness of conducting polyaniline coated fabrics at 101 GHz. *Synthetic Metals*. 2002; 125:389-393.
- [129] Dhawan SK, Singh N, Venkatachalam S. Shielding behaviour of conducting polymer-coated fabrics in X-band, W-band and radio frequency range. *Synthetic Metals*. 2002; 129:261-267.
- [130] Saini P, Choudhary V, Vijayan N, Kotnala RK. Improved electromagnetic interference shielding response of poly (aniline)-coated fabrics containing dielectric and magnetic nanoparticles. *Journal of Physical Chemistry A*. 2012; 116(24):13403-13412.
- [131] Shalu K, Smita D, Savadkar C, Niranjana. Polypyrrole-coated jute substrate for electromagnetic shielding. *AATCC Journal of Research*. 2015; 2(1):11-15.
- [132] Wei Z, Les J, Ravi S, Silva P, Lei MK. The effect of plasma modification on the sheet resistance of nylon fabrics coated with carbon nanotubes. *Applied Surface Science*. 2012; 258(20):8209-8213.
- [133] Dierk K, Eckhard S. Electrically high-conductive textiles. *Synthetic Metals*. 2009; 159:1433-1437.
- [134] Molina J, Esteves MF, Fernández J, Bonastre JF. Polyaniline coated conducting fabrics. Chemical and electrochemical characterization. *European Polymer Journal*. 2011; 47(10):2003-2015.
- [135] Chi-Yuan H, Wen-Wei M, Ming-Lih R. The influence of heat treatment on electroless-nickel coated fibre (ENCF) on the mechanical properties and EMI shielding of ENCF reinforced ABS polymeric composites. *Surface & Coatings Technology*. 2004; 184(2-3):123-132.
- [136] Yun J, Im J, Lee YS, Kim H. Effect of oxyfluorination on electromagnetic interference shielding behaviour of MWCNT/PVA/PAAc composite microcapsules. *European Polymer Journal*. 2012; 46(5):900-909.
- [137] Dervishi E, Li Z, Xu Y, Saini V, Biris AR, Lupu D, et al. Carbon nanotubes: synthesis, properties, and applications. *Particulate Science and Technology*. 2012; 7:107-125.
- [138] Nergis DG, Ismail U. The effect of multiwalled carbon nanotube (MWCNT) ratio on electrical properties and electromagnetic shielding effectiveness of PA 6/MWCNT-coated cotton fabrics. *The Journal of the Textile Institute*. 2014; 105(7):770-778.
- [139] Lihua Z, Chuntao L, Xiangpeng L, Songlin Z, Yiping Q, Ying M. Superhydrophobization of cotton fabric with multiwalled carbon nanotubes for durable electromagnetic interference shielding. *Fibers and Polymers*. 2015; 16(10):2158-2164.

- [140] Mingwei T, Minzhi D, Lijun Q, Shaojuan C, Shifeng Z, Guangting H. Electromagnetic interference shielding cotton fabrics with high electrical conductivity and electrical heating behaviour: Via layer-by-layer self-assembly route. *RSC Advances*. 2017; 7:42641-42652.
- [141] Sundaramoorthy P, Veronika T, Jiri M. Fiber-based structures for electromagnetic shielding – comparison of different materials and textile structures. *Textile Research Journal*. 2017; 88(17):1992-2012. <https://doi.org/10.1177%2F0040517517715085>
- [142] Tellakula1 RA, Varadan VK, Shami TC, Mathur G N. Carbon fiber and nanotube based composites with polypyrrole fabric as electromagnetic absorbers. *Smart Materials and Structures*. 2004; 13:1040–1044.
- [143] Renata RB, Elias S, Tahir S. Characterization of electromagnetic shielding fabrics obtained from carbon nanotube composite coatings. *Synthetic Metals*. 2014; 187:1-8.
- [144] Mazeyar PG, Arash A, Mahyar PG. Preparation of electromagnetic reflective wool using nano-ZrO₂/citric acid as inorganic/organic hybrid coating. *Sensors & Actuators: A Physical*. 2012; 187:1-9.
- [145] Singh BP, Veena C, Parveen S, Mathur RB. Designing of epoxy composites reinforced with carbon nanotubes grown carbon fabric for improved electromagnetic interference shielding. *AIP Advances*. 2012; 2:022151.
- [146] Mazeyar PG, Shima TG, Sara VA, Arash M, Amir K. Electromagnetic shielding response of uv-induced polypyrrole/silver coated wool. *Fibers and Polymers*. 2015; 16(3):585-592.
- [147] Lihua Z, Li Y, Zhenzhen X, Changliu C, Ving CL, Yiping Q. The optimization of nanocomposite coating with polyaniline coated carbon nanotubes on fabrics for exceptional electromagnetic interference shielding. *Diamond and Related Materials*. 2020; 104: 107757.
- [148] Nitin B, Sanjay R, Yudhajit B, Arup G, Tamal D, Tushar KD, et al. Multifunctional smart textile derived from Merino wool/ Nylon poly nanocomposites as next generation microwave absorber and soft touch sensor. *ACS Applied Materials Interfaces*. 2020; 12(15):17988-18001.
- [149] Shivam G, Ching C, Aswin KA, Chaih HL, Nyan HT. Reduced graphene oxide/zinc oxide coated wearable electrical conductive cotton textiles for high microwave adsorption. *Composites Science and Technology*. 2020; 188:107994. <http://doi.org/10.1016/j.compscitech.2020.107994>
- [150] Mengwei D, Yinghao Z, Yong Z. A green approach to prepare hydrophobic electricity conductive textiles based on water born polyurethane for electromagnetic interference shielding with low reflectivity. *Chemical Engineering Journal*. 2020; 421(2):127749 <http://doi.org/10.1016/jcej.2020.127749>
- [151] Vu QT, Duong NT, Duong NH. Polypyrrole/Al₂O₃ nanocomposites preparation characterisation and electromagnetic shielding properties. *Journal of Experimental Nanoscience*. 2009; 4(3):213-219.
- [152] Aminoddin H, Rouhollah SR, Ahmad MS. Improved microwave shielding behaviour of carbon nanotube-coated PET fabric using plasma technology. *Applied Surface Science*. 2014; 311:593-601.