

Review Article

Studies in Finishing Effects of Clay Mineral in Polymers and Synthetic Fibers

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The use of clay mineral in modifying the properties of polymeric material is improved in application. The current interest in modifying the polymeric materials, particularly polyethylene, polypropylene, polystyrene, and nylon using clay mineral for improved flame retardancy, thermal stability, peak heat release rate, fracture, and strength properties generated significant research literature. This paper aims to review some of the important recent modification achieved in the performance of polymeric materials using organoclay mineral. Degradation of clay mineral-polymer (nm) composite is discussed with appropriate known examples. Clay mineral (nm) loading of 5 wt.% to 7 wt.% that was significantly smaller than the percent loading of conventional fillers in polymeric materials introduced significant improvement in terms of thermal and physical stability. An attempt is made to emphasize flammability and thermal stability and to indicate the areas that are relatively little explored in modification of fiber-forming polymers to enhance further research interest.

1. Introduction

The study of clay mineral application for improved desired effects in the performance of polymeric materials is an important subject that received significant research interest. Several effects are possible where clay minerals may be useful in improving the polymer performance for commercially acceptable products.

This review describes how the production of clay mineral-polymer (nm) composite was achievable for selected desired effects in polymeric material. Since montmorillonite (Mt) clay type has received a relatively increased interest in modifying the polymeric properties, its applications are discussed in particular.

An important aspect of this study is to discuss the advancement in fibers and fiber-forming polymers through the utilization of clay mineral. Therefore, Mt-polymer composite structure for nylon, polypropylene, polyethylene, poly(methyl methacrylate), and polycarbonate are discussed for the improved desired effects including flame retardancy, peak heat release rate, thermal degradation (molecular degradation with increasing temperature, mode of heat distribution, and transmission), char formation, and smoke release.

A major part of studies, in clay mineral utilization with nanometer (nm) dimensions, concentrated on the naturally available minerals; however, some interest was realized for synthetic clay mineral. Therefore, an introduction is made for the synthetic clay mineral utilization in polymer modification. The later sections described the recent emerging interest in the application of clay mineral-polymer (nm) composite for improved effects in important polymeric fibers and textile substrates. The possible modes of using clay mineral-polymer (nm) composite to produce fibrous material are described in achieving flame-retardant and heat-resistant effects.

A variety of synthetic polymers can be produced in fiber form using polymer solution or polymer melt. Significant market consumption of nylon and PET fibers poly(ethylene terephthalate) requires a particular discussion. These fibers are followed by the description of polyolefin when clay mineral-polyolefin (nm) composite is used.

The important factors, related with the exfoliation and dispersion of clay mineral nanocomposite, are described. The effects of exfoliation and dispersion of clay mineral (nm) composite on the performance of polymeric material are described.

Generally, this review study provides details for selected clay mineral and its effects on the polymer performance. The processing methods are discussed a little since these are covered in cited literature. However, an introduction of processing methods is provided. Description of processing methods was limited to an introduction of necessary details.

Optimistically, this review paper will provide useful study and comprehension in enhancing further research work for improved desired effects using clay mineral in polymeric material and fiber-forming polymers.

2. Clay Mineral Utilization

The properties of clay particle to resist heat, flame, material weathering, and strength enhancement were important in past centuries. However, the science and technology of nanometer- (nm-) sized composite particle of clay mineral in modifying the polymer matrix are the recent advancement and received significant interest to develop polymer materials for high performance and technical applications.

The use of silicate particles in manufacturing the ceramics was known in history; for example, in China, the use of Kaolinite traditionally called China clay is traced to the 3rd century BC. The variety of clay minerals that may be used in producing the performance effects in polymers was discussed by Uddin [1].

Murray [2] discussed the application of clay mineral including kaolin, smectite, palygorskite (attapulgitite), and sepiolite for material including paper, ceramic, paint, plastic, and rubber [3], and expansion in usage was expected to grow with improved processing methods and equipment, surface treatment, and organoclay mineral technology.

Interesting improvement in application properties, including abrasion resistance, UV resistance, strength characteristics, thermal stability, and flame retardancy, were achievable in finished polymer using nanoparticle form of clay mineral [4].

Clay mineral particle with nm dimensions received an increased interest. A single human hair may have width or diameter of 80,000–100,000 nm [5, 6]. A water molecule is almost 0.3 nm wide. Clay mineral at nanometer-sized dimensions available in market with a range of products having varying composition is achieved using various means of production. Nanocomposite of clay mineral can be produced from several types of hydrous aluminosilicate differing in chemical composition and crystal structure [7].

Clay mineral-polymer nanocomposite is a polymer (thermoplastic, thermoset, or elastomer) reinforced with small quantity (less than 5% by weight) of nanometer-sized particles [8].

The essential raw clay mineral used in producing nanocomposite is montmorillonite (Mt).

Nanometer-sized particle of clay mineral has layered structure where its thickness is far less than the remaining two dimensions [9]. An individual particle thickness may be just one nm; however, surface dimensions are generally 300–600 nm.

The general discussion on structure, properties, and surface modification of clay mineral and the enhanced properties (mechanical, barrier, thermal, electrical conductivity, biodegradability, etc.) of clay mineral-polymer (nm) composite were reported by Zeng et al. [10].

Thermal and photo aging durability of clay mineral-polymer (nano) composite and the enhancement achieved in polymer durability using layered silicates against the influence of light, microwave energy, heat, and mechanical abrasion were reviewed by Pandey et al. [11].

An important form of material is textile fiber that requires improved strength, flame retardancy, and thermal stability in various applications. Clay mineral used as an additive or as constituent ingredient in finishing formulation might introduce the desired effects in textile fibers and would possibly receive an increasing research and innovation interest in the future. There were several synthetic fibers produced from polymers, for example, various grades of nylon, polyester and polyolefin, and cellulose-derived fibers where finishing using clay mineral may produce the desired effects.

2.1. Clay Mineral-Chemical Complex. Raw Mt is hydrophilic. Generally, the polymers are organophilic; therefore, unmodified Mt is difficult to disperse in polymer. The process of compatibilization that may be termed as intercalation modifies the clay mineral surface to produce organophilic clay mineral. Compatibilized clay mineral readily disperses in polymer or resin matrix. Therefore, the clay mineral-polymer (nm) composite available in market is a clay mineral-chemical complex that shows variation in meeting the specific requirements for performance effects.

Compatibilization is essential for exfoliation of clay mineral particle, that is, separating nanoparticles from one another in polymer matrix. During exfoliation, particles at the outermost region of each aggregate cleaved off resulting in the reduction of particle size and changed shape from cubical blocks to flat particles. The shape of clay mineral particle sized to nm dimension was generally exhibited as aspect ratio (length to thickness ratio of particle) of greater than 300.

Larger specific surface area of clay mineral sized to nm dimensions was possible through exfoliation. However, an increased loading of clay mineral particle provided reduced interparticle distance in the structure of clay mineral-polymer (nm) composite. For example, a loading of 1 wt.% of Mt produced interparticle distance of 250 nm that was reduced to 10 nm at loading of 20 wt.%. A description of processing stages used in converting raw clay mineral into a clay mineral sized in nm could be presented (Figure 1) [12].

The important types of clay mineral-polymer (nm) composite may be presented in Table 1 [13].

Reinforcing the engineering polymers using clay mineral was improved by modifying the external and internal surfaces of layers in clay mineral particle. It was indicated by Legaly [14] that formation of clay mineral-polymer (nm) composite is enhanced through the reduction in the tendency of silicate layers to form face-to-face aggregate.

Physical adsorption and chemical grafting methods for the surface modification of clay mineral using polymers were

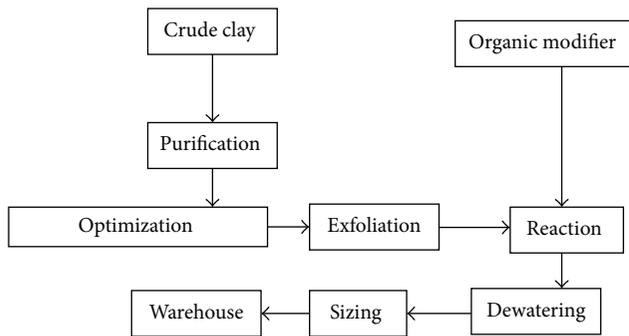


FIGURE 1: Stages involved in the conversion of crude clay into nanoclays [12].

reviewed by Liu [15]. The surface physical and chemical properties of clay mineral-polymer (nm) composite were important in reinforcing the engineering polymers, as catalyst, adsorbent, and so forth.

In addition to flame-retardant and heat-resistant effects, the other properties of polymer can be modified using clay mineral. An example may be seen in Mt-polyimide hybrid. Dimethylacetamide (DMAC) solution of poly(amino acid) and a DMAC dispersion of Mt intercalated with an ammonium salt of dodecyl amine were used to synthesize Mt-polyimide hybrid [16]. Length and thickness of Mt particle were 2000 Å and 10 Å, respectively. Mt-polyimide hybrid showed reduced thermal expansion coefficient; however, particular influence was observed on gas barrier property. A loading of 2 wt.% of Mt in Mt-polyimide hybrid reduced the gas permeability coefficient to less than the half value of ordinary polyimide.

2.2. Montmorillonite (Mt) Application. Mt application showed significant enhancement in the desired performance of various materials. Mt was used in composite for cars, packaging materials, antiseptics, abrasives, paints, coatings spectacles, electronics, flame-retardant finishing, and so forth [7].

Possibly, the variety of fiber and polymers types demand enormous research work to explore improvement achievable by using nm particles of Mt in particular, and generally the other clay minerals.

To date, there is significant interest in using Mt to modify the application properties of polymers or plastics. When nm-sized particles of Mt are incorporated in polymers/fibers, the resultant material structure exhibited greater resistance to electricity, chemicals, heat, and flame and an enhanced ability to block UV-light.

The diversity in using the clay mineral-polymer (nm) composite for a large number of polymeric fibrous products may be perceivable. The applications of nanofibers produced using clay mineral-polymer (nm) can be presented in Figure 2 using the summarized description introduced by Huang et al. [17].

3. Processing Methods for Clay Mineral-Polymer (nm) Composite

Indeed, a number of interesting articles are available that comprehensively discuss the processing methods important for producing clay mineral-polymer (nm) composite. This review is particularly addressing the flame-retardant and heat-resistant properties of polymers produced by using the clay mineral-polymer (nm) composite or using nanocomposite as filler in improving the said properties.

Smectite-type clay minerals including hectorite and Mt are important layered silicates for the production of nanocomposite. The obvious reasons for the interest in using the smectite-type clay mineral include its high cation exchange capacity, surface area, surface reactivity, and adsorption; increased viscosity and high transparency are achievable, in addition to these properties, with hectorite. The important features associated with the production of smectite mineral-polymer (nm) composite including preparation, characterization, melt rheology, and processing were reviewed by Ray and Okamoto [18].

Clay mineral-polymer (nm) composite to be used as filler was discussed by Gao [19]. Composites produced particularly using hectorite, montmorillonite, and synthetic mica were described. Performance feature of clay mineral-polymer (nm) composites in terms of particle size, layered structure (bonding between atoms and geometry of particle), and aspect ratio were discussed.

Perhaps interesting details elucidating the scientific principles and mechanisms associated with the processing methods and manufacturing of polymer nanocomposite were reviewed by Hussain et al. [20].

Amorphous and crystalline polymer matrices were used in producing polymer nanocomposite. Such matrix structure affects the morphology of nanocomposite produced. Processing method, and its effect on mechanical performance, and a discussion on morphology of polymer nanocomposite were presented by Jordan et al. [21].

The present study particularly assesses the enhancement in the interest of the production of polymer nanofibers. Therefore, important aspects of polymer nanofiber processing through electrospinning are discussed.

An interesting study on the development in the production of polymer nanofiber in recent time was made by Huang et al. [17]. The study provided interesting details covering processing conditions, structure and characterization relationship, and process simulation.

Several processing methods were known for the production of polymer nanofibers. The processing techniques of interest in recent time include drawing, template synthesis, phase separation, self-assessing, and electrospinning.

However, electrospinning is the technique successfully utilized for the production of a variety of polymer nanofibers. The significant utilization of electrospinning technique for polymer nanofiber production is recognizable in the literature.

The published research literature indicates continuous interest in the production of polymer fibers using electrospinning. Importantly, about one hundred various polymers were

TABLE I: Important types of clay mineral-polymer (nm) composite.

S. no.	Clay mineral-polymer (nm) composite	Characteristics	Effects on polymer performance
1	Intercalated nanocomposite	(i) Polymer chains are regularly inserted in layered silicate structure (ii) Regular crystal structure (iii) Repeat distance of few nanometers at any polymer to clay ratio	(i) Increased tensile properties (ii) Increased flexural properties (iii) Reduced gas permeability (iv) Flame retardancy (v) Improved heat distortion temperature (vi) Improved thermal and photo aging (vii) Improved biodegradability
2	Flocculated nanocomposite	Intercalated and stacked silicate layers partially flocculated	Same as above
3	Exfoliated nanocomposite	Silicate layers are separated in polymer matrix (depending upon clay loading)	Same as above

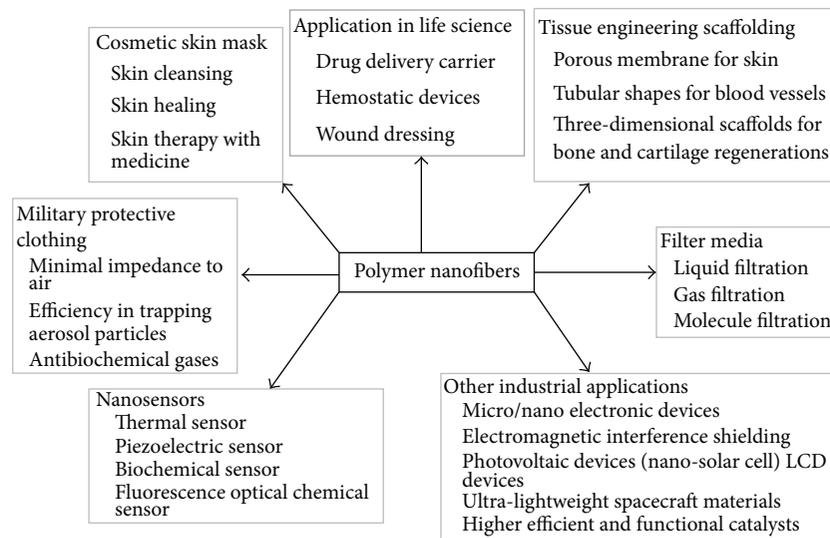


FIGURE 2: The possible applications of polymer nanofibers produced using clay mineral-polymer (nm) composite [17].

electrospun using polymer solution and polymer melt. Table 2 describes some important polymers with the solvent used to produce electrospun fibers from polymer solution.

A polymer solution, or a polymer melt, and the electrostatic force between the two charged electrodes were the important factors in producing polymer nanofiber through electrospinning.

The polymer solution is ejected between two electrodes, possessing opposite polarity, leading to the formation of polymer filament fiber. One electrode is in the solution and the other one is in metal collector. The charged solution jet, following the evaporation of solvent content, is collected on metal electrode as nonwoven nanofiber. Figure 3 presents a simple diagram for electrospinning technique showing the polymer nanofiber formation at the collector electrode.

The important factors that may influence the characteristics of polymer nanofiber produced through electrospinning include, however not limited to, solution viscosity, surface tension, dielectric permeability, electric field strength, solvent properties to evaporate, polymer molecular weight, and concentration. Studies of such factors for a particular

polymer-substrate solution would provide the control on the characteristic properties of nanofibers. For example, it was indicated that low viscosity solution of polymer produced shorter and finer fibers, and those obtained from viscous solution were continuous.

4. Mt-Polymer Composite

4.1. Mt-Nylon Composite. Nylon polymer, derived from a diamine and a dicarboxylic acid, produced important textile fibers used in home, fashion, and technical textile products. Nylon 66 (polyhexamethylene adipamide), and nylon 6 (polycaprolactam) are the two common types shown in Figure 4. It was developed in 1930s by the scientists, headed by Wallace Hume Caruthers at Du Pont, and indicated as the first truly synthetic fiber commercially known [22]. Among the several varieties of nylon available in commercial market including nylon 6, 11, 12, 6/6, 6/10, and 6/12. The important types for textile industry products are nylon-6 and nylon-6/6.

Presently, nylon fibers are consumed in significant amount to produce various textile products around the world.

TABLE 2: Some important polymers and the solvent used in producing electrospun fibers [17].

S. no.	Polymer	Solvent Used
1	Nylon 6,6, (PA-6,60)	Formic acid
2	Nylon 4,6	Formic acid
3	Nylon 6/Mt	Hexafluoroisopropanol
4	Polyurethanes	Dimethyl formamide
5	Polybenzimidazole	Dimethylacetamide
6	Polycarbonate	Dimethyl formamide : tetrahydrofuran (1 : 1)
7	Polyacrylonitrile (PAN)	Dimethyl formamide
8	Poly(methyl methacrylate) (PMMA)	Dimethyl formamide : toluene (1 : 9)
9	Polyethylene terephthalate (PET)	Dichloromethane and trifluoroacetic acid (1 : 1)
10	Polyethylene	Dichloromethane and trifluoroacetic acid
11	Polystyrene	Tetrahydrofuran, dimethylformamide, carbon disulfide (CS ₂), and toluene
12	Cellulose acetate	Acetone, acetic acid, and dimethylacetamide
13	Mixture of poly(acrylic acid)-poly(pyrene methanol) and polyurethane	Dimethylformamide
14	Polycaprolactone	Chloroform : methanol (3 : 1), toluene : methanol (1 : 1), and dichloromethane : methanol (3 : 1)
15	Polyvinyl alcohol	Distilled water
16	Poly(vinylidene fluoride) (PVDF)	Dimethylformamide : dimethylacetamide (1 : 1)
17	Poly(2-hydroxyethyl) methacrylate	Ethanol : formic acid (1 : 1)

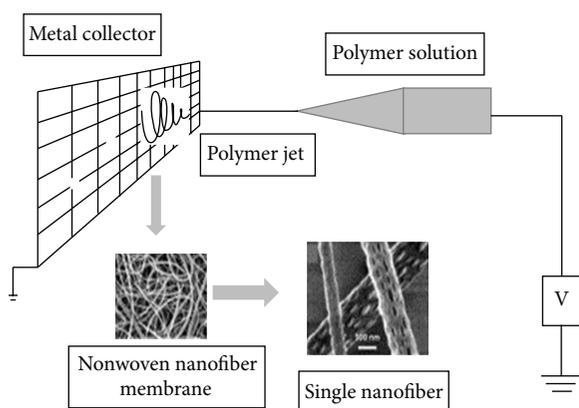


FIGURE 3: Nanofiber production using polymer solution in electrospinning technique [17].

In year 2010, global production and consumption of nylon fibers were estimated to be 3.6 million and 3.5 million metric tons, respectively. The consumption of nylon fibers was increased 6% in 2010 relative to 2009. Its production was forecasted in a world petrochemical report to grow at an average of 2.5% per year from 2010 to 2015, however, increasing to 5.4% per year from 2015 to 2020 [23]. Generally, nylon-6 and nylon-6/6 were used in producing the textile fibers, and the consumption of these fibers was 60% and 26%, respectively, in 2010.

Usuki et al. [24] reviewed clay mineral-nylon (nm) composite and clay mineral-polyolefin (nm) composite, including the synthesis and composite properties, discussed the production methods, and attempted to identify the future challenges in the subject area.

Mt was indicated to be used as UV blocker in nylon composite fiber. Loading of Mt. wt. 5% in nylon produced 40% enhancement in tensile strength, 68% greater tensile modulus, 60% higher flexural strength, and 126% increased flexural modulus. Moreover, heat distortion temperature (HDT) increased from 65°C to 152°C [25]. Table 3 presents the important effects of clay mineral on the performance of polymeric material including nylon.

Thermoplastic character of nylon 11 showed lacking in flame retardancy and high strength with increased thermal stability for various product applications. However, modification of nylon 11 using nm particles (Mt, silica, carbon fibers) in melt processing assisted to enhance these properties and expanded the market for the producers of nylon 11 resin [26].

Loading of Mt (nm) around wt. 7% content was comparable to 20–30 wt.% of conventional inorganic fillers (glass fiber, mineral fiber, etc.) for improving strength and heat resistance in nylon 11. Therefore, nylon 11 with low specific gravity and increased flame retardancy was possible using Mt.

Producing Mt-nylon-6 (nm) composite through melt bending or compounding technique followed by injection molding using percent loading of various Mt-organo (nm) composites, ranging over 0–5 wt.% content, produced improvement in tensile and flexural properties; the desired properties were indicated optimum at 5 wt.% loading [27]. Storage modulus, stiffness, and heat distortion temperature were improved with the reduction in water absorption relative to virgin nylon-6.

Morphological modification in nylon-6 was studied. Commercial grade Mt-nylon-6 (nm) composite was subjected to a large-scale simple orientation process, and the resulting morphology of composite was studied [28]. The orientation and aspect ratio of Mt were alterable by simple shear

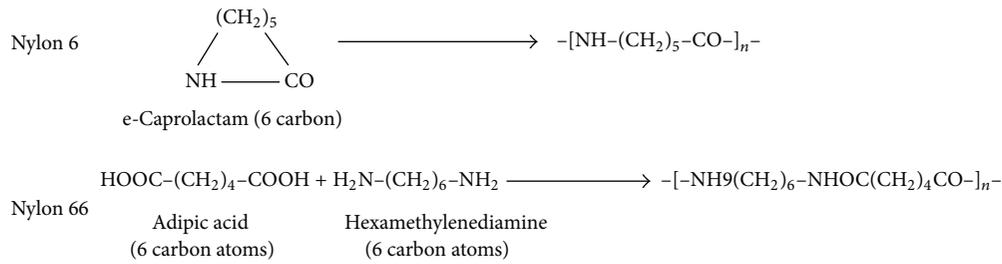


FIGURE 4: Two types of important nylon structures, nylon 6 and nylon 66 [22].

TABLE 3: Possible effects of clay mineral on the performance of polymeric material.

S. no.	Clay Mineral	Polymeric Material	Method	Performance effects
1	Mt, Silica	Nylon 11	Melt processing	(i) Improved flame retardancy (ii) Improved thermal stability (iii) Increased tensile strength
2	Mt	Mt-nylon 6 (nm) composite	Melt bending or compounding technique	(i) Increased tensile and flexural strength (ii) Increased stiffness (iii) Increased heat distortion temperature
3	Mt-modified with quaternary ammonium salt	Polypropylene	Introduced in polypropylene prior extrusion	(i) Improved uptake for acid and disperse dyestuff (ii) Enhanced eco-friendly dyeing
4	Mt (nm) commercial grades	Polyethylene (LLDPE, HDPE)	Mixed in preground virgin polyethylene resin	Postponed the onset of gross melt fracture
5	Surface-modified Mt (nm) commercial grades	Maleic anhydride-modified polypropylene	Compounded in twin-screw extruder	(i) Improved tensile strength (ii) Increased stiffness (iii) Crack growth resistance
6	Fluorinated synthetic mica	Fluorinated synthetic mica-polypropylene (nm) composite	Melt compounding	Reduced heat release rate was slightly better relative to natural clay mineral

process. Percent crystallinity and chain mobility of nylon-6 were greatly reduced by the incorporation of well-dispersed Mt in its matrix. Subsequently, the possible molecular mechanisms leading to the final morphology of the Mt-nylon-6 (nm) composite were discussed.

Mt, saponite, hectorite, and synthetic mica were used to synthesize clay mineral-nylon-6 hybrid materials. Subsequently, injection molded specimen were studied to assess selected mechanical properties using ASTM. The relative comparison in terms of the mechanical properties of four types of hybrid material indicated that Mt-nylon-6 hybrid is superior in performance [29].

Interaction between nylon-6 molecules and silicates in the hybrid was indicated as the possible cause of difference in the mechanical properties studied. It was found in the ^{15}N -NMR results that Mt-based intercalated compound produced greatest positive charge density on nitrogen relative to other clay mineral-based intercalated compound. The greater positive charge density on nitrogen (N^+) introduced stronger ionic interaction of Mt with the molecules of nylon-6.

4.2. Mt-Polyolefin (nm) Composite. Polymer (nm) composite each containing polystyrene, poly(methyl methacrylate), and polycarbonate with alumina and SiO_2 nanoparticles and

carbon nanotubes were studied [30]. Miniaturized, microdimensional samples were produced to enable good control of morphology and distribution of particles. The study showed that with appropriate dispersion of particles of a few 10 nm in polymer composite structure, the effect on toughness enhancement lacks the problem of agglomerates as they generally appear in large samples.

Polypropylene fibers were difficult to dye being lacking in dye-attracting or dye-holding spaces. Mt clay modified with quaternary ammonium salt and included in polypropylene prior extrusion may impart increased dyeing ability to polypropylene fibers for acid and disperse dyes. An increased dyeability of polypropylene fiber produced the shade depth with reduced amount of dyestuff and improved the environment-friendly nature of dyeing.

Polyethylene grades of varying melt indices were modified using Mt. The influence of Mt on the processing of film grade linear low-density polyethylene (LLDPE) of melt index 0.8, below molding grade of high density polyethylene (HDPE) of melt index 0.95, metallocene LLDPE of melt index 1, and polypropylene resin were investigated [31].

There were five grades of commercially available Mt (nm) studied. Three were the unmodified Mt (nm) grades including Nanoclays PGV and PGW from Nanocor and Cloisite Na

from Southern Clay Products. The remaining two grades were organically modified Mt (nm) including Nanoclay 1.44 PA (Nanacor), and Cloisite 10A (Southern Clay Products). Each Mt grade was investigated through mixing with an appropriate amount of preground virgin resin and using specified procedures to achieve uniform dispersion of Mt into polyolefin resin. Complete dispersion of Mt was confirmed using scanning electron microscope (SEM) and was noted as a necessary condition for the good performance of processing aids, including the fluoropolymer processing aids.

Organically modified Mt (nm) was easy to disperse into polyolefin, and its improved dispersion was confirmed by SEM pictures. The organically modified Mt (nm) eliminated the onset of shark skin (surface deterioration) melt fracture and significantly postponed the onset of gross melt fracture to much higher shear rates in polyolefin.

Melt fracture behavior of linear polyethylene (sharkskin and gross melt fracture) was closely related to high-rate extensional melt rheology. It was indicated that the growth suppression of tensile stress was mainly responsible for the ability of additives, including organically modified Mt (nm) and boron nitride, to eliminate melt fracture.

Fracture properties of maleic anhydride-modified polypropylene compounded with commercially available surface-modified Mt (nm) in a twin-screw extruder were investigated [32]. The mechanical and fracture properties of Mt (nm)-filled polypropylene were evaluated. Tensile strength and stiffness increased steadily with an increase in the Mt loading. Crack-growth resistance was observed in the Mt (nm)-filled polypropylene.

Important enhancement was achievable in polymer performance using clay mineral fillers in terms of improved flame retardancy and thermal stability. These effects are of significant interest in product application. The following section is particularly included to discuss the useful details.

5. Flammability and Thermal Stability

5.1. Flame Retardancy and Peak Heat Release Rate. Flame retardancy and resistance to thermal degradation were two important characteristics significantly useful in numerous applications of polymeric materials. Polyester resin was studied using clay mineral as flame retardant [33]. X-ray diffraction studies revealed that the dispersion of functionalized clay mineral particle, in polyester resin, was dependent upon the type of its functional group. Flammability assessed by using cone calorimeter indicated that the inclusion of 5% w/w of clay mineral in polyester matrix reduced peak heat release rate (PHRR) by 23–27% and total heat release values by 4–11%. Fire growth rate index was reduced to 23–30%.

The incorporation of small amount of clay mineral (nm), 5% w/w, in combination with the char promoting flame retardants (condensed-phase flame retardants), such as ammonium polyphosphate, melamine phosphate, and alumina trihydrate, resulted in the total reduction of PHRR in the range of 60–70%. Ammonium polyphosphate particularly showed the improved effects.

Three different silica-polymer (nm) composites each containing poly(methyl methacrylate), polystyrene, and polycarbonate were studied for flammability, thermal, and mechanical properties [34]. The reduction in PHRR and total heat release were observed using cone calorimetry; however, flammability assessment by oxygen index and horizontal Bunsen burner tests did not exhibit flame retardancy. Polycarbonate materials were V2 rated by vertical burning testing; however, 1% inclusion of silica significantly reduced its after flame times.

The significant contribution of clay mineral in retarding the flame spread in developing the fire in hybrid materials was reviewed [35]. The review indicated the clay mineral's presence in polymer was not beneficial to retard the flame at ignition in the case of fully developed fire. Therefore, the requirement of using conventional flame retardants in clay mineral-polymer (nm) composite was discussed for achieving any possible improvement.

An alternative way would be the study of the influence of clay mineral types and their interaction with particular polymers that might be investigated to provide ignition resistance and flame retardancy in clay mineral-polymer hybrid material.

An important concern in the selection of flame retardant additive for polymer material was the impact on the overall requirements of finished polymer material. For example, in commodity polymer, the flame retardant used should be of reduced cost (unit kg price and processing cost). It should be exhibiting an environment-friendly character and not creating significant reduction in the desired performance properties of the finished polymer. It was observed that silicate-polymer (nm) composite provided desired flame retardancy and improved physical properties [36].

5.2. Thermal Degradation. An important concern in the understanding and assessment of nanoparticles in modifying the performance of polymeric material for particular application was the effect created when the polymeric material experienced thermal degradation. Continuous increase in temperature, mode of heat distribution, transmission, and molecular degradation mechanism in polymeric material are modifiable by nanoscale fillers.

On receiving heat, the thermal degradation of polymer material begins after reaching a particular temperature. Gilman [36] indicated that boiling temperatures of most of the thermal degradation products of polymer material were much lower than their thermal degradation temperature; therefore, the degradation products were superheated as they formed. Heated surface of polymeric material has bubbles beneath that grew with the supply of degradation products and evolved into the gas phase as fuel vapors. To enhance the flame retardancy, clay mineral-polymer (nm) composite should inhibit this bubbling process during thermal degradation of polymer.

No reduction in bubbling by degradation products might be interpreted as no improvement in polymer flame retardancy; this idea was supported with an example of poly(methyl methacrylate) (PMMA) (nm) composite

containing silica (nm) (13% mass fraction). This silica-poly(methyl methacrylate) (nm) composite showed strong bubbling on heating and insignificant effect on flame retardancy, resulting in a residue containing granular, coarse particles.

Review of clay mineral-polymer (nm) composite pyrolysis during combustion indicated that the organically layered silicon particles migrated to and accumulated on the surface of molten polymer at temperatures far below the pyrolysis temperature [37]. The important reasons indicated for this migration were:

- (i) gradient of temperature and viscosity gradient of the melt with regard to heat source,
- (ii) propelling the organically layered silicate to the surface by gas bubbles from the decomposing surfactant and polymer,
- (iii) the difference in surface free energy between the polymer and the clay mineral-polymer aggregate.

Clay mineral accumulation by migration to surface of clay mineral-polymer (nm) composite at a range of temperature was indicated by X-ray diffraction and attenuated total reflectance Fourier transform infrared (ATR-FTIR) measurements on the isothermally heated samples [38]. Above 200°C, organic layered silicate began to decompose with the gradual destruction of nanocomposite prior the pyrolysis and combustion. However, the silicate particles (nm) tend to form a continuous protective solid layer on the heated surface of polymer. This protective layer is composed of clay mineral and carbonaceous char. Lateral surface cracks might appear in clay mineral layer during polymer combustion that enhanced the bubbling and flammability. Studies in eliminating such cracks were required to enhance the polymer flame retardancy using clay mineral (nm) fillers.

The layer of clay mineral (nm) might cause cross-linking and increase in carbonaceous char formation. In cases where char formation did not occur, it was the quality of clay mineral residue that influenced the flame-retardancy. The rate of gas escape from the polymeric melt and dripping during pyrolysis was reduced by the homogeneous dispersion of clay mineral (nm) particles in the polymer melt.

Obtaining the information and understanding of clay-mineral filled polymers, the molecular structure and thermal stability in terms of decomposition temperature, its rate, and the resulting degradation products were studied using thermal gravimetric analysis, infrared spectroscopy, and mass spectroscopy. The influence of alkyl chain length, number of alkyls, and degree of unsaturation of clay mineral-polymer (nm) composite on thermal stability were discussed [39].

5.3. Flammability and Smoke Release. Flammability and smoke release assessment of a broad range of thermoplastic and thermoset polymers using oxygen index and XP-2 tests showed that the polymers with aliphatic backbones were highly flammable with reduced level of smoke generation [40]. The polymers containing an aromatic group in the side chain, such as polystyrene, were highly flammable and highly smoke releasing, and the polymers with aromatic group in

main chain exhibited intermediate properties. The inclusion of any filler as flame retardant alters the proportion of flammability and smoke generation. This study did not cover the effects of clay mineral (nm) on polymer flammability; however, it was indicated that halogen-containing polymers were usually nonflammable with high oxygen index values and generate an increased level of smoke.

In general, clay mineral (nm) showed flame retardant effects in terms of reduction in peak heat release rate for most of the thermoplastic polymers including polystyrene, polyamide-6, polypropylene, polyamide-12, poly(methyl methacrylate), polyethylene, and ethylene vinyl acetate (EVA) [41]. However, the decomposition mechanism and the thermal decomposition products would vary in each polymer.

Mt and fluorohectorite were used to study the mechanism of flame-retarding in polypropylene-graft-maleic anhydride and silicate-polystyrene (nm) composite. Controlled combustion in cone calorimetry was investigated to assess the heat release rate and flammability. Silicate-polystyrene (nm) composite and combustion residue analyzed by the transmission electron microscopy and X-ray diffraction showed the flame retardancy resulted from the type and dispersion of silicate and processing degradation [42].

Combustion behavior and thermal oxidative degradation of clay mineral-polypropylene (nm) composite were studied through the utilization of compatibilizer, alkylammonium, organoclay, protonic clay, and pristine clay. The reduction in heat release rate resulted from the delay of thermal oxidation decomposition of hybrid material indicated to introduce several effects including the catalysis to initial decomposition and the ignition of the composite. However, interestingly, active site also catalyzed char formation. Consequently, an enhanced thermal-oxidative stability and reduced heat release rate were achieved [43].

5.4. Flammability and Thermal Properties of Synthetic Clay Mineral-Polymer Composite. An important progressive concern in modifying the thermal and flammability properties of polymers using clay mineral is the evaluation of synthetic clay mineral. The primary advantages from the production of synthetic clay mineral would include the elimination of extraction, purification, and surface treatment stages and the availability of desired structures in the type of clay mineral produced.

Some of the advantages and disadvantages of using the natural and synthetic clay minerals in (nm) composite were discussed by Morgan et al. [44]. Refined raw montmorillonite and fluorinated synthetic mica (=synthetic clay mineral) were used as inorganic clay minerals for control experiments on polystyrene, then converted into an organoclay mineral by ion exchange using alkyl ammonium salt. Organoclay mineral-polystyrene (nm) composites were synthesized by melt compounding. It was found in this study that the synthetic clay mineral performed slightly better in reducing the heat release rate relative to natural clay mineral; however, both the clay mineral types greatly reduce the heat release rate.

All the samples, including the inorganic clay mineral-polystyrene (nm) composites showed reduced time to ignition; however, this reduction was more significant in organoclay mineral (nm) composites, attributable to alkyl quaternary ammonium moiety of organoclay mineral.

6. Clay Mineral (nm) in Fibers

6.1. Clay Mineral-Polymer (nm) Composite in Textiles. Modifying fibers, improving the textile performance, and introducing the smart textiles are the important textile finishing developments achieved recently using particles (nm) as fillers and finish (nm) formulations. The major advancement in the nanotechnology of textile and fiber finishing is in the following areas [45].

- (1) Nanofinishing of textile fabrics and fibrous materials using the finish formulation comprising particles (nm).
- (2) Production of fiber (nm) composite by using selected filler (nm).
- (3) Study of organic additives influencing the performance of filler (nm).
- (4) Physical and chemical optimal process control for finishing (nm) of fibrous materials.

Some important effects of clay mineral in fibrous polymeric material (filament and fabric) are summarized in Table 4. The application of inorganic particle (nm) and their composite was perceived as an alternative antimicrobial finishing technique to prevent the toxic or harmful effects of conventional finishes. Therefore, particle (nm) of various materials including clay mineral and clay-polymer (nm) composite, metallic and nonmetallic TiO₂ (nm) composite, carbon nanotube, silver-based materials (nm), and so forth, were reviewed by Dastjerdi and Montazer [46].

Studies were conducted to produce flame retardancy through the utilization of Mt-PU (nm) composite and polyhedral oligomeric silsesquioxanes (POSS)-PU (nm) composite. Polyester and cotton fabrics were coated using the said composites, and the coated fabric specimen were analyzed using the cone calorimetry and thermogravimetric analysis. Subsequently, the effects of Mt-PU (nm) composite and POSS-PU (nm) composite were discussed; however, POSS showed relatively significant flame retardancy [47].

In special finishing, surface coating of textile might generally be used including the flame retardancy and water repellency. Polyurethane (PU) resin coating on textile fabric was known for imparting water repellency and reduced air permeability. However, PU was possibly an important study area to coat the fabric using clay mineral-based formulation and to assess the resulting physio-chemical effects. Depending upon the clay mineral structure, fixing agent used and application technique improvement in flame retardancy and thermal stability would be obtainable.

Flame retardant coating composition containing branched polyethylenimine (BPEI) and sodium montmorillonite (NaMt) was produced. Four water-based coating

recipes containing BPEI (pH 7 and 10) and NaMt (0.2 and 1 wt.%) were applied to cotton fabric [48].

Thermogravimetric analysis showed that coated fabric, relative to an uncoated fabric, left as much as 13% char when heated to 500°C. That amount of char was 2 orders of magnitude more than an uncoated fabric. The coated fabric showed reduction in afterglow time in vertical flame test.

An interesting finding was the preservation of weave structure and fiber shape, revealed by SEM examination, in postburn residue of all the coated fabrics. The coating recipe based on BPEI pH 7 and NaMt 1 wt.% content was significantly effective.

The total heat release and heat release capacity, observed in microcombustion calorimeter testing, was reduced in all coated fabrics relative to an uncoated fabric.

The findings on clay mineral coated cotton fabric properties were the significant realization in advancing the study of clay mineral application using water-based composition and known technique. The conventional fiber finishing industry significantly utilized water-based composition.

6.2. Poly(Ethylene Terephthalate (PET)) Composites. A significant amount of polymers were used in the form of fibers or filament; however, the subject of modifying the performance of polymers in fiber or filament form using clay mineral (nm) received little research interest to date. Improving the flame-retardancy of synthetic-polymer fibers using the clay mineral (nm) is presently a demanding area to explore several fibers including nylon, polypropylene, polyester, and polystyrene.

Production of man-made microfibers using electrospinning process was known since 1930s. Production of synthetic polymer fibers having diameter in the micrometer range was possible using electrospinning. The process of electrospinning provided significant opportunities to produce nanofillers using the polymer solution. Some important electrospun nanofibers produced using a particular solvent are shown in Table 2.

Some of the work done was limited to poly(ethylene terephthalate) (PET). It was chemically modified using ethylenediamine prior to electrospinning. Cellulose acetate, polyethylene glycol, or polyethylene oxide each was studied as additive. PET fibers-polymer (nm) composite obtained showed sufficient physical properties including tensile strength and percent at break relative to other electrospun materials such as nylon which lose significant strength on electrospinning. Addition of polyethylene glycol or polyethylene oxide in PET solution brought no improvement in fiber strength [45].

The various types of polymer systems to produce nanofibers using electrospinning technology include high performance polymers, liquid crystalline polymers, polymer blend, and biopolymer [49].

An important review, produced by Horrocks et al. [50], of flame retardant textiles had indicated that inclusion of clay mineral in polymer was found to enhance flame retardancy in terms of reduced peak heat release rate.

6.3. Clay Mineral (nm)-Polypropylene Composite. Preparation of Mt-polypropylene (nm) composite was reviewed by

TABLE 4: Clay mineral effects on filament fibers and fabric.

S. no.	Composite	Method	Performance effects
1	Clay mineral (nm) polypropylene	Melt compounding propylene in twin-screw extruder	(i) Increased filament modulus (ii) Increased char formation (iii) Insignificant effect on flame retardancy
2	Clay mineral (nm) polypropylene Compatibilizer used was maleic anhydride grafted polypropylene	Melt spinning	(i) Filament produced showed improved tensile strength and thermal stability (ii) Enhanced dynamic mechanical properties (iii) Creep resistance
3	Mt-polyurethane (nm) (Mt-PU (nm)) Polyhedral oligomeric silsequioxanes-polyurethane (nm) (POSS-PU)	Coated on polyester and cotton fabric	Relative to Mt-PU, POSS-PU (nm) coating showed improved flame retardancy
4	NaMt-branched polyethyleneimine	Coated on cotton fabric	(i) When heated to 500°C, the amount of char produced was 2 orders of magnitude relative to uncoated fabric (ii) Reduced afterglow time (iii) Reduced total heat release (iv) Reduced heat release capacity

Manias et al. [51]. Two forms of constituent materials were described useful for producing Mt/propylene nanocomposite:

- (1) functionalized polypropylene and organo-Mt,
- (2) unmodified (=neat) polypropylene and half-fluorinated organic silicate.

The necessary conditions, the characteristics of polypropylene filaments, and tapes containing dispersion of functionalized clay mineral were studied to assess flame retardancy [52]. Clay mineral (nm)-polypropylene composite was produced by melt compounding polypropylene in a twin-screw extruder. Subsequently, polypropylene filament containing clay mineral (nm) was produced and assessed. The presence of dispersed clay mineral increased the filament modulus. Filament samples exhibited sufficiently acceptable textile properties to enable their knitting into fabric. Burning behavior of fabric and film samples was evaluated by limiting oxygen index and cone calorimetry at 35 kW/m² external heat flux. The presence of clay mineral showed no influence on burning character, and the effect on flame retardancy was insignificant; however, char formation was encouraged.

Influence of clay mineral (nm) on the physical properties of polypropylene was evaluated [53]. Clay mineral (nm)-polypropylene composite filaments were produced by melt spinning. The compatibilizer used was maleic anhydride grafted PP. Clay mineral (nm) loadings up to 1 wt.% with compatibilizer up to 3 wt.% were investigated. Results achieved indicated significant improvement in the tensile, thermal, and dynamic mechanical properties and creep resistance in clay mineral (nm)-polypropylene composite filament relative to virgin polypropylene at small clay mineral (nm) loadings of 0.25–0.5 wt.% and a compatibilizer/clay mineral ratio of 2 : 1.

6.4. Cellulose Composite. Use of clay mineral was indicated in producing cellulose composite [54]. Technology was developed to produce clay mineral-cellulose (nm) composite using various sources of cellulose including grass, kenaf, cotton fiber, and cotton plant material. Thermal stability of clay mineral-cellulose (nm) composite was improved suitable for end-products such as nonwovens, papers, and filament fibers.

7. Clay Mineral Performance

Exfoliation and dispersion of clay mineral particles are two significant properties. The effects of clay mineral on polymer performance are closely related with exfoliation and dispersion. Therefore, these two factors are discussed in this section.

Level of exfoliation and dispersion of clay mineral (nm) particle are the important factors in improving the effects of clay mineral. The use of ultrasonics, to improve exfoliation/dispersion of clay mineral (nm) in polypropylene, was studied by Lee et al. [55] using selected isotactic polypropylene of various molecular weights reinforced with organophilic Mt (nm) at 4–6 wt.% loadings. The effectiveness of the ultrasonic processing used was evaluated by X-ray diffraction and transmission electron microscopy. Results obtained indicated that the ultrasonic processing of clay mineral (nm)-polymer composite in the melt state could improve exfoliation and dispersion of clay mineral.

Therefore, it is not unusual to see the recommendations from clay mineral producer for achieving good level of dispersion in polymer. For example, one of the Mt producers, Nanocor, recommends high-shear processing equipment for incorporating Nanocor clay mineral into polyolefin resins [56]. Since polyolefin were hydrophobic, use of a compatibilizer was recommended for improved performance.

Use of infrared method to permit quantitative determination of organoclay mineral dispersion in terms of delamination and layer alignment was discussed by Wouter et al. [57].

The dispersion of clay mineral particle (nm) in polypropylene was investigated. Clay mineral-polypropylene (nm) composites were produced by a solution technique and a subsequent melt-mixing process [58]. To improve the compatibility of the clay mineral particle (nm) in polypropylene, a titanate coupling was used. The dispersion of clay mineral particle (nm) was studied using X-ray diffraction and transmission electron microscopy. There was an increased d -value of clay particle in (nm) composite. The number of intercalated layers in a single clay mineral crystallite was found to be 4. The results achieved indicated presence of single-layered particle with improved dispersion in polypropylene.

Dispersion of exfoliated organically modified Mt (type Cloisite 30 B) in a solution of poly(methyl methacrylate) in methyl methacrylate was studied using ultrasound [59]. A number of factors including the sonication power, clay mineral loading, use of a swelling agent, and moisture content of the modified Mt were found to affect the exfoliation process. Addition of a range of titanate coupling agents was experimented, where one of the coupling agents was found to reduce the viscosity of exfoliated Mt dispersion without influencing the extent of exfoliation.

It was indicated elsewhere that interlayer spacing and dispersion of the clay mineral were significantly influenced by the polar forces between the clay mineral and the polymeric matrix material [60].

Influence of processing machine on clay mineral exfoliation was studied for some polymers. The effect of screw speed of the corotating twin-screw extruder on the clay mineral exfoliation and composite (nm) properties was examined [61]. The organically modified Mt was used as reinforcing material in polypropylene, and maleic anhydride grafted polypropylene oligomer was used as a compatibilizer to improve clay mineral dispersion and adhesion.

The results obtained indicated the clay mineral-polypropylene (nm) composite had both intercalated and exfoliated structures depending upon the screw speed of extruder. Transmission electron microscopy images showed that the dispersion of silicate layers significantly influenced by the screw speed. The mechanical properties of clay mineral (nm)-polymer composite were not remarkably affected with increased exfoliation of silicate layers.

Use of organic surfactants with Mt to improve the desired properties of clay mineral-polystyrene (nm) composite was investigated [62]. Organo-Mt-polystyrene (nm) composite was produced by free radical polymerization of styrene in the dispersed organophilic Mt. Results obtained showed that the Mt-polystyrene (nm) composite, with 5.0 wt.% content of organo-Mt, exhibited greatest improvement in thermal stability; and with 7.5 wt.% content of organo-Mt (nm), the resulting Mt-polystyrene (nm) composite acquired the greatest improvement in mechanical properties relative to virgin polystyrene.

It was indicated that the alkyl chain length of surfactant in organo-Mt was important in modifying the polystyrene structure through the glass transition temperature. The

longer the alkyl chain length of surfactant, the higher the glass transition temperature of Mt-polystyrene (nm) composite.

Apparently, the subject of using surfactant in producing organo-Mt (nm) requires more studies to establish the advantages possible in the desired performance of polystyrene composites.

Improved thermal stability and storage moduli of Mt-nylon 1010 (nm) composite were experienced in melt intercalation using a corotating twin-screw extruder [63].

8. Conclusions

Use of clay mineral in improving the desired performance of polymers received research interest particularly in polyolefin finishing. Significant enhancement in the flame retardancy, resistance to thermal degradation, reduction in peak heat release rate, and physical properties were achievable with clay mineral at reduced loading levels relative to the traditional fillers.

An important research demanding area was the utilization of clay mineral in the finishing of textile fiber and fiber forming polymer for improved effects of flame retardancy, increased heat and abrasion resistance, and strength properties.

A loading 5 wt.% to 7 wt.% content of clay mineral showed significant improvement in mechanical-thermal properties of clay mineral-polyolefin and clay mineral-nylon (nm) composites. Improvements were also observed in poly(methyl methacrylate), polycarbonate, and cellulose composites.

In general, clay mineral utilization showed flame retardant effects, with varying decomposition mechanisms and released products, in terms of reduction in peak heat release rate for most thermoplastic polymers including polystyrene, polyamide 6, polypropylene, polyamide 12, poly(methyl methacrylate), polyethylene, ethylene vinyl acetate (EVA).

There were applications of polymeric materials in the form of filament fiber where the inclusion of clay mineral received relatively reduced interest to date. Flame retardancy and thermal stability for these filaments was particularly desired in protective wear. Therefore, known clay mineral may be investigated for improvement in desired effects.

References

- [1] F. Uddin, "Clays, nanoclays, and montmorillonite minerals," *Metallurgical and Materials Transactions A*, vol. 39, no. 12, pp. 2804–2814, 2008.
- [2] H. H. Murray, "Applied clay mineralogy today and tomorrow," *Clay Minerals*, vol. 34, no. 1, pp. 39–49, 1999.
- [3] H. H. Murray, "Overview: clay mineral applications," *Applied Clay Science*, vol. 5, no. 5–6, pp. 379–395, 1991.
- [4] F. Uddin, "Advancement in nanotechnology of polymers and fibres," *International Dyer*, vol. 193, no. 2, pp. 33–35, 2008.
- [5] L. Christoph, *Opportunities and Risks of Nanotechnologies*, Allianz Center for Technology, OECD International Futures Program, Munich, Germany, 2005.
- [6] Anon., *Plastics, Additives and Compounding*, 2007, <http://www.addcomp.com/>.

- [7] Anon., Laviosa Chemical Mineraria, 2007, <http://www.laviosa.it/>.
- [8] W. E. Gacitua, A. A. Ballerini, and J. Zhang, "Polymer nanocomposites: synthetic and natural fillers—a review," *Maderas Ciencia y Tecnología*, vol. 7, no. 3, pp. 159–178, 2005.
- [9] Nanocor-Technical, *Nanoclay Structures*, Nanocor, Hoffman Estates, Ill, USA, 2008.
- [10] Q. H. Zeng, A. B. Yu, G. Q. Lu, and D. R. Paul, "Clay-based polymer nanocomposites: research and commercial development," *Journal of Nanoscience and Nanotechnology*, vol. 5, no. 10, pp. 1574–1592, 2005.
- [11] J. K. Pandey, K. Raghunatha Reddy, A. Pratheep Kumar, and R. P. Singh, "An overview on the degradability of polymer nanocomposites," *Polymer Degradation and Stability*, vol. 88, no. 2, pp. 234–250, 2005.
- [12] B. Bob, *Nanoclays: Counting on Consistency*, Southern Clay Products, Gonzales, Tex, USA.
- [13] S. Sinha Ray and M. Okamoto, "Polymer/layered silicate nanocomposites: a review from preparation to processing," *Progress in Polymer Science*, vol. 28, no. 11, pp. 1539–1641, 2003.
- [14] G. Lagaly, "Introduction: from clay mineral-polymer interactions to clay mineral-polymer nanocomposites," *Applied Clay Science*, vol. 15, no. 1-2, pp. 1–9, 1999.
- [15] P. Liu, "Polymer modified clay minerals: a review," *Applied Clay Science*, vol. 38, no. 1-2, pp. 64–76, 2007.
- [16] K. Yano, A. Usuki, A. Okada, T. Kurauchi, and O. Kamigaito, "Synthesis and properties of polyimide-clay hybrid," *Journal of Polymer Science A*, vol. 31, no. 10, pp. 2493–2498, 1993.
- [17] Z. M. Huang, Y. Z. Zhang, M. Kotaki, and S. Ramakrishna, "A review on polymer nanofibers by electrospinning and their applications in nanocomposites," *Composites Science and Technology*, vol. 63, no. 15, pp. 2223–2253, 2003.
- [18] S. S. Ray and M. Okamoto, "Polymer/layered silicate nanocomposites: a review from preparation to processing," *Progress in Polymer Science*, vol. 28, no. 11, pp. 1539–1641, 2003.
- [19] F. Gao, "Clay/polymer composites: the story," *Materials Today*, vol. 7, no. 11, pp. 50–55, 2004.
- [20] F. Hussain, M. Hojjati, M. Okamoto, and R. E. Gorga, "Review article: polymer-matrix nanocomposites, processing, manufacturing, and application: an overview," *Journal of Composite Materials*, vol. 40, no. 17, pp. 1511–1575, 2006.
- [21] J. Jordan, K. I. Jacob, R. Tannenbaum, M. A. Sharaf, and I. Jasiuk, "Experimental trends in polymer nanocomposites: a review," *Materials Science and Engineering A*, vol. 393, no. 1-2, pp. 1–11, 2005.
- [22] R. R. Hegde, A. Dahiya, and M. G. Kammath, Nylon fibers, 2004, <http://utnrl.engr.utk.edu/>.
- [23] IHS, "Nylon fibers," World Petrochemical Report, 2012, <http://chemical.ihs.com>.
- [24] A. Usuki, N. Hasegawa, and M. Kato, "Polymer-clay nanocomposites," *Advances in Polymer Science*, vol. 179, pp. 135–195, 2005.
- [25] Q. Lei and J. P. Hinestroza, "Application of nanotechnology for high performance textiles," *Journal of Textile and Apparel, Technology and Management*, vol. 4, no. 1, pp. 1–7, 2004.
- [26] S. Lao, W. Ho, K. Ngyuen et al., "Microstructural analysis of nylon 11 nanocomposites," in *Proceedings of the 37th ISTC Conference*, Seattle, Wash, USA, November 2005.
- [27] S. Mohanty and S. K. Nayak, "Effect of clay exfoliation and organic modification on morphological, dynamic mechanical, and thermal behavior of melt-compounded polyamide-6 nanocomposites," *Polymer Composites*, vol. 28, no. 2, pp. 153–162, 2007.
- [28] J. I. Weon, Z. Y. Xia, and H. J. Sue, "Morphological characterization of nylon-6 nanocomposite following a large-scale simple shear process," *Journal of Polymer Science B*, vol. 43, no. 24, pp. 3555–3566, 2005.
- [29] A. Usuki, A. Koiwai, Y. Kojima et al., "Interaction of nylon-6-clay surface and mechanical properties of nylon-6-clay hybrid," *Journal of Applied Polymer Science*, vol. 55, no. 1, pp. 119–123, 1993.
- [30] H. H. Kausch and G. H. Michler, "Effect of nanoparticle size and size-distribution on mechanical behavior of filled amorphous thermoplastic polymers," *Journal of Applied Polymer Science*, vol. 105, no. 5, pp. 2577–2587, 2007.
- [31] S. G. Hatzikiriakos, N. Rathod, and E. B. Muliawan, "The effect of nanoclays on the processibility of polyolefins," *Polymer Engineering and Science*, vol. 45, no. 8, pp. 1098–1107, 2005.
- [32] L. Chen, S. C. Wong, and S. Pisharath, "Fracture properties of nanoclay-filled polypropylene," *Journal of Applied Polymer Science*, vol. 88, no. 14, pp. 3298–3305, 2003.
- [33] S. Nazaré, B. K. Kandola, and A. R. Horrocks, "Flame-retardant unsaturated polyester resin incorporating nanoclays," *Polymers for Advanced Technologies*, vol. 17, no. 4, pp. 294–303, 2006.
- [34] F. Yang and G. L. Nelson, "Polymer/silica nanocomposites prepared via extrusion," *Polymers for Advanced Technologies*, vol. 17, no. 4, pp. 320–326, 2006.
- [35] P. Kiliaris and C. D. Papaspyrides, "Polymer/layered silicate (clay) nanocomposites: an overview of flame retardancy," *Progress in Polymer Science*, vol. 35, no. 7, pp. 902–958, 2010.
- [36] J. W. Gilman, "Flammability and thermal stability studies of polymer layered-silicate (clay) nanocomposites," *Applied Clay Science*, vol. 15, no. 1-2, pp. 31–49, 1999.
- [37] M. Lewin, "Reflections on migration of clay and structural changes in nanocomposites," *Polymers for Advanced Technologies*, vol. 17, no. 9-10, pp. 758–763, 2006.
- [38] M. Lewin, E. M. Pearce, K. Levon et al., "Nanocomposites at elevated temperatures: migration and structural changes," *Polymers for Advanced Technologies*, vol. 17, no. 4, pp. 226–234, 2006.
- [39] W. Xie, Z. Gao, K. Liu et al., "Thermal characterization of organically modified montmorillonite," *Thermochimica Acta*, vol. 367-368, pp. 339–350, 2001.
- [40] L. G. Imhof and K. C. Stueben, "Evaluation of the smoke and flammability characteristics of polymer systems," *Polymer Engineering and Science*, vol. 13, no. 2, pp. 146–152, 2004.
- [41] G. W. Jeffrey, "Flame retardant mechanism of polymer-clay nanocomposites," in *Flame Retardant Polymer Nanocomposites*, B. A. Morgan and A. W. Charles, Eds., John Wiley and Sons, 2007.
- [42] J. W. Gilman, C. L. Jackson, A. B. Morgan et al., "Flammability properties of polymer-layered-silicate nanocomposites. Polypropylene and polystyrene nanocomposites," *Chemistry of Materials*, vol. 12, no. 7, pp. 1866–1873, 2000.
- [43] H. Qin, S. Zhang, C. Zhao, G. Hu, and M. Yang, "Flame retardant mechanism of polymer/clay nanocomposites based on polypropylene," *Polymer*, vol. 46, no. 19, pp. 8386–8395, 2005.
- [44] A. B. Morgan, L. L. Chu, and J. D. Harris, "A flammability performance comparison between synthetic and natural clays in polystyrene nanocomposites," *Fire and Materials*, vol. 29, no. 4, pp. 213–229, 2005.

- [45] F. Uddin, "Some aspects in textile nanofinishing," in *Proceedings the 86th Textile Institute World Conference*, The Hong Kong Polytechnic University, November 2008.
- [46] R. Dastjerdi and M. Montazer, "A review on the application of inorganic nano-structured materials in the modification of textiles: focus on anti-microbial properties," *Colloids and Surfaces B*, vol. 79, no. 1, pp. 5–18, 2010.
- [47] E. Devaux, M. Rochery, and S. Bourbigot, "Polyurethane/clay and polyurethane/POSS nanocomposites as flame retarded coating for polyester and cotton fabrics," *Fire and Materials*, vol. 26, no. 4-5, pp. 149–154, 2002.
- [48] Y. C. Li, J. Schulz, S. Mannen et al., "Flame retardant behavior of polyelectrolyte-clay thin film assemblies on cotton fabric," *ACS Nano*, vol. 4, no. 6, pp. 3325–3337, 2010.
- [49] A. Agic and B. Mijovic, "Mechanical properties of electrospun carbon nanotube composites," *Journal of the Textile Institute*, vol. 97, no. 5, pp. 419–427, 2006.
- [50] A. R. Horrocks, B. K. Kandola, P. J. Davies, S. Zhang, and S. A. Padbury, "Developments in flame retardant textiles: a review," *Polymer Degradation and Stability*, vol. 88, no. 1, pp. 3–12, 2005.
- [51] E. Manias, A. Touny, L. Wu, K. Strawhecker, B. Lu, and T. C. Chung, "Polypropylene/montmorillonite nanocomposites. Review of the synthetic routes and materials properties," *Chemistry of Materials*, vol. 13, no. 10, pp. 3516–3523, 2001.
- [52] A. R. Horrocks, B. K. Kandola, G. Smart, S. Zhang, and T. R. Hull, "Polypropylene fibers containing dispersed clays having improved fire performance. I. Effect of nanoclays on processing parameters and fiber properties," *Journal of Applied Polymer Science*, vol. 106, no. 3, pp. 1707–1717, 2007.
- [53] M. Joshi and V. Viswanathan, "High-performance filaments from compatibilized polypropylene/clay nanocomposites," *Journal of Applied Polymer Science*, vol. 102, no. 3, pp. 2164–2174, 2006.
- [54] K. V. Singh, P. S. Sawhney, N. D. Sachinbab et al., "Applications and future of nanotechnology in textiles," in *Proceedings of the 2006 Beltwide Cotton Conferences*, pp. 2498–2500, San Arntonio, Tex, USA.
- [55] E. C. Lee, D. F. Mielewski, and R. J. Baird, "Exfoliation and dispersion enhancement in polypropylene nanocomposites by in-situ melt phase ultrasonication," *Polymer Engineering and Science*, vol. 44, no. 9, pp. 1773–1782, 2004.
- [56] Nanocor, "Nanomer products for polyolefin nanocomposites," Technical Data P-801, Nanocor, Hoffman Estates, Ill, USA, 2008.
- [57] W. L. Ijdo, S. Kemnetz, and D. Benderly, "An infrared method to assess organoclay delamination and orientation in organoclay polymer nanocomposites," *Polymer Engineering and Science*, vol. 46, no. 8, pp. 1031–1039, 2006.
- [58] G. Mani, Q. Fan, S. C. Ugbolue, and Y. Yang, "Morphological studies of polypropylene-nanoclay composites," *Journal of Applied Polymer Science*, vol. 97, no. 1, pp. 218–226, 2005.
- [59] M. McAlpine, N. E. Hudson, J. J. Liggat, R. A. Pethrick, D. Pugh, and I. Rhoney, "Study of the factors influencing the exfoliation of an organically modified montmorillonite in methyl methacrylate/poly(methyl methacrylate) mixtures," *Journal of Applied Polymer Science*, vol. 99, no. 5, pp. 2614–2626, 2006.
- [60] K. Y. Lee and L. A. Goettler, "Structure-property relationships in polymer blend nanocomposites," *Polymer Engineering and Science*, vol. 44, no. 6, pp. 1103–1111, 2004.
- [61] P. Peltola, E. Välipakka, J. Vuorinen, S. Syrjälä, and K. Hanhi, "Effect of rotational speed of twin screw extruder on the microstructure and rheological and mechanical properties of nanoclay-reinforced polypropylene nanocomposites," *Polymer Engineering and Science*, vol. 46, no. 8, pp. 995–1000, 2006.
- [62] W. Xie, J. M. Hwu, G. J. Jiang, T. M. Buthelezi, and W. P. Pan, "A study of the effect of surfactants on the properties of polystyrene-montmorillonite nanocomposites," *Polymer Engineering and Science*, vol. 43, no. 1, pp. 214–222, 2003.
- [63] A. R. Horrocks, B. K. Kandola, G. Smart, S. Zhang, and T. R. Hull, "Polypropylene fibers containing dispersed clays having improved fire performance. I. Effect of nanoclays on processing parameters and fiber properties," *Journal of Applied Polymer Science*, vol. 106, no. 3, pp. 1707–1717, 2007.



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