



*Review Article*

## **A Review on Nano Fibre Technology in Polymer Composites**

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### **ABSTRACT**

The enormous attention and interest by both academics and industrial field for greener, biodegradable and renewable materials implicate a persuasive trends towards the encroachment of nano-materials science and technology in the polymer composite field. Nanocomposites creates high impacts on the development of nano materials with advanced features to solve potential risks with their wider industrial applications. Nano fibres are highly engineered fibres with diameters less than 100 nm that offer several advantages over conventional fibres. One dimensional (1D) nanostructure fillers such as carbon nano fibre and cellulose nano fibre are the most common, promising and unique for developing multifunctional nanocomposites with better properties and extensive applications compared to micro size fibres. Nano fibre technology brings revolution by providing products that are completely safe, truly greener, reliable and environmentally friendly for industries, researchers and users. This review article is intended to present valuable literature data on research and trend in the fields of carbon and cellulose nano fiber, nanocomposites with specific focus on various applications for a sustainable and greener environment..

*Keywords:* Nano filler, nano fibre, nano fibres processing, carbon nano fibre, cellulosic nano fibre, nanocomposites

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### **INTRODUCTION**

The nanotechnology provides new challenges and contests to fulfil various demands in the fields of medicine, automotive, computer science, transportation, biotechnology,

agriculture, food packaging, military, cosmetics, solar cells and textile sectors, intelligent fabrics, composites and power industries (Lee et al., 2012, pp. 4078-4086; Rhim et al., 2013, pp. 1629-1652; Bilbao-Sainz et al., 2011, pp. 1549-1557; Varshney & Naithani 2011, pp. 43-61; Amritkar et al., 2011, pp. 45-53).

Nanocomposites gained worldwide research interest and are reported as the 21st century multiphase solid material having at least one dimensions phases in the nanometre range ( $1 \text{ nm} = 10^{-9} \text{ m}$ ) (Saba et al., 2014, pp. 2247-2273). Nanocomposite materials are considered as potential substitutes to overawe the drawbacks of conventional composites and monolithic, usually at lower nano filler loadings (3-5 wt.%), owing to nanometric size effects (Mariano et al., 2014, pp. 791-806; Rhim et al., 2013, pp. 1629-1652). In particular, nanomaterials/nano filler are regarded as highly potential filler materials for the enhancement of physical, mechanical and thermal properties of polymeric matrix materials (thermoplastics or thermosets) chiefly by increasing the counter face adhesion, matrix modulus and strength (Saba et al., 2014, pp. 2247-2273; Raza et al., 2015, pp. 9-16). Nano scale materials or fillers are classified into three groups, based on the number of dimensions in the nano metre range, as nanoparticles, nanotubes and nano-layers (Chrissafis & Bikiaris, 2011, pp. 1-24). The different types of nano materials are shown in Figure 1.

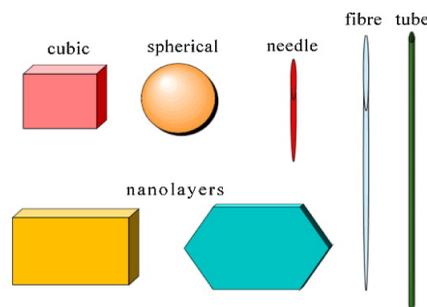


Figure 1. Types of nanoscale materials  
 Source: Chrissafis & Bikiaris, 2011, pp. 1-24

These nanoparticles interact with the polymeric chains, either physically or covalently, resulting nanocomposite network having unique properties (Gaharwar et al., 2014, pp. 441-453; Schexnailder & Schmidt, 2009, pp. 1-11; Mariano et al., 2014, pp. 791-806).

### Nanocomposite Synthesis and Characterisation Techniques

The nanocomposite structure typically consists of polymer matrix material reinforced with the nano-sized filler components in the forms of fibres, particles, whiskers and nanotubes. Interestingly there are five different routes to synthesise the nanocomposites including template synthesis, intercalation of polymer or prepolymer from solution, in-situ intercalative polymerisation, direct mixing between the polymer and particles and melt intercalation process (Mittal, 2009, pp. 992-1057; Alateyah et al., 2013; Tanahashi, 2010, pp. 1593-1619). The different methods of processing nanocomposites are illustrated in Figure 2.

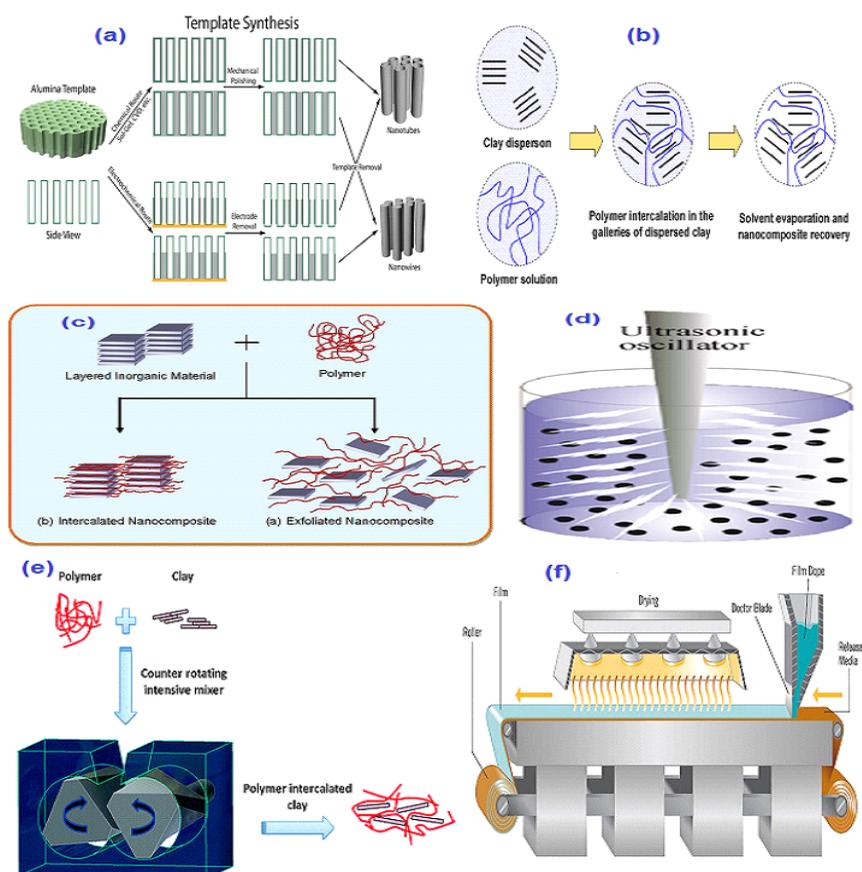


Figure 2. (a) Template Synthesis of Nanostructured Materials, (b) Intercalation of polymer or prepolymer from solution, (c) *In-Situ* Intercalative Polymerisation, (d) Direct mixing, (e) Melt intercalation, and (f) solvent casting method for nanocomposites fabrication

The same methods have also been applied for the preparation of layered silicates based on nanocomposites (Tanahashi, 2010, pp. 1593-1619). However, melt mixing, solvent casting, electrospinning and *in situ* polymerisation are important techniques for the fabrication of nano fibre based polymer composites (Zimmermann et al., 2010, pp. 1086-1093).

Different equipment and techniques are being used for the characterisation of nano fibres and their nanocomposites, including scanning tunnelling microscopy (STM), fourier transformed infrared spectroscopy (FTIR), nuclear magnetic resonance (NMR), atomic force microscopy (AFM), X ray photoelectron spectroscopy (XPS), wide-angle X-ray scattering (WAXS), scanning and transmission electron microscopy (SEM/TEM) and differential scanning calorimetry (DSC) (Camargo et al., 2009, pp. 1-39).

## Nano Fibres

Nano fibres are the highly engineered textiles, defined as fibres with diameters less than 100 nm. Nano fibres possess several unique properties and show several advantages over micro such as:

- Lightweight material, builds network structures
- Renewable resource, biodegradable (cellulosic nano fibres only)
- High strength and stiffness
- Transparent, translucent, water storage capacity and rheology modifier
- High surface area and aspect ratio
- High reactivity, barrier properties (Chen et al., 2011, pp. 1804-1811)

Researchers around the globe are developing new imaginable applications possibilities for nano fibres. The two most common and established nano fibres in the field of polymer composites are carbon nano fibres and cellulose nano fibres (shown in Figures 3a-b).

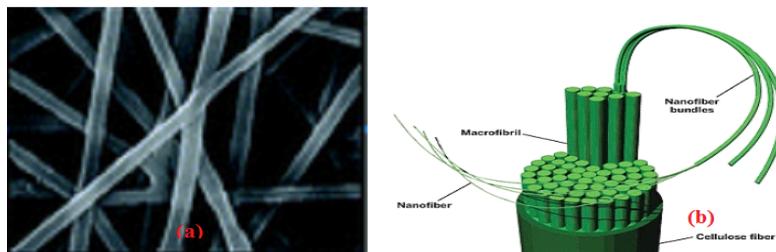


Figure 3. (a) Carbon nano fibres and (b) Cellulose nano fibres

Source: Kalluri et al., 2013, pp. 25576-25601

Source: Chen et al. 2014, pp. 1517-1528

## General Methods for Manufacturing Nano Fibres

Currently, various techniques such as electrospinning, self-assembly, meltblowing, bicomponent spinning, force-spinning, phase-separation, drawing and flash-spinning are being used to overcome the growing demands for the fabrication of polymeric nano fibres. However, electrospinning is a widely used technique for the fabrication of continuous nano fibres because of its simplicity and suitability for a variety of polymers, ceramics and metals (Ahmed et al., 2015, pp. 15-30). Some of the methods are explained in brief.

### Electrospinning

The most common and reliable method for the production of smooth nano fibres from a variety of polymers with controllable morphology is observed through electrospinning (Figure 4). It shares the characteristics of both electro spraying and conventional solution dry spinning of fibres based on the effect of electrostatic force on liquids. Electrospinning process can be

classified into two groups according to the method of preparing the polymer, namely, solution electrospinning and melt electrospinning (Nayak et al., 2012, pp. 129-147; Wang et al., 2013, pp. 1173-1243).

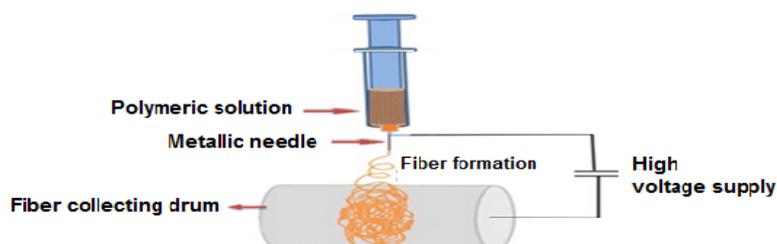


Figure 4. Electrospinning technique  
(Source: Ahmed et al., 2015, pp. 15-30)

### Solution blow spinning

A solution blow spinning technique was developed using elements of both electrospinning and meltblowing technologies as an alternative method for making non-woven webs of micro and nanofibres (Figure 5). The produced nano fibres possess comparable diameters but fibre production rate (measured by the polymer injection rate) is several times higher with those made by the electrospinning process (Medeiros et al., 2009, pp. 2322-2330; Oliveira et al., 2011, pp. 3396-3405).

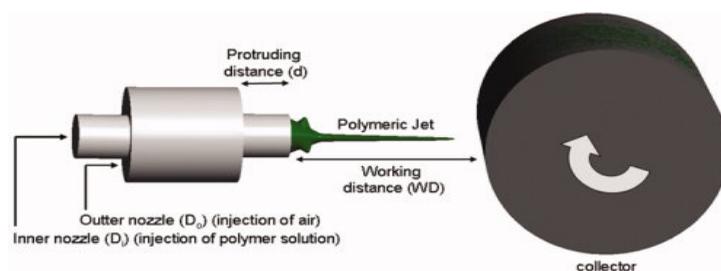


Figure 5. Solution blowing technique

### Meltblowing

Meltblowing is a simple, versatile and one-step process for the production of materials in micrometre and smaller scale. In the meltblowing process, a molten polymer is extruded through the orifice of a die (Figure 6). The fibres are formed by the elongation of the polymer streams coming out of the orifice by air-drag and are collected on the surface of a suitable collector in the form of a web. The average fibre diameter mainly depends on the throughput rate, melt viscosity, melt temperature, air temperature and air velocity. The meltblowing apparatus consists of two extruders with different barrel diameters to create different shear rates. The

process is suitable for many melt-spinnable commercial polymers, copolymers and their blends such as polyesters, polyolefins, polyurethanes, nylons, poly vinyl chloride, polyvinyl acetate and ethylene vinyl acetate. The meltblown fibres significantly reduced average diameter and enhanced surface area to mass ratio compared to conventional meltblown fibres (Nayak et al., 2012, pp. 129-147; Hassan et al., 2013, pp. 336-344).

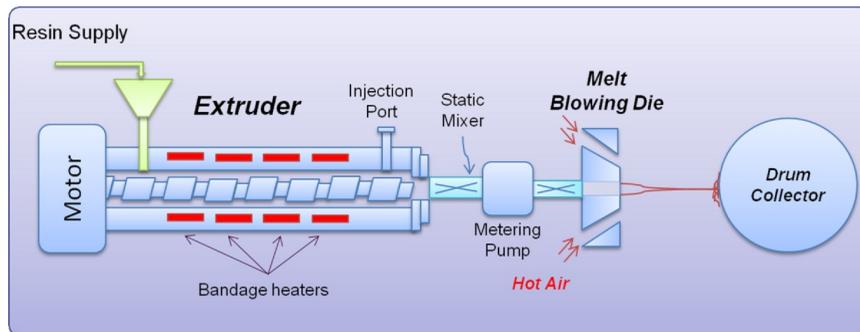


Figure 6. Meltblowing technique (Hassan et al., 2013, pp. 336-344)

### Phase separation

Phase separation process is a relatively simple procedure and its requirements are very minimal in terms of equipment compared with the electrospinning and self-assembly techniques (Vasita & Katti 2006, p. 15). A schematic representation of phase separation is shown in Figure 7.

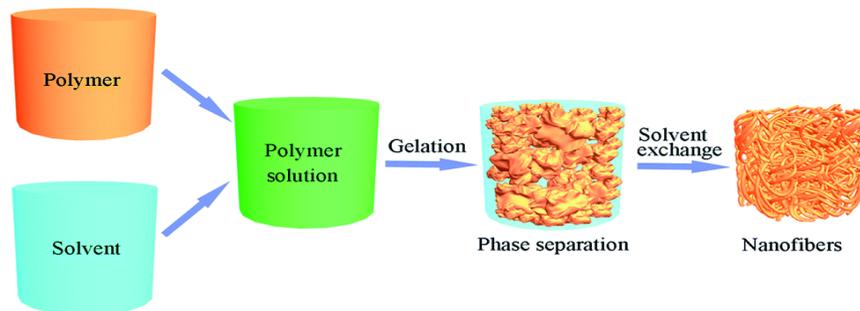


Figure 7. Phase separation technique (Vasita & Katti, 2006, p. 15)

### Nano Fibre Reinforcement Effects

Fibrous nano materials such as nano fibres and carbon nanotubes, in addition to polymer matrix, provide reinforcing efficiency because of their high aspect ratios (Luo & Daniel, 2003, pp. 1607-1616). Some of the reinforcement effects imparted by nano-particulate/fibrous that are being added to polymer matrix include the improvement in gas barrier properties, mechanical properties (tensile strength, stiffness, toughness), dimensional stability, thermal conductivity,

flame retardancy, thermal barrier, chemical and ablation resistance when compared to conventionally filled materials (Saba et al., 2014, pp. 2247-2273).

However certain disadvantages are also found to be associated involving optical, sedimentation and dispersion problems, viscosity improvement and black coloured offered by dispersing carbon nanofibre (CNT). Alternatively, dispersion of the nano fibres and adhesion at the nanofibre–matrix interface play crucial roles in determining the mechanical properties of the nanocomposite (Hussain et al., 2006, pp. 1511-1575).

### Carbon Nano Fibres

Carbon nano fibres are promising one dimensional carbon based nanomaterials used as fillers in developing multifunctional nanocomposites (Poveda & Gupta, 2014, pp. 416-422). Carbon nano fibres are a thousand time smaller than conventional fibres (CF) and larger than nanotubes. The fibres are made up of interlocking sheets of graphenes, which in turn are made up of carbon atoms. The major differences between conventional carbon fibres (CFs) and carbon nano fibres are their size and methods of preparation or synthesis. Conventional CF has diameters of several micrometres, while carbon nano fibres have diameters of 50–200 nm (Feng et al., 2014, pp. 3919-3945). Unlike conventional fibre spinning techniques (wet spinning, dry spinning, melt spinning, gel spinning), which are capable of producing polymer fibres with diameters down to the micrometre range, carbon nano fibres are produced by electrostatic spinning or through electrospinning process in the submicron to nanometre diameter range (Raghavan et al., 2012, pp. 915-930). Figure 8 gives a schematic illustration of the difference between carbon nano fibre and conventional ones (CF).

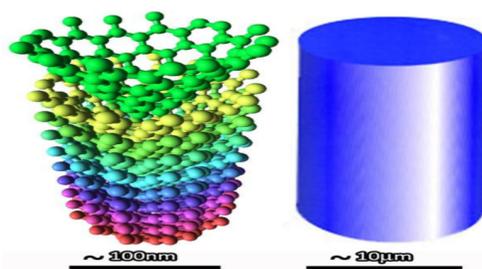


Figure 8. A schematic illustration of carbon nano fibre and conventional carbon fibre (Source: Feng et al., 2014, pp. 3919-3945)

Currently, carbon nano fibers are prepared mainly by two methods, namely, catalytic thermal chemical vapour deposition growth (VG) and electrospinning, followed by heat treatment (Feng et al., 2014). Researchers observed that vapour grown carbon nano fibres (VGCNF) are very similar to multi-walled carbon nanotubes (MWCNTs) in morphology but they have larger diameters than MWCNTs (Raza et al., 2015). MWCNTs and single walled carbon nano tubes (SWNTs) are 2–3 times more expensive than VGCNFs. VGCNFs are regarded as strong potential alternatives to carbon fibres (CFs) and carbon black (high structured

CB) due to their lower loading concentration compared with CF and CB in certain electrical conductivities apparatus (Al-Saleh et al., 2009, pp. 2-22).

Some researchers also stated that the carbon nano fibres have higher reinforcing capabilities than micro carbon fibres (Al-Saleh et al., 2011, pp. 2126-2142). The sensitivity of CNFs and their composites mainly count on their electrical performances (Feng et al., 2014, pp. 3919-3945).

### Cellulose Nano Fibres

Cellulose, being the most abundant material and renewable resource on the earth, has received more interest from researchers for a decade (Langan et al., 2014, pp. 63-68; Miao et al., 2014, pp. 109-113; Orehek et al., 2013, pp. 10-17; Giudicianni et al., 2013, pp. 213-222). Typical chemical structures of cellulose are shown in Figure 9 below.

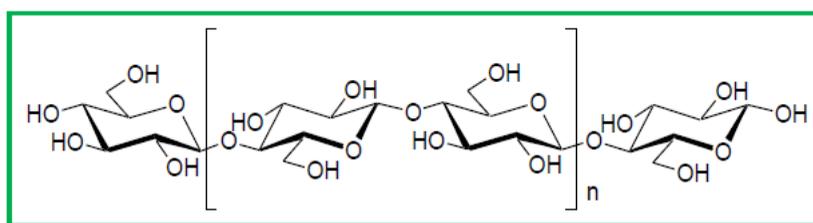


Figure 9. Typical chemical structure of cellulose  
Source: Siqueira et al., 2010, pp. 728-765

Cellulose nano fibres being extracted from cellulosic materials are one of the most advanced engineered biomass materials. Cellulose nano fibres can be extracted from the cell walls of different renewable sources including cotton, bacteria, wood, straw and sea animals called tunicates either by simple mechanical methods or a combination of both chemical and mechanical methods (Kalia et al., 2011; Wang & Sain, 2007, pp. 538-546; Tang & Weder, 2010, pp. 1073-1080). Several processes have been used to extract highly purified nano fibres from cellulosic materials. The most established are through mechanical techniques (cryocrushing, grinding, high-pressure homogenizing), chemical treatments (acid hydrolysis, antioxidants), biological treatments (enzymatic hydrolysis), electrospinning and ultra-sonication methods (Chen et al., 2011, pp. 453-461; Chen et al., 2011, pp. 1804-1811). Cellulose nanocrystals (CNCs) are also termed as cellulose nano fibres, whiskers, micro-crystallites, microcrystals, nanoparticles or nano-fibrils by many researchers; however, there are some contradictions on these terms (Siqueira et al., 2010, pp. 728-765; Kalia et al., 2011). Figure 10 displays the nano material definition standard terminology by the technical association of the pulp and paper industry (TAPPI).

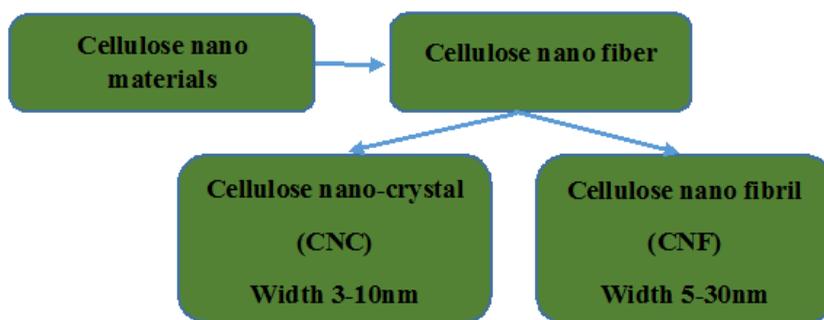


Figure 10. Standards terminology of cellulose nano materials by TAPPI  
 Source: Mariano et al., 2014, pp. 791-806

Furthermore, cellulose nano fibres have significant properties such as low cost, light weight, raw material availability, nanoscale dimension, renewability, outstanding mechanical, electrical, thermal properties, biodegradation properties along with unique morphology (Cao et al., 2013, pp. 819-826; Tang & Weder, 2010, pp. 1073-1080). The many steps involved in the preparation of nano cellulose particles are summarised in Figure 11.

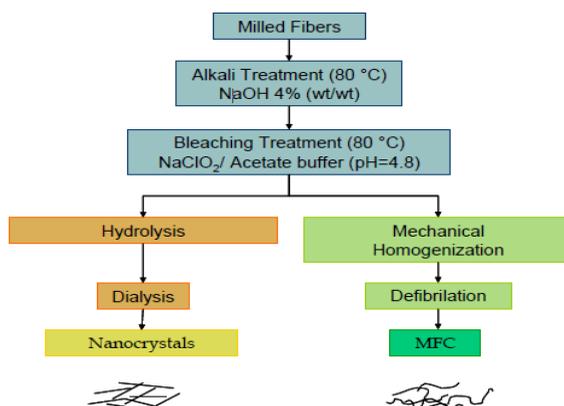


Figure 11. Steps for the preparation of nano cellulose  
 Source: Siqueira et al., 2010, pp. 728-765

The milled raw fibres are acquiesced to alkali and bleaching treatments with NaClO<sub>2</sub>. Under optimal conditions, lignin and hemicelluloses contents are allowed to get eliminated in these steps, while cellulose moieties remain intact. The bleached fibres are then hydrolysed (acid hydrolysis treatment) or disintegrated (mechanical shearing at high pressure) (Siqueira et al., 2010, pp. 728-765). However, the only drawback of cellulose nano fibres is that they are made by treating wood pulp with strong acids and oxidants, followed by mechanical division of cellulose fibres into their nanoscale subunits, which are quite expensive (Chen et al., 2014, pp. 1517-1528).

## Nano Carbon Fibres Based Polymer Composites

Currently the researchers expressed a great attention in fabrication of nano composites with multifunctional properties by the incorporation of cheaper and easily available nano carbon fibres. The carbon nano fibres hold superior electrical conductivity, mechanical and thermal properties such as low density, high aspect ratio, high modulus and negative CTE in developing bulk composite materials for various structural applications (Ghasemi et al., 2015, pp. 519-527; Jung et al., 2012, pp. 21845-21848). The dispersion of nano carbon fibres in polymer matrix can be realised mainly by two approaches: the melt mixing process and the sonication process in low viscosity solutions (Feng et al., 2014, pp. 3919-3945). The overall performances of the nano carbon fibres/polymer composites are largely governed by the dispersion of the nano carbon fibres in the polymer matrix (Feng et al., 2014, pp. 3919-3945; Eslami et al., 2015, pp. 22-31). Some of the important studies reported on carbon nano fibre composites are tabulated in Table 1.

Table 1  
Reported recent research work on carbon nano fibres reinforced composites

Matrix/Reinforcement	References
(PAA)/MnO- Carbon nano fibers	(Wang et al., 2015, pp. 164-170)
Epoxy/ Carbon nano fibers	(Sánchez et al., 2011, pp. 1-11)
Cement/ Carbon nano fibers	(Xie et al., 2012, pp. 3270-3275)
PLA/ (VGCNF)	(Teng et al., 2011, pp. 928-934)
Epoxy/Carbon nano fibers	(Poveda & Gupta, 2014, pp. 416-422)
Phenolic/ Carbon nano fibers-MWCNT	(Eslami et al., 2015, pp. 22-31)
Epoxy/ Carbon nano fibers-CNT	(Ghasemi et al., 2015, pp. 519-527)
Polypyrrole/ Carbon nano fibers-BC	(Zhang et al., 2015, pp. 552-559)
(PAN)/(C/MnFe <sub>2</sub> O <sub>4</sub> )	(Kidkhunthod et al., 2016, pp. 436-442)
Polyester/Carbon nano fibers-Cloisite Na+ clay	(Zhao et al., 2009, pp. 2081-2087)
Epoxy/Carbon nanofiber paper-(SWCNT)-(MWCNT)	(Wu et al., 2010, pp. 1799-1806)
Epoxy/Carbon nano fiber-(MWCNT/GNP)	(Zhou et al., 2013, p. 83)
Epoxy/(VGCNF)	(Raza et al., 2015, pp. 9-16)
(PAN)/Carbon nano fiber-(Si NP)	(Wang et al., 2015, pp. 164-170)
Epoxy/Carbon nano fibers-CF	(Ma et al., 2015, pp. 65-74)
UP/ Carbon nano fiber	(Gou et al., 2010, pp. 192-198)
Epoxy/Carbon nano fiber-CNT	(Sharma & Lakkad, 2011, pp. 8-15)
Cement/Carbon nano fiber-CF	(Baeza et al., 2013, pp. 841-855)

*Note.* Polyamic acid (PAA), Silicon (Si), Nano particles (NP), Multi walled carbon nanotube (MWCNT), Graphene nanoplatelet (GNP), Polyacrylonitrile (PAN), Bacterial cellulose (BC), Vapour-grown carbon nanofibre (VGCNF), Elecrospon Carbon-Manganese ferrite (C/MnFe<sub>2</sub>O<sub>4</sub>), Polylactic acid (PLA), Single-walled carbon nanotube (SWCNT), Multi-walled carbon nanotube (MWCNT) membranes (buckypaper), Unsaturated polyester (UP), Carbon fibre (CF).

## Nano Cellulose Fibres Based Polymer Composites

Cellulose nano fibres and their composites, either in whisker or crystal form, offer a great deal of interest for both researchers and scientist. Moreover, the cellulose nano fibres or nanocrystals (CNCs), acid hydrolysate of cellulose, are attractive environmentally friendly nanomaterials for the preparation of low-density nanocomposites (Neto et al., 2013, pp. 480-488; Rosli et al., 2013, pp. 1893-1908). The solvent casting Siqueira et al., 2010, pp. 728-765) and melting compounding is the most common technique to prepare cellulose nanoparticles reinforced composites (extrusion method) (Nakagaito et al., 2009, pp. 1293-1297). A further classification of solvent casting includes three systems (water soluble polymers, polymer emulsions, non-hydrosoluble polymers), depending on the type of polymer matrix (shown in Figure 12) (Siqueira et al., 2010, pp. 728-765).

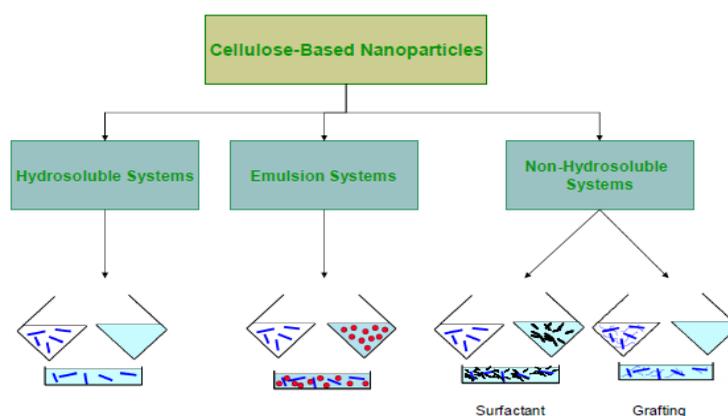


Figure 12. Solvent casting technique for the fabrication of cellulose based nanocomposites  
Source: Siqueira et al., 2010, pp. 728-765

Reinforced cellulose nano fibres offer high strength, stiffness, biodegradability and renewability to the polymer resin for the fabrication of nanocomposites (Kalia et al., 2011; Eichhorn et al., 2010, p. 1; Kohler & Nebel, 2006, pp. 97-106). Cellulose nanoparticles reinforcement, however, has some weaknesses like poor wettability, high moisture absorption, unusual processing temperature and incompatibility with most of polymeric matrices (Siqueira et al., 2010, 728-765). A lot of research works have explored a broad range of different polymer matrices such as polyethylene, polypropylene, polybutadiene, poly (butyl methacrylate), polyurethanes and poly (vinyl chloride) (Tang & Weder, 2010, pp. 1073-1080). Some of the reported research works on nano cellulose reinforced composite are presented in Table 2.

Table 2  
Some of the recent research works on nano cellulose reinforced matrix composite

Matrix/Reinforcement	References
Optically curable (SLRs)/ CNCs	(Kumar et al., 2012, pp. 5399-5407)
(NBR)/CNCs	(Cao et al., 2013, pp. 819-826)
PLA latex/ NFC	(Larsson et al., 2012, pp. 2460-2466)
(PLLA)/CNCs	(Lizundia et al., 2015, pp. 256-265)
PP/CNCs	(Khoshkava & Kamal, 2014, pp. 8146-8157)
PVA/CNCs of Phormium tenax and Berlinka Flax	(Fortunati et al., 2013, pp. 825-836)
PLA/CNCs	(Pei et al., 2010, pp. 815-821)
PLA/CNCs	(Fortunati et al., 2012, pp. 948-956)
PLA/(s-CNC)-(Ag-NP)	(Fortunati et al., 2012, pp. 2027-2036)
PU/CNCs	(Rueda et al., 2011, pp. 1953-1960)
(PLA-PHB)/(CNCs)films	(Arrieta et al., 2014, pp. 16-24)
MAH grafted (PLA)/CNCs	(Zhou et al., 2013, pp. 3847-3854),
(PVA)/(CNC (PLGA(NPs)	(Rescignano et al., 2014, pp. 47-58)
PLA/Pristine CNCs-(s-CNC)/(Ag-NP)	(Fortunati et al., 2013)
PLA/ CNCs	(Pracella et al., 2014, pp. 3720-3728)
(PVA)/Corncob CNCs	(Silvério et al., 2013, pp. 427-436)
(PVA)/Corncob CNCs	(Silvério et al., 2013, pp. 427-436)
PVA/(CNCs) extracted from Flax, Phormium (MCC)	(Fortunati et al., 2013, pp. 837-848)
Isotactic (PP)/Cellulose whiskers	(Ljungberg et al., 2006, pp. 6285-6292)
Elastomeric (PU)/Isocyanate-rich CNCs	(Rueda et al., 2011, pp. 1953-1960)
PLA/(CNCs)from Phormium tenax leaves	(Fortunati et al., 2014, pp. 77-91)
PVA/(CNCs) from okra bahmia (Abelmoschus Esculentus) bast fibers	(Fortunati et al., 2013, pp. 3220-3230)
(PMMA)/CNCs	(Dong et al., 2012, pp. 2488-2495)
SBR/(CNCs) isolated from cotton	(Annamalai et al., 2014, pp. 967-976)
(PHBV)/(CNC-S)-(CNC-H)	(Yu et al., 2013, pp. 22-28)
(PGMA)/(BCNW)	(Martínez-Sanz et al., 2013, pp. 2062-2072)
(PLA)/(CNF)	(Jonoobi et al., 2010, pp. 1742-1747)
Polystyrene/CNCs	(Lin & Dufresne, 2013, pp. 5570-5583)
(PHEMA)/CNCs from cotton	(Tatsumi et al., 2012, pp. 1584-1591)
(PVA)/NFC-BC	(Yuwawech et al., 2015, p. 69)
Epoxy/MFC-BC	(Shao et al., 2015, pp. 244-254)

*Note.* Poly(lactic acid) (PLA), Poly(L-lactide) (PLLA), Nanofibrillated cellulose (NFC), Bacterial cellulose(BC), Micro fibrillated cellulose (MFC), Stereolithographic resins (SLRs), cellulose nanocrystals (CNCs), Spray dried cellulose nanocrystals (CNCSD), Polypropylene (PP), Polyurethane (PU), Poly(lactic acid)-poly(hydroxybutyrate) (PLA-PHB), Surfactant modified (s-CNC), Maleic anhydride (MAH), Polyvinyl alcohol (PVA), Polypropylene (PP), Microcrystalline cellulose (MCC), Nanoparticles (NPs), Poly(methyl methacrylate) (PMMA), Styrene butadiene rubber (SBR), Poly (d, l-lactide-co-glycolide) (PLGA), Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV), Cellulose nano particles obtained by sulphuric acid hydrolysis (CNC-S), Cellulose nano particles obtained by hydrochloric acid hydrolysis (CNC-H), Poly(glycidyl methacrylate) (PGMA), Bacterial cellulose nanowhiskers (BCNW), Cellulose nanofibre (CNF), Poly(2-hydroxyethyl methacrylate) (PHEMA), Cellulose nanocrystallites (CNC), Silver nano particles (Ag-NP), Nitrile rubber (NBR).

## Applications of Nano Fibres

Nano fibres exhibit special properties mainly due to extremely high surface to weight ratio and extremely small size, which make them appropriate for a wide range of applications. The wider applications of nano fibres in different industrial fields are shown in Figure 13 [<http://www.nano109.com>]. Nano fibres developed by electrospinning and solution blowing also show extensive applications particularly for biomedical due to their high surface area, excellent mechanical properties and enhanced porosity in diverse tissue engineering field as potential scaffolds, musculoskeletal tissue engineering, bone tissue engineering, cartilage tissue engineering, ligament tissue engineering, skeletal muscle tissue engineering, skin tissue engineering, blood vessel tissue engineering and neural tissue engineering. Nano fibres have also been used for DNA, protein and enzyme delivery (Vasita & Katti, 2006, p. 15).

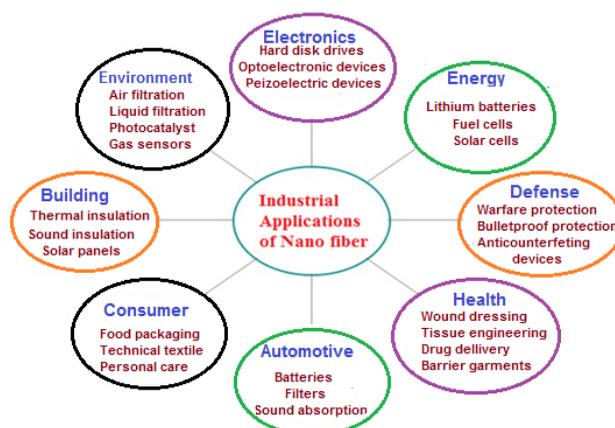


Figure 13. Industrial applications of nano fibres (Adapted from Nano109, 2010, <http://www.nano109.com>)

Cellulose nano fibres have shown great potential in several applications including biomedical, bioimaging, nanocomposite, gas barrier films and optically transparent functional materials (Chirayil et al., 2014, pp. 20-28). In air filtration, medicine, drug delivery and acoustic science, nano fibre materials are integrated deep inside finished products and they function as a unique component. Thus, cellulose nano fibre is seen as a promising alternative or substitute for use in a wealth of fields including filter material, electronic devices, high gas barrier packaging material, foods, cosmetics, medicine and health care. The carbon nano fibre is also regarded as a prospective material in many industrial fields of electronics, energy conversion, electromagnetic shielding, self-sensing, nanostructured core processor, storage, and nanostructured carbon filler in the polymer composite industries (Baeza et al., 2013, pp. 841-855; Vilaplana et al., 2013, pp. 4776-4786) and as a superior anode material for lithium-ion batteries (Wang et al., 2015, pp. 285-292).

## Applications of Nano Fibres Based Polymer Composites

Currently, nanocomposite research and technology gets extensively broader showing diverse and widespread submissions that encompass areas of bio-medical, data storage, computing and electronics, furniture, appliances, bulletin board substrate, lubricants and scratch free paints, UV protection gels, anti-corrosion barrier coatings, sporting goods, aerospace components, automobiles and military applications (Alateyah et al., 2013). Nanocomposites have also been introduced in structural applications such as constructional parts, gas barrier films, scratch/abrasion resistant materials, scratch-resistant coating, flame-retardant cables, etc. Moreover, resin transfer molding (RTM), vacuum assisted resin transfer moulding (VARTM), resin film infusion (RFI), autoclave processing and filament winding techniques can be used to manufacture nanocomposite parts for various applications including commercial aircraft structures for Boeing, Airbus, as well as many products in the industrial markets (Hussain et al., 2006, pp. 1511-1575). Nanocomposites show a great interest in numerous automotive and general/industrial applications, on the account of their potential usage for utilisation as mirror housings on various vehicle types, door handles, engine covers and intake manifolds, timing belt covers, fuel tank and fuel line components for cars (<http://tifac.org.in/index>) (Jeon & Baek, 2010, pp. 3654-3674). Moreover, some general applications that are currently being considered include their usage as impellers and blades for vacuum cleaners, mower hoods, power tool housings and covers for portable electronic equipment such as mobile phones, pagers, etc. The applications of polymer nano fibres are shown in Figure 14 (<http://www.azonano.com/article.aspx>).

Nano fibre polymer composites also receive attention in structural application sectors such as scratch-resistant coating, gas barrier films and flame-retardant cables. Wide opportunities for nanocomposites in biomedical applications can precisely be for drug delivery, regenerative medicine, while their uses as bio-actuators and biosensors are also well recognised (Gaharwar et al., 2014, pp. 441-453).

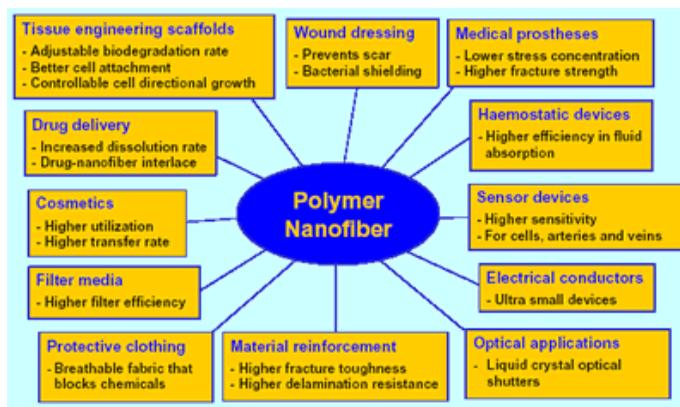


Figure 14. Applications of polymer nano fibres in different fields  
(Adapted from polymer Nano fibers - an Overview of Applications and Current Research into Processing Techniques, 11<sup>th</sup> Nov 2015 from <http://www.azonano.com/article.aspx>)

Nano fibre composites also provide diversity in applications beyond niche and functional markets in the high-performance bodies and components of airplanes and aircrafts. Nowadays, nano fibres based composites have also been introduced as an emerging technology in the automotive industry worldwide. They are used as interior and under-bonnet parts, coating and fuel system components, external body parts in automotive and military components owing to their superior and extraordinary properties. Carbon nano fibre based polymer composites are able to be applied as promising materials in many fields including electrical devices, electrode materials for batteries, supercapacitors and sensors (Feng et al., 2014, pp. 3919-3945; Eslami et al., 2015, pp. 22-31).

## **CONCLUSION AND FUTURE PERSPECTIVES**

Currently, materials science research and engineering technology are more inclined towards the production of thinner, lighter, cheaper and stronger composite structures through incorporation of nano fillers in the matrix. Multifunctional nanocomposite materials clasp the potentiality of redefining the matter of conventional composite materials in many potential engineering applications, in terms of high performance, outstanding optical, electrical, thermal and mechanical properties. Nano fibres are alike to the other nano-sized fillers exhibiting special property such as extremely high surface to weight ratio, which makes them appropriate for a wide range of applications. The high aspect ratio of the nano fibres offers benefits in a much smaller weight fraction compared to micro-sized fibres in high performance applications. Nano fibres from natural resources (nano cellulose) and nano carbon are presently considered as an active area of research. Carbon nano fibres are the most promising alternative to the expensive carbon nano tubes and high functional carbon black in various applications. Their low cost and ease of dispersion in polymers compared to carbon nanotubes make them suitable fillers for producing heat dissipating polymer composites (TIMs). Nano cellulose fibres are the other one dimensional and renewable nanomaterials used as fillers within polymeric matrix in developing multifunctional nanocomposites.

In the future, the nano green fibres from agricultural bio wastes such as oil palm wastes (oil palm ash, OPEFB, trunk and frond), rice and wheat husk, coconut wastes and straw will bring more opportunities to create new and unique composite materials for extending the application field in crafting higher value-added consumer products. Furthermore, green nanocomposites or biodegradable nanocomposites will bring revolution in managing the world's major waste disposal problems and other related activities.

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