## FONDAZIONE ISTITUTO ITALIANO DI TECNOLOGIA

**A TECHNOLOGY TEASER**

# SMART FIBERS

ISTITUTO ITALIANO DI TECNOLOGIA

*Released on January 2015*

# NEW MATERIALS

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*The Foundation is intended to promote Italy's technological development and advanced education, consistent with national policies for scientific and technological development, thus strengthening the national production system.*

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*- develops innovative methods and know-how, in order to facilitate new high-level practices and positive competitive mechanisms in the field of national research;*

*- promotes and develops scientific and technological excellence, both directly, through its multi-disciplinary research laboratories, and indirectly, through a wide collaboration with national and international laboratories and research teams;*

*- carries out advanced training programs as a part of wider multi-disciplinary projects and programs;*

*- fosters a culture based on sharing and valuing results, to be used in order to improve production and for welfare-related purposes, both internally and in relation to the entire national research system;*

*- creates technological understanding about components, methods, processes and techniques to be used for the implementation and interconnection of innovative products and services, in strategic areas for the competitiveness of the national production system;*

*- pools research scientists operating in various research institutes and establishes cooperation agreements with high-level, specialized centers;*

*- promotes interactions between basic research and applied research facilities, encouraging experimental development;*

*- spreads transparent, merit-based selection mechanisms for research scientists and projects, in compliance with globally approved and established criteria.*

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# EXECUTIVE SUMMARY

"Intelligent" fibers to fabricate various types of materials have attracted much interests in the last decade. Such interest derives from several problematics that smart fibers can solve, from hampering water absorption, fungal growth, loss of mechanical properties, water soaking, etc. (based on water resistance, water repellence and hydrophobicity characteristics), as well as protecting against mineral and vegetable oily fluids.

IIT has developed a new technology able to protect by coating several types of fibers with no apparent formation of polymeric coating on the fibrous material.

These technologies represent a unique chance for companies active in textile market. IIT assets appear well positioned for an out-licensing strategy, providing the licensee partner with the ability to take care of the late stage development, CE certification, scale-up and production process. The licensee should guarantee a high probability of market success based on consolidated marketing & distribution organization. A typical licensing strategy based on entry fee and subsequent royalties on net sales can be envisaged.

# INTELLECTUAL PROPERTY

| | |
|---|---|
| **PCT International Application #** | PCT/IB2011/055904 - 22 December 2011 |
| **Priority Application #** | TO2010A001040 - 22 December 2010 |
| **Regional Patent Applications filed** | **EP** 11813425.3, **US** 13/995204, **CA** 2822781, **JP** 2013-545617, **CN** 201180062593.9, **KR** 2013-7019241, **RU** 2013134001, **BR** 1120130159219 |
| **Applicant** | Fondazione Istituto Italiano di Tecnologia |
| **Inventors** | Roberto CINGOLANI, Athanassia ATHANASSIOU, Ilker S. BAYER |
| **Title** | A process for providing hydrorepellent properties to a fibrous material and thereby obtained hydrophobic materials and articles. |

**Short Description**

The present invention relates to a process for conferring properties of water resistance, hydrophobicity and water repellence on fibrous materials and then to a process for production of fibrous materials and finished articles, having the aforementioned properties together with other properties, such as in particular better fireproof properties.

| | |
|---|---|
| **PCT International Application #** | PCT/IB2014/061457 - 15 May 2014 |
| **Priority Application #** | TO2013A000396 - 16 May 2013 |
| **Regional Patent Applications filed** | **EP** 14731050.2, **US** 14/890913, **JP** 2016-513486, **CN** 201480026929.X |
| **Applicant** | Fondazione Istituto Italiano di Tecnologia |
| **Inventors** | Ilker S. BAYER, Elisa MELE, Roberto CINGOLANI, Athanassia ATHANASSIOU |
| **Title** | Process for the production of poly(cyanoacrylate) fibres |

**Short Description**

The present invention relates to a process for the production of micro- and nanofibers of poly (cyanoacrylate), to continuous, uniform coating layers obtained from said fibers and to substrates or articles provided with said coatings. The production of polymer nanofibers, which are characterized by their high surface area/volume ratio and by their mechanical properties, is of considerable interest in various applications such as the production of reinforced composites, of materials used as tissue scaffolds, as filter media and for controlled drug delivery.

| | |
|---|---|
| **PCT International Application #** | PCT/IB2014/066964 - 16 December 2014 |
| **Priority Application #** | TO2013A001037 - 18 December 2013 |
| **Applicant** | Fondazione Istituto Italiano di Tecnologia |
| **Inventors** | Elisa MELE, Ilker S. BAYER, Athanassia ATHANASSIOU, Roberto CINGOLANI |
| **Title** | Method for the encapsulation of liquid |

**Short Description**

The present invention relates to a process for the production of globular structures comprising a liquid nucleus within a solid envelop which wrap said nucleus, and to globular structures having micro- and nano-metric dimension so obtained.

# IIT TECHNOLOGY

## *Hydrophobic and oleophobic treatments for textiles and food packaging*

"Intelligent" fibers to fabricate various types of materials have attracted much interests in the last decade. Such interest derives from several problematics that smart fibers can solve, from hampering water absorption, fungal growth, loss of mechanical properties, water soaking, etc. (based on water resistance, water repellence and hydrophobicity characteristics), as well as protecting against mineral and vegetable oily fluids. Materials that are best positioned to benefit from this process are paper, cardboards, textiles, shoes, crockery, etc. (Figure 1). Clothing industry, particularly sportswear and activewear segments, billboard industry as well as household items are mostly benefiting from innovation of the above mentioned materials.

**Figure 1.** Materials best positioned for benefit from hydrophobic coating process

IIT has developed a new technology able to protect by coating several types of fibers with no apparent formation of polymeric coating on the fibrous material. The paper sheets and the textiles for example feel unaltered upon contact, but every single fiber is protected by an ultrathin polymeric layer (polymeric nanocomposite, Figure 1 and Figure 2). For each type of fibrous substrate a different kind of polymer treatment is used.

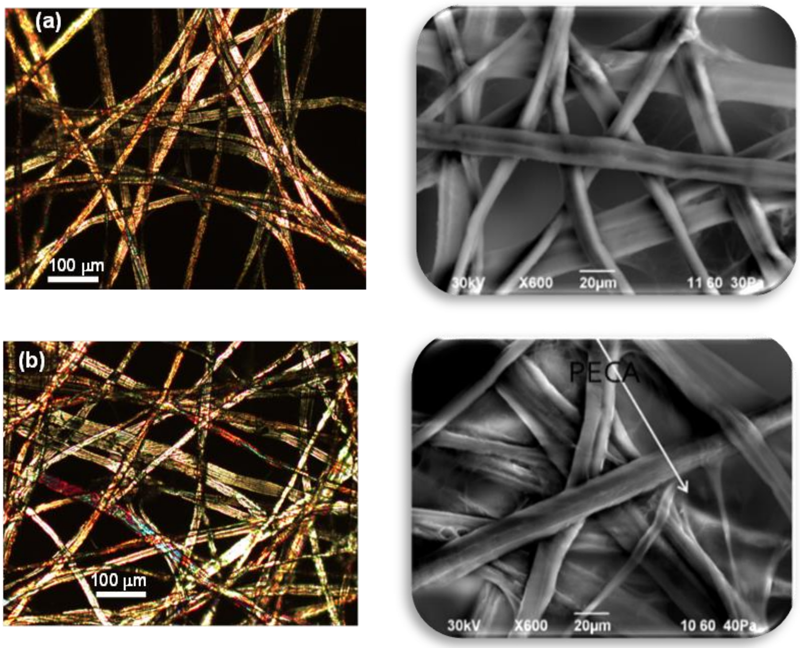


**Figure 2.** Optical and electronic microscope images of (a) untreated and (b) treated cellulose fiber networks with acrylate-based polymer (fibers are clearly visible in both cases and the breathability is conserved after the treatment)

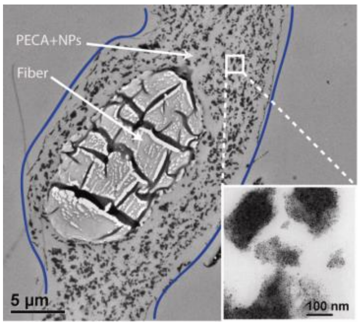


**Figure 3.** Cross section of a single cellulose fiber with the polymeric composite material cladding around it (electronic microscope)

Figure 4 shows the capability of IIT technology to produce water proof cellulose sheets: dyed water cannot enter the central area of the paper treated with the nanocomposite material, whereas figure 5 shows that newspaper prints and printing capability of copy paper are not affected by the treatment.

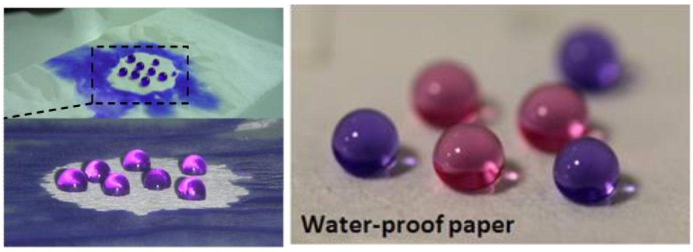


**Figure 4.** Hydrophobic properties: dyed water cannot enter the treated central area of the paper

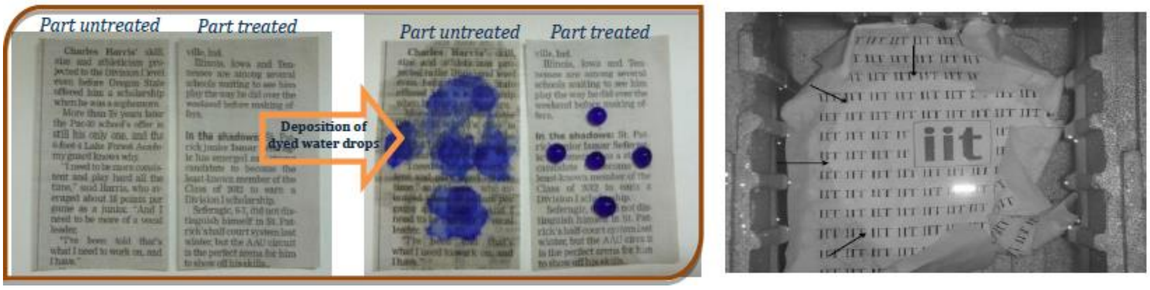


**Figure 5.** Newspaper prints and printing capability of copy paper are not affected by the treatment

Finally, fluoroacrylic polymer treated textiles show superhydrophobic and oleophobic properties (Figure 6).


**Figure 6.** Images of a water (left) and oil (right) droplet on a cotton textile before and after treatment

IIT technology consists of a treatment with polymeric nanocomposite materials. It can provide different functionalities to the treated fibrous sheets, related to the properties of the nanoparticles used in the nanocomposites: hydrophobic, magnetic, antibacterial, luminescent.

In the Packaging Industry, IIT technology can be used on different kinds of cellulosic containers that are used in food packaging in order to avoid the migration of toxic substances from the paper to the food or to avoid water and oil leakage from the food to the food containers. All the polymers used for this scope are FDA approved. Cellulose is a natural polymer that is extensively used for the production of paper and paperboard. Although cellulose is an environmentally friendly material, its water/humidity absorbance limits the applicability in the food packaging area, particularly when paper containers come in direct contact with food of high content of water. To solve this drawback, the side of the paper container in contact with food is often coated with films of synthetic materials to achieve water barrier properties. Unfortunately, in this way, the final product loses its natural and biodegradable properties, as well as its recyclability. Moreover, the fabrication of this type of containers requires different steps that complicate the production process and increase the cost of the final product. IIT developed a technology that is able to add new functionalities to cellulose-based fibrous materials, reaching a high degree of water and oil resistance. Composite polymeric materials are used to effectively treat each single fiber of the network without altering their appearance. The treatments are applied on the fibrous materials in the post-production phase and the recyclability of the final products is not affected. Moreover, the polymeric shell can be functionalized with nanoparticles having specific properties, like fluorescent, magnetic and antibacterial.

Paper obtained by recycling urban wastes contains mineral oils and contaminants derived from newspapers, magazines and catalogs. When recycled, paper is used for food packaging; these substances can migrate to dry food (such as pasta, cereals and biscuits) and adulterate it, with consequent negative effects on human health. In the developed procedure, the fibers constituting the paper network are encapsulated in a thin shell of polymeric composites that act as barrier against the migration of mineral oils (Figure 7). Moreover, the resulting paper possesses characteristics of water and oil resistance.

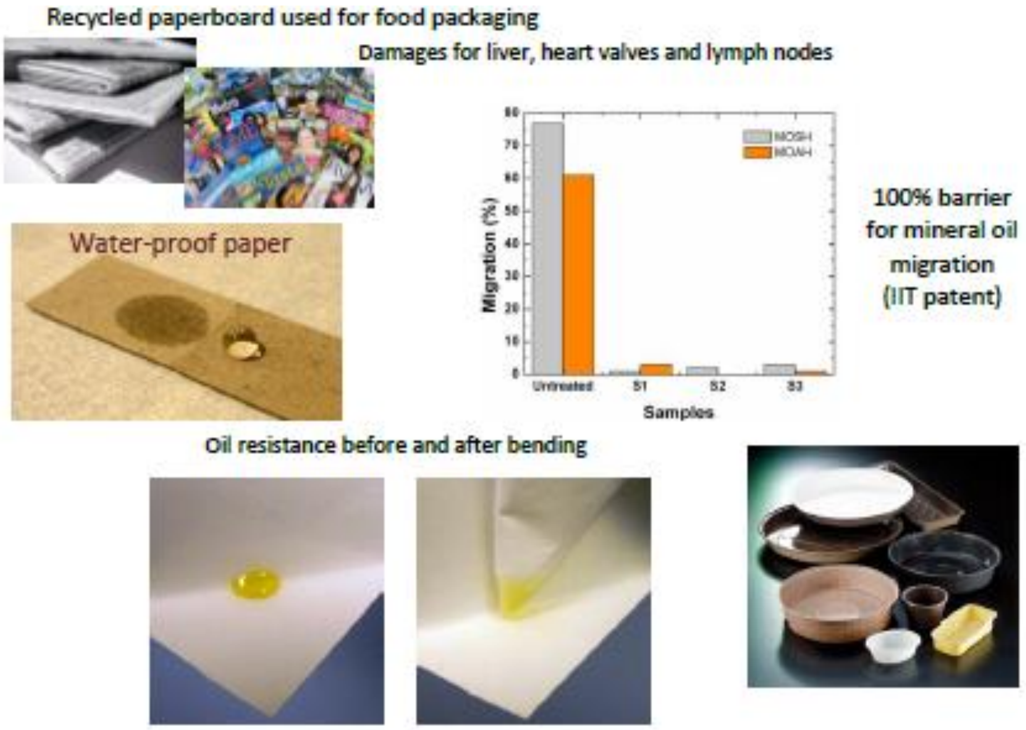


**Figure 7.** Polymeric composite nanomaterial as a barrier to mineral oil migration

### *Electronspun nanofibers for Wound Dressing*

Electrospinning, namely the extrusion of polymer fibers by means of high electric fields (Figure 8), is an interesting technology for the development of innovative biomedical devices for wound care. In fact, in this sector the ultrafine size of the electrospun fibers guarantees:

- mechanical flexibility and consequently excellent conformability of the non-woven mat to the wound site;
- complete coverage of the injured tissue and protection against infections and dehydration, as well as thermal insulation;
- permeation of gases, transport of nutrients, retention of moisture and absorption of exudates, thanks to the high porosity of the electrospun mesh;
- adhesion, proliferation and differentiation of cells during tissue regeneration;
- delivery of drugs (e.g. antioxidant, anti-inflammatory and antimicrobial agents) to the wound.

IIT technology use polymers derived from **natural sources**, such as alginate, cellulose and chitosan, for the production of functional nanofibers with controlled size, morphology and degradation rate. These biopolymers offer remarkable advantages in terms of biocompatibility, biodegradability and environmentally friendliness.

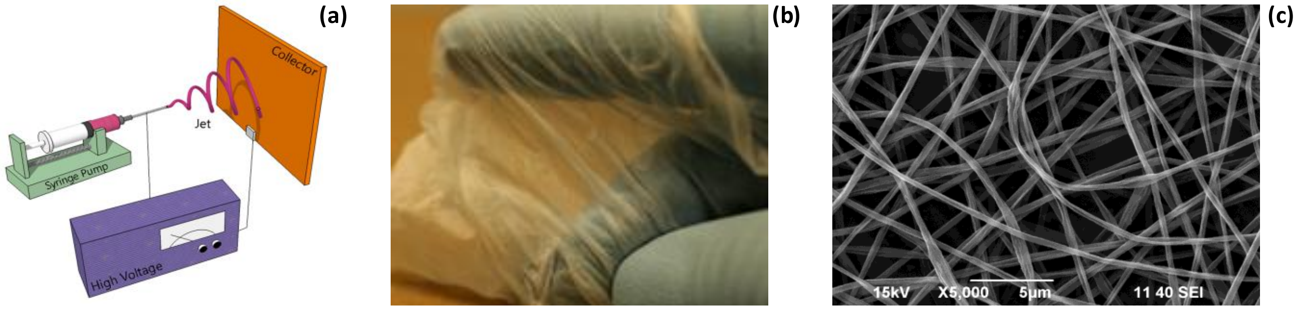


**Figure 8**: (a) Electrospinning apparatus consisting of a syringe pump for the delivery of the polymer solution and a plate for the collection of the fibres. The high voltage is applied between the metallic needle and the collector. (b) Photograph of an electrospun mat and (c) corresponding scanning electron microscope (SEM) image.

**Alginate Nanofibers with controlled degradation rate**

Alginate is a polysaccharide derived from brown algae that exhibits excellent biocompatibility, low toxicity, non-immunogenicity, and relatively low cost. It finds application in tissue engineering for skin, nerve, bone and cartilage regeneration, and in drug delivery systems.

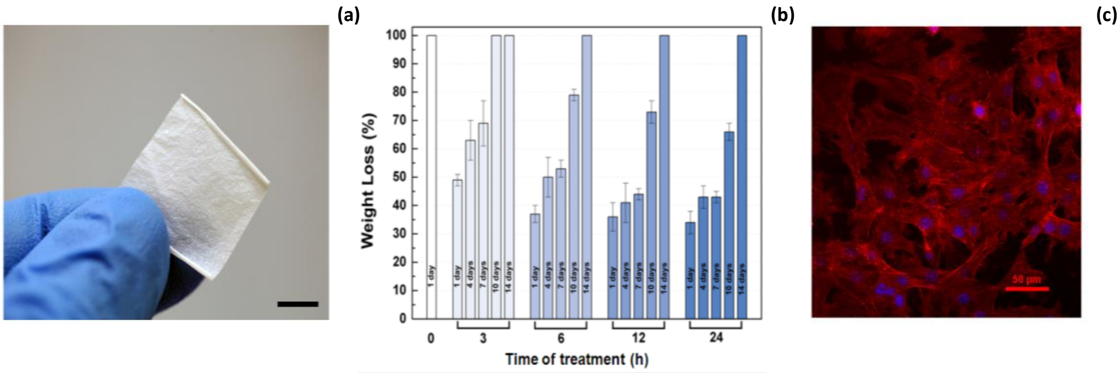


**Figure 9**: (a) Photograph of the nanofibrous scaffolds after 24 h of the acid procedure. Scale bar = 0.5 cm. (b) Analysis of the biodegradation properties of the alginate nanofibres after the acidic procedure at different time intervals (3, 6, 12 and 24 hours). The weight loss of the samples was measured after 1, 4, 7, 10 and 14 days of PBS incubation under physiological conditions (37 °C, pH 7.4). (c) Fluorescence micrographs of DAPI (nucleus) and phalloidin (actin filaments) stained fibroblast cells, cultured on the treated alginate nanofibres.

Due to its high water solubility, the corresponding nanofibers are poorly stable in aqueous environments, and their real applicability in biomedical sectors is strongly limited. IIT has set-up the know-how to stabilize alginate nanofibers in aqueous environments (Figure 9).

**Cellulose Acetate Nanofibres encapsulating essential oils with antimicrobial activity**

Preventing infections is one of the main focus of wound care. The colonisation of wounds by microorganisms can in fact have negative consequences on the healing process, delaying it.

We use essential oils as natural antimicrobial agents for cellulose-based fibrous dressings. IIT has developed the production of composite electrospun fibers that effectively encapsulate three different types of essential oils (cinnamon, lemongrass and peppermint, Figure 10). The fibrous scaffolds are able to inhibit the growth of *Escherichia coli*, even when small amounts of essential oils were used. At the same time, they are not cytotoxic, as proved by biocompatibility assays on skin cell models. The created dressings are promising as advanced biomedical devices for topical treatments in skin inflammation, burns and wound healing.

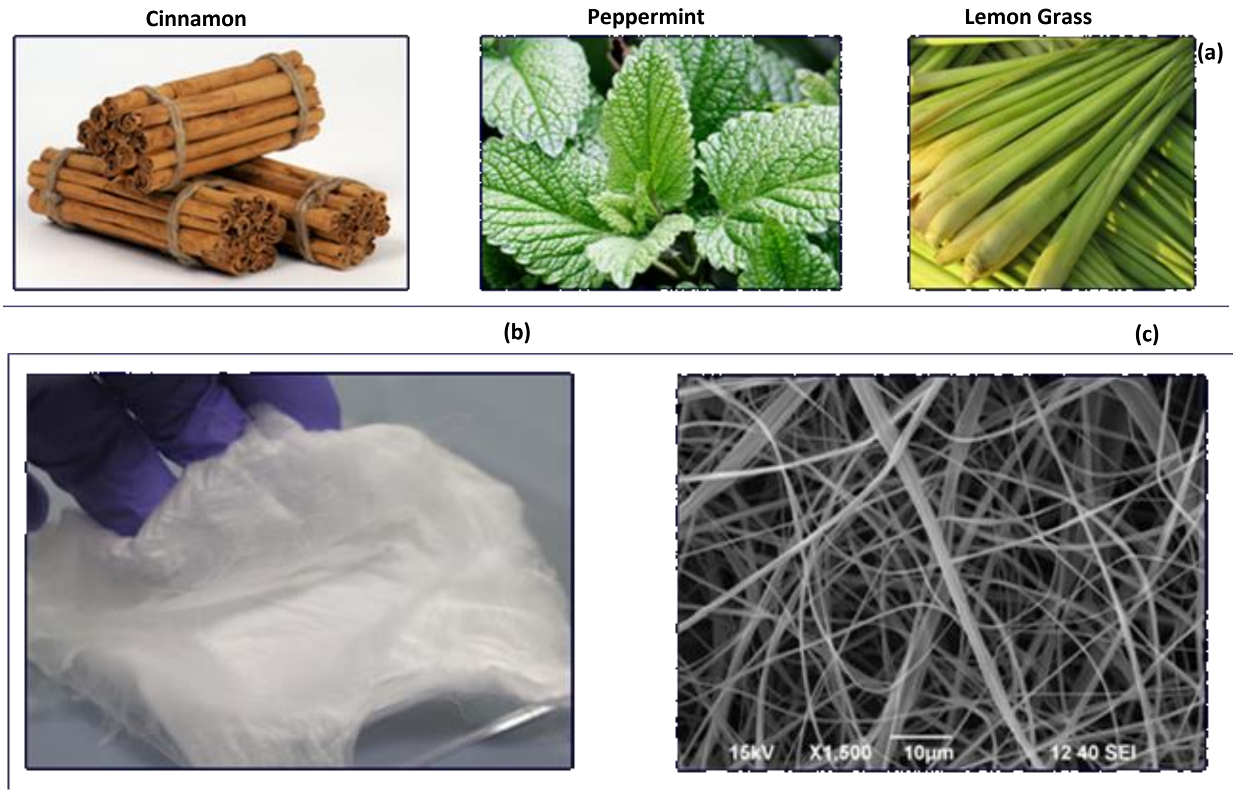


**Figure 10**. (a) Photograph of the plants used for the extraction of the essential olis. (b) Photograph of the produced electrospun mat and (c) corresponding SEM image.

# MARKET ANALYSIS

Based on IIT inventions described in published WO 2012/085879 and WO 2014/184761, and PCT application PCT/IB2014/066964, internal documentation and know-how on the technology, and related literature publications by the inventors and competitors, the Nanocoatings Market and the Wound Dressing Market have been identified as the targeted markets. The Wound Dressing Market was already investigated and analyzed in a previous report, so the reader should refer to it also in this case. Accordingly, the Nanocoatings Market has been analyzed for its current dimension and future trends through a web search-based retrieval of specific information. Key players have been identified and their websites have been reported.

In particular, the Nanocoatings Textile Market and the Nano-enabled Food & Beverage Packaging Market have been identified as most specific market segments for the IIT technology described herein, which appears best positioned to compete for composite nanomaterials able to confer to textile and cellulose fibers water and oil repellent, antimicrobial and selfcleaning properties rather than de-icing, anti-fogging, antireflective, anti-corrosion and anti-fouling properties typical of the highly demanding aerospace, marine, automotive, optometric and pipes industry sectors. Key players have been identified also for these specific market segments, and their websites have been reported.

### *Nanocoatings Market*

Transparency Market Research (TMR), a US-based research firm in its latest research report published in December 2014 and titled *"Nanocoatings Market - Global Industry Analysis, Size, Share, Growth, Trends and Forecast, 2013 - 2019"*, sheds light on the global nanocoatings market. The report states that the nanocoatings market will reach a value of USD 6.75 billion by end of 2019 during the forecast period of 2013 to 2019 (http://www.transparencymarketresearch.com/nanocoatings-market.html).

The global nanocoatings market demand was valued at USD 1.45 billion in 2012 and with a healthy 24.7% CAGR during the forecast period, the market will grow more than four-times its worth in 2012. Stringent regulations from government bodies such as EPA (Environmental Protection Agency) and other regulatory organizations on the use of VOCs (Volatile Organic Compounds) tend to contribute to the growth of the nanocoatings market, since nanocoatings are more environment-friendly due to their low VOCs content. According to geography, the market of nanocoatings is segmented into North America, Europe, Asia Pacific, and Rest of the World (RoW). North America dominated the nanocoatings market in 2012, which was followed by Europe. However, analysts at TMR predict that Asia Pacific is expected to witness the highest growth during the forecast period due to the expanding electronics and automotive industries in China and India. The demand for nanocoatings in the Asia-Pacific region will grow at 25.8% CAGR during 2013-2019. Massive demand from automotive and medical coatings companies will drive the growth of the nanocoatings market. Product-wise, the global nanocoatings market is segmented into anti-microbial, anti-fingerprint, easy-to-clean and anti-fouling, self-cleaning (photocatalytic and bionic), and others. Anti-microbial nanocoatings segment accounted for around 29.6% of the global demand in the nanocoatings market in 2012. Anti-fouling and easy-to-clean nanocoatings segment grabbed the second spot in the market in terms of consumption, and is expected to grow within the forecast period due to their increasing demand in industrial engineering, food manufacturing, marine, energy, automotive, textile and other sectors. On the other hand, anti-fingerprint nanocoatings segment is forecasted to be the fastest growing segment during 2013-2019 due to their increasing demand from industries such as medical, electronics, and healthcare. The medical industry will continue to be a high growth area for nanoscale coatings in the coming few years as a large number of companies exploit the nanocoatings technology, especially in the anti-microbial domain. In 2012, the demand for nanocoatings was highest from medical and healthcare industry, accounting to around 14% of the global demand.

In another market report by the Grand View Research Inc. (http://www.grandviewresearch.com/industry-analysis/nanocoatings-market) published in October 2014, the global nanocoatings market revenue is expected to reach USD 8.17 billion by 2020, from the 2013 value of USD 1.84 billion, quite in line with the previous projected data by TMR.

Medical & healthcare was the largest application market for nanocoatings, with demand estimated at 43.7 kilo tons in 2013 owing to increased use of anti-fingerprint and anti-microbial coatings for maintaining clean and hygienic environment in patient care facilities. The segment is also expected to be the fastest growing application, at an estimated CAGR of 22.7% from 2014 to 2020. Nanocoatings are used in automotive applications in order to retain color and gloss, with estimated demand of 39.8 kilo tons in 2013.

Further key findings from the study suggest:

- Global nanocoatings market volume was 309.5 kilo tons in 2013 and is expected to reach 1,262.9 kilo tons by 2020, growing at a CAGR of 22.3% from 2014 to 2020.
- Anti-microbial nanocoatings were used widely in applications including medical & healthcare and building & construction to avoid infestation of disease spreading microbes. The segment demand was estimated at 90.9 kilo tons with revenue of USD 541.6 million in 2013 and is expected to grow at a CAGR of 22.9% from 2014 to 2020.
- Anti-fingerprint nanocoatings are expected to be the fastest growing product segment at an estimated CAGR of 23.2% from 2014 to 2020. The segment is expected to witness growth on account of its usage in electronics and automotive application.
- North America was the dominant regional nanocoatings market with an estimated demand of 128.7 kilo tons in 2013. Increased infrastructural spending in the current fiscal budget coupled with high demand for automobiles and advanced healthcare facilities in the region are expected to be major factors responsible for nanocoatings market development.
- Product innovation plays a key role as the fragmented nature of market results in companies developing new products to gain competitive advantage. The nanocoatings market is expected to gradually move towards consolidation over the next six years, with raw material supply being a focal point which may trigger a trend of mergers, acquisitions and strategic alliances.

In the Report by Frost & Sullivan titled:*"Superhydrophobic Coatings - The Road Ahead: Prospects for Technology and Application Potential"* published in March 2013, key industrial developments in nanocoatings (Figure 11) and the road ahead to 2020 (Figure 12) are highlighted.

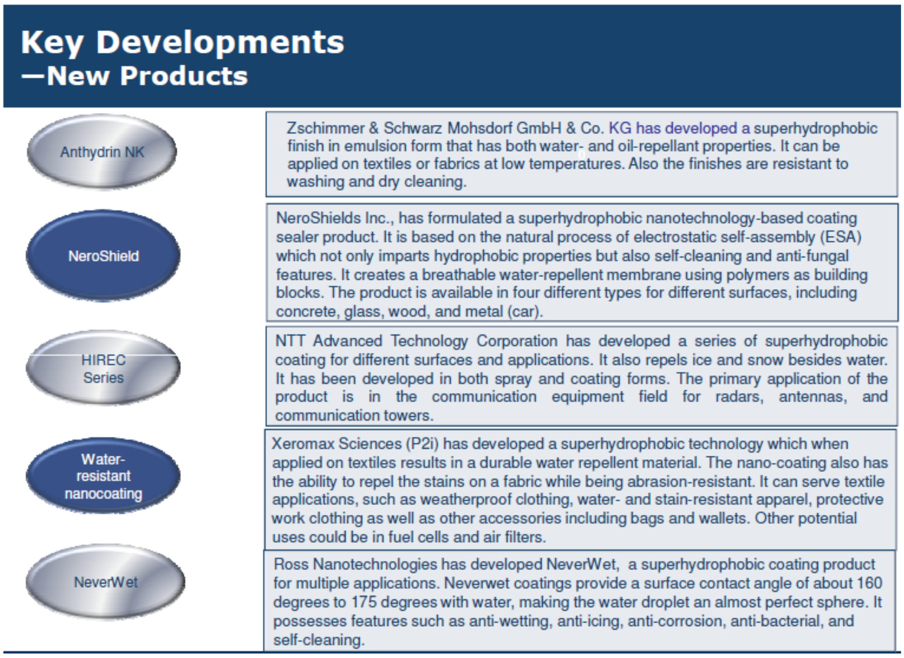


**Figure 11.** Key Developments, new products and innovative companies in nanocoatings

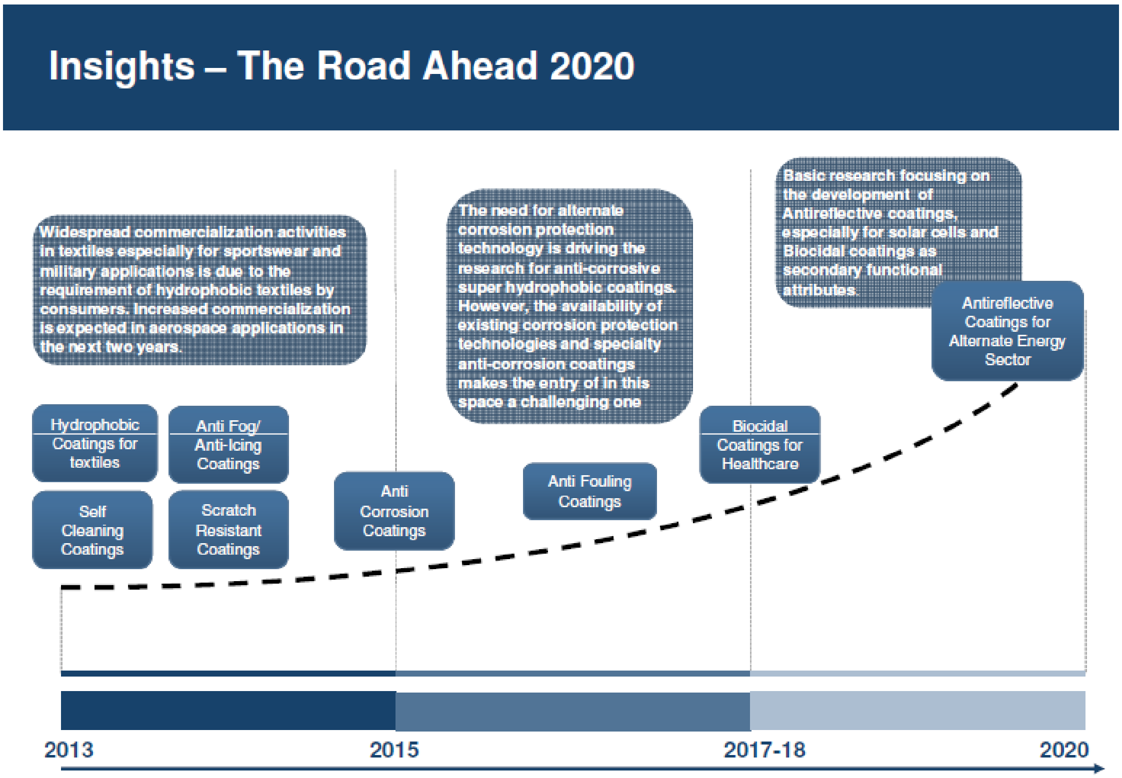


**Figure 12.** The Road Ahead to 2020 in nanocoatings market application

## *Nanocoatings Textile Market*

Advancements in protective clothing applications include super-repellent coatings, nanotechnology and intelligent textiles. This is well described in *Specialty Fabrics Review* (November 2012) by Dr. Eugene Wilusz (http://specialtyfabricsreview.com/articles/1112_fot_protective_clothing.html). The category of protective textiles is broad, and the applications demanding. Textiles are expected to provide protection against ballistic and blast events, flames, chemicals, biological agents, punctures, insects, rain, cold, ultraviolet (UV) radiation and extreme heat. Furthermore, defense must be provided without compromising on comfort. Traditional textiles provide a certain degree of protection, but when more is needed, it can come from blends, laminates, additives, coatings, finishes, novel fibers and novel-textile structures.

Some of the most interesting developments involve super repellent coatings, electrospun nanofibers, fibers with novel cross sections, intelligent textiles, and biomimetic (inspired by nature) materials. Super repellent coatings can make fabrics superhydrophobic, where water rolls off as spherical droplets. These materials mimic the structure of lotus leaves and other materials found in nature. Recent work has demonstrated that it's possible to construct fabrics that are oleophobic (oil repellent) and even superoleophobic.

One of the ways novel fibers are being developed is through the extrusion of fibers with unique cross-sectional shapes. The channels and added surface area in these fibers make them useful as wicking fibers and in apparel for sun protection, incorporating UV-absorbing material. Other novel fibers are multicomponent, and the arrangements may include sheath/core, islands-in-the-sea and pie cross-sections.

Some of the most exciting or intriguing developments are in smart or intelligent textiles, including the integration of electronics. These include flexible antennas, sensors and soft keyboards. Fibers can be fabricated by a new method of drawing a cylinder of polymer containing electronics or photonics within its core.

Electrospun nanofibers can increase the efficiency of air filters, can be used in medical applications, such as wound dressings, masks and gowns, and serve as matrix layers for adsorbents and catalysts.

The market is demanding sustainable, high-performance textiles that are lightweight and reasonably priced. The military needs textiles that can provide a high level of protection against bullets, fragment projectiles, blasts and flames, which requires textiles made of high-modulus fibers and other high performance materials.

Some of these materials, such as aramids (strong, heat-resistant synthetic fibers), are expensive, so cost-effective alternatives are needed. Chemical-protective clothing, including fully encapsulated suits, is heavy and uncomfortable and necessitates the development of lighter-weight ensembles. New technologies are steadily finding their markets, including medical applications, military and civilian protective clothing, clothing for active sports and outdoor activities, tents and soft shelters. The markets for some of these applications are tempered by the added cost of the particular technology. Fast-drying fabrics with high moisture-vapor transport have become very popular. In these fabrics, two technologies are combined in one fabric: a water-repellent treatment on the outside and a moisture-absorbent function inside. Hollow-core fibers are being utilized for their lightweight insulation properties. Similar to polar bear hair, they provide extraordinary insulation with minimal weight, and their increased surface area allows for fast wicking and evaporation of moisture. Microencapsulated phase-change materials have been incorporated into gloves, apparel, bedding and outdoor gear for cooling or warmth, depending on the choice of material.

The manufacture of electrospun nanofibers on a commercial scale is expanding and evolving as demand increases. These fibers can also be produced by splitting of bicomponent fibers and by nozzle-free centrifugal spinning. Reactive extrusion has the potential to produce a variety of multifunctional products. Coatings of metal oxides by atomic layer deposition have been used to modify the properties of fabrics, such as their surface energy.

Properties associated with current nanotechnology research for use in textiles include:

- Water repellent (hydrophobic)

- Oil repellent (oleophobic)
- Shrink resistance
- High strength
- Self-cleaning
- Antimicrobial
- Stain resistance
- Electrical conductivity
- Static protection
- Fire resistance
- UV protection
- Aesthetics & Safety (e.g., luminescence)
- Fragrance release
- Wrinkle resistance
- Moisture management

Many products use, or with commercialization will use, chemical, physical or electronic technologies to respond passively or actively to thermal, chemical, biological, electromagnetic and mechanical stress. These products include warming and cooling textiles, conductive textiles, communicating textiles, textile sensors and actuators, digital fashion, chromatic textiles, etc., with applications in the medical field, sport and leisure, the military and first-responders market, and intelligent applications in buildings.
These are properties and applications with potential to provide value in products. Some can be achieved by conventional means, e.g., wrinkle resistance, but with research, alternatives or improved means via nanotechnologies may be found. Lower processing costs, less energy usage or reduced chemical processing may be other value-added factors resulting from the use of nanotechnologies. Much of this is at a research/concept stage, with some application in products now. How is this being achieved in textiles? Integration of nanotechnologies into textile products is being realized in coatings, treatments, fiber material composites and nanoscale fibers. Nanotextiles have been subdivided into four major types:

- Nanofinished textiles
- Nanocomposite textiles
- Nanofibrous textiles
- Nano-enabled nonwovens

In particular, nanofinished textiles are those that apply a nanoscale property added after the base textile has been fabricated. This includes post-manufacture treatments and coatings to apply nanomaterials or create nanostructured surfaces on fiber media. Additive nanomaterials to date include metal nano-objects (such as silver for antimicrobial functionality) or clay nano-objects (for fire resistance). Nanostructured surfaces may include those roughened by treatments (hydrophobicity for self-cleaning). For existing process lines, nanofinished textiles may only require the addition of intermediate steps for coating or treatment. The majority of nanotextiles already on the consumer market fall within this category.

According to T. Malik and T.K. Sinha in "Nanofinish in textile: An emerging technology" published on the web in November 2014 (**http://www.constructionupdate.com/Newslist.aspx?nid=80686**), finish is the final step in the fabric manufacturing process, the last chance to provide the properties that customer will value. Finish give it special functional properties including the final ´touch´ and nanotechnology is one of the emerging technologies used for textile finishes.

From the fiber level to surface coatings, new developments in nanotechnology impact many specialty fabrics markets. According to S. Tornquist, *Specialty Fabrics Review*, October 2013, ways of manufacturing specialty fabrics have been around for decades, but what does that mean in terms of opportunities for manufacturers, particularly in regard to coatings?

(http://specialtyfabricsreview.com/articles/1013_f3_small_mighty.html)

Besides the textiles that are able to confer to the fibers waterproof, windproof and scratchproof properties, current applications include military camouflage clothing that can change color as a function of the environment, textiles that capture bacteria in mass transportation systems and textile filtration devices that lower toxic emissions from industrial manufacturers. And that's only the beginning.

- **Manipulating the molecules.** When dealing with fabrics and coatings, nano-scale technologies can be used in coatings or at the fiber level. *"What we do in our laboratory has to do with two things"* says professor Juan P. Hinestroza, Associate Professor of Fiber Science and Director of the Textiles Nanotechnology Laboratory at the College of Human Ecology of Cornell University, Ithaca, N.Y. *"One of the things we do is to use objects that have those dimensions below 100 nanometers to coat existing fibers, such as cotton, polyester and nylon; but also the same nanotechnology term can apply to making fibers with smaller diameter, less than 100 nanometers. The first aspect is where we modify the existing materials to make them behave in a way that they don't like to behave"* Hinestroza says. *"For example, we make cotton conduct electricity and/or kill bacteria or create color without using dyes. These are properties we can manipulate by controlling the interfaces between the small materials and existing materials."* The other aspect - manipulating the size of fibers - results in capturing particles in the air. "*We developed technology to capture industrial toxic chemicals as well as chemical warfare agents"* Hinestroza says.
- **Cleaner, safer.** The environmental dangers associated with the use of fluorocarbons are driving scientists to find new ways to coat fabrics for soil and oil resistance. *"The international restrictions of fluorocarbons were the main reason for our investment and development activities"* says Oliver Sonntag, Head of International Sales at Nano-Care AG, Saarwellingen, Germany. *"By the latest technologies it is now possible to manufacture environmentally friendly and food-safe textile finishes that have no impact on the touch - or feel - of the textile. These finishes are based on a natural raw material: silicon dioxide [$SiO_2$]. Due to their nonstick characteristics, they can save cleaning efforts. Furthermore, they come in water-based solutions so they are environmentally friendly and easy to handle regarding worker protection."* Sonntag points out additional benefits that are the result of $SiO_2$ coatings' ability to be delivered in concentrated forms: shipping cost savings and, in turn, reduced $CO_2$ emissions. Using the sol-gel method (a chemical process that deposits coatings on a substrate) Nano-Care is developing self-drying $SiO_2$, that is ultra thin; the average coating size is 100 nanometers. Because the finishes dry at room temperature and are easily applied (by spraying), Nano-Care expects the product to be marketed to consumers as dirt protection for home textiles.
  One step further than coatings that repel stains is bacteria-killing coatings. Dr. Manfred Heuberger, Head of the Laboratory for Advanced Fibers at EMPA (Swiss Federal Laboratories for Materials Science and Technology), is working on a nano-composite coating with antimicrobial properties. *"We have implemented the generation of a novel nano-composite coating using plasma technology"* Heuberger says. *"While a thin polymer layer is grown on a surface, nanoparticles of silver are produced inside the polymer layer. These coatings have strong antimicrobial action during short times - hours to days - until all silver is consumed. Hence, no silver is wasted and only very small overall amounts of silver are used, which makes this method economical and environmentally friendly."*
- **Military applications.** Perhaps a clue to what some applications might be for nanotechnology and textile coatings lies in who's funding the research. *"We get a lot of funding through the Department of Defense, Department of Commerce, the National Science Foundation and the Defense Threat Reduction Agency"* Hinestroza says. *"And now more and more we are getting funding from*

*overseas."* Military and threat reduction applications are among those currently in use, products that protect users from contaminants and provide high-tech camouflaging properties. *"We have developed a technology to capture industrial toxic chemicals as well as chemical warfare agents"* Hinestroza says. Hinestroza's work is also used in military interactive camouflage. *"Interactive camouflage is clothing that can change color as a function of the environment"* he says. *"If you are in the jungle the uniform becomes greenish and if you're in the desert it becomes a sandy color."* The color change is a result of controlling the interactions between the particles and the light.

- **New printing techniques.** As a part of his research, Hinestroza also works with 3-D printing, *"to assemble the molecules on top of the fibers"* he says. *"Before we had to immerse the fabric or the fiber into a solution that had the molecules we wanted to attach. Now with this technology, we can print the molecule on top of the fiber and we can layer one on top of another."* He cites the benefits of printing as the ability to produce small batches for samples and the ability to apply coatings to only those areas intended to perform a specific function. For instance, odor-fighting coatings can be applied to the underarms of a T-shirt and UV-resistant coatings to the remainder of the shirt.
- **Safety first.** As with any new technology, there are concerned about what the long-term effects of the products and processes will be. *"There is an ongoing discussion about the safety of nanotechnology, which strongly affects market introduction"* Heuberger says. *"Manufacturers and consumers consider the reputation of nanotechnology in the society, which has become a delicate balance between the fear of adverse effects and the enthusiasm for new opportunities. Scientists know today that nanotechnology is a safe technology if basic precautions are taken."*

### *Nano-enabled Food & Beverage Packaging Market*

The *"Global Nano-enabled Food and Beverage Packaging Market 2014-2018"* research report published by ReportsnReports (RnR) in October 2014 forecasts this market to grow at a CAGR of 10.48% over the period 2013-2018 (http://globenewswire.com/news-release/2014/10/30/678195/10105423/en/Beverage-Packaging-Market-Review-Nano-Enabled-F-B-Packaging-Industry-Forecasts.html). Nano-enabled food and beverage packaging products use nano-engineered materials to enhance food safety and quality; such nano-engineered materials include solutions such as nanocoatings and nanocomposite-based packaging films. Active, intelligent, and controlled release technologies are the major types of nano-enabled food and beverage packaging technologies (Figure 13).

In another report by RnR, the beverage packaging market is projected to grow at a CAGR of 4.4% from 2014 to 2019. In 2013, the Asia-Pacific region was the largest beverage packaging market, wherein China dominated this market. New technologies have initiated the emergence of innovative packaging designs, but stringent regulations challenged the beverage packaging manufactures to prioritize environment health. Developing countries present a viable market for this industry as the regions of the western world have become a saturated market for beverage manufacturing and beverage packaging companies as well. To calculate the market size, the report considers the revenue generated through the sales of nano-enabled food and beverage packaging solutions by vendors in the market. The research has been prepared based on an in-depth market analysis with inputs from industry experts. The report covers the Americas, and the APAC and EMEA regions; it also covers the Global Nano-enabled Food and Beverage Packaging market landscape and its growth prospects in the coming years.

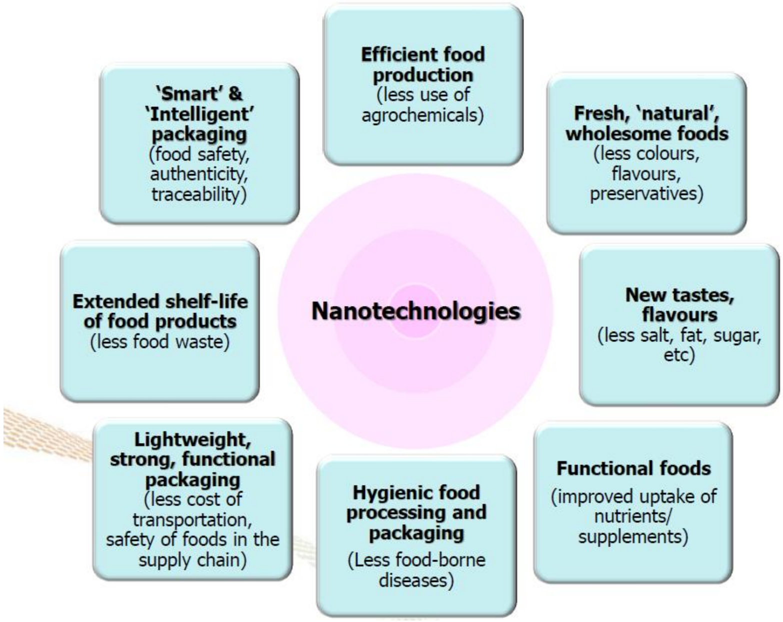


**Figure 13.** Potential benefits of nanotechnologies in Food & Beverage Packaging applications (taken from Dr. Qasim Chaudhry's presentation titled *"Nanotechnology Applications for Food Packaging"* by The Food and Environment Research Agency)

In addition to product protection from packaging, consumers want to see the food they buy; they want it to stay fresh for a longer period; they want it to be safe to eat; and, above all, they want it to be tasty. Food-purchasing decisions are based on taste and appearance as well as convenience, making excellent barrier quality to maintain product freshness vital in food packaging - not only to extend shelf life, but also to protect brand image. Number one with the public is food safety, and active or barrier packaging that can help prevent spoilage or contamination is in strong demand.

Recalls can be particularly damaging to brand image and the company's bottom line. Most companies understand the added expense of improving packaging to help prevent recalls or a liability case is often far less than the cost of losing many customers because of an unhealthy or unsafe product. Consumers want easy-to-open, see-through economic packaging that also protects against oxygen, water vapor and aromas (Figure 14).

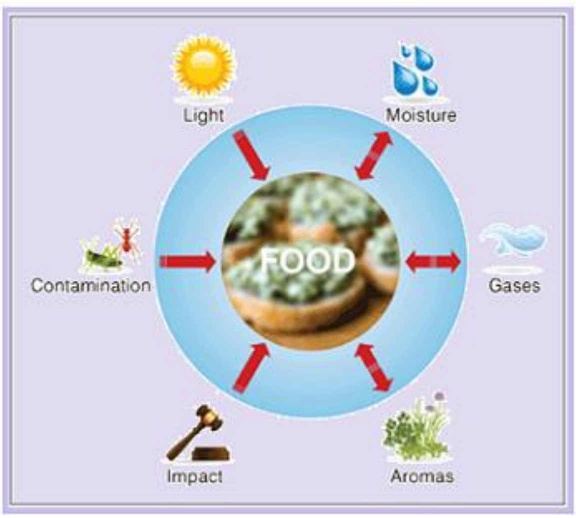


**Figure 14.** Threats and opportunities for Food & Beverages Packaging

Nanotechnology is enabling new food and beverage packaging technologies to address the needs for longer shelf life and the ability to monitor food safety and quality based upon international standards. Government policy and regulations are also impacting barrier plastic packaging design. The use of nano-based packaging for food products has raised various safety, environmental and regulatory issues with the European Food Safety Authority (EFSA) and the Food and Drug Administration (FDA) in the USA. Packaging waste is a growing environmental concern, and consumers are seeking more sustainable packaging choices, driving food packagers to look for bioplastic materials with good barrier properties. The presence of $O_2$-sensitive unsaturated fats is also fueling development of active and barrier packaging in flexible and rigid formats.

The global functional additives and barrier coatings market for plastic packaging is expected to be worth USD 752 million in 2014 and projected to greatly grow in the next four years and to reach almost USD 3.7 billion by 2018 (http://www.foodproductiondaily.com/Markets/Growth-projected-in-additives-and-barrier-coatings-for-plastic-packaging), according to a report published in 2013 by SmithersPira.

Barrier coatings will grow 4.6% annually on average, while functional additives are expected to expand at a slightly more modest 3.9%. The growing footprint of large retail chains in developing markets is expected to stimulate the sales of packaged food including barrier packaging.

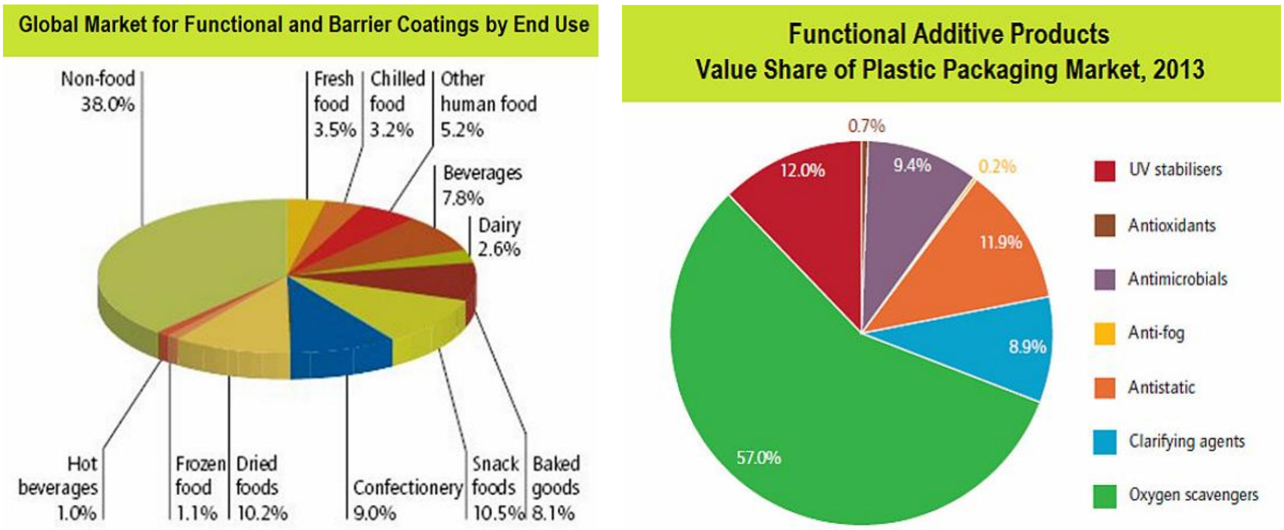


**Figure 15.** Global market for functional and barrier coatings by end use (left); Functional additive products value share of plastic packaging market, 2013 (right)

Functional and barrier coatings cover a broad spectrum of materials that are coated onto substrates to provide a barrier of some sort to protect the materials inside, and/or to enable the substrate to act as a suitable package for its contents. Although the market is broad in scope and application (Figure 15), over 60% of the market for functional and barrier packaging covers a wide range of food stuffs. Barrier requirements for food packaging include protection against water and water vapor; oil and grease; oxygen and aroma.

Material developments and new packaging processes are allowing food to be kept fresh much longer without altering taste or aroma. While traditional barrier materials extend product shelf life by impeding $O_2$ migration into a package, $O_2$ scavengers go one step further "capturing" $O_2$ present within a sealed package to ensure it does not react with the food product. By combining active and barrier packaging, processors can increase shelf life, protect flavor profiles and maintain food's appearance without adding preservatives.

Antimicrobials as a coating or compounded into the plastic are helping address outbreaks of foodborne illnesses.

Combinations of barrier technology and processing advances such as microwave pasteurization of chilled ready meals are resulting in unique food-product advances. Nanotechnology is also being used to enhance packaging barrier properties. New nano-based food packaging materials with improved mechanical, barrier and antimicrobial properties, and nano-sensors for traceability and monitoring food condition during transport/storage are key development areas for nanotechnology in food packaging. Some developments are geared toward improving application properties by using active substances on the nanoscale that are incorporated into packaging materials.

The use of nano-based packaging for food products has raised various safety, environmental and regulatory issues. The main concerns stem from the lack of knowledge regarding long-term effects of nano-sized materials on consumer health and the environment and the lack of definition as to what constitutes a nanomaterial. The EFSA recently defined nanomaterial in its development of procedures for obtaining approval for use of nanomaterials in food contact applications. The FDA is also outlining a roadmap for discussion on nanotechnology; the agency has issued draft guidance for the use of nanotechnology in the food and cosmetics industries.

New clear barrier materials are being developed to replace aluminum foil and other opaque barrier materials resulting from a trend toward packaging food products in clear materials. Lightweighting in the beverage industry adds another dimension to the barrier coating challenge as thinner walls increase permeation in non-barrier bottles. Reduction of material in blow-molded PET containers is driven both by cost reduction (material, transportation) and by consumer demand for sustainable packaging. In Europe, there is significant latent potential for barrier PET bottles in beer, wine and specialty alcoholic beverages where penetration of these plastic bottles remains low, below 10%.

In another report by Don Rosato, titled: *"New barrier plastic packaging materials advancing rapidly"* published on the web (http://www.multibriefs.com/briefs/exclusive/barrier_packaging_2.html), a deep analysis of the technologies and material advances for effective barrier films in the food & beverage packaging market is illustrated. It is important for food packaging to provide good protection against factors crucial to product quality to ensure product shelf life. Depending on product sensitivity, it is vital to provide food packaging protection with proper barrier components. For example, some products are susceptible to moisture, oxygen or both, or to other gases. Barrier films often consist of multi-layers or coated films designed to be impervious to gas and moisture migration, as single-layer films are in general quite permeable to most gases. Commonly used layered barrier film materials include (see Figure 16):

- PP (polypropylene): Mechanical properties and water vapor barrier;
- PE (polyethylene): Sealing/water vapor barrier;
- mLLDPE (metallocene catalyzed linear low density polyethylene): Good optical and mechanical properties
- Polyamide (nylon): Aroma/$O_2$ barrier with stiffness;
- EVOH (ethylene vinyl alcohol): High $O_2$ barrier - provides excellent barrier properties to gas and water vapor. It is also environmentally friendly and clear. However, it is not suitable for high-temperature processes;
- EVA (ethylene vinyl acetate): Good for sealing;
- PLA (polylactic acid): Biodegradability.

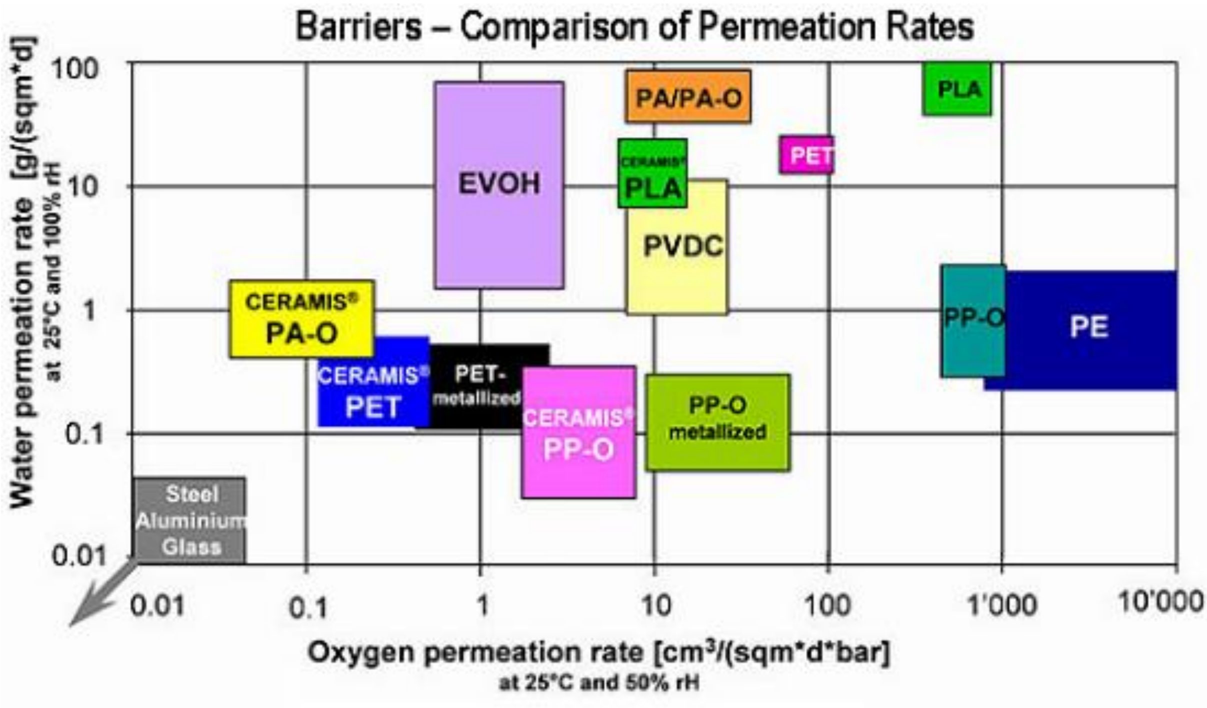


**Figure 16.** Oxygen and water permeation rates for various types of barrier films

Various approaches can be taken to improve barrier properties in the plastics packaging sector; the technologies include film resins, inks, adhesives and primers and meet food packaging barrier requirements:

- Barrier layers can be applied onto plastic using vacuum coating (i.e. aluminum or transparent oxides such as aluminum oxide or silicon oxide applied to PET - polyethylene terephthalate, or BOPP - biaxially oriented polypropylene films);
- Multiple-layer structures can be used;
- Nanoparticles can be compounded into the polymer matrix to form a nanocomposite that inhibits gas permeability.

Traditional multilayer packaging films are neither recyclable nor compostable. They are comprised of multiple layers of traditional plastics and adhesives needed to provide the barriers, colorful print and necessary adhesives that bond all the layers together. These various materials are not easily separated for disposal, making recycling problematic, and the chemicals those layers are made from cannot be composted. Some examples on the marketplace are:

- **Imperm®** (ColorMatrix Europe):
  used in multi-layer PET bottles and sheets for food and beverage packaging to minimise permeation of O2 and loss of CO2 from beverages;
- **Duretham®** KU 2-2601 (LANXESS Deutschland GmbH):
  uses Nanocor's clay to produce a film with increased barrier properties in the plastic. Example applications include paperboard juice containers;
- **Aegis® OX** (Honeywell Polymers):
  a polymerised nanocomposite film contains a blend of active and passive nylon that incorporate active O2 scavengers and passive nanocomposite clay particles to enhance barrier properties.

A new completely compostable multilayer food packaging barrier film has been developed by **BASF** (Figure 17). Fully compostable, the new packaging material can go to industrial composting facilities instead of landfill.


**Figure 17.** Compostable multilayer barrier film by BASF New Business Division Gmbh

BASF's compostable packaging material consists of a six-layer film:

- Ecoflex and ecovio (compostable polyester film);
- Joncryl SLX (printing ink layer);
- Epotal P 100 ECO (adhesive coating);
- Metallization layer;
- Versamid (premetal primer);
- Ecoflex and Ecovio (compostable polyester film).

The innovative design of the packaging and its materials allows for the entire structure to be composted.

# COMPETITIVE SCENARIO

## *Leading Companies in the Nanocoatings Market*

The following list of key companies has been assembled from different report sources; the vast majority of them are companies headquartered in the USA.

- Aculon (USA, www.aculon.com/)
- AdMat Innovations (India, www.admatinnovations.com/)
- Alcoa (USA, www.alcoa.com/global/en/home.asp)
- Annex Paint (USA, http://www.annexpaint.com/)
- Arkema (France, www.arkema.com/en/index.html)
- Ashland (USA, www.ashland.com/about)
- Biocoat (USA, www.biocoat.com/)
- Bio-Gate AG (Germany, www.bio-gate.de/page.asp?lang=e&websubs=home)
- Boral (Australia, www.boral.com.au/home.asp)
- Buhler Partec GmbH (Germany, www.buhlergroup.com/global/en/home.htm)
- Cima NanoTech Inc. (USA & Singapore, www.cimananotech.com/company/about-us)
- Diamon-Fusion International (USA, www.dfisolutions.com/)
- Drywired (USA, www.drywired.com/,
- DSM (USA, www.dsm.com/corporate/home.html)
- Eastman (USA, www.eastman.com/Pages/Contact_Us.aspx)
- Eikos Inc. (USA, www.eikos.com/)
- Enviro Ltd. (Hong-Kong, www.enviro.com.hk/)
- Evonik Corp. (USA, www.corporate.evonik.com/en/Pages/default.aspx)
- High Tower Supply (USA, www.hightowersupply.com/)
- Industrial Solutions USA (USA, www.industrialsolutionsusa.com/)
- Inframat Corp. (USA, www.inframat.com/)
- Innovia Films Inc. (USA, www.innoviafilms.com/)
- Integran Technologies Inc. (Canada, www.integran.com/)
- Liquidoff (USA, www.liquidoff.com/)
- Michelman (USA, www.michelman.com/)
- Nanotech SST (UK, www.nanotechsst.co.uk/)
- Nanoteks (USA, www.nanoteks.lv/en/)
- Nanotex (USA, www.nano-tex.com/, is a Crypton Co. subsidiary USA, www.cryptonfabric.com/)
- Nanocare AG (Germany, www.nanocare-ag.com/ueberuns/)
- Nanoclear (New Zealand, www.nanoclear.co.nz/)
- Nanocoatings (USA, www.nanocoatings.com/#./home)
- Nanofilm Ltd. (USA, www.nanofilmusa.com/contact/)
- Nanogate Technologies Gmbh (Germany, www.nanogate.de/en/nanogate_technology)

- Nanophase Technologies Corp. (USA, www.nanophase.com/)
- Nanovere Technologies LLC (USA, www.nanocoatings.com/#./home)
- NBD Nano (USA, www.nbdnano.com/)
- NeroShield Inc. (Canada, www.neroshield.com/)
- NTT Advanced Technology Corp. (USA, www.ntt-at.com/)
- P2i (UK, www.p2i.com/)
- Pilkington (UK, www.pilkington.com/)
- Pureti (USA, www.pureti.com/)
- Ross Nanotechnologies (USA, www.rosstechnology.com/index.htm)
- ShineTech (USA, www.shinetechinc.com/)
- Techmetals (USA, www.techmetals.com/)
- Tough Guard (USA, www.toughguard.com/)
- Ultrahydrophobic Coating (USA, www.ultrahydrophobiccoating.com/)
- Xeromax Sciences (USA, www.xeromaxsciences.com/)
- Zschimmer & Schwarz Mohsdorf GmbH (Germany, www.zschimmer-schwarz.com/mohsdorf)

### *Leading companies in the Nano-enabled Food & Beverage Packaging Market*

- 3M (USA, www.3m.com/)
- Agion Technologies (USA, www.agion-tech.com/)
- Alcoa Inc. (USA, www.alcoa.com/global/en/home.asp)
- Allied Glass Containers (UK, www.allied-glass.com/)
- Amcor (Australia, www.amcor.com/)
- Aptar (USA, www.aptar.com/)
- Ardagh Group (USA, www.ardaghgroup.com/)
- all Corp. (USA, www.ball.com/)
- BASF (Germany, www.basf.com/en.html)
- Bayer (Germany, www.bayer.com/)
- Bemis (USA, www.bemis.com/)
- Braskem (Brasil, www.braskem.com.br/)
- Groupa Can-Pack SA (Poland, www.canpack.eu/)
- CCL Industries (Canada, www.cclind.com/)
- Chevron-Phillips Chemical (USA, www.cpchem.com/en-us/Pages/default.aspx)
- CKS Packaging (USA, www.ckspackaging.com/)
- ColorMatrix (USA, www.colormatrix.com/en)
- Crown Holdings, Inc. (USA, www.crowncork.com/)
- Danaflex-Nano (Russia, www.danaflexnano.ru/en/about/)
- DS Smith (UK, www.dssmith.com/)
- Evergreen Packaging (USA, www.evergreenpackaging.com/)
- Genpak (USA, www.genpak.com/)
- Gold Road Glasses Industrial Co. Ltd. (China, www.goldroad.gmc.globalmarket.com/)
- Honeywell (USA, www.honeywell.com/Pages/Home.aspx)

- InMat (USA, www.inmat.com/)
- Innovia Films (USA, www.innoviafilms.com/)
- International Paper (USA, www.internationalpaper.com/)
- Kraft Foods Group (USA, www.kraftfoodsgroup.com/home/index.aspx)
- Man Luen Plastic Packaging Co. Ltd (China, www.wanliansl.com/eng/about.aspx)
- Meadwestvaco (USA, www.mwv.com/en-us/)
- Mitsubishi Gas Chemical (Japan, www.mgc.co.jp/eng/)
- Mondi Group (South AQfrica, www.mondigroup.com/)
- Multisorb Technologies (USA, www.multisorb.com/),
- Nanocor (USA, www.nanocor.com/),
- Pactiv LLC, (USA, www.pactiv.com/),
- Owens-Illinois (USA, www.o-i.com/),
- PPG Industries (USA, www.corporate.ppg.com/Home.aspx),
- Plastipak Packaging (USA, www.plastipak.com/),
- Printpack (USA, www.printpack.com/),
- Promens (Iceland, www.promens.com/desktopdefault.aspx),
- Reynolds Group Holdings Limited (New Zealand, www.reynoldsgroupholdings.com/),
- Rexam plc (UK, www.rexam.com/),
- Ripesense (New Zealand, www.ripesense.com/),
- Saint-Gobain (France, www.saint-gobain.com/fr),
- Sealed Air Corp. (USA, www.sealedair.com/),
- Sidel (Switzerland, www.sidel.com/),
- Silgan Holdings (USA, www.silganholdings.com/),
- Sonoco (USA, www.sonoco.com/),
- Stora Enso (Finland, www.storaenso.com/),
- Tetra Laval International SA (Switzerland, www.tetralaval.com/),
- Tetra Pak International (Sweden, www.tetrapak.com/),
- Timestrip Ltd. (UK, www.timestrip.com/),
- Toppan Printing (Japan, www.toppan.co.jp/english/),
- Toyo Seikan Kaisha (Japan, www.toyo-seikan.co.jp/e/),
- Triton Systems (USA, www.tritonsys.com/),
- W. R. Grace (USA, www.grace.com/en-us).

### *Leading companies in the Nanocoatings Textile Market*

A key report in this market sector, titled: *"Smart Textiles and Nanotechnology: Applications, Technologies and Markets"* has been published by Cientifica Research in September 2014. The following companies are reported therein, and therefore this table can be considered as the most complete list of active companies in this market.

| | | | |
|---|---|---|---|
| Adidas | Canada Goose | ELMARCO s.r.o. | JR Nanotech |
| Adidas Wearable Sports | Cardinal Health | EMPA | JX Nippon Oil |
| Advanced Nano Products Inc. | CC-NanoChem | Endor Nanotechnologies | Kanebo |
| AdvanPro Ltd. | Chamchuree | Energenics | Kanebo Spinning Corp |

| | | | |
|---|---|---|---|
| Ahlstrom Vaporcool | Chonbang Co. Ltd. | ETTLIN Textiles | Kao Corp. |
| AiQ Smart Clothing Inc. | Ciba Specialty Chemicals | Evonik | Kennedy & Violich Architecture |
| Alexium | Clariant | Exlan Co. Ltd | King's Metal Fiber Technologies |
| Algebra | Clothing+ | Fibretronic Limited | KJUS |
| Alltracel Pharmaceuticals | Cocona Fabric | Formosa Taffeta | Kolon |
| Andeson Bio-tech Co. | Columbia Sportswear Co. | Forster Rohner AG | Kolorgen Ltd. |
| Applied DNA Sciences | Cook Medical | Foster Miller | Konarka Technologies Inc KVA Matx |
| Applied EM | CTT Group | Fountain Set Ltd. | Land's End Inc. |
| ARC Outdoors | Cube | Fuji Electric | Lea Lea Group |
| ARC Technologies | CuteCircuit | G3i Technology Innovations | Lee Jeans |
| Arcteryx | Cyanine Technologies srl | Gap | Levi Strauus |
| Asahi Kasei | Dainese | Garmont | LG Chem |
| ASICS | Danfoss PolyPower | Goldenlady | Liberec |
| ATHOS | Daniel Hechter | Greenyarn | Lindenfarb Textilveredlung Julius Probst |
| Avelana | Degussa | Guahoo | Lindstrand Technologies |
| Balton Sp. Z.o.o | Delta Galil Industries Ltd | Haojey Co. | LLBean |
| BASF | Denizli Basma ve Boya Sanayii | Henry Lloyd | Lockheed Martin Corp. |
| Beijing ChamGo Nano-Tech | Donaldson | Hills Inc. | Louis Vuitton |
| Bekaert Textiles | Dow Corning | Hövding | Mammut |
| Belt Tech | Drapilux | Hugo Boss | Märkische Faser |
| Berlei | Duke University | Hyosung | Marks & Spencer |
| BigSky Technologies LLC | DuPont | Industrial Nanotech Inc. | MBody |
| Bluestar | DuPont Speciality Chemicals | Innotech Textile Co. Ltd. | MC10 |
| Bonar Technical Fabrics AG | Duro Textiles | International Flavours and Fragrances | Misfit Wearables |
| Bridgedale | Eddie Bauer | Ironman | Mission Ready Services |
| Brooks Bros. | Eleksen | J-Teck | Mitsubishi |
| Bruck Textiles | Element 47 | J2LFA Co. Ltd. | Nano Phase Technologies Corporation (NTC) |
| Burlington Industries Inc. | Elmarco | Jack Wolfskin | Nano-Group Holdings Ltd. |
| Nano-Tex | Odlo | Salomon Socks | Tex-Ray |
| NanoCare | Ohmatex | Samsung | Texnology Nano Textile (China) Ltd. |
| NanoChem | Old Navy | Schill+Seilacher | Textronics |
| Nanocid Pars Nano Nasb | Oxonica | Schmitz | The North Face |
| Nanocomp Technologies Inc. | Paul Stuart | Schoeller Medical AG | Thomson Research Associates Inc. |
| Nanocyl | Peerless Plastics & Coatings | Schoeller Textiles AG | Toray Industries Inc. |

| | | | |
|---|---|---|---|
| | Ltd. | | |
| Nanoglide | Peter Brehm | Sefar AG | Toyobo, Ltd. |
| NanoHorizons | PGA | Seger | Trangoworld |
| Nanophase | Philips Lighting | Sensing Tex S.L. | TRG/Victorinox |
| Nanoscience Technologies Inc. | Piedmont Chemical Industries Inc. | Shanghai Hengjia Textile Company | TWE |
| NanoSonic Inc. | Pikeur | Simmons | U-Right International Holdings Ltd. |
| Nanyan Textiles | Polar Elektro | Simms | United Textile Mills |
| nCoat Inc. | Polo Ralph Lauren | SNS Nanofiber | VDS Weaving NV |
| New Balance | Protex | Soane Labs | W.L. Gore |
| Nike | Quest International | Sony | Wacker |
| No-Contact | Radiation Shield Technologies Inc. | SparkFun | WEEL Technologies |
| Nordstrom | Radici | Sphelar Power Corp. | Westaim Corporation |
| NovaThera | Reebock | Struktol | Wibur Ross |
| Nucryst Pharmaceuticals | Reliable | Suzutora | Wirth Fulda |
| NuMetrex | Roudière | Takeda Chemical Industries | XS Labs |
| Nylstar | Salewa | Teijin Fibres Ltd. | Zephyr Technology Ltd. |

# FOR FURTHER READING


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