Chapter 28
Future Man-Made Fiber

Akira Yonenaga

Abstract The demand for synthetic fibers is increasing with the burgeoning global population and the rising level of disposable income in developing countries. Given the shortage of natural resources, concepts such as sustainability and recycling are increasingly important. The future will see the development of 'super functional' fibers: biomimicked fiber, design-driven cellulose fiber, spider silk fiber, intelligent fiber, and bio-base fibers.

Keywords Sustainability • Functional fiber • Biomimicked fiber • Cellulose fiber • Spider silk fiber • Intelligent fiber • Bio-base fiber

28.1 Introduction

In this, the final chapter of this memorial publication, we describe the textiles of the future and their production in terms of global changes in society and work life. We consider only the near future, allowing us to focus on the likely reality rather than merely speculating.

28.2 General Future Forecast

Any predictions around the future of the fiber industry must consider not only potential technologies but also the ongoing social and environmental surroundings in which it will operate [3].

The Fiber Engineering Program at Shinshu University [1] and the special issue regarding the exploration of the function and materials of bio-fibers [2] inform this chapter.

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28.2.1 Social Structural Change: From Consumption to Sustainable Society

Consumption-based society is nearing its end; the way of the future involves sustainable resources and environments. This will not only be a fundamental change to our social structure but will also affect the demand for and consumption of textiles.

28.2.2 Explosive Increase in Global Population

The global population is predicted to increase from the present 6.8 billion to 9 billion in 2030. This increase will mainly come from under-developed countries, whereas developed countries will exhibit a declining population growth. This global population growth will lead to substantial increases in the demand for textiles.

28.2.3 Aging Society

Humanity as a whole is moving towards a population that comprises a growing number of elderly people, fewer children, later marriage, and international marriage. Medical and welfare services will need to adapt to meet the needs of this aging society.

28.2.4 Limited Global Capacity for Food and Natural Resources

Looking to the future of foods and natural resources, the forecast is obviously that of a scarce food supply and a worldwide increased demand for marine products. Thus, shortages in food and natural resources are likely to become a serious social problem.

28.2.5 Serious Shortage of Water Supply

Water is going to be in short supply in most under-developed countries. This will have various associated negative effects, not only on human life and industrial activities but also on the growth of plants and forests.

28.2.6 *Multi Polarized Society: Economic Bloc and Resource Nationalism*

Trends toward economic blocs could intensify, and the protection of natural resources may lead to pronounced resource nationalism.

28.2.7 *Government Conversion: Localization and Autonomic Dispersion Style*

Governments are likely to localize systems to concentrate interests and autonomic dispersion systems, which will in turn affect more complicated industrial management systems. These changes to social structures will undoubtedly affect the supply balance of textile fibers. Under these various changes, foreseeable demands of textile fibers are basically upward and will be tighten in future.

28.3 Forecast of Future Fiber Trend

One must understand textile dynamics before making conclusions about the development of textiles in the future. Assuming the long-term average annual growth rate remains unchanged, the textile market would account for 106 million tons in 2020 and nearly 139 million tons in 2030, corresponding to an increase in average per capita consumption (Fig. 28.1) from12.2 kg in 2012 to 13.9 kg in 2020 and 16.7 kg in 2030 [4]. Thus, this picture naturally portrays an increasing global demand for textile fibers.

28.3.1 *Coping with Increased Demands*

Our ability to increase the production of natural fibers is evidently limited, meaning the only way forward is to increase the production of synthetic fibers. However, this reality is also constrained by the availability of raw materials, particularly raw fossil material, which continues to both rely upon and disregard the environment. Any increase in fiber production will necessitate serious study both of the availability of raw material and of how best to create a sustainable society.

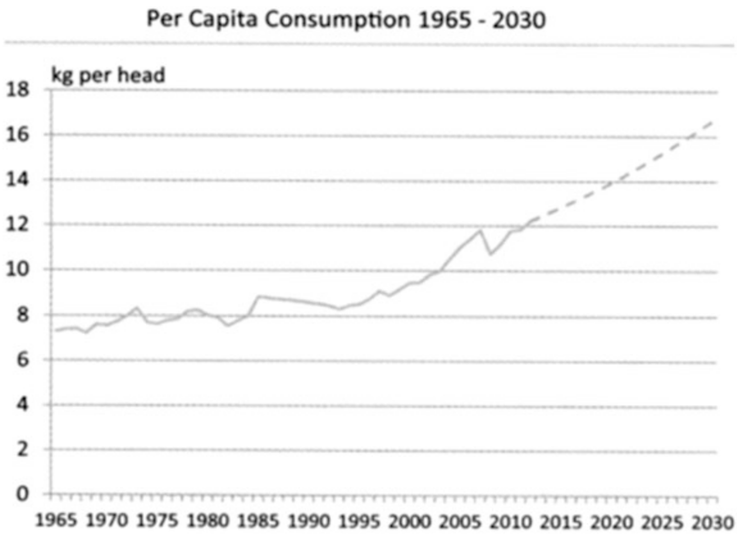

Fig. 28.1 Per capita fiber consumption trends (Source: Fiber Journal October 2013)

28.3.2 Decreasing the Costs of Fiber Production

Cost competitiveness will be an essential component of the future survival of synthetic fibers. Developing countries have the advantage of being able to provide cheaper labor and services, but the cost of raw materials applies equally to any country. Therefore, news from the USA that shale gas technology was a reality was exciting, and it will certainly assist in the cost-competitive creation of synthetic fibers.

Raw materials from shale gas, such as ethylene and ethylene glycol, will provide a cost advantage of more than 40 %, providing practical support to the survival of synthetic fibers (Fig. 28.2), via not only decreases in the costs of raw materials but also savings applied throughout the manufacturing process.

28.3.3 Development of Recycling Technology

The ability to recycle synthetic fibers is already broadly developed and routinely used; it is paving the way for the production of specific materials, such as polylactic acid (PLA) and bio-fibers. The Japanese recycling specialist, Takayasu Co., has reported that super-fine recycled polyester fibers <1.0 dtex. have been developed for automotive nonwoven fabric [6]. Diversification of recycled synthetic fibers will be a foundation material source.

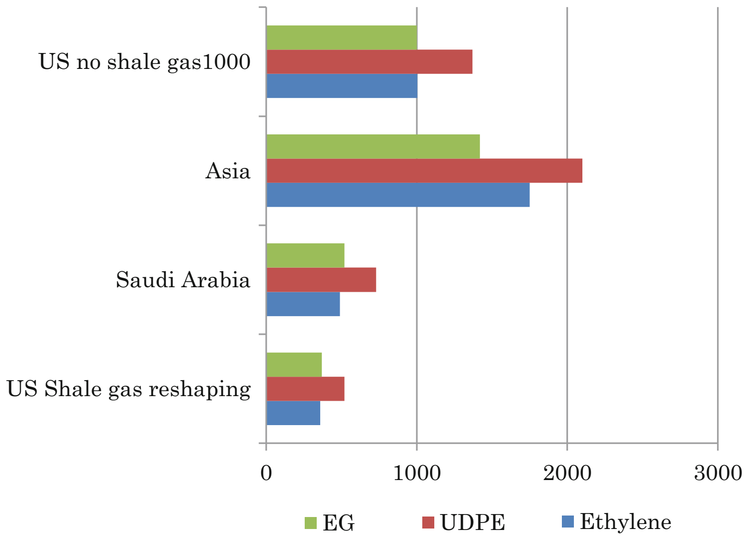

Fig. 28.2 Shale gas reshaping the US chemical industry (*horizontal bar* unit: $/ton) (Source: Management Sensor P187-8/2013) [5]

28.3.4 Expansion of Man-Made Fiber Areas

Cellulose and natural resources such as kenaf, kapok, bamboo, and banana will attract attention in terms of sustainability. However, the availability of these fibers will be limited.

28.3.5 Development of Biomass Fiber

See Sect. 28.4.5 for details on the development of biomass fiber.

28.4 Future Super-Functional Fiber

It is essential that textiles perform well. As such, the laboratory is often the starting point in the development of textiles, and this provides further potential to explore new fibers in the future. Various fields have explored high-functioning and super-performance fibers such as high-temperature resistant, flame-retardant, super-high strength, and anti-microbial fibers. However, consumers and markets expect fibers with further sophisticated functions and enhanced qualities that will survive in the market place. The super-high functional synthetic fibers of the future will provide various pictures of the potential to furnish human life.

28.4.1 Biomimicked Fiber

Synthetic fibers were originally developed to mimic natural fibers, for example, viscose rayon yarn to imitate silk yarn. Such products have since met many challenges, and further development of more sophisticated functions is expected in the future [7].

1. Pine core: Smart breathing textile
   Academic organizations in the USA and Japan have reported the development of fibers that imitate the botanical structure of pine cones, which open and close in response to moisture levels. Thus, this product can alleviate the feeling of dampness by increasing the air permeability of textiles and yarns as moisture builds up around them. Briefly, the developers report that the fabric remains dryer for longer and dries rapidly in extreme conditions [8].
2. Morpho's wings: "Morphotex" colorful textile
   The colors of the beautiful South American Morpho butterfly change depending on the angle of light from which they are viewed because of the complex scale structure on the wings. Teijin Fibers Limited, Japan, mimicked this with a heavily engineered filament fiber called Morphotex. It consists of no less than 60 separate nanolayers in a 15–17 μm structure. There will be interest in enhancing this unique structure for future development (Fig. 28.3).
3. Lotus effects: Perfect waterproof textile
   Various textile coatings have imitated the "lotus effect". The papillae on the lotus leaf ensure that only 2–3 % of its surface comes into contact with water droplets. This contact is confined to the outermost tips of papillae, meaning the adhesive force that would otherwise cause a droplet to spread is also minimal.

Fig. 28.3 Morpho's wing (Source: Future Materials 2/2013)

Fig. 28.4 Lotus effect (Source: Future Materials 2/2013

Instead, the surface tension forces of the water prevail and invariably cause the droplet to form a spherical globule, leading the water to simply roll off. Textiles with these properties are expected to be produced in the near future (Fig. 28.4).

4. Gecko's feet: adhesive cloth

   The gecko is able to stick without glue to flat surfaces by the soles of its feet, which have millions of tiny hairs with split ends. At the tip of each split is a mushroom-shaped cap less than one-thousandth of a millimeter across. These ensure the gecko's toes continuously maintain very close contact with the surface. Many have attempted to replicate this in bonding and adhesive systems, and future applications in building and in household use are expected.

5. Polar bears: thermal control

   Polar bears are superbly insulated by up to 10 cm of blubber, in addition to their hide and their fur; they overheat at temperatures above 10 °C and existing happily at −50 °C. The polar bear's fur consists of a dense layer of 'under fur' and an outer layer of guard hairs that appear white to tan but are actually transparent. The guard hair is 5–15 cm long over most of the bear's body. ITV Denkendorf, Germany, are creating a textile that imitates these properties, and expect to contribute to sophisticated piping, heat capture, and heat storage systems.

28.4.2 Design-Driven Cellulose Fiber Products

The largest natural resource for textile fibers is cellulose from forest wood, which accounts for >60 % of potential textile fiber uses. However, the tight binding of the molecule means it is currently difficult to utilize properly. Elaborate development

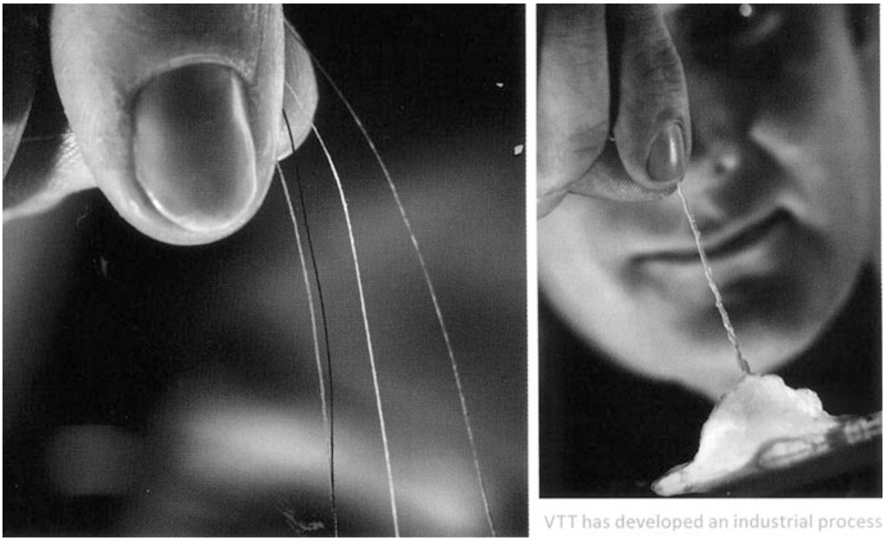

Fig. 28.5 Cellulose fiber yarn made directly from pine fibers (Source: Future Materials P286/2013)

work to use a huge reserve of buried cellulose has begun. State-of-the-art cellulose processing technologies could generate significant production value for future uses of valuable buried natural cellulose resources. A project currently being developed involves the replacement of cellulose wet spinning with extrusion technology, which will resolve the issue of environmental harm [9] (Fig. 28.5). This research project provides an opportunity to use design methods to turn raw cellulose into products and business projects.

28.4.3 Spider Silk Fiber

Artificial spider silk represents another great vision soon to become a reality. The fiber exhibits extensive physical properties that are expected to find applications in the automotive, industrial, and other fields. The latest news has come from Japan-based Spiber Inc., a venture business firm out of Keio University that has developed a mass production process for artificial spider silk. In collaboration with Spiber Inc., automotive parts manufacturer Kojima Press Industry constructed a pilot method to supply 100 kg per month of the yarn in 2013. The process uses raw material from a microbiological protein with the same components and characteristics of spider silk, but with a revised micro-molecular arrangement to enable it to be used with other materials (Fig. 28.6).

At this stage, annual production is 1.2 tons, which is expected to increase to 10 tons by 2015. The new artificial spider silk yarn has high tensile strength and

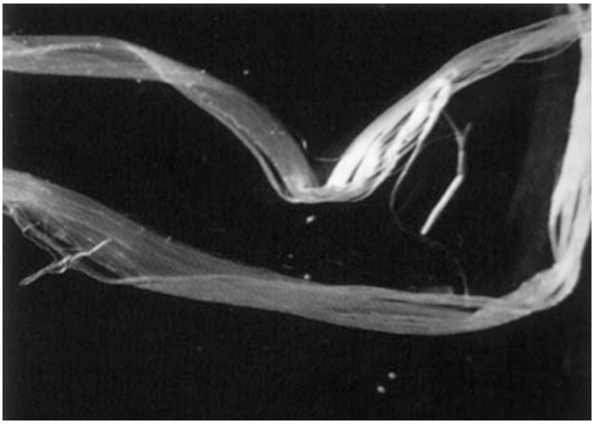

Fig. 28.6 Spiber Inc. artificial spider silk (Source: Nonwovens Report International 4/2013)

elastic properties. Spiber Inc. already owns 16 patents, and the spider silk yarn is regarded as the future of fiber. Meanwhile, recombinant spider silk has also reached the laboratory stage in the USA and Europe. The scale is still at the 50-kg stage, but excellent tensile strength could lead to military uses such as in the creation of ballistic cloth [10, 11].

28.4.4 Intelligent Fiber: Semi Conductor in Fiber with Light-emitting Diode (LED)

The intelligent textile industry is currently focusing on multi-functional textile products, the electronic functionality of which is intended for various medical, protective, military, and sports applications. Electro-conductive fiber for use in electronic textiles (so-called E-textiles) has already appeared on the market. In the near future, lighter and more effective functional semi-conductive chips will be processed directly into the heart of the fiber to be processed into electronic textiles.

Nottingham Trent University (NTU) in the UK is reportedly undertaking intensive development of textile fibers containing semi-conductor chips (Fig. 28.7). This new development will possibly lead to the creation of wearable and washable computers within garments that can easily function to retain possible communication with outside world and to control every possible textile function. The researchers at NTU hope for medical applications such as checking humidity and temperature, as well as more sophisticated chips that can conduct chemical analysis and monitor perspiration.

The researchers have highlighted this electronic integration using light-emitting diodes (LEDs) in a demonstration garment to enable people to see the technology at work (Fig. 28.8). LED textiles can also result in variations of washable and wearable computers that can monitor vital signs of wellbeing, provide intelligent textiles for military, such as invisibility cloaking capabilities, and create flexible

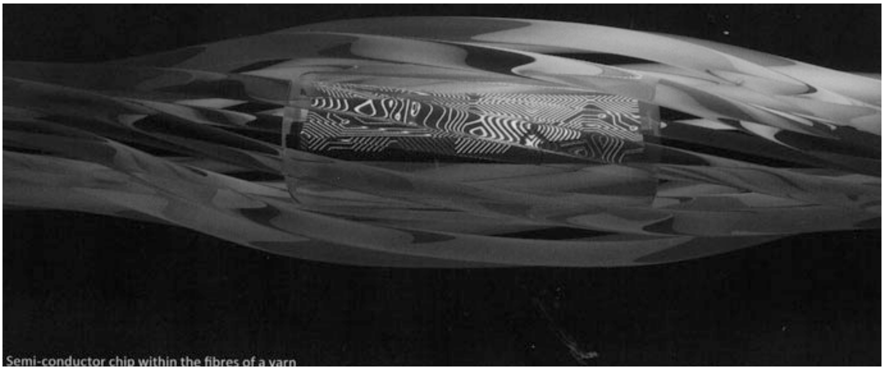

Fig. 28.7 Semi-conductor chip within the fiber of a yarn (Source: Future Materials P10, 4/2013)

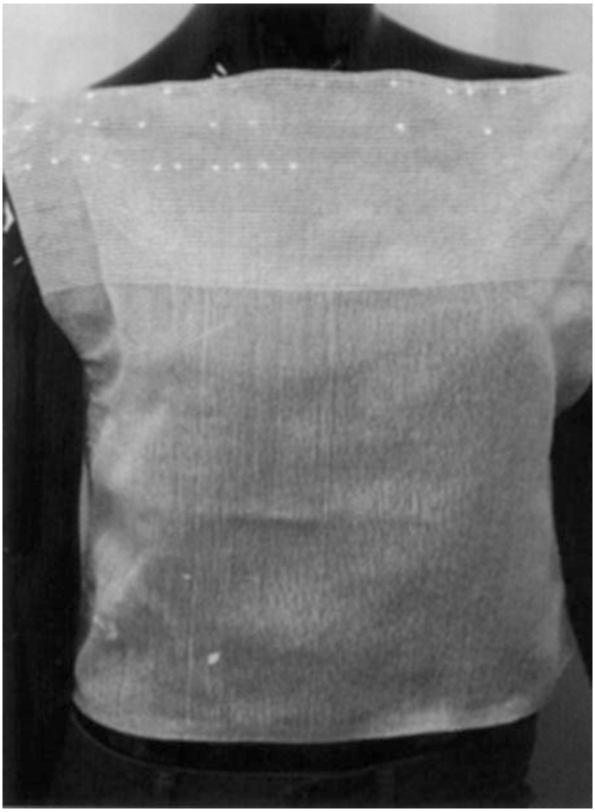

Fig. 28.8 Prototype light-emitting diode (LED) garment (Source: Future Materials P11, 4/2013)

and comfortable displays. In the future, we also expect it will be possible to introduce radio-frequency identification (RFID) chips into yarn so manufacturers can follow the garments all the way from production to retail. In addition, the technology could allow the military to monitor the atmosphere to identify harmful chemicals [12].

Various types of highly functional and multi-functional fibers, such as phase-change material (PCM), fiber robotics, and textiles with built-in bacterial control, smart color, and optical electronics, are also under development and expected to appear on the market. Super-performance fibers such as carbon fibers and aramid fibers have already been marketed substantially in limited applications on a commercial basis. These fibers will also certainly maintain a share of the future.

28.4.5 Sustainability of Future Fiber: Bio-base Fibers

Sustainability has become an increasingly important topic all the way along the textile chain. Against a background of scarce resources, understanding how to secure and handle resources and generate—besides using nature—raw materials for the production of fiber in the future is crucial. The most interesting and serious approaches focusing on sustainability—recycling, biopolymers, and sustainable natural resources—are common in the world of textiles. The resources may seem unlimited, but fossil resources are not. The concerns of both textile producers and customers have resulted in a drive for sustainable textiles. Consequently, a large number of projects intending to increase the use of biopolymers for fibers and textiles are underway [13].

Bio-base polymers are classified as either natural high-molecule polymers or synthetic polymers. The former comes primarily from polysaccharide from natural resources. Simply refining the material from its natural state is difficult because of the hard binding; however, many projects are currently developing cellulose nano fiber. The current development of new polymers from natural resources using microbes is increasing, as is the creation of synthetic biopolymers via fermentation. Representative bio-base polymers under development are shown in Table 28.1.

Poly(trimethylene terephthalate) (PTT) can be produced by standard condensation polymerization of 1,3-propanediol (PDO) and terephthalic acid. DuPont has commercialized PTT under the trade name of Sorona® with its bio-content of 35.9 %, using bio-PDO as a raw material. Although the thermal properties (the melting point and glass transition temperature) of PTT fall between PET and PBT, the molecular structure of PTT is quite unique kink (not linear) mode which provides a soft touch with comfortable stretch and recovery properties to the PTT fiber that are suitable for carpet and textile applications [14].

Recently, polylactic acid (PLA) has been highlighted as a carbon-neutral bioplastic because of its availability from agricultural renewable resources. PLA

Table 28.1 Representative bio-based polymers under development

Class	Polymer	Monomer	Synthetic method of monomer
Polyesters	PTT	1, 3-Propanediol	Bio-conversion from glucose/ glycerin
	Copolyester	Succinic acid	Fermentation
		Butanediol	Fermentation
	PLLA	L-Lactic acid	Fermentation
	sc-PLA	L- and D-Lactic acid	Fermentation
	PBS	Succinic acid	Fermentation
	PHB	Bacterial polyester	Biosynthesis by genetic engineering
Polycarbonates	PC	Isosorbide	Chemical conversion from sorbitol
Polyamides	Nylon 54	Succinic acid	Fermentation
	Nylon 4	γ-Aminobutyric acid (2-Pyrrolidone)	Decarboxylation of glutamic acid
	Nylon 610	Sebacic acid	Chemical synthesis from castor oil via ricinoleic acid
	Nylon 11	11-Aminoundecanoic acid	Chemical synthesis from castor oil
Acrylics	Butyrolactones	Tuliparin	Plant-based
		MMT	Chemical conversion from levulinic acid
Polyurethanes	PU	Plant oil-based polyols	Chemical conversion from castor oil

Source: H. Nakajima, Y. Kimura, "Bio-Based Polymers", Y. Kimura *ed.*, CMC Publishing Co., Ltd., Japan, pp. 1–23 (2013)

is also biodegradable when exposed in biologically active natural environments and is compostable under very specific conditions of high temperature (>60 °C) and high humidity (>80 % RH), typified by the conditions for composting.

Recent advances in the fermentation of glucose obtained from sugar beet, sugar cane or corn have led to a dramatic reduction in the cost of manufacturing the lactic acid necessary to produce PLA polymers. In addition, the technology to produce PLA economically on a commercial scale has been developed worldwide by several companies. Notably, NatureWorks LLC currently operates the world's largest commercial plant for PLA (Ingeo®) with a production capacity of 140 000 tons per year at Blair, Nebraska, USA. NatureWorks has developed a low-cost continuous ring-opening polymerization (ROP) process that is the polymerization of the cyclic dimer of lactic acid, lactide, for the production of PLA.

Lactic acid is a well-known, simple α-hydroxy acid with an asymmetric carbon atom, which is synthesized by the bacterial fermentation of carbohydrates such as sugar from starch. Lactic acids are optically active compounds, including L- and D-forms. PLA polymers that are currently commercially available are ordinarily called poly(L-lactic acid), PLLA, although they are random copolymers containing large amounts of L-units and small amounts (0.5–20 %) of D-units in the polymers.

The melting point of PLA increases with decreasing content of D-isomer, ranging from about 130 to 180 °C.

PLA is a crystalline polymer of aliphatic polyester with thermoplastic processability. Therefore, it can be melt-spun into various types of fibers and nonwovens by conventional melt-spinning machines, and its yarn properties are relatively similar to those of PET. However, PLA fibers are highly functional, coupled with the intrinsic characteristics of PLA such as biodegradable/compostable, bacteriostatic, flame-retardant, weather-resistant and moisture management (fast wetting/drying performance) properties, when compared with PET fibers [15]. Furthermore, the environmental impact study by LCA (Life Cycle Assessment) revealed that the total CO_2 emission of PLA from cradle to grave (feedstock + processing + disposal) is the lowest (3650 kg/ton) among existing conventional plastics/fibers including PET (6443 kg/ton) and viscose rayon (14,680 kg/ton) [16].

Unitika Ltd.. Japan, is a leading company manufacturing the PLA fibers/nonwovens (Terramac®) in the world. Potential applications of these fibers and nonwovens include geotextiles (vertical drain sheet, sand bag, erosion protect and slope stabilization), agricultural/horticultural products (plant cover, plant pots, strings), home furnishings & clothing (towel, bedding, furniture wadding and filling, tea bag filters, casual wear), hygienic products (wipes, disposable diapers, personal care products) and industrial uses (air/liquid filters, cabin parts of vehicles) etc.

The vision of producing sustainable raw materials equipped with new functionalities is already within reach. The advent of genetic engineering means technology has reached a stage where the creation of sustainable biomaterials using genetically modified microorganisms instead of plant-based resources or oil is possible [17].

Gevo Inc. is leading the way in developing and implementing renewable technology to produce bio-based chemical products and next-generation biofuels that replace petrochemicals, with a focus on isobutanol as a platform chemical. Gevo's technology team has developed proprietary yeast to efficiently convert fermentable sugar into isobutanol through synthetic biology and metabolic engineering.

It is fascinating that we can now create not only biotechnology fiber but also the raw materials for the production of fiber.

In the post-fossil world of the future, it is likely that textiles will be made via biotechnology using bacteria or fungi. Current research projects are focused on the wet-spun biopolymer fibers of alginate and chitosan, produced with biotechnology. By varying fermentation conditions, nutrition media, and biopolymer isolation protocols, the characteristics of the raw materials can be adjusted, which in turn directly affects the properties of fibers made from those biopolymers.

In addition, modern biotechnology allows the genetic modification of microorganisms, thus influencing polymer output and characteristics from the very beginning [18] (Fig. 28.9). Thus, in the near future, biotechnology and textiles will combine in the use of microorganisms to synthesize fibers and yarns.

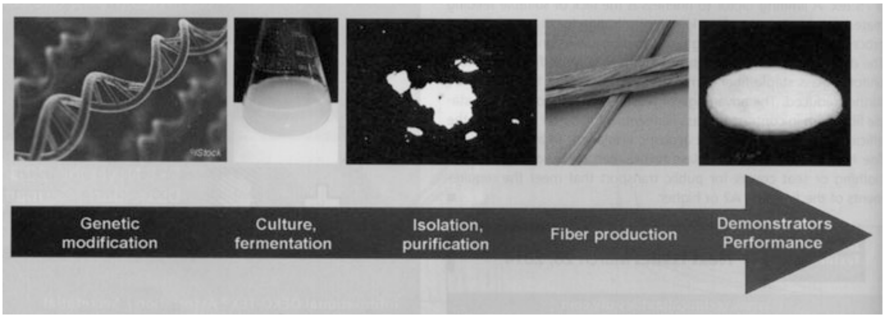

Fig. 28.9 Biopolymer from bacteria—adjustment of materials from the beginning (Source: Technical Textiles P E224 5/2013)

28.4.6 Challenges for Fiber Producers in a Sustainable Future

Japanese fiber producers are being challenged to increase their already substantial efforts in the construction of a sustainable society.

Toray Industries has set up a broad brand "Ecodear," which encompasses the company's bio-mass development projects. Furthermore, Toray has not only marketed PLA and PTT fiber but also has been jointly developing fully bio-based PET fiber with Gevo, using terephthalic acid via Gevo's renewable paraxylene from bio-based isobutanol and commercially available renewable mono ethylene glycol (MEG); that is a world first fully renewable PET fiber -i.e., all of the carbon in this PET is from renewable feedstocks. Nylon has made the transition from sebacic acid to make nylon 610, and Toray has been collaborating with the giant food manufacturer Ajinomoto Co., Ltd. to develop bio-base nylon 56. These bio-base synthetic fibers are expected to arrive on the commercial stage in the near future [19].

"Asahi Kasei Corp. works under the slogan "healthy life and comfort living under co-living with environment"." This company has created high-grade artificial leather using chemical recycling and excellent energy-saving processes. Teijin Limited has developed a complete recycling system for polyester fiber: "Eco circle" recycles the polyester chemical component to reduce consumption of chemical materials, energy, and carbon dioxide emission. Kuraray Group's "Ecotalk" brand is based on carbon dioxide reduction products and typical sustainable artificial leather, "Tirrenina," which uses no solvents and a completely closed recycling system based on the "Clarino Advanced Technology System" (CATS) [20].

In the fiber and textile business, Unitika enhances the applications of industrial fibers/nonwovens by further promoting a shift to bio-based materials. In addition to PLA fibers/nonwovens (Terramac®) as above-mentioned, bio-polyamide Nylon11 fiber (Castron®) has been developed in collaboration with Arkema. Furthermore, Unitika has developed a bio-based (bio-content: 56 %) high performance polyamide 10T (XecoT®) with high heat resistance over 300 °C and low moisture absorption, using bio-based 1,10-decanediamine from castor oil via sebacic acid, as a super engineering plastic/fiber for the next generation.

Rayon fiber is referred to generically as a regenerated cellulosic fiber commonly derived from wood pulp via the chemical manufacturing process. Rayon is the first man-made fiber, having the history of three generations of technology/product called viscose, modal or lyocell respectively.

Viscose rayon fiber, a typical sustainable fiber, previously had a negative image concerning its environmental burden and costs compared with other synthetic fibers. However, the product has made a comeback because of efforts to find environmental solutions and a renewed and positive assessment of its position in a sustainable future.

The third generation rayon fiber, Lyocell (Tencel®), manufacturing process is an extremely environmentally friendly process when compared with the first generation viscose rayon, in which the solvent is recovered and reused up to 99.8 % and the remaining emissions are broken down in biological water treatment plants although it uses a substantial amount of energy, and uses an organic solvent of petrochemical origin.

These days, viscose rayon is a leader of sustainable material for the textile industry, and its future is certain. Lenzing Corporation, Austria, is a leading rayon fiber producer with the capacity to create more than one million ton cellulose rayon fibers worldwide, and various professional rayon fiber producers all over the world will follow this trend. Japanese rayon fiber manufacturers—Daiwabo and Omikenshi—are developing a variety of modified viscose rayon fibers based on sustainable systems.

Daiwabo has already created rayon fibers with a variety of special qualities, such as heat ray shields, ultraviolet (UV) cut-off incorporated ceramics, heat retention qualities, and deodorants, under the company’s eco-friendly line up. Further multi-functional fibers are expected to appear on the market in the near future.

Omikenshi Co., Ltd not only develops functional viscose rayon fibers but is also using natural cellulosic materials such as kenaf and jute—fully advanced sustainable fibers of annual plants— under the brand “Li Terra”. Kenaf fiber has already appeared on the market, and other practical sustainable fibers will follow.

28.4.7 The Outlook for Textile Fibers

Synthetic fibers have progressed to the present day supported by substantial innovative technical developments. Various line-ups such as super-functional fibers, nano-fibers, and sustainable series of fibers have appeared on the market, and further advances can be expected. Manufacturers of synthetic fibers will pursue both fashionable and high-function fields to ensure the future of textile applications. The market forecasts that fiber applications will aim at industrial, medical, and living fields in the future (Fig. 28.10), and that, with diversification and high-functioning applications, more technological high-grade fiber will be developed in the near future. Practical applications for high-functioning fiber will be seen in

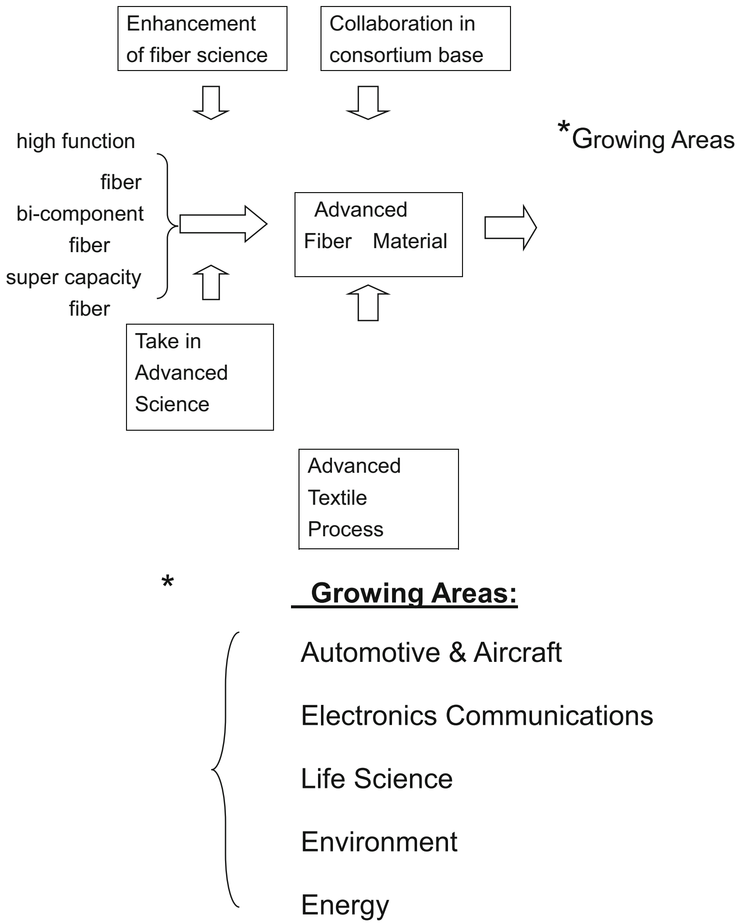

Fig. 28.10 Advanced fiber materials catch up in growing areas

lightweight transportation materials, medical materials, electric battery/condenser separators, electronic parts, E-textiles, and in the building and construction, marine, and airspace fields. Moreover, new industrial and life science applications will invite the creation of further innovative technical fibers.

In the future, technical fiber developments will extend to searches for new polymers, super high-performance fibers, comfortable fibers, and high-functioning fibers. New applications will be developed for these new materials.

Using innovative advances, such as nano-technology and bio-technology, as well as super-high-performance capacities, fiber technology is expected to have a future role in areas such as transportation, life sciences, electronics, environment, and energy fields, in particular.

In conclusion, we consider the global textile and fiber industry has the potential for a positive future, supported by growing consumer demand for fiber and increasingly swift and advanced technical developments [21].

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