Application of Biotechnology in the Processing of Textile Fabrics

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Abstract Biotechnology, a new impetus in the last few years, has seen rapid developments in genetic manipulation techniques (genetic engineering) which introduces the possibility of producing organisms in order to optimize the production of established or novel metabolites of commercial importance and of transferring genetic material (genes) from one organism to another. Industrial biotechnology is the application of technical advances in life sciences to develop commercial products or to incorporate in industrial processes. Enzymes are being used in numerous new applications in the food, feed, agriculture, paper, leather, and textile industries which results in enhanced product quality along with significant reductions in cost and environmental pollution. The potential to harness biotechnology and produce new or modified fibers as well as improving the production yields of existing fibers is being studied. Novel fiber-forming biopolymers with biocompatibility and biodegradability are now being manufactured using large-scale fermentation equipment for medical applications. Natural biological fibers from natural raw materials possessing properties of synthetic fibers have entered the textile field. Enzymatic processes have replaced chemical methodologies in textile manufacturing to obtain a sustainable biobased economy. Biological processes play a major role in the removal of contaminants. The elimination of a wide range of waste materials and polluting substances from the environment is an absolute requirement to promote a sustainable development of our society with low environmental impact. Without such advances in science and technology, the move to a more biobased economy would result in rapid depletion of renewable resources and environmental degradation. The natural protein molecules, enzymes, have paved the way for interdisciplinary partnerships with various textile applications for exploring new avenues in the textile industry. Further research is required for the implementation of commercial enzyme-based processes for the biomodification of synthetic and natural fibers.

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1 Introduction to Industrial Biotechnology

1.1 Meaning and Importance

With the continued pace of world economic growth, sustainable socioeconomic development will depend upon a secure supply of raw material inputs for agriculture, industry, energy, and related sectors. Currently there is a heavy reliance on nonrenewable resources, namely fossil fuels and various minerals and chemical and thermochemical processes. The role of biological processes in the global economy is small but is growing fast as there are initiatives from both the public and private sectors that support the supply of industrial products and energy needs through biological processes and/or biomass resources. The biobased economy can be explained as consisting of those sectors that derive a majority of their market value from biological processes and/or products derived from natural materials, as opposed to products and processes associated with nonrenewable resources or purely chemical processes [1].

A sustainable raw material supply is one of the most important issues for the transition towards a biobased economy. Hence the resource base needs to be recognized from the perspective of supply and demand. The biomass that is to be exploited is obtained from many sources such as specially grown crops, waste materials of food and fodder production, and residues from forest and marine sources. Potential resources for biobased products and services also include municipal waste, manure, and animal products. Areas where biobased products and processes can substitute for mineral-based products, fossil, or chemical processes would serve to be of high importance in a bioeconomy. This substitution would help to make various industrial sectors become more sustainable in the long run and would also help in reducing greenhouse gas emissions and requirements for land disposal [2].

Biotechnology is the foundation for biobased products and services from a sustainable raw material supply to frame a bioeconomy. It helps to manufacture products intended to improve the quality of human life by using biological processes, organisms, or systems [3]. The Organization for Economic Co-operation and Development (OECD) has defined biotechnology as “the application of science and technology to living organisms, as well as parts, products and models thereof, to alter living or non-living materials for the production of knowledge, goods and services.” In other words, biotechnology is derived from biological knowledge and finally is associated with the evolution of biological science. In short, biotechnology harnesses cellular and biomolecular processes to develop technologies and products that help improve our lives and the health of our planet [4].

The science of biotechnology can be divided into subdisciplines called red, white, green, and blue as given in Fig. 1.

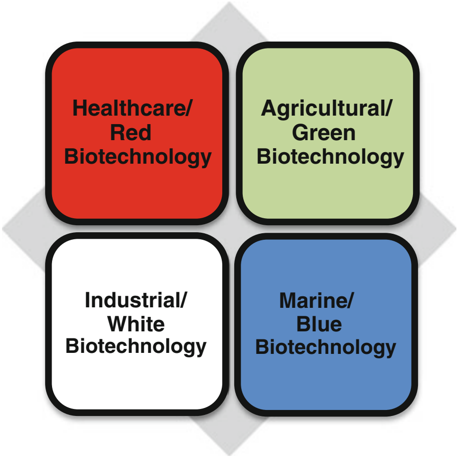


Fig. 1 Subdisciplines of biotechnology

- **Healthcare/Red Biotechnology** plays a vital role in drug discovery and is improving outcomes for patients today and addressing the medical needs for the future.
- **Agricultural/Green Biotechnology** or plant biotechnology provides farmers with the technology to grow food, feed, fuel, and fiber with less input and less impact on the environment.
- **Industrial/White Biotechnology** uses fungi, yeasts, bacteria, and/or enzymes as cell factories to make sustainable energy, chemicals, detergents, vitamins, paper, and a host of other everyday things.
- **Marine/Blue Biotechnology** includes processes in marine and aquatic environments, such as controlling the multiplication of harmful waterborne organisms [3].

The role of biotechnology in different application areas is multifold. As healthcare has become a significant part of government expenditure, many organizations have undertaken research that has brought many medical innovations that enhance the quality of life. Plant biotechnologies produce new high-yielding nutritious crops with disease and drought resistance. Biotechnology also plays a vital role in saving aquatic life and marine environments. White biotechnology has huge prospects in creating natural biobased products with biodegradability features, modifying and developing new processes with enzymes, using biomass as feedstock for the generation of fuels and energy, and also envisaging drastic reductions in environmental pollution and emissions. The use of proteins which form the basis of biotechnology in all walks of life highlight its importance in being a significant tool in producing useful biobased products for the development of human life.

1.2 Salient Features of Industrial Biotechnology

Industrial biotechnology, known as white biotechnology, is the use and application of biotechnology for industrial solutions, including manufacturing, alternative energy (or bioenergy), and biomaterials. It involves the practice of using microorganisms or components of cells, namely enzymes, to generate useful products of industrial importance. It uses biotechnology for industrial processing and production of chemicals, materials, and fuels. Components of microorganisms such as enzymes can generate industrially useful products, substances, and chemical building blocks with specific capabilities that conventional petrochemical processes cannot provide. The conversion of renewable biomass to products that are used in the consumer, chemical, or energy industries, is the most important characteristic of industrial biotechnology. Systems biology and synthetic biology may open new fields of application in any of the biotechnology areas by producing a new database of knowledge. Progress in nanobiotechnology and bioprocessing is needed in the next few years to bring biobased products into the market. It should extend from in vitro synthesis via cells to whole production processes and should be a vibrant part of the overall bioengineering strategy.

Nanobiotechnology has become a main contributor to green chemistry, where sugars or vegetable oils which are renewable resources are transformed into a variety of chemical substances such as fine and bulk chemicals, pharmaceuticals, biocolorants, solvents, bioplastics, vitamins, food additives, biopesticides, and biofuels. Apart from these substances many intermediate products are produced at different stages in the different value chains which are very complex and require analysis and experimentation. Biorefineries, which manufacture biotechnological products, have a strong interdisciplinary approach in producing biobased products. The wide and diverse applications of industrial biotechnology indicate that it is much more than a sole industrial or economic sector but form the basis for a biobased economy [5].

The aim of industrial biotechnology is to create biobased products and processes for sustenance. Certain techniques are handled by biotechnologists to carry out such work. They are.

- **DNA/RNA**: Genomics, pharmacogenomics, gene probes, genetic engineering, DNA/RNA sequencing/synthesis/amplification, gene expression profiling, and use of antisense technology
- **Proteins and other molecules**: Sequencing/synthesis/engineering of proteins and peptides (including large molecule hormones); improved delivery methods for large molecule drugs; proteomics, protein isolation and purification, signaling, identification of cell receptors
- **Cell and tissue culture and engineering**: Cell/tissue culture, tissue engineering (including tissue scaffolds and biomedical engineering), cellular fusion, vaccine/immune stimulants, embryo manipulation

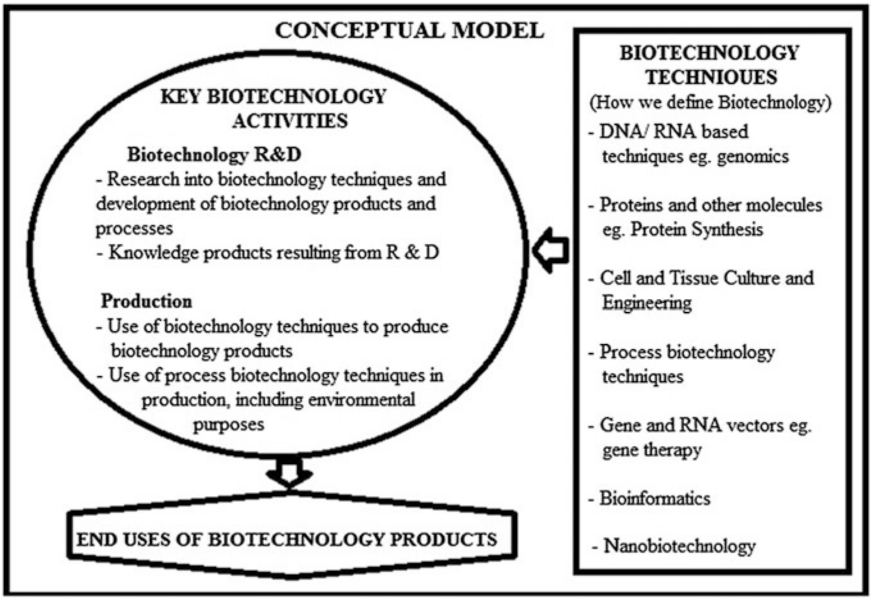


Fig. 2 Conceptual model of biotechnology [6]

- **Process biotechnology techniques**: Fermentation using bioreactors, bioprocessing, bioleaching, biopulping, biobleaching, biodesulphurization, bioremediation, biofiltration, and phytoremediation
- **Gene and RNA vectors**: Gene therapy, viral vectors
- **Bioinformatics**: Construction of databases on genomes, protein sequences; modeling complex biological processes, including systems biology
- **Nanobiotechnology**: Applies the tools and processes of nano/microfabrication to build devices for studying biosystems and applications in drug delivery, diagnostics, and the like [6]

Extensive research in the techniques used for biotechnology results in the development of biobased products and processes which creates a knowledge base for further research and development. These techniques are used in the production of biobased products and also in the processing sequence of industrial production resulting in environmental benefits. The conceptual model is given in Fig. 2.

The five core R&D areas of the USA Biomass program (Biomass Program USA, 2005) show the scope of industrial biotechnology and highlight the processes that use biomass to generate energy and finished products. The five core R&D areas of the Biomass program are shown in Fig. 3 [7].

Biorefineries that produce fuels, power, heat, chemicals, and other by-products use the huge supply of lignocellulosic biomass feedstock. The biomass is broken down into basic component sugars by means of chemical and biological processes

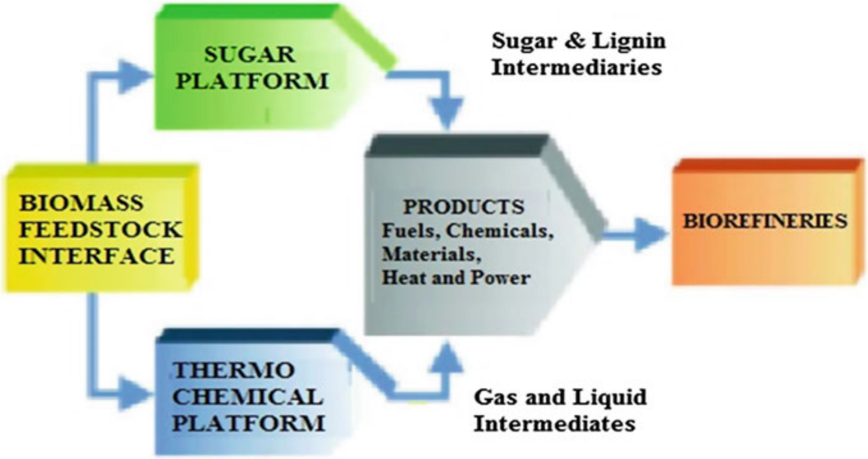


Fig. 3 Biomass program five core R&D areas [7]

as depicted in the sugar platform. The thermochemical platform performs the function of converting the biomass or biomass-derived residues to intermediates such as pyrolisis oil and syngas which can be used as raw fuels or products. These products can also be further refined to produce alternatives to existing commercial commodities such as oils, gasoline diesel, synthetic natural gas, and high-purity hydrogen. Maximum utilization of biomass takes place when integrated biorefineries convert the energy, sugar, and lignin intermediates into final products. The final products include a range of fuels, combined heat and power, chemicals, and materials that play a crucial role in sustainability [7].

1.3 Challenges Facing Industrial Biotechnology

Some of the challenges that face the growth of industrial biotechnology are green growth, climate change, and sustainable development.

1.3.1 Green Growth

Basically, any system that generates increasing prosperity coupled with the protection of natural systems that are sustainable, is termed a green economy. A major factor that can be a long-term driver for economic growth is the green concept, for example, investments made in efficient use of energy and raw materials and in renewable energy. This underlying principle of "going green" in industrial biotechnology can upgrade the performance of the industry and give value addition to the product. As this technology grows and matures, it will provide extensive viable green solutions for the healthy growth and sustenance of our environment.

1.3.2 Climate Change

Our planet has been severely misused ever since the industrial revolution took place under the name of economic growth. This principle has been challenged by industrial biotechnology and disrupts resource consumption by reviewing the conventional industrial processes. Alternatives and options for the traditional industrial processes can pave the way towards better economic growth along with savings in water, energy, raw materials, and reduction in waste. According to the World Wide Fund for Nature (WWF) report, the industrial biotechnology sector globally eludes the formation of 33 million tons of CO_2 each year through various applications of biotechnology, without taking ethanol use into consideration, while globally emitting 2 million tons of CO_2. This organization has also highlighted the potential of industrial biotechnology in building a green economy by reducing CO_2 emissions. The WWF report concludes that by 2030 the use of biotechnology processes and biobased products will reduce emissions between 1 billion and 2.5 billion tons CO_2 equivalent per year. This value represents more than Germany's total reported emissions in 1990 [1].

1.3.3 Sustainable Development

It is essential to estimate the impact of white biotechnology on sustainable development based on three elements, namely people, planet, and profit. The effect of industrial biotechnology on society is analyzed over a range of areas of societal concern namely employment (job retention/creation), innovation (development of new technology platforms), and responsibility (decrease in dependence of society on the usage of fossil resources). This would help to conserve resources for future generations.

The role of industrial biotechnology in decreasing the carbon footprint is very important as it is one of the greatest challenges facing the world. Due to increased process efficiency and renewable feedstock there is a reduction in greenhouse gas emissions, water and air pollution, raw material consumption, and waste production. The application of this technology in the most polluting chemical industry has paved the way for lower greenhouse gas emissions. This attribute helps to position industrial biotechnology as a great tool to address global warming.

Many industries such as chemicals, leather, textiles, animal feed, pulp and paper, energy, metals and minerals, and waste recycling are using biotechnology processes. When the uptake of biological industrial processes is fast, additional value is produced as lower costs in processing and raw materials. Furthermore, additional benefits are derived from smaller investments in fermentation plants and enhanced income from new or high-performance products [8].

The trend today is to question the sustainability aspect of all industrial, societal, and economic activity. Consumers want to know about the impact of their consumption and companies advertise their claims about the sustainability of their products. More than the lifecycle of products and services, the consumption of products by households accounts for more than 60 % of the impact. Industrial biotechnology has principles rooted in cleaner and greener concepts which leads to an economy that is not dependent on fossil fuels and industrial raw materials but on biorenewable carbon sources. The most promising strategy is the concept of biorefineries that work on the processing and fractionation of renewable raw materials to produce biobased products. Synthetic biology produces chemicals from natural pathways and from modified base materials which would open new areas of research and development. When industry becomes more sustainable there is scope for knowledge-driven professions, innovative technology platforms, and conservation of environment.

1.4 Role of Industrial Biotechnology for a Low Carbon Economy

Industrial biotechnology can enable a shift towards a biobased economy. A biobased economy is based on production systems that rely on biological processes and with natural ecosystems that use natural inputs, spend minimum amounts of energy, and do not produce waste as all materials discarded by one process are reused as inputs for another process. Biotech applications encourage new services, behavior, and institutional structures that result in reduced CO_2 emissions over the long term, giving rise to a low-carbon feedback. The contribution of industrial biotechnology may be summarized as improved efficiency, the substitution of fossil fuels and oil-based materials, and a closed loop system with the potential to eliminate waste. All four dimensions play an important role in reducing pollution and also play a vital role in the amount of carbon feedback they generate.

1.4.1 Improved Efficiency

Conventional industries, including the food, pulp and paper, leather, and textile industries, are using natural organisms or enzymes in a number of processes. This results in more efficient use of natural resources and lower energy usage during the production stage or in connected stages along the value chain. The resource usage, GHG emissions, and pollution are greatly reduced when biological methods are used in the lower rung of the value chains and the efficiency is multiplied at the end of the production chains. Industrial biotechnology is expected to penetrate the market with energy-saving efficient solutions and grow, giving great benefits and advantages in conserving the environment.

Efficiency gains and resources can be spent on low GHG investments and knowledge, infrastructure, and processes that can be adopted to reduce carbon feedback. In industries, biotech applications enable the use of smaller areas of land. This land can be used for other biobased applications that will bring many benefits.

1.4.2 Switching to Biofuels

The use of biofuels and their adoption in industrial processes has given rise to the substitution of fossil fuels by about 20 %. It has been reported that this substitution has the capacity to reduce one billion tons of emissions by 2030. Without the speedy introduction of second-generation biofuels, the emission reduction potential would be 50 % lower at 530 Mt CO_2e. Creation of infrastructure and essential logistical systems are some of the dynamic effects of the innovative biotechnologies in the biofuel production sector.

The basic chemical, ethanol, can be used for the production of a variety of other compounds. There is a low-carbon feedback when biotechnological processes is used for the production of biobased materials which is based on the ability to produce large volumes of bioethanol efficiently. The switchover from fossil fuels to biofuels will help the growth of short-term emissions and promote the development of technologies and infrastructures that will help to establish a very strong market for biobased materials. This process will further assist in bringing down GHG emissions and increase low-carbon feedback on a long-term basis [9].

1.4.3 Replacing Petrochemicals with Biobased Material

Many petrochemicals such as HDPE (high-density polyethylene), PTT (polytrimethylene terephthalate), Nylon 6, PET (polyethylene terephthalate), ethyl lactate, and maleic anhydride have been replaced by biobased chemicals. A number of biorefineries have developed which produce a wide range of chemicals and end-products. A huge amount of waste reduction results as the biorefineries can work on the remains of production which enter as raw material for the next production cycle. On analyzing the lifecycle of biobased products there have been significant reductions in energy consumption and GHG emissions showing that these processes have a low-carbon feedback.

1.4.4 Closing the Loop

The carbon present in waste streams forms a valuable source for energy generation. It has been estimated by the Intergovernmental Panel for Climate Change (IPCC) that approximately 900 Mt of such waste was produced worldwide in 2002, and over 33 tons of BOD[16]/day were present in industrial wastewaters.

When carbon is disposed of in anaerobic conditions, methane may be produced, and if it is released into the atmosphere it can cause global warming. Biogas harvested from digesters and wastewater streams may be utilized for many applications reducing energy consumption from fossil fuels. The biotechnology solutions for waste management systems reduce the negative impact of existing systems by recycling the natural carbon as feedstock [9].

Hence biorefineries help to transform any biobased materials into feedstock which in turn produces biomaterials or biofuels. The gap between waste and production will be eliminated as many systems that are created produce less waste and the organic materials produced and disposed of after consumption, re-enter the production cycle of biorefineries as feedstock. Thus biorefineries can close the loop between waste and production and give advantages including the ability to produce biobased materials with fewer GHG emissions and the creation of biobased renewable carbon stored in end-products to be reused continuously for forthcoming production processes.

2 Fibers and Biopolymers

Advancements in chemistry and materials science have given rise to a number of novel synthetic polymers such as nylon, polyethylene, and polyurethane over the past century. These polymers are produced from nonrenewable resources and are not biodegradable. Their strength and durability make them remain in some form in the environment and create problems in disposal. During the production of synthetic polymers toxic chemicals are used and toxic by-products are generated. Currently great attention has been focused on biopolymers that are derived from natural raw materials or may be produced using modern technologies having biotechnical origin.

The growth of industrialization over the past century has raised issues about patterns of production and consumption. As the economic activities around the globe have increased 50-fold, the impact of industrial practices on the environment have been the focus of many environmentalists. Great attention has been focused on the concept of sustainable economic systems that are based on renewable sources of energy and materials. Biopolymers, which are derived from biological origin, would emerge as an important factor in economic development. Biopolymers are used in many applications including packing industrial chemicals, medical implant devices, and computer storage media. The manufacturing systems used to create biopolymers would help in minimizing energy consumption and waste generation [10].

2.1 Green Polymers

Green polymers are biodegradable recyclable biopolymers from renewable resources. The raw materials for the production of these polymers may be either renewable (based on agricultural plant or animal products) or synthetic. There are four main types of green polymer, namely:

- ***Starch-Based Polymers***—Found as granules in plant tissue and can be modified to be melted and deformed thermoplastically (injection molding and extruding). They have good oxygen barrier properties but can sustain only brief contact with water.
- ***Sugar-Based Polymers***—Polyhydroxibutyrate is made from sucrose or starch by a process of bacterial fermentation; polylactides (lactic acid polymers) are made from lactic acid, made from lactose (or milk sugar). It can be formed by injection molding, blowing, and vacuum forming; and used for medical applications, for example, surgical implants that do not require removal by operation.
- ***Cellulose-Based Polymers***—The use of cellulose as raw material for making packaging material such as cellophane has been established. It material may be available in the form of pure cellulose or of a nitrocellulose coating that is biodegradable; applications of cellophane include packaging for confectionery and cigarettes.
- ***Synthetic Materials-Based Polymers***—The high price of biodegradable polymers from synthetic raw materials, for example, aliphatic aromatic copolyesters, makes them unsuitable for consumption. Large-scale production will increase availability and reduce prices. These polymers are used for making substrate mats.

Biopolymers are renewable because they are made from plant materials such as agricultural nonfood crops, which can be grown indefinitely. Hence, the use of biopolymers would create a sustainable industry when compared to the feedstock derived from petrochemicals that will diminish and die out eventually. In addition, biopolymers have the prospective to reduce carbon emissions and minimize CO_2 quantities in the atmosphere. During the degradation of biopolymers CO_2 is released and these gases are reabsorbed by crops grown for raw material, making this process carbon neutral. There is an interest for biopolymers among consumers as they believe that conventional plastics are not eco-friendly to the environment [11].

Textiles are made up of fibers that are giant molecules called polymers. Polymers are made up of several molecules called monomers that are able to bond to form long chains. This linking up of monomers is called polymerization Monomers form polymers by addition or condensation reactions; for example, nylon is a condensation polymer [12]. The structure of the monomer and polymer are given in Fig. 4.

Most polymers are obtained from petroleum products and crude oil but some polymers may be available in nature. Chemically they are based on carbon

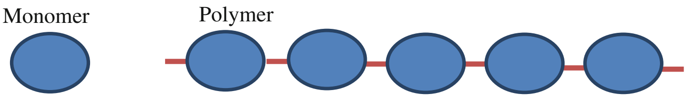


Fig. 4 Structure of the monomer and polymer

although some polymers are based on noncarbon compounds. Natural biopolymers contain macromolecules produced by living organisms such as starch or proteins whereas synthetic biopolymers have macromolecules manufactured from biomolecules. When biomass monomer forms the basis of polymers, they are termed “renewable polymers.” This is because the source can be replaced by growing more biomass and repeating the process of extraction. Moreover, the source should also be replenished at a pace that equals or is faster than the rate of consumption. Biopolymers, which include polysaccharides, polyesters, and polyamides, are produced from natural processes with the help of microorganisms. The properties may be based on the composition and molecular weight of the polymer and may be available from viscous solutions to plastics. Genetic engineering plays a vital role in the manipulation of microorganisms which helps in producing biopolymers with predetermined properties suitable for special medical applications such as tissue engineering and drug delivery [13, 14].

To manufacture sustainable new textile fibers, two different approaches may be adopted. Genetic engineering forms the base of one method where suitably designed genes are tailor-made to make monomeric protein molecules. These molecules are separated and converted into fibers. In the second case transgenesis is followed where modification of fibers is undertaken and other proteins are expressed internally, for example, cotton with high strength characteristics and colored cotton [12].

2.2 New and Modified Raw Materials

2.2.1 Cellulose-Based Fiber

- Cotton (biopesticides, BT cotton, colored cotton)

The domination of natural fibers especially cotton continues with approximately 20 million tons grown/year by about 85 countries. This fiber is a highly essential tool for bringing about change in the technical and economic sectors. Some of the major problems facing cotton cultivators have been addressed by biotechnological means in two ways. The first method is to develop improved resistance to insects, diseases, and herbicides which is a short-term approach. Development of cotton fiber with modified properties such as improved strength, length, appearance, maturity, and color, seems to be the long-term directive [15, 16].

- Transgenic Cotton

One of the major cotton pests, the pink bollworm, has been destroyed by the use of a completely new kind of biotechnology tool. A toxin gene from a soil bacterium called BT is inserted into the cotton plants to create a caterpillar-resistant variety. Monsanto scientists report that the gene is DNA that carries the instructions for producing a toxic protein that kills caterpillars by paralyzing their guts when consumed. Plants with the Bt toxin gene produce their own toxin and thus can kill caterpillars throughout the season without being sprayed with insecticide. This variety is safe for the public and the environment as it attacks only the caterpillars and is harmless to other organisms. This Bt gene technology for transgenic cotton has been registered under the trademark Bollgard® and the cotton variety carrying the patented gene can be cultivated by obtaining seeds from authorized seed companies. Other Bts are now being developed for the suppression of loopers and other worms in cotton as the use of insecticides is challenging the green image of cotton. A "wound-inducible promoter" gene capable of producing a localized dose of toxin within 30–40 s of insect biting, is being developed for insect resistance [15].

- Colored Cotton

Oligo-genes which give color to cotton, are genes that contain chromosomes. Colored cotton is a naturally colored fiber with color in the lumen area. The application of color is by two methods, namely conventional genetic selection and by direct DNA engineering [17]. DNA engineering crosses the colored strain Gossypium hirsutum with a white strain to produce hybrids with better qualities such as fiber length, strength, and color fastness when compared to the parents of colored cotton [11, 15].

Naturally colored cotton in deep fast shades would help to change the face of the wet processing industry. Based on the colored intensity of lint, Gossypium species are grouped into different color groups, namely *aridum, hirsutum* (brown), *arboretum, harbaceum* (medium brown), *armourianum, mustlinum, anomalum* (very light brown)*, arboreum* (Khaki), and *hirsutum* (Green). Pollution and hazards due to dyeing will be greatly reduced by natural blue cotton and would serve to be an important savior in jeans production. The process is aimed at the jeans market ($10 billion in the United States and £800 million in the United Kingdom) and involves the transfer of a gene from a blue flower to the cotton plant [10]. Further research and development are aimed to modify the cotton plant genetically to yield colored cotton with modified properties in physical properties and pesticide and herbicide resistance. The color range is limited and there is a small niche market for colored cottons. The future dream of textile industries will be to sell their products under the eco-friendly banner by using transgenic intensely colored cottons (blues and vivid reds), which is nature's gift to preserve the environment [16, 18, 19].

- Hybrid Cotton

Polyhydroxybutyrate (PHB) is a natural polyester grown in the hollow core of the hybrid cotton fiber, thereby creating a natural polyester/cotton fiber. A 1 % polyester content has contributed to 8–9 % heat retention in the end-product. Other fibers and proteins may be introduced to suit various needs. New properties that enhance the performance of the end-products could be introduced such as greater fiber strength, enhanced dyeability, improved dimensional stability, reduced tendency for shrinking and wrinkling, and altered absorbency. To reduce pollution by pretreating fibers with fewer pectins, waxy materials, and containing enzymes that can biodegrade environmental contaminants could be engineered to assist in the filtration of contaminated water [15].

2.2.2 Protein-Based Fibers

- Spider Silk

Spider dragline silk is a marvelous material that has been engineered to be five times as strong as steel, twice as elastic as nylon, waterproof, stretchable, and exhibit the unusual behavior that the strain required to cause failure actually increases with increasing deformation. A goat embryo is genetically combined with spider DNA, when the goats with modified genes produce milk which contain spider silk. The fibers retrieved from goat milk are made of a polymerized protein fibroine and are reported to be stronger than Kevlar and could be used for making bulletproof vests [20]. Advantageous textile properties have been transferred to microorganisms that are multiplied by bulk fermentation processes. Similarly spider DNA is transferred into bacteria to manufacture proteins with increased strength and resilience of spider silk [16, 21].

- Naturally Colored Silk

Worldwide attempts have been made for producing natural colored silk by modifying the genes of silkworms. The Kyoto Institute of technology, Japan, has taken the credit for producing fluorescent green silk by genetic alteration of the silkworm. Carotenoids, carotenes, and xanthophylls derived from mulberry leaves have been used to color the cocoons and are found to be appearing in the sericin which coats the fibroin of the silk filament. However, based on the pigment permeability on the different parts of the cocoon, the genetic constitution of the silk glands, and the differences in fiber pigment according to the color of the cocoon, variations in color seem to occur. The gene modification technologies are very difficult and are under research and development [19].

- Wool

Biotechnology has various new tools that would influence animal fiber production. New technologies in animal breeding and health care include in vitro fertilization, embryo transfer, diagnostics, genetically engineered vaccines, and therapeutic drugs. Extensive research in genetic modification of sheep has been undertaken by Australia's national research organization, CSIRO. Resistance to the attack of blowfly larvae has been developed by modifying the sheep to secrete an insect repellent from the hair follicles to drive off the insect. Biotechnology-based "artificial epidermal growth factor" is injected into the sheep to interfere with hair growth. Breaks appear in the hair follicles of the sheep after a month and the fleece is pulled off, saving energy and time. Much research has been undertaken by countries all around the world to produce fine valuable wool through the use of biotechnology [15, 16, 18].

2.3 New Fiber Sources

2.3.1 Bacterial Cellulose

Bacterial cellulose is cellulose produced from bacterial origin and not from plant origin. The bacteria employed for cellulose production is Acetobacter xylinium because it produces good amounts of cellulose, making it industrially viable as the cellulose can be produced from a variety of substrates. Cellulose produced from bacterial origin is pure in nature and does not contain other compounds such as lignin or hemicellulose seen in plants. Similar to polymerization, the cellulose is formed as an extracellular polysaccharide with the appearance of a ribbon-like structure. Bacterial cellulose is characterized by properties including high tensile and tear resistance and good hydrophilicity that differentiates it from plant cellulose. Sony Corporation of Japan uses bacterial cellulose in acoustic diaphragms for audio speakers. Other applications include the production of activated carbon fiber sheets for absorption of toxic gas, as thickeners for special cosmetic applications, and as reinforcing material with aramid fibers. It is used as a skin substitute and in wound-healing bandages in the field of medicine [11, 19]. Furthermore, in vitro cultivation of plant cells would produce a secure supply of pure cellulose not bound by climatic or geographic limitations [18].

2.3.2 Biopolymers for Wound Dressing

Polysaccharides, chitins, alginate, dextran, and hyaluronic acid are some of the biopolymers used for wound healing in the field of medicine. Chitin, found in the shells of crustaceans, consists of long linear polymeric molecules of β-(1-4) linked glycans and with aminated, acetylated carbon atom. Fabrics produced with chitins are antimicrobial and antifungal in nature and are converted to end-products such as wound dressings and stockings. Chitosan is used in fabric finishing, wool shrink proofing, filtration systems, and recovery of materials including precious metals and dyestuffs from wastewater. Many industries are employing biomaterials for the development of new eco-friendly products. Courtaulds markets calcium alginate fiber-based wound dressing under the brand name “Sorbsan.” Many species of bacteria such as Leuconostoc mesenteroides are used for the fermentation of sucrose to produce Dextran, a fibrous nonwoven for special end uses including wound dressings. A British biotechnology company, Fermentech, is producing hyaluronic acid through fermentation. Hyaluronic acid, found in the connective tissue of vertebrates and in the capsules of some bacteria, is a polydisaccharide of *D*-glucuronic acid and *N*-acetyl glucosamine. This biopolymer is now available in large scale proving that biopolymer production has increased and manufacturers are following biotechnological processes for a clean and green production of industrial products [15, 18].

2.3.3 Biopolymers for Bioplastics

The application of biotechnology for industrial processes has opened the doors to sustainable development. Alternatives to nonbiodegradable plastics is the highest goal in industrial biotechnology. The term *bioplastics* means biodegradable plastics made from various sources such as plant material sources as modified polymers or polymers made by microorganisms or plants and by polymers made from monomers obtained by fermentation. It has been estimated that the production of biobased polymers on the global level was 0.36 billion tonnes in 2007 and its market share is expected to be 10–20 % by 2020 [1, 22]. Some of the biomaterials available across the world have been discussed herewith.

The project, “Living Chemistry for Quality of Life” has been taken up by an Italian research group Novamont where agriculture, the environment, and chemistry are integrated to serve mankind. Mater-Bi® is a biopolymer that uses maize starch as the raw material for production. This is the first biopolymer made from agricultural sources and the chemical structure developed during photosynthesis is also preserved. Starch and other biodegradable agents are combined to produce an array of molecular superstructures with a wide range of properties. The biodegradable agents may be from renewable or synthetic sources or a combination of the two. Mater-Bi can be converted easily to products that have properties even better than traditional plastics. These products are biodegradable and compostable in a single composting cycle [23, 24].

Polyhydroxyalkanoate-based bioplastic marketed as “Mirel” by Cambridge has been certified as soil and marine degradable there by making it sustainable and eco-friendly. The polylactic acid fiber is made from lactic acid which is obtained by the fermentation of corn starch. This fiber termed “Lactron” has strength, stretch, and many other properties equivalent to nylon and polyester. Lactron, manufactured by Kanebo Spinning and Kanebo Gohsen of Japan, is available as yarn, thread, and woven and nonwoven fabrics. Another biodegradable fiber from corn is “Ecodear” manufactured by Toray Industries. Spare-tire covers and floor mats are made of this new sustainable material for the Toyota Motor Company’s redesigned compact car Raum which was launched in 2003 [15, 25].

Biotechnology has utilized the carbon stored in plants by photosynthesis for the synthesis of a range of polylactide (PLA) (2-hydroxypropionic acid) biopolymers. These biopolymers under the brand name, "Ingeo" are patented by NatureWorks. A process of fermentation and separation is used to convert the carbon and other elements in these sugars into biopolymers. Injection molding, thermoforming, and extrusion are some of the methods used to convert the polylactide resin into products such as plastic goods, film applications, packaging, and textile uses. Properties including resistance to ultraviolet light, low flammability and smoke generation, and hydrophilicity make it a valuable fiber for blending with cotton and wool. Currently production is around 180,000 tons, but is expected to reach a target of over 800,000–950,000 tons by 2020. The demand for this sustainable fiber is currently outstripping growth in EU supply [20].

Another important eco-friendly fiber is DuPont^{TM} "Sorona" made from corn. The partnership of scientists from DuPont and Genencor resulted in the development of the organism that would utilize glucose from corn starch to produce PDO. A special fermentation process was followed by a cleaning and distillation step, to obtain a pure form of Bio-PDO^{TM}. Properties such as quick drying, permanent stain resistance, resiliency comparable to nylon, and softness equal to polyester make it suitable for automotive technical textiles including carpets, mats, and fabrics. Thus it offers fabrics with good performance characteristics and is compatible with different fibers for blending [19, 26, 27].

The synthetic biopolymer "Biopol," produced currently, is formed by the fermentation of sugars by the bacterium Alcaligenes eutrophus. These bacteria grow in tanks with a carbon-based food source. The polymer produced is separated and purified. Attempts have been made to genetically engineer bacteria such as E. coli for the viable and economic production of PHA. Plants such as cress and potatoes have been genetically engineered to produce biopolymers instead of storing the starch. The resultant biopolymers have the same structure as those formed by bacteria [29].

A sustainable plastic "Green Polyethylene" is made from a renewable raw material, sugarcane, in contrast to traditional polyethylene which uses raw materials such as oil or natural gas. The sugarcane juice is fermented at the distillery to form ethanol. Ethanol is subjected to dehydration and is converted into green ethylene. This material undergoes polymerization when it is changed to Green Polyethylene. The Green Polyethylene process cycle is given in Fig. 5. Braskem's Green Polyethylene is made from Brazilian sugarcane. During the production of Green Polyethylene, CO_2 from the atmosphere is captured and fixed thereby helping to reduce greenhouse gas emissions. It has been estimated that 1 kg of green PE captures 2.5 kg of carbon dioxide during sugarcane production as compared to the fossil-fuel-based PE which releases 2.5 kg of carbon dioxide per kg into the atmosphere [23, 28].

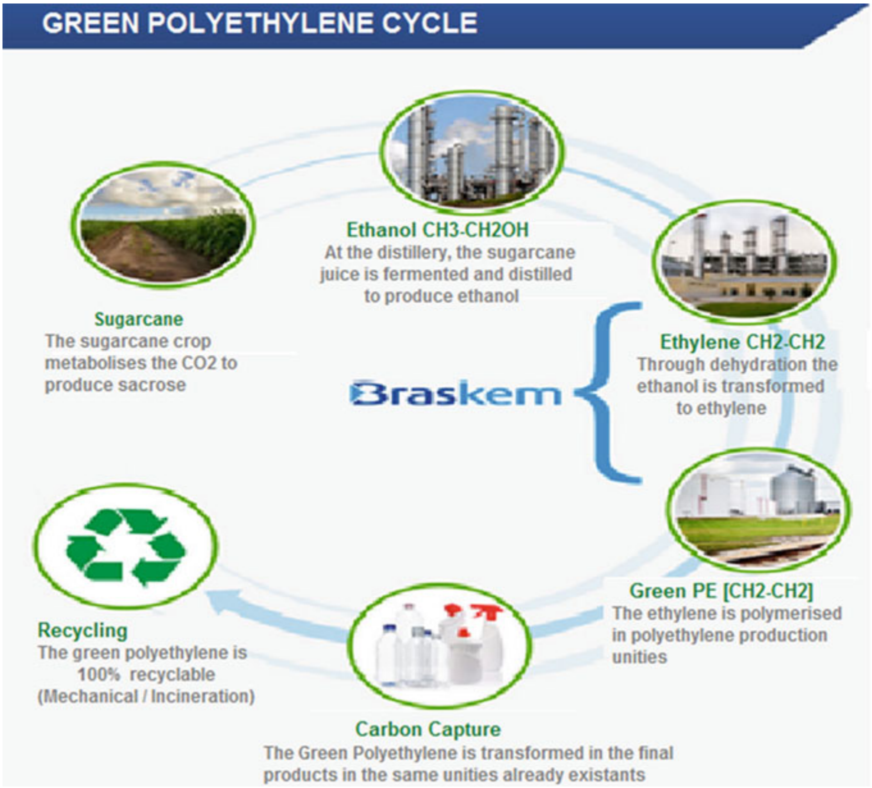


Fig. 5 Green polyethylene cycle [28]

2.4 Dyestuffs and Intermediates

Pigments that have been synthesized using the fermentation processes can serve as chromophores. On chemical modification they can produce dyes or pigments with a wide range of colors. Carotenoids, flavonoids, quinones, and rubramines are some of the stable pigments produced by microorganisms. It has been reported that fermentation processes have higher yield in pigments with lower residues when compared to animal and plant sources [30]. Both bacteria and fungi have been employed to synthesize dyes for the textile industry, for example, indigo. Some microfungi are capable of producing pigment up to 30 % of their biomass [21]. Certain fungal pigments have been from anthraquinone derivatives, which resemble vat dyes. Hence fungi can be used for the direct production of textile dyes or dye intermediates with the benefit of developing colored antimicrobial textiles. Colors developed from fungi include bright red pigment prodigiosin from *Vibrio spp*. and *Serratia marcescens*, bluish-purple from *Janthinobac-terium lividum*, violet pigment violacein from *Chromobac-terium violaceum*, and so on.

Currently the production of microbial pigments and evaluation as textile coloring agents is being analyzed at BTTG, Manchester, UK [31].

The use of soya bean for developing a wide range of products has been in existence for a long time. Recombinant genetic biotechnology has been used to alter the lipid profile of soya beans to provide a wider range of biohydrocarbons for industrial applications. The applications of amides, esters, and acetates of biohydrocarbons are varied and used in the manufacture of plasticizers, antislip agents, and mold-release agents for synthetic polymers. When amines, alcohols, phosphates, and sulfur groups are linked with biohydrocarbons they can be used as fabric softeners, surfactants, emulsifiers, corrosion inhibitors, antistatic agents, hair conditioners, ink carriers, biodegradable solvents, cosmetic bases, and perfumes. Similarly with aluminum and magnesium, the biohydrocarbons are used to produce greases and lubricating materials. When the raw material for intermediaries and auxiliaries are renewable, the processing sequence would be green and sustainable leading to a clean environment [32].

3 Enzymes for Bioprocessing

Enzymes are biocatalysts made up of protein molecules that have specific functions depending on their complex structure. Enzymatic reaction takes place in a specific part of the enzyme called the active site the remaining parts of which act as a support framework. The amino acids of the protein molecules in the active site get attached to the substrate while the reaction takes place. Thus the enzyme is target specific as the other molecules in the enzyme will not fit into the active site due to incorrect shape.

In a reaction catalyzed by enzymes, the substrate gets attached to the active site to create an enzyme–substrate (ES) complex. The product formed is released thereby leaving the enzyme free for the next substrate molecule. The conditions inside the active site including pH, water concentration, and charge, are made congenial for the reaction to take place. These conditions are quite different from the environment outside the active site.

During enzyme reaction the substrate with higher energy will be converted into the product with lower energy levels to bring about equilibrium. It is always essential for the substrate to overcome the activation energy before it changes into the product. When the activation energy is large, the rate of reaction will be slow. However, the biological reactions that have large activation energies are quickened with the help of enzymes. In a reaction enzymes reduce the activation energy so that the kinetic energy of the molecules proceeds with the reaction.

There are many factors that affect the rate of enzyme reactions such as temperature, pH, enzyme concentration, substrate concentration, and inhibitors. Enzymes work best at optimum temperature. Because the enzyme and substrate molecules have more kinetic energy they collide more often, and a large number of molecules have sufficient energy to overcome the activation energy. pH is an important factor that affects the activity of the enzyme. Inappropriate pH affects the charge of the amino acids at the active site, so the properties of the active site change and the substrate can no longer bind. The enzyme concentration and substrate concentration are very important for the activity of the reaction. As the enzyme concentration and substrate concentration increase the rate of the reaction also increases, because there are more enzyme molecules creating more active sites available to catalyze the reaction. Therefore more enzyme–substrate complexes form. At higher concentrations adding more substrate does not make much difference, as the enzyme molecules become saturated with substrate, and there are few free active sites.

Inhibitors inhibit the activity of enzymes, reducing the rate of their reactions. They may be competitor, noncompetitor, or feedback type. A competitive inhibitor molecule has a similar structure to the substrate molecule and hence it can fit into the active site of the enzyme thereby competing with the substrate and slowing down the reaction. A noncompetitive inhibitor molecule is different in structure from the substrate and does not fit into the active site. It binds to another part of the enzyme molecule, changing the shape of the whole enzyme, including the active site, so that it can no longer bind substrate molecules. The feedback inhibitor works by regulating the reaction pathway. The activity of some enzymes is controlled by certain molecules binding to a specific regulatory (or allosteric) site on the enzyme, distinct from the active site. Different molecules can either inhibit or activate the enzyme, allowing control of the reaction rate. They are generally activated by the substrate of the pathway and inhibited by the product of the pathway, so the pathway is used only when it is needed. This process is known as feedback inhibition [33].

3.1 Amylases

After the fabric is woven the size material should be removed for further processing of the textile. The process of removing the size material from the woven fabric is known as desizing. During enzymatic desizing, certain starch degrading enzymes such as amylases are used to reduce the molecular weight of amylose and amylopectin molecules of the starch. This makes the starch water soluble and it is removed by a washing process. According to the type of sugars produced the starch hydrolyzing enzymes are classified as α-amylases, β-amylases, and iso-amylases. The most commonly used amylase for industrial processes are from filamentous fungal and bacterial sources [34].

Starch is made up of a mixture of two polymers namely amylose, a linear polymer, and amylopectin, a branched polymer. In amylose, several thousand glucose molecules form the linear polymer which is made up of glucose residues joined by an α-1,4 glycosidic bond. In amylopectin, the branched polymer has glucose residues joined by either the α-1,4 or α-1,6 glycosidic bond. The source of starch will determine the proportion of the two polymers. A combination of α-amylases, β-amylases, and iso-amylases will help in the complete removal of the starch molecules. These amylases are further classified as endo-acting and exo-acting enzymes. α-amylases are endo-acting and hydrolyze linkages randomly in both amylose and amylopectin, creating linear and branched oligosaccharides. Starch is degraded to shorter polymeric fragments called dextrins and maltose which are disaccharide and contain two glucose residues. In the case of β-amylase and iso-amylase they are exo-acting enzymes and attack the substrate from the nonreducing end, producing oligo- or monosaccharides [35].

3.2 Pectinases

A group of enzymes called pectinases are used for the degradation of pectic substances. Pectic substances are polysaccharides present in plant cell walls in the middle lamella region. Pectin-degrading enzymes are referred to as pectic enzymes and include pectolyase, pectozyme, and polygalacturonase. Pectin is a jellylike substance that unites the plant cells. Cellulose fibrils are embedded in this substance. Polygalacturonase is the commonly used enzyme that involves the degradation of plant materials.

An efficient enzyme which belongs to the family of pectinases is the enzyme pectate lyase. It facilitates the hydrolysis of pectins which are the salts of polygalacturonic acids in the primary wall matrix. In the biopreparation bath, the enzymes hydrolyze the biological cement, pectin, and the noncellulosic components of the primary wall are released and emulsified by the surfactants and mild chelating agents. The enzymatic hydrolysis of pectin in cotton fiber primary wall with alkaline pectate lyase is shown in Fig. 6. This enzyme works in alkaline conditions therefore it is beneficial for pretreatment processes. The loss percentage in weight and strength is lower when compared to conventional scouring. Only a small amount of wax present in the fiber is reduced, creating a good feel and hand [36].

3.3 Catalase

Bleaching is a process of removing the natural color and imparting whiteness to the material. The commonly used bleach is hydrogen peroxide. The efficiency and evenness of dyeing is dependent on the complete removal of the bleach before dyeing. Extensive use of water and energy is avoided by the use of catalase enzyme. The enzyme breaks the hydrogen peroxide to nonreactive molecules of oxygen and water under mild temperature conditions.

$$2\mathrm{H_2O_2} \xrightarrow{\text{Catalase}} \mathrm{O_2} + 2\mathrm{H_2O}$$

.

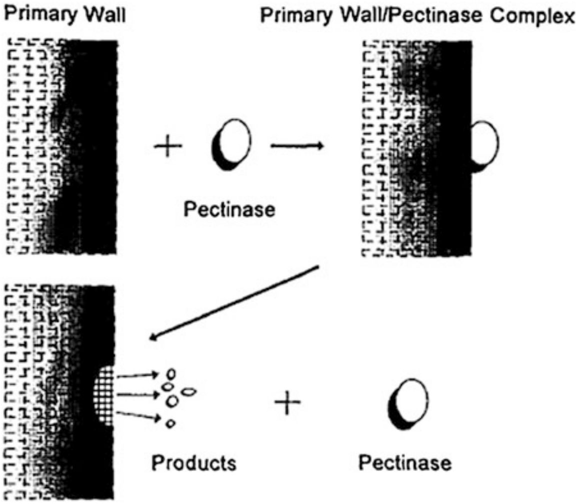


Fig. 6 Schematic of enzymatic hydrolysis of pectin in cotton fiber primary wall with alkaline pectate lyase [36]

The activity of the enzyme is 10 KCIU/g. One KCIU activity unit (kilo catalase international unit) is the amount of enzyme that breaks down 1mM of hydrogen peroxide per minute under standard conditions, namely 50 °C, pH 7.0, 10 mM H_2O_2 [37].

3.4 Proteases

Wool is a protein fiber that is hydrophobic in nature. This is due to the fatty acids in the epicutical surface membranes and the impurities such as wax and grease. Alkaline scouring using sodium carbonate, pretreatment using potassium permanganate, sodium sulphite, or hydrogen peroxide treatment is undertaken to remove these substances. Another disadvantage of wool fiber is the tendency to felt and shrink on wet processing. The small particle size of the protease enzyme facilitates entry into the fiber cortex causing damage to the fiber. Microbial transglutaminases (MTG) are a group of thiol enzymes that prevents damage caused by the protease enzyme. They catalyze the posttranslational modification of proteins by protein-to-protein cross-linking through the covalent conjugation of polyamines, lipid esterification, or by the deamidation of glutamine residues. MTG can catalyze acyl transfer by forming covalent crosslinks among proteins, peptides, and primary amines. This leads to an increase in protein stability and resistance to chemical and protease degradation. Moreover, they do not require calcium for activity and have a broad substrate specificity with low production cost. These properties are advantageous for industrial applications.

Transglutaminase-treated wool shows shrink resistance, tensile strength retention, handle, softness, wettability, and consequently dye uptake, as well as reduction of felting tendency and protection from the use of common detergents. Research and development in the application of these enzymes on leather and wool is underway [38, 39].

Cysteine proteases help in the hydrolysis of many compounds and can be divided into exopeptidases (e.g., cathepsin X, carboxypeptidase B) and endopeptidases (papain, bromelain, ficain, cathepsins). The peptide bond proximal to the amino or carboxy termini of the substrate is cleaved by exopeptidases whereas endopeptidases cleave peptide bonds distant from the N- or C-termini. Papain is the best-known cysteine protease that can cleave various peptide bonds and, therefore, have fairly broad specificity. Papain is used for the cocoon boiling and degumming of silk to remove the sericin, a proteinaceous substance that covers the fiber. Papain is also used to shrinkproof wool fabric [39].

3.5 Cellulase

The cellulose enzyme is produced by fungi embedded in soil and bacteria. This multicomponent enzyme is classified into three types depending on the activity range as acid cellulases, neutral cellulases, and alkaline cellulases. Acid cellulases work efficiently in pH lower than 7, whereas alkaline cellulases are active in a pH above 7. Endoglucalases (EGs) and cellobiohydrolase (CBHS) cellobiases are the active components in cellulases. The activity of the enzymes consist of three major steps, namely:

(1) Endoglucanases or β-1,4-glucanohydrolase: The endoglucanases attack the amorphous regions of the cellulose chains and randomly hydrolyze the cellulose polymers present along the chains which affects the interior of the polymer to generate new ends.
(2) Exoglucanases or β-1,4 glucan cellobiohydrolase: Here cellobiose is released by the action of exoglucanases on the nonreducing ends of the polymer chains.
(3) β-Glucosidase: The cellobiose formed in the previous stage is hydrolyzed into glucose by the action of β-glucosidase.

Cx
|
G—G—G—G - - G - - - - - - - - - G—G—G—G—G ----------- (1)

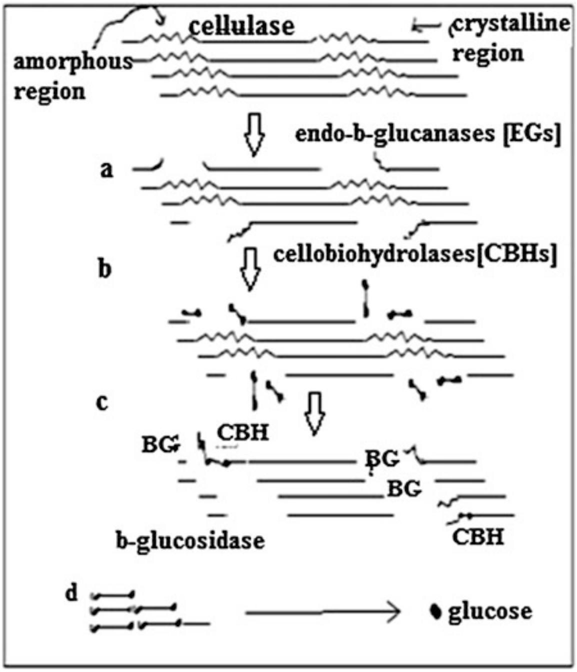
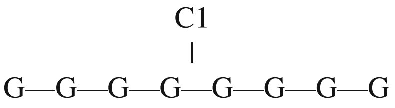
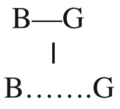


Fig. 7 Synergistic action of cellulase enzyme [40]



$$G—G—G—\overset{\substack{\text{C1}\\ |}}{G}—G—G—G—G \qquad \text{------------} \ (2)$$



$$\begin{array}{l} B—G \\ \quad\ | \\ B\ldots\ldots.G \end{array} \qquad \text{------------} \ (3)$$

The three components of cellulase, endoglucanases, exoglucanases, and β-glucosidase work in harmony to convert cellulose to glucose. This is represented diagrammatically in Fig. 7. The β-glucose residues in the cellulose molecules are connected by the oxygen link called the 1,4-glucoside linkage. This link is formed by glucose condensation due to the elimination of water molecules in the cellulosic fiber. The cellulase enzyme acts on the 1,4-linkage of the glucose residues located in the cellulose molecules through catalytic reaction. By hydrolysis of this linkage, the long cellulose chains are converted to smaller chains which are further reduced to glucose [40, 41].

3.6 Laccases

Laccases (EC 1.10.3.2) are blue oxidase enzymes containing copper commonly found in plants, fungi, and microorganisms. This enzyme is dependent on oxygen as a second substrate for the enzymatic action. To detect laccases spectrophotometry is used with substrates such as ABTS, syringaldazine, 2,6-dimethoxyphenol, and dimethyl-p-phenylenediamine. The enzyme activity can be observed with the help of an oxygen sensor inasmuch as the oxidation of the substrate will occur by the reduction of oxygen to water. There are four copper centers that create monoelectronic oxidations of the substrate catalyzed by Type 1 copper. The transference of electrons from Type 1 copper to the trinuclear cluster of Type 2 and Type 3 copper brings about the reduction of oxygen and the release of water without the generation of toxic intermediaries. Nonenzymatic reactions such as ring cleavage of aromatics, crosslinking of monomers, and degradation of polymers can work on the oxidation products [42].

Laccase enzyme can decolorize many compounds making it a versatile biocatalyst for many applications especially in the field of dyeing and wastewater decolorization. It reacts with the insoluble indigo dye through a mediator compound, when electrons from the indigo dye are transferred to oxygen causing the cleavage of the double bond between the carbonyl groups of the indigo dye. Decolorization occurs due to the destruction of the dye chromatophore. Generally, textile dye effluents contain all types of dyes and auxiliaries in different combinations and successful decolorization of the effluent is a difficult task. A biodecolorization system that can maintain its activity upon contact with various dyes is essential. The oxidation of both phenolic and nonphenolic compounds can be performed with the help of laccase enzymes leading to the mineralization of a wide range of synthetic dyes. Thus laccase enzymes serve as a useful biological tool for several textile applications that would otherwise be very polluting in nature [43].

4 Innovative Biotextiles

Technical textiles have become an emerging area and these developments are due to the technological improvements and research that has been undertaken in this sector. Technical textiles represent 40 % of the entire textile production and the innovation aspect makes them the futuristic trends in the fast-growing textile industry. This field calls for the interdisciplinary conglomeration of diverse scientific fields that contribute to engineer several functions into one fabric which has endless applications in all walks of life. Technical textiles have become a vital part of industries including car manufacture, space technology, agriculture, and biomedical technology [44–46].

The role of biotechnology in producing these innovative textiles is extensive. The range of products may be wound dressings, marquee fabrics, or clothing for special technical applications. In all cases, biotechnology plays a major part in product development and intermediate processes. Taking nature as inspiration many micro and nano products have been developed with the integration of several disciplines such as nutrition sciences, environmental technology, and the textile industry. Many innovative projects have been developed by the collaboration of biotechnology with the textile industry [47, 48].

4.1 Medical Textiles

The medical field has many innovative materials and applications that may range from simple wound dressings to complex tissue engineering techniques and implants. Many biologists and engineers combine their ideas and develop highly technical biomaterials and implants and methods of making them compatible with the human body. A good example of this feature are the three-dimensional fleeces which promote the growth of cartilage cells of the patient. Textile implants refined with a touch of biotechnology will help to inhibit the wear and tear of bones and cartilage or help in the growth of the bones suitable for dental implants. Hence textiles provide the medium and biotechnology provides the technology for the development of medical textiles [44–46].

Many medical implants including vascular prosthesis, heart valves, and sutures use polymer materials proving to be great achievements in the surgical field. The most important issue in tissue regeneration is the controlled revascularization of epidermal tissue which requires naturally occurring porous polymeric supports on which the cells are seeded with the required factors for growth. In vitro growth of biological tissue can be performed by the use of textile materials as scaffolds. Thus tissue engineering forms an integral part of biotechnology [21]. Products such as composite mesh with absorbable and nonabsorbable barriers for intraperitoneal placement, macroporous mesh, and xenogeneic and allogenic biological meshes are some of the unique implants developed for tissue engineering [49].

In general and clinical practice there are many patients with vascular diseases encouraging surgeons to work closely with medical technologies and textile industries to develop artificial biomedical products for patients. Considerable diagnostic and therapeutic advances have given rise to the technology of prostheses that uses artificial biomedical tools such as biotextiles, or synthetic materials or parts used to replace body parts. This makes the natural replacement of defective body parts or transplantation obsolete. While performing grafting, the major problems associated with conventional ePTFE is suture hole bleeding and sweating which has been addressed by the use of a biomedical sealant. Sulzer Vascutek's hydrolyzable gelatin (water soluble protein) sealant called SEAL-PTFE$^{\mathrm{TM}}$, is used to coat and seal the external surface of the graft preventing suture hole bleeding and sweating and excellent handling properties may be achieved with antibiotic bonding [50].

4.2 Healthcare Textiles

The role of fabrics with antibacterial and antiviral mechanisms are currently important to arrest infection and diseases. These mechanisms are considered essential in hygiene products used by many consumers. Many products such as antiviral towel rolls and antibacterial products are used in hospitals and hotels [44]. It has been reported that enzymatic pretreatment combined with the simultaneous deposition of biopolymers and nanoparticles under ultrasonic irradiation, have helped in eliminating infectious organisms from textiles used for medical applications. Furthermore these fabrics have improved adhesion of the antimicrobial nanoparticles and durability of the finish has been tested for 70 laundry cycles. These fabrics serve to fight nosocomial infections and hospital-acquired infections which are a major challenge facing hospitals. This research work has been carried out by scientists at the Universitat Politècnica de Catalunya Barcelona Tech (UPC) in Spain [51]. Another report states that antibacterial textiles for hospitals have been developed with the help of zinc and chitosan nanoparticles, enzymes, and ultrasound. This research serves to develop medical antibacterial textiles that prevent infections due to hospital gowns and sheets of hospital beds [52].

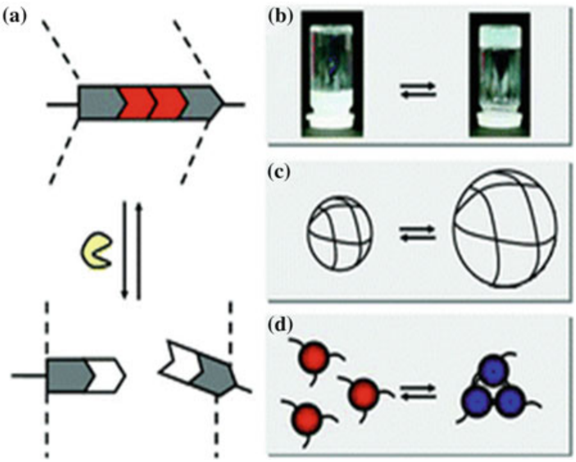
4.3 Intelligent Textiles

This segment of innovative textiles is multidisciplinary and requires expert knowledge from many fields. Intelligent textiles are those incorporating microsystems that help to measure and observe vital parameters such as blood pressure, pulse, or breathing [45, 46]. Other applications include sports and leisure wear that require thermoregulation based on incorporation of phase-change materials. The use of shape-memory materials for medical textiles and protective clothing is bringing about special functionalities to textiles. In an environment of extensive heat, these systems protect the body from getting overheated. In very high temperatures the shape-memory materials in the apparel produce an insulating layer by returning to their original shape. These textiles are used for uniforms of motor racing and gasoline pump attendants, and fire brigades, among others. Enzyme-catalyzed functionalization of fibers and immobilization of enzymes are two techniques that help in producing specialty fibers with unique functional characteristics [53].

4.3.1 Enzyme Responsive Materials

A class of materials that respond to stimulus and have a wide range of applications in biological settings is known as enzyme responsive materials (ERMs) [54]. These smart materials are highly sophisticated and undergo macroscopic

Fig. 8 Enzyme responsive action [55]



transitions by the activation of selective catalytic actions of enzymes. Extensive and new applications in the field of biology and medicine are possible through the use of enzymes as stimuli to generate a series of mechanical responses as shown in Fig. 8. The prospective applications are in the areas of regenerative medicine, diagnostics, and drug delivery. Based on technologies of supramolecular assemblies, chemically crosslinked gels, and (nanoparticle) surfaces, ERMs are divided into three different classes [55].

Over the past decade tremendous growth has been evident in the fundamental research of responsive polymers that are widely used in fields ranging from drug or gene nanocarriers, imaging, diagnostics, smart actuators, and adaptive coatings, to self-healing materials. A lot of research and experimentation has been undertaken in developing EMRs as per the end use. All living organisms and soft matter are susceptible to respond and adapt to external stimuli. This fundamental principle has formed the base of generating responsive polymers that undergo changes in chemical structures or physical properties that may be reversible or irreversible. These changes occur in response to specific signal inputs such as pH, temperature, ionic strength, light irradiation, mechanical force, electric and magnetic fields, and analyte of interest (e.g., ions, bioactive molecules) or a combination of them. The most favorable tool for triggering responses and reactions are enzymes and they have been used to design many special responsive polymers. Enzymes are an integrated part of all biological and metabolic processes of living organisms. The reactions catalyzed by enzymes are very selective, substrate specific, and work efficiently under mild conditions. The combination of enzyme-catalyzed reactions with responsive polymers opens a new opportunity for design flexibility and wide applications by equipping the responsive polymers with specific and selective triggering ability. The applications in the areas of drug controlled release, biocatalysis, imaging, sensing, and diagnostics is possible by using three different types of systems, namely enzyme-triggered self-assembly and aggregation of synthetic polymers, enzyme-driven disintegration and structural reorganization of polymeric assemblies and nanoparticles, and enzyme-triggered sol-to-gel and gel-to-sol transitions.

Enzyme-responsive biomaterials are very useful in the fields of regenerative medicine, diagnostics, and drug delivery. Because they respond to a biological signal they could be used in medical devices that release drugs on receiving a biological signal from a living cell. These materials function by detecting, responding, and ultimately mending biological processes. The first steps in engineering bioresponsive materials is to exercise control of the flow of molecules into and out of polymer particles by using specific enzyme controls and to mimic the in vivo feedback systems that control enzyme activity to enhance the response of these materials [56].

When transition of biopolymers occurs from one state to another based on the environment and requirement, they are termed as pH-sensitive and thermosensitive smart polymers. At the University of Washington, United States, researchers have developed a clever way to use smart polymers that provide size-selective switches to turn proteins on or off. If the smart polymer chain is attached to the protein molecule farther from the active site, the extended polymer chain would shield the side and prevent attachment of the macromolecule. However, when the polymer chain is coiled there will be no blockade for the macromolecule to bind with the active site. Such polymers could act as a kind of shield or molecular gatekeepers that regulate based on the size and kind of molecules that bind with the active site. Bioengineers could use this technology to control the functions of the proteins and design powerful diagnostic and sensing devices for medical applications [57, 58].

4.3.2 Biosensors

A device that identifies and quantifies chemical constituents of a substance (water, food, blood, or urine) from a sample is known as a biosensor [59]. They are diagnostic devices that integrate a biological or biologically derived material within a physicochemical transducer or transducing microsystem [32]. A bioassay or a bioanalytical system is different from biosensors in terms of requirement of additional processing steps such as reagent addition and construction of the device by permanent fixation of assay design [60]. The need for monitoring processes and a consciousness for better environmental control has motivated the development of biosensors to provide fast, reliable, and sensitive measurements with lower cost at on-site analysis.

Luminescent bacteria, *Vibrio fischeri*, are used to measure toxicity or biological impact from environmental samples such as water or soil. Measurement of cellular metabolism and assessment of toxic chemicals in aquatic samples is made possible by bacterial bioluminescence. Currently bioassay methods are integrated in biosensors, for example, Cellsense®. These are amperometric sensors that detect ions in a solution based on the electric current or changes in electric current. This sensor incorporates *Escherichia coli* bacterial cells for rapid ecotoxicity analysis. The electrons from the respiratory system of the immobilized bacteria of a suitable carbon electrode are diverted by applying a soluble electron mediator such as ferricyanine. The resultant current is a measure of bacterial respiratory activity, and change in the magnitude of the current indicates the agitation by pollutants [61].

The application of microbial capability to transform complex organic molecules into simpler inorganic constituents is known as bioremediation. There are many parameters that influence the growth of bacteria such as nutrient availability, metal ions, pH, dissolved oxygen, and temperature. Biosensors use the luciferase expression system to monitor these parameters for better control of the bioremediation process. The biological component in this molecular biosensor is a recombinant plasmid in which a foreign DNA fragment has been inserted. This also has an aspecific promoter, whose expression is sensitive to a target molecule. Biosensor-based methods can be used for the quick measurement and quantification of many substances, for example, BOD measurement. The biosensor consists of a microbial film centered between a porous cellulose membrane and a gas-permeable membrane as the biological recognition element. This film can bio-oxidize the organic substrate to be measured. A change in the concentration of dissolved oxygen or any other phenomenon such as light emission is taken as a response [62]. An amperometric sensor for measuring dissolved oxygen is used for measuring the bacterial respiration rate in close proximity to a transducer [61].

4.3.3 Novel Biocatalysts for Specific Applications

The development of biocatalysts to face special environments and the tailoring of efficient biocatalytic processes are the need of the hour for sustainability in industrial manufacturing. The biocatalytic processes in manufacturing include textile pretreatments, synthetic fiber modification (hybridization), and functionalization and biocatalysts such as extremozymes are able to withstand high temperatures, pH, and oxidative conditions in areas including fiber spinning and conventional textile wet processing. Some of the novel biocatalysts include those with specific on–off control for future processes and products based on functionalization of surfaces of textile membranes. Surface coating used as a tool for biofunctionalization of the existing range of synthetic and natural fiber substrates reduces the maturity time of new, customized functionalities such as moisture management and thermoregulation, breathability, self-cleaning, stain removal, wellness, and healthcare. This is based on regenerated protein, a combination of silk–wool protein-based systems and graft copolymerization of functional monomers onto fibers that have been initiated with enzymes [53].

4.3.4 Functional Finishes with Enzymes

An alternative to conventional finishing methods is functional coating methods that have many advantages such as not being affected by fabric type, use of low quantities of additives, and flexibility to make combinations of different

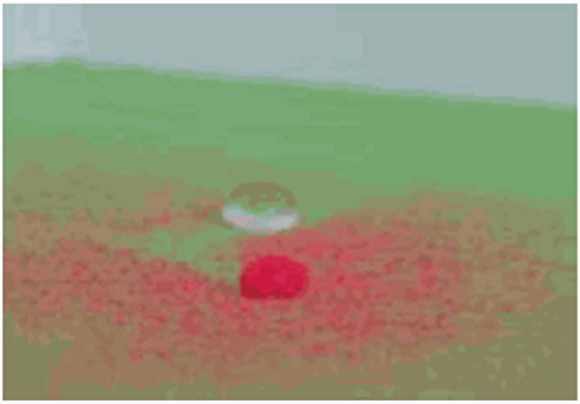


Fig. 9 Lotus effect finishes (*Source* BIOPRO)

functionalities in a simple manner. Some of the technologies include immobilization of enzymes, layer-by-layer assemblies, and nanocoatings. The permanent attachment of the enzyme to the textile substrate, so that it continues to catalyze the intended reactions again and again is known as enzyme immobilization. Wang et al. reported that the immobilization of lysozyme enzyme on wool with covalent bonds showed good antimicrobial effect against *S. aureus*. Immobilized preteolytic enzymes trypsin, lysosome, and lysoamidase on cotton, wool, and other dressings were found to be effective in healing wounds. The methods used for immobilization of the enzyme are adsorption, covalent bonding, entrapment, encapsulation, crosslinking, and nanocoatings. This concept reduces enzyme cost and provides a permanent bioactive textile substrate. The next technique is layer-by-layer assembly. In order to build a series of polyelectrolyte multilayer films on the substrate oppositely charged polycations and polyanions are sequentially adsorbed to form a layer-by-layer assembly. Functional molecules such as charged nanoparticles, dyes, and enzymes can be incorporated into the layers in a controlled manner to produce functional finishes on fabrics by using such assemblies [63]. Nano coatings get their inspiration from nature. Nature has come up with surfaces to which dirt is unable to attach due to complex micro and nanostructures. The self-cleaning effect of hydrophobic micro- and nanostructured plant surfaces was discovered and clarified by W. Barthlott at the University of Heidelberg in 1975. This is known as the "lotus effect" and is incorporated into textiles for outdoor clothing and marquees in retail stores. The lotus effect finish is presented in Fig. 9. Apart from these applications it is also useful in the medical field [64].

4.4 Packaging Textiles

Polylactide (PLA) is an innovative material from plant sources. It is commonly used in biodegradable catering dishes and packaging. Polylactide is a popular material used by apparel manufacturers for high-performance clothing and technical textiles.

PLA are fibers made from plant carbons when compared to nylon and polyester fibers which are made from nonrenewable petrol. PLA uses carbon that is absorbed by maize plants during photosynthesis from the air [45, 46].

5 Biotechnology for Sustainable Textiles

An ideal tool that reduces energy and material consumption and minimizes the generation of waste and emissions is modern biotechnology. Industrial biotechnology uses microorganisms and biological catalysts (enzymes) to produce clean industrial products and processes that will bring great benefits to industry over the next decade. Regulations are expected to intensify for both textiles and leather manufacture and the industries have to focus their attention on using less polluting technologies that generate less waste. Use of enzymes for a wide range of textile applications has been enhanced only in the past decade. Biotreatment in fiber preparation, pretreatment, and value-added finishing processes greatly affect effluent quality and cause reductions in effluent load. Savings will also be achieved in energy and water as enzymes are target specific and will work in mild conditions [32, 47].

The central feature of living systems is the facilitation of chemical reactions by catalytic proteins (enzymes). With protein engineering, enzyme-improved characteristics of specificity, selectivity, stability, and performance are being produced. The use of microbial enzymes in many other areas of the textile industry replacing existing chemical or mechanical processes is inevitable. Enzymes have been used in starch size removal by amylases, removal of hydrogen peroxide prior to dyeing by catalase, removal of fuzz from the surface of cellulosic fibers, and stonewashed effects by cellulases. The requirement for optical activity of chemicals such as polymer precursors is likely to grow.

The biocatalytic transformation of one chemical to another is defined as biotransformation. Certain cells, an extract from such cells, or an isolated enzyme may be used as the catalyst system of a specific reaction. The concentration of individual enzymes in cells is less than 1 %; gene amplification techniques can increase this percentage. Biotransformations will slowly overcome the production of bulk chemicals by oil-based processes and will transform the industrial processes into greener ones. The requirement for optical activity of chemicals such as polymer precursors is likely to grow and here the biotransformation route will rule over traditional chemical methods [18].

5.1 Enzymatic Desizing

In the textile industry fabrics made from cotton or blends require coating the warp threads with an adhesive substance known as “size” to lubricate and protect the yarn from abrasion and prevent the threads from breaking during weaving. After weaving, the sizing agent and natural noncellulosic materials present in the cotton must be removed in order to prepare the fabric for dyeing and finishing. Amylase is a hydrolytic enzyme that catalyzes the breakdown of starch to sugars, dextrin, and maltose. An amylase enzyme can be used for desizing processes at low temperature (30–60 °C) and optimum pH is 5.5–6.5. The enzyme is starch specific and does not affect the other components of the fabric [65].

Although many compounds have been used to size fabrics, starch and its derivatives are commonly used owing to good film-forming capacity, availability, and relatively low cost. After weaving the size and natural noncellulosic materials present in the cotton are removed to make the fabric suitable for the following processes such as dyeing and finishing. Desizing used to be carried out by treating the fabric with acid, alkali, or oxidizing agents at high temperatures but the process was not effective in total removal of starch causing imperfections in dyeing and degradation of the cotton fiber. Amylases are commercialized and used extensively in pretreatment due to many advantages including high efficiency and specificity, and complete removal of the size without any harmful effects on the fabric. The starch is randomly cleaved into water-soluble dextrins to be removed by washing. The added benefits were reduction of the discharge of waste chemicals as effluent and improved working conditions [66].

5.2 Bioscouring

The use of pectinases as agents for scouring cotton was quite popular but much research was focused on optimization of the conditions of their activity. Many conditions were important in the performance of the enzymes such as concentration of the enzymes in the bath, time and temperature of treatment, pH of the bath, additives, and the mechanical treatment. In addition to the above, the pH of the environment is crucial for the activity and stability of the enzyme which ranges between 5 and 9. An alkaline or acidic environment depends on the type of pectinases. Acidic pectinases function in a slightly acidic medium (pH between 4 and 6) and alkaline pectinases function in a slightly alkaline medium (pH between 7 and 9). In acidic medium the pectin structure degrades without adding the pectinases which results in better functioning of the acidic pectinases over the alkaline pectinases. Care must be taken to monitor the pH as extreme values lead to the three-dimensional form of the enzymes collapsing and the enzymes losing their catalytic behavior.

A nonionic surfactant and a sequestering agent help in the smooth functioning of the scouring process. Pectin acts as a type of cement or glue that stabilizes the primary cell of the cotton fibers. During scouring with enzymes, a complex is formed between the pectinase and the pectin that causes the hydrolysis of the pectin substances leading to the hydrolysis of the pectin substances. The result of hydrolysis is a split of the bond between the cuticle and the cellulose body. The outer layers are destabilized and removed in the following procedures of rinsing. The enzymes are released to bond again with the pectin. The procedure is continuously repeated until the enzyme is destroyed chemically, with the change in pH or in the temperature. Removal of pectin and other noncellulose substances results in softer fibers with a low whiteness index when compared to conventionally scoured cotton with enzymes inasmuch as seed-coat fragments are not completely removed. Advantages such as a higher quality of the fibers which are softer to touch, better strength, less wastewater, economy of energy, and compatibility with other procedures, equipment, and materials has made enzyme scouring commercially suitable for the industry.

Bioscouring is simple, repeatable, and safe and can be recommended as a standard procedure to the textile industry. The removal of pectin and noncellulosic components from cotton improves the water absorbency of the fibers and helps in the penetration of the dye and other substances into the fiber. Bioscouring can also be used for blends of cotton and silk, wool, and cashmere as the fibers are less damaged. The effluent is less harmful as the load is comparatively lower than the conventional sodium hydroxide scouring pretreatment which results in a highly toxic effluent [18, 67].

5.3 Biobleaching and Biobleach Cleanup

Scouring is regularly followed by a bleaching process, which removes the natural coloration of cotton fibers. Cellulose fibers are bleached with hydrogen peroxide (HP) resulting in high uniform degrees of whiteness and increased water absorbency. However, during the decomposition of hydrogen peroxide, radicals formed cause damage to the fibers. For this reason, organic and inorganic stabilizers and chelators are added to the treatment bath. Hydrogen peroxide (redox potential is 1.78 eV) (1) is ecologically friendly but the large amount of water used to rinse and neutralize the alkaline scoured and peroxide-bleached textiles is ecologically disputable. The bleaching process is conducted in an alkaline bath at pH 10–12 and at temperatures ranging from 90 to 120 °C. Due to the high working temperature, a large amount of energy is consumed. Auxiliary chemicals added into the bath increase the TOC and COD values of effluents. On neutralization of the alkaline waste baths, large amounts of salts are produced. Consequently, the textile industry is considered one of the biggest water, energy, and chemical consumers. Enzymes such as glucose oxidases produce hydrogen peroxide in water solutions in the presence of glucose from oxygen dissolved in water. The degree of whiteness attained in this procedure is lower than the degree of whiteness of the fibers bleached in a classic procedure with hydrogen peroxide. Peracid bleaching can be used as an alternative to hydrogen peroxide bleaching when a medium degree of whiteness is required. Cotton fibers bleached with peracetic acid have good water absorbency, the fibers are not damaged, and the effluent is biodegradable [18].

After the bleaching process peroxide remains in the pretreatment bath and has to be removed before the fabric is to be dyed. The residual peroxide in the bath interacts with the dye molecule and changes the dye shade, causing uneven dyeing. Conventionally, residual peroxide removal has been performed using several sequential rinses with abundant water or by using reducing chemicals such as bisulphite to break the peroxide. The use of a catalase enzyme breaks down hydrogen peroxide into water and molecular oxygen as shown below

$$H_2O_2 + \text{Catalase} \longrightarrow H_2O + O_2$$

The specificity of the catalase enzyme makes the process more sustainable, as no treatment procedure is required .to clean the bath after catalase bleach cleanup is performed. Moreover, there is reliability in peroxide removal ensuring consistency for subsequent dyeing. Savings in total process cost, reductions in water consumption, and wastewater disposal have made the use of catalases one of the most popular enzyme applications in textiles in recent years [53].

5.4 *Biofinishing*

The use of cellulase enzyme for denim stonewashing and biopolishing of garments and fabrics in the textile industry has been carried out for the past two decades. Initially products were based on the natural ability of certain microbes to degrade cellulose but the growth environment of these microbes showed that a wide variety of proteins are formed that work in several ways to break down cellulose. Modern biotechnology has various tools with which scientists could create new, better enzymes for specific applications. This concept has created a new generation of cellulase products containing different kinds of protein molecules or molecule blends contributing to improved performance features.

Different combinations of the components in cellulase enzyme have been created with biotechnology tools to create new products such as enriching endoglucanase activity, removal of exo-acting cellobiohydrolase activity, or tailoring enzymes with a single type of cellulase molecule. Choosing the right type of enzyme is essential to optimize the cellulose enzyme on a certain fiber type as different fabric types have varying susceptibility for cellulase hydrolysis. Most denim garments are given their worn look using cellulases, either alone or in combination with a reduced amount of stones. The action of cellulases involves loosening the surface fibers of denim for mechanical action in a washing machine which enhances the breaks on the surface to remove the indigo dye to reveal the white core of the ring-dyed yarns. The benefits of this process have been increased washing capacity for the laundries, reduced damage to garments and washing machines, and diminished environmental effects from pumice stone mining and disposal [68].

Table 1 Types of enzymes and their effectiveness against various stains

Enzyme	Effective for
Proteases	Grass, blood, egg, sweat stains
Lipases	Lipstick, butter, salad oil, sauces
Amylases	Spaghetti, custard, chocolate
Cellulases	Color brightening, softening, soil removal

A peach skin treatment involves fibrillation resulting in a soft and smooth fabric surface and biopolishing can be used to clean up the fabric surface prior to a secondary fibrillation process. The peach skin treatment imparts interesting fabric aesthetics and the cellulase enzyme is highly suitable for viscose, modal, and Tencel fabrics. The process time may be 30–40 min and enzyme action is terminated using a high temperature or low pH. A weight loss of 3–5 % is common but reduction in fabric strength can be controlled to within 2–7 %. The entrapment of the fiber residues inside the tubular cotton knitted fabric instead of being washed away is a problem to be addressed [69].

The decolonization of denim has been facilitated by a group of enzymes called laccases, or phenol oxidases. They have the ability to catalyze the oxidation of a wide range of phenolic substances such as indigo dye. Basically laccases are not effective as bleaching agents but require a mediator molecule which is the actual substrate of the laccase. In conjunction with the mediator molecule, laccase helps in the electron transfer from indigo dye to molecular oxygen. Laccase-mediator systems have been used to bleach indigo, enhance abrasion levels, and reduce back staining [66, 68].

5.5 *Textile Aftercare and Wastewater Treatment*

Enzymes have been used in detergents ever since 1960. This trend has increased drastically and washing powders are referred as “biological” because they contain enzymes. A wide range of enzymes are now available that can degrade many types of stains; their use saves energy and protects the fabric as washing is performed in milder washing conditions at lower temperatures. Some of the major classes of enzymes and their effectiveness against common stains are summarized in Table 1.

The use of advanced granulation technology has addressed the early problems of allergic reactions associated with the use of enzymes. The use of sodium perborate in detergents has been reduced by 25 % and the release of salts into the environment has also been curtailed after enzyme adoption in the detergent formulation process. However, enzymes have to make a corresponding impact upon the commercial laundering market which causes a considerable amount of pollution to environment. High investment costs in continuous-batch systems and tunnel washers cannot accommodate new concept machines. This washing equipment allows a residence time of 6–12 min which is not sufficient to fulfill the adequate performance of the present enzyme systems. Moreover, the methods of enzyme deactivation are not suitable because of the degree of water recycling in modern washers [21].

The extreme conditions of processing have given rise to a popular area of research to investigate enzymes that can tolerate or be activated in hot and cold temperatures. The search for thermotolerant and cryotolerant enzymes has been undertaken as they are desirable for improving laundry processes in hot water cycles and/or at low temperatures for washing colored and dark fabrics. They are also useful for industrial processes where high temperatures are required and for bioremediation under harsh conditions (e.g., arctic).

Technologies using different DNA techniques such as site-directed mutagenesis and DNA shuffling have contributed to form recombinant enzymes that are engineered proteins for special end uses [70].

The degradation of toxic wastes has entered a new perspective through the use of microbes or their enzymes. Color removal from dyehouse effluent and disposal of toxic heavy metal compounds and pentacholorophenol, are some of the hazards facing the textile industry which needs the attention of biotechnologists [16, 71]. Treatment of waste materials and effluent streams from the textile industry has been formulated using natural and enhanced microbial processes. In most cases conventional activated sludge and other systems are generally able to meet BOD and related discharge limits. Synthetic dyes have inherent characters that makes them resistant to microbial degradation under the aerobic conditions. Furthermore, their water solubility and the high molecular weight inhibit permeation through biological cell membranes. The organic contaminants in textile waste are converted to methane and carbon dioxide by anaerobic processes. These processes require less space and treat wastes containing 30,000 mg/l of COD with the benefits of lower running costs and the production of less sludge [21, 72].

Combinations of different enzymatic processes in the same bath will help streamline several processing stages and ultimately result in savings in the usage of time, energy, water, and cost. Some examples are given here.

- Combined bleach clean-up and dyeing: Using catalase enzyme the hydrogen peroxide is first removed, followed by dyeing in the same bath as the enzyme neutralizes the bleach and does not affect the dyes.
- Combined bioscouring and biopolishing: Using two different enzymes with overlapping temperature and pH profiles, one for bioscouring and other for biopolishing have produced a synergistic effect to give better results.
- Combined desizing and bioscouring: The pH and temperature profiles for these two products overlap and this allows for combining the processes of desizing and bioscouring in pad-batch conditions.

There are many problems in the textile industries and with new ecoregulations cropping up, an efficient remedial system is essential to opening new solutions. The focus is on improving the quality of bast fibers such as hemp and linen, wool, and even synthetic fibers; finding alternative ways of dealing with sizing agents other than starch; and evolving methods to break down dyestuffs in the effluents from dye houses and denim-finishing laundries. With this background and the need to move towards sustainable development, biotechnology can help the textile industries by providing useful solutions in the form of specially engineered enzymes tailored to meet the demands of the new process flows and sequences developed for the future goals of clean ecological processing [73].

6 Future Trends

The European federation of biotechnology has reported that to facilitate the technological applications of the potential of microbes and cultured tissue cells the integrated use of biochemistry, microbiology and chemical engineering is essential through biotechnology [21]. Industrial biotechnology is a conglomeration of biology, microbiology, biochemistry, molecular biology, chemistry, process engineering, and so on, and this can be a great strength as combining knowledge from different scientific disciplines can create unexpected results. To achieve innovation and sustainability, projects with members from multidisciplinary fields would help in the development of research. The textile industry, a major contributor to pollution, is a key sector for the application of biotechnology towards sustainability. The awareness is currently very low though the opportunities are high. Novel methods can be adopted in the textile industry for sustenance in the competitive world where eco-friendliness and clean technologies are of primary importance [19].

Some of the advanced techniques of biotechnology suitable for the textile sector are nucleic acid (DNA/RNA)-related technologies, protein/peptide-related technologies, metabolite-related technologies, and cellular and subcellular level related technologies.

6.1 Nucleic Acid (DNA/RNA)-Related Technologies

Sequencing of genome, gene, DNA, DNA synthesis and amplification, genetic engineering, and antisense technology are some of the technologies that come under this group.

- DNA, RNA, gene or genome sequencing is a process for formulating the nucleotide sequence of a DNA/RNA fragment/a gene/whole genome. The entire hereditary information of an organism encoded in the DNA, inclusive of the genes and the noncoding sequences make up the genome. A specific trait, condition, or disease brought through inheritance is due to genes that are definite regions of the genomic sequence. The information from DNA to the protein synthesis sites are encoded and carried by messenger RNA (mRNA). The study of the genome of an organism and the information contained in it, termed genomics, will help in understanding and manipulation of the genes. The study of the expression level of genes is called transcriptomics, measured either in one set of all mRNA molecules or in a cluster of biological cells for a specific set of environmental conditions. Toxicity of the cotton seed in the species Gossipium australe is due to the production of a harmful substance called gossypol. Tao et al. have reported that the transcriptome sequencing, differential gene expression analysis, and delayed gland morphognesis of the above variety of cotton has produced seeds with less gossypol making it less toxic [31].

- DNA sequencing involves the identification of genome structures called genomics mapping, the comparative analysis of gene sequences in order to find similar sequences and the prediction of protein structures. One of the main tools for high-throughput whole genome sequencing is microarrays. A DNA microarray is produced by using cellular mRNA to make segments of the complementary DNA. The complementary DNA (cDNA) segments are attached to a nylon or glass surface at known regions to hybridize into a sample DNA.
- DNA synthesis and amplification. The technique of reproducing a known sequence of nucleotides into genes or gene fragments through polymerase chain reaction (PCR) is called DNA synthesis. DNA amplification is the duplication of DNA sequences and is used to detect very small amounts of DNA. Specific techniques are used for the identification of individuals and for distinguishing between individuals of the same species using only samples of their DNA by genetic fingerprinting or genotyping. All these techniques will be able to identify the DNA in raw material which will help to improve the properties and also give more benefits to the manufacturers and textile industries whose process parameters are based on raw materials. In a patented study, DNA was extracted from a mature cotton fiber sample and subjected to polymerase chain reaction techniques that enable the identification of a particular cotton species utilized in the textile or cotton material of interest [30]. As each individual has a specific DNA profile, the PCR technique will be a good identification tool that will be useful in plant and animal breeding. Genes with significant effects can be specifically targeted in selection and detected by genome mapping.
- Antisense technology prevents the transcription of a DNA using antisense mRNA. The DNA is double stranded and when transcription takes place the sense strand of the DNA produces mRNA. The complementary strand of the DNA is termed antisense. Antisense mRNA is a RNA strand complementary in sequence to the mRNA. The presence of an antisense mRNA can inhibit gene expression by base-pairing with the specific mRNAs. This concept is used to assess the gene function of the particular gene by adding its antisense mRNA transcript. Raemakers et al. have reported the development of amylose-free improved cassava starch by antisense inhibition of granule-bound starch. This starch with improved functionalities is used for paper and textile manufacturing [55].

- Genetic engineering is a specialized tool in biotechnology that modifies organisms to optimize production of existing or new metabolites of industrial importance and for transferring genetic material called genes from one organism to another. An understanding of the responsibility of the genes in determining the characteristics and properties of a living organism and methods of isolating the DNA which carries the genetic code to manipulate them outside the cell, has given rise to new developments in tailoring properties into organisms. The next step would be to introduce fragments of DNA obtained from one organism into another, to transfer some of the properties of the first to the second. For example, scientists working for the leading enzyme producer, Novo of Denmark, discovered that an enzyme produced in minute quantities by one particular fungus had very desirable properties for dissolving fats. The relevant genes were spliced into another microorganism that was capable of producing the desired enzyme at much higher yield. The methods used in genetic engineering for the production and modification of textile fibers have been under extensive study. One approach in genetic engineering systems is to produce monomeric protein molecules in solution from appropriately engineered genes. These can be manifested in bacteria, cell cultures, or in the milk of transgenic animals such as goats or sheep. The protein monomers are then isolated from the system and may be spun or drawn into fibers. The other approach is to modify keratin fibers such as wool by expressing other proteins in the internal components by trangenesis. The fiber obtained from the animals such as sheep will have new and modified properties as per the features exhibited by the transgenes.

6.2 Protein-Related Technologies

High-throughput protein/peptide identification, quantification and sequencing, protein/peptide synthesis, and protein engineering and biocatalysis are some of the protein-related technologies that can be used in the field of textiles. High-throughput protein identification, quantification, and sequencing use a number of techniques that help proteomics which is the study of the structure and function of proteins. The techniques include two-dimensional gel electrophoresis, mass spectroscopy, and nuclear magnetic resonance. The methods used to separate, identify, and quantify levels of proteins and peptides in a mixture are known as gel-electrophoresis (GE). Telke et al. have stated that using sodium dodecyl sulfate polyacrylamide gel electrophoresis purified laccase enzyme with 66 kDa was obtained. The purified enzyme decolorized structurally different azo dyes with variable decolorization rates and efficiencies ranging from 68 to 90 % [56]. For the identification of proteins or other macromolecules through their molecular weights (mass) and to determine the composition and order of amino acids, called sequencing of protein molecules, mass spectroscopy (MS) is used. First the protein molecules are separated through gel electrophoresis followed by alkylation and breakdown in specifically known ways using enzymes into peptides. The third technique nuclear magnetic resonance (NMR) is used to describe the three-dimensional structure of proteins, peptides, and other macromolecules.

Peptide synthesis is another technology where the chemical construction of a known protein or peptide molecule is studied by solid-phase synthesis. Here molecules are bound to a bead and created step by step in a reactant solution with constituent amino acids repetitively coupled to a growing polypeptide backbone. This backbone is attached to a substrate or polymeric support. Automated synthesizers are useful to synthesize proteins in this manner.

Protein engineering and biocatalysis: In industrial production processes and in bioremediation applications, enzymes are engineered by the selective, deliberate design and synthesis of proteins in order to alter specific functions. This process is known as protein engineering. Biocatalysis is the use of enzymes as catalysts to perform transformations in organic compounds. Enzymes for protein engineering and biocatalysis can be used in isolated form, or inside living cell lines, or as microorganisms such as bacteria, fungi, and yeasts. There are two general strategies for protein engineering. One strategy involves the use of detailed knowledge of the structure and function of the protein to make desired changes termed rational design. The second strategy is random mutagenesis such as DNA shuffling applied to a gene and a selection system used to pick out variants that have the desired qualities called directed evolution. DNA shuffling involves taking a set of closely related DNA sequences, segmenting them randomly, and reassembling the fragments into genes. A combination of positive or desired mutations can be rapidly formed and the output of this cycle will form the input of the next cycle. This systemic DNA shuffling leads to directed evolution and can be applied to evolve any protein rapidly although the structure or the catalytic mechanism is unknown [60].

6.3 Metabolite-Related Technologies

These include high-throughput metabolite identification and quantification and metabolic pathway engineering. Molecules that are the intermediates and products of metabolism are called metabolites. They are the end product of the gene expression process and are involved in the normal growth, development, and reproduction of living organisms.

- High-throughput technologies for identification, quantification, and analysis: MS and NMR are the two leading technologies for metabolomics. MS is used to identify and to quantify metabolites after separation. The mostly commonly used separation technology is gas chromatography in combination with MS.
- Metabolic pathway engineering: Metabolic pathway engineering includes the modification of endogenous metabolic pathways of microorganisms and the

> introduction of metabolic pathways into new host organisms. In addition, metabolic engineering also deals with the upregulation of the production of molecules. It is one of the most important tools in industrial biotechnology. John and Keller state that *Alcaligenes eutrophus* genes encoding the enzymes, β-ketothiolase (*phaA*), acetoacetyl-CoA reductase(*phaB*), and polyhydroxyalkanoate synthase (*phaC*) catalyze the production of aliphatic polyester poly-*D*-(–)-3-hydroxy-butyrate (PHB) from acetyl-CoA. Transgenic cotton fibers were produced by particle bombardment of (*phaB*) and (*phaC*) genes. The presence of PHB in the transgenic cotton fibers resulted in measurable changes in thermal properties [57].

Metabolic pathway engineering encompasses a combination of technologies, including those used in genomics and proteomics studies, genetic engineering, and so on. The metabolism of microorganisms is engineered in order to improve their suitability for biotechnical processes and for efficient production of many sorts of chemical compounds.

6.4 Cellular and Subcellular Level-Related Technologies

These technologies include cell hybridization/fusion, hybridoma technique, cell and tissue culture and engineering, and embryo technology.

6.4.1 Cell Hybridization/Fusion

When the cell contents of two or more cells of different species origin combine, in vitro, into a single cell, it is known as cell fusion. The nucleus of the donors may either remain separate or fuse together, but the following cell divisions would have a single spindle so that the new cell has a single nucleus containing complete or partial sets of chromosomes from each parent.

6.4.2 The Hybridoma Technique

Here cell fusion techniques are used for the production of monoclonal antibodies. The product of fusion is called hybridoma which is a synthetic hybrid cell. The monoclonal antibodies are often used in immunoassays as they usually bind to only one site of a particular molecule. The monoclonal antibodies produced by hybridoma react on a single antigenic determinant of an antigen. On the basis of the reaction of an antibody to its antigen, an immunoassay measures the level of a substance in a biological liquid. Monoclonal antibodies serve as a specific and accurate biochemical test that measures both presence of antigen or antibodies.

6.4.3 Cell and Tissue Culture and Engineering

The mainstream technologies under cell culture technologies are the in vitro growth of cells isolated from multicellular organisms. These technologies vary for plant cell cultures and for animal and human cell cultures. The in vitro growth and/or regeneration of plant material under controlled conditions is called micropropagation. Tissue engineering is a more advanced culture technique where specific animal or human cells are induced to grow and form entire tissues that can be implanted in the human body. Another method is to inject relevant compounds such as growth factors or growth hormones or living cells into the body to grow and form desired tissues. To develop biological alternatives that restore, maintain, or improve tissue function, tissue engineering uses a combination of cells, engineering materials, and biochemical factors. The required cells are embedded into the scaffolds which are artificial structures that promote three-dimensional tissue formation. The seed cells can come from the same body to which they will be reimplanted, from another body, or even from other species. Ing et al. have mentioned the contributions made by researchers for the development of innovative resorbable porous scaffolds for tissue engineering and regenerative medicine [74].

6.4.4 Embryo Technology

Embryo technology involves the removal of an embryo from a donor and immediately transferring it to a surrogate mother. This technology may be more complicated and advanced by performing microsurgery on the embryo and maintaining the embryo in special culture systems before transferring the embryo to the surrogate mother which may be in vivo and in vitro embryo production. Embryo technologies are being adapted to livestock as embryo transfer, embryo splitting, and cloning. In embryo transfer, animal embryos are transferred to recipients via artificial inembryonation. Embryo splitting is the splitting of young embryos into several sections; each section develops into an animal that is genetically identical to the others. Cloning involves the asexual processes of creating an identical genetic copy of the original organism without the interchange or combination of genetic material. The members of the clone have genetic compositions that are identical. It has been reported that Dr. Shah, a pashmina goat cloning pioneer had made interesting reflections of his work at the Cashmere World 2012 conference [74]. In the production of embryonic stem cells, the new egg is stimulated to start dividing to form a blastocyst after which embryonic stem cells are harvested. These embryonic stem cells are employed to generate chimeric animals. Chimeric animals are animals whose cells are not all genetically identical, which may be due to somatic mutation, grafting, or because the individual is derived from two or more embryos or zygotes. These are further used to produce knockout animals that are used mainly in research. Apomixis is associated with cloning used in plants. Here the plant seeds are genetically identical to the parent plant as biological reproduction is done without fertilization.

6.5 Fermentation and Downstream Processing

The anaerobic breakdown of complex organic substances such as carbohydrates, by microorganisms to yield energy is fermentation. In the industry fermentation is the term used for aerobic, anaerobic, microaerofilic culturing of defined microorganisms and the culturing of mammalian and insect cells. In a fermenter or bioreactor, organisms, cells, cell extracts, or biochemically active substances derived from organisms act on complex organic substances. After the fermentation process is completed, a large quantity of a dilute mixture of substances, products, and microorganisms is produced. These products must be separated in a controlled way and the product should be concentrated, purified, and converted into a useful form. This process is called downstream processing. A bioreactor is a device or system to grow cells or tissues in culture as in tissue engineering. They are commonly cylindrical and made of stainless steel, ranging in size from a liter to several cubic meters. A variety of products is produced through fermentation including biomass, primary and secondary metabolites, bioconversion products, enzymes, and recombinant products which are used in many biological and industrial applications. The separation and purification of the products to make them suitable for the required end use is the work of downstream processing. These two processes go hand in hand to produce new and unique products that are biologically friendly to the environment.

6.6 Bioinformatics

Bioinformatics is the creation, collection, storage, and efficient use of data and information from all fields of biotechnology and combinatorial chemistry research. Examples of the data that are manipulated and stored include gene sequences, biological activity or function, pharmacological activity, biological structure, molecular structure, protein–protein interactions, and gene expression products, amounts, and timing. Major research efforts in the field include sequence alignment, gene finding, genome assembly, protein structure alignment, protein structure prediction, prediction of gene expression and protein–protein interactions, and the modeling of evolution. The terms "bioinformatics" and "computational biology" are often used interchangeably. Bioinformatics is the database loaded with information whereas computational biology deals with algorithm development and specific computational methods.

There are many challenges confronting biotechnology while focusing on textile applications. The specific key areas that requires special attention are as follows.

- Synthetic biology and metabolic pathway engineering are examples of emerging technologies that will significantly increase the diversity of biotechnological processes and products, driving the development of innovative products.
- Some biobased products will require further chemical processing and unless these chemical processes are made available there will be no market for these precursors. Therefore dedicated research on the combination of technologies such as biochemical and chemical processes should be undertaken.
- Another important field is the development of efficient and robust enzymes, particularly for the conversion of lignocellulosic material. This should enable the conversion of a variety of feedstock.
- Specific research is also needed to improve feedstock yield and/or the composition of biomass involving both plant genomics and new breeding programs, and also incorporating further research into efficient crop rotation, land management and land-use change issues [75].

In order to make a fast and efficient shift towards more integrated and sustainable production and processing systems, many measures are to be taken. Attention should be to extend support of technological progress and increase public and private R&D investment in industrial biotechnology and related technologies, through multidisciplinary research programs at both the national and international levels. Efforts need to be made to build networks between industry and academia to overcome the competence hurdle and knowledge gap to stimulate and support technology transfer in the area of industrial biotechnology and green technologies. Sufficient resources must be mobilized to support large coordinated research initiatives, focusing on the market perspective covering the whole value chain. Programs to accelerate and alleviate risks of transforming knowledge into commercial products, by financially supporting access to pilot and demonstration facilities and by integrating production processes need to be established.

7 Conclusion

A product is sustainable only when all the input and output parameters of materials and processes are harmless to living beings and the environment in all stages of the product lifecycle. Renewable and recyclable sources are essential for energy, material, and process inputs. It also means that the products manufactured must be capable of returning safely to their natural or industrial systems in all stages of the product lifecycle to ensure social well-being, health, and safety. Sustainability in the field of textiles can be attained by the use of biotechnology as all the techniques and processes are biologically safe and natural.

The main culprits of pollution in textile and apparel production are water, energy and chemical use, and pollution. The factors for sustainable production are to be reviewed from the raw material to the finished product in terms of selection, sourcing, manufacture packaging and supply, warehousing, and retailing. Once the product is used and worn its impact on the environment is also accountable. In all stages of the product lifecycle researchers, manufacturers, and industrialists must take care to look for sustainable solutions to overcome the problems facing the textile industry. Most of the raw materials and energy are from nonrenewable resources and the freshwater supply is becoming scarce. Industries have to take note of the carbon foot print and modify their conventional style of working to start introducing green and clean processes to stay in the competitive market that is globally accessible to all consumers. Sustainability has been extended from environmental issues to social issues and many laws and regulations have been passed to maintain the safety of humans and environment from the hazards of pollution.

Industrial biotechnology would serve to solve many problems faced by the textile industry. Many novel tools and techniques in modern biotechnology can help the industry, such as improving the performance and yield of the raw materials such as textile fibers, wool and silk, creating new materials from renewable natural resources, aiding in the processing of fabrics with enzymes, biological dyes, and improved methods that would save water and fuels and resources for future use. Enzymes in processing would save time, energy, raw materials, water, and cost and would make the entire process viable, sustainable, and eco-friendly. Manipulation of genes and embryos give rise to new combinations for suiting different requirements. Bioremediation methods can also be used for clean-up processes to help in bringing about zero discharge. Thus biotechnology can serve all areas of textiles and create an awareness of the eco-friendly methods to be adopted by the textile industry. Government aid for undertaking research in all areas of biotechnology for textile applications is a prospective need and will help the textile industry to blossom and flourish in a sustainable way for future well-being and happiness.

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