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Genetically engineered/modified fibres for the 21st century textiles and fashion

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Abstract

When a journalist asked Steve Jobs what the greatest innovation of the 21st century would be?, he said, "I think the greatest innovation of the 21st century will be the combination of biology and technology" [1]. At that time, almost no one thought that this applied to the textile and fashion industry as well, although genetically engineered (GE) textiles and genetically modified (GM) textile fibres were becoming more and more present in our wardrobes and everyday life. From the early nineties of the last century, when the first ex vitro cultivation of GM cotton was realised, until today, when fibres can be biologically designed, i.e. genetically engineered (GE) according to our needs, GM fibres of plant and animal origin, as well as GE textile fibres of various origins, have become increasingly present as raw materials in the textile and fashion industries, despite numerous controversies surrounding their use. The paper presents an overview of the achievements made in the field of genetically engineered/modified fibres, so far, as well as a review of their use in the context of contemporary thinking on sustainable textiles and fashion.

Keywords: *genetically modified fibres, genetically engineered textiles, fashion industry, sustainable textiles.*

1. Introduction

The twentieth century brought about revolutionary changes in science and technology, which had far-reaching consequences for our lives. [2]. Computers and the Internet were invented, a wide range of synthetic fibres were offered to the market, and the human genome was found and sequenced, all of which allowed biotechnology to become the most popular and promising scientific discipline. Although some forms of biotechnology have been present since the beginning of civilization, through the domestication of plants and animals and the discovery of fermentation, public awareness of the possibilities of biotechnology and genetic engineering is a relatively recent phenomenon, a phenomenon of the 21st century [3]. Biotechnology and genetic engineering are often used interchangeably, although biotechnology represent much broader term that implies the usage of biology in the development of new products, methods and organisms intended to improve human health and society. It can be defined as any technique that uses living organisms to make or modify a product to improve plants or animals or to develop microorganisms for specific use [3-7].

Genetic engineering, also regularly called genetic modification, is just one part of modern biotechnology (along with tissue culture and cloning). It is a collection of current biological techniques used to change an organism's genetic features, such as introducing, modifying or eliminating certain genes, while also allowing for gene transfer across unrelated species. As a result, a genetically modified organism (GMO) contains additional or modified characteristics encoded by the introduced gene(s) [8]. Through genetic engineering, organisms can be given targeted combinations of new genes, and thus new combinations of properties that do not appear in nature (**Fig. 1.**), i.e. cannot be developed naturally or through long-term and repeated selection of several generations.

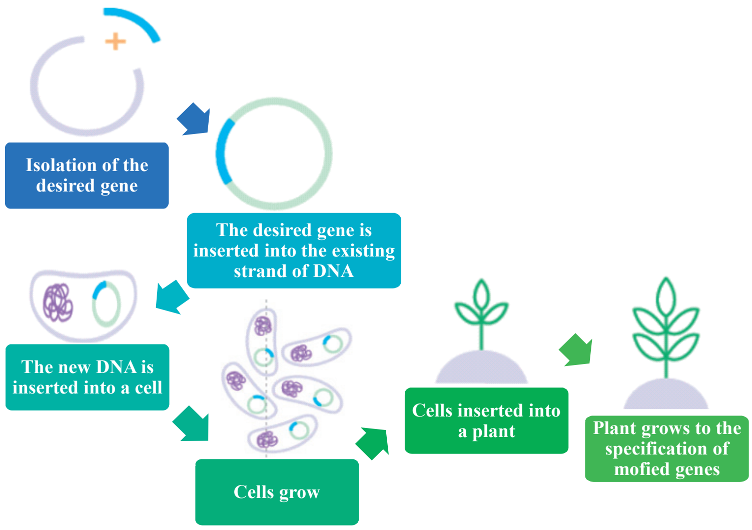


Fig. 1. GMOs depend on genetic engineering for their creation and can be modified in any way a scientist chooses [9]

The possibilities of such genetic manipulation, as well as its benefits, are the main reasons why genetics is today seen as a promising science, and biotechnology as one of the leading industries.

Although, among wider population the textile industry is not perceived as a modern and inventive industry, but as an industry that uses non-renewable raw materials to a greater extent and contributes significantly to environmental pollution, it is worth pointing out that the textile and fashion industries were the first to recognize and use the potential of biotechnology several decades ago. Namely, enzymes are routinely used (**Fig. 2.**) for washing and bleaching textiles, giving the desired fashionable effect of a worn look to denim clothes, preventing shrinkage of wool, etc. [10].

According to some predictions, the new wave of biotechnology and the imperative of sustainable development could lead to the situation where our clothes and functionalised textiles would be made and dyed by living organisms, microbes or bacteria. In this scenario, many of the chemical treatments and manufacturing processes, which are currently most accountable for the negative perception of the textile and fashion industry, could be avoided [11].

Since fibres are the basic building block of every textile product (**Fig. 3.**), it is not surprising that they were the starting point for the implementation of biotechnology and genetic engineering in the textile and fashion industries.

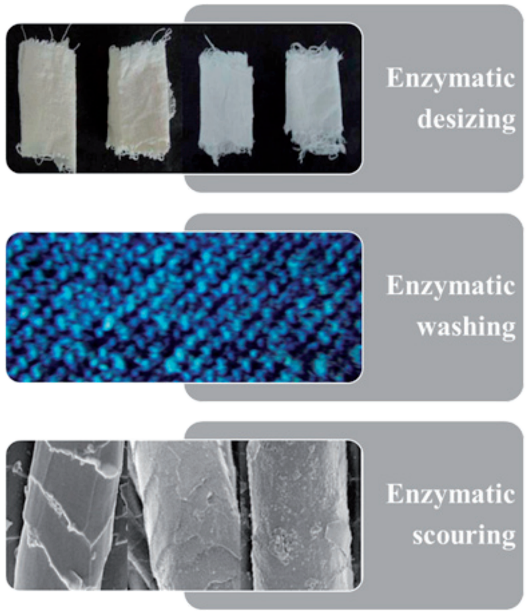


Fig. 2. Some examples of old well-established biotechnology usage in textile industry

Fig. 3. From fibre to final textile product

2. Genetically engineered/modified natural fibres

Nature has created different types of fibreforming plants and animals, with fibres exhibiting unique properties, resulting from their genetic structure [12]. The genetic traits of naturally occurring fibrous materials are based on the structure and function of DNA (deoxyribonucleic acid), which is the basic carrier of genetic information in all living organisms. DNA is composed of four nucleotides: adenine, thymine, cytosine and guanine, which are covalently linked in a specific order, forming a gene, the functional unit of inheritance [13]. Genes determine the production of specific proteins, which make up the structure and function of all biological systems, including natural fibres. After the discovery of the structure of DNA, in 1953 by Watson and Crick, genetic modification enabled the development of genetic engineering techniques that also found their application in the textile industry [4]. Genetic engineering provides scientists with the possibility of direct intervention in genetic organisms. It allows them to add, remove or modify the existing gene in order to modify certain characteristics of natural fibres [14]. This process uses a variety of methods, including recombinant DNA technology, a process that combines DNA sequences from different sources into a single molecule, CRISPR-Cas9 gene editing, a method for precise gene editing that uses a molecular tool to “cut” and “paste” DNA at desired locations in the genome and transgenesis, the procedure by which the genes of one species are transferred and integrated into the genome of another species, creating so-called transgenic organisms [15-18]. Genetic modification of fibres (namely plants and animals) for the needs of the textile and fashion industries takes place in several directions: increasing fibre yield with less environmental impact, improving the properties of natural fibres and creating new, high-tech fibres, to be used for the production of additionally resistant, durable, more fashionable and environmentally friendly textiles [19-23].

2.1. Genetically engineered/modified plant fibres

Cotton is the seed fibre of the plant of the same name belonging to the *Gossypium* genus of the *Malvaceae* family, and which can be said to be the most important conventional textile fibre despite the increased consumption of different artificial fibres. Thanks to its fineness, strength, shapeability and ability to absorb moisture, cotton is one of the most commonly used materials in the production of clothing [19, 24]. Despite its numerous advantages, conventional cotton also has significant shortcomings, including the need for a significantly high use of water and pesticides during cultivation, and susceptibility to diseases and pests [20, 22]. Only four of the 39 cotton plant species are grown for fibre production: *G. hirsutum*, G. *barbadense*, *G. herbaceum* and *G. arboreum* [25]. Genetic diversity, the increase in crop profit and utilization, and the geographical and market spread of cotton inspired the interest of biotechnologists and geneticists in cotton at the end of the 20th century already. Cotton genetic modification aimed to achieve two primary objectives: to create resistance to pests and tolerance to glyphosate, an herbicide that is often used in agriculture and intensive cotton cultivation [19, 20, 22]. To reduce crop failures, scientists modified cotton genetically by inserting a gene known as Cry2AX1 into the cotton genome. This gene comes from the bacterium *Bacillus thuringiensis* (Bt), which produces a toxin that is harmful to certain species of cotton pests [26]. Successful incorporation of this gene into the cotton DNA creates plants that produce their own pesticide (**Fig. 4.**), resulting in a reduced need to spray chemicals on them. This approach has been used for many years and has proved to provide effective protection against certain types of pests, such as *Helicoverpa armigera*, one of the most dangerous cotton pests [20, 27, 28]. Bt cotton was introduced into commercial use in 1996 [29] and since then has significantly reduced the use of pesticides in many regions of the world, which has had a positive impact not only on the environment, but on human health as well [20, 27, 28].

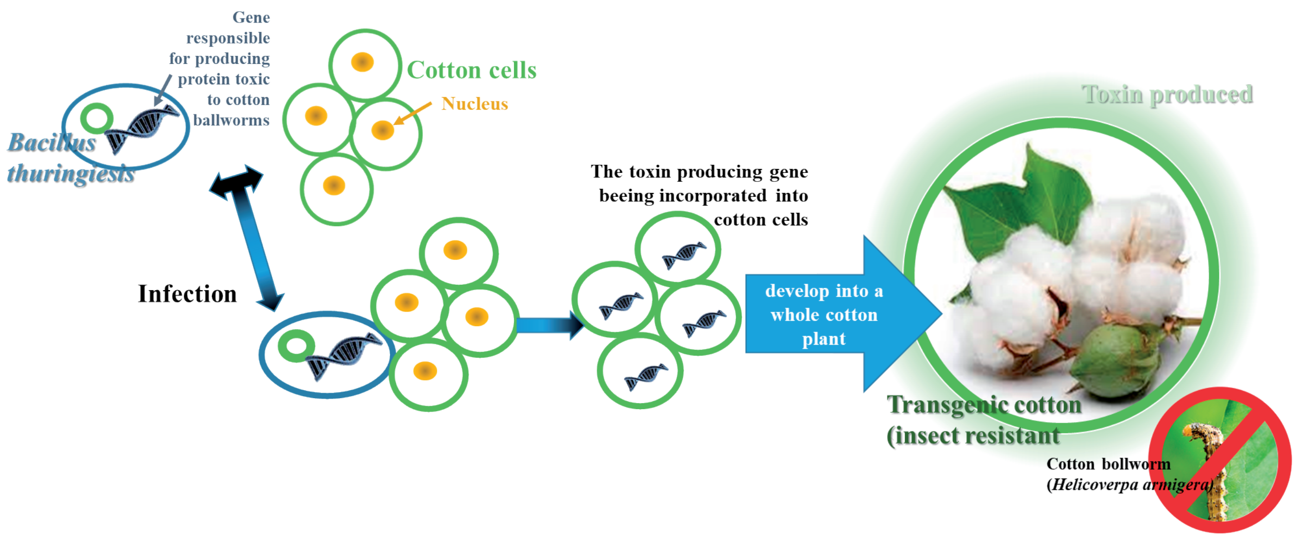


Fig. 4. Production of Bt Cotton

After the successful introduction of Bt cotton, researchers continued to develop new varieties of genetically modified cotton with additional improvements. Namely, cotton (in intensive and extensive cultivation) is sensitive to glyphosate, i.e. one of the most commonly used herbicides in agriculture, which limits its use in cotton fields. To solve this problem, scientists have genetically modified cotton to develop varieties that are resistant to glyphosate [6, 30]. Glyphosate is a broad-spectrum herbicide that in turn inhibits an enzyme known as 5-enolpyruvylshikimate-3-phosphate synthase (EPSPS). This enzyme is crucial for the biosynthesis of essential amino acids, making it necessary for plant growth and development. By modifying the cotton genome, cotton plants can survive glyphosate treatment, which enables effective weed control without crop damage [20, 22, 23]. In order to achieve genetic modification various techniques might be used, including for example the transformation by the bacterium *Agrobacterium tumefaciens*. This method exploits the natural ability of the bacterium for genetic engineering and the ability to transfer new genes into plants [22]. Usually, a modified CP4-EPSPS gene from the bacterial strain *Agrobacterium sp*. is used for this purpose since CP4 strain is naturally resistant to glyphosate [23].

Naturally coloured cotton has grown in popularity in recent years as a result of the ever-present intersection of ecology and fashion, as well as the growing public interest in environmental concerns and environmentally responsible production processes. Coloured cotton, as a type of genetically modified fibre, has become popular in the textile industry due to its environmental friendliness and potential to reduce the costs of textile dyeing [31]. However, there are certain disadvantages of this fibre that reduce consumer enthusiasm for choosing naturally dyed cotton fabrics. The fibres are too short and weak to be used for finer pieces of fabric, and there is a limited selection of desired shades and colours [32]. Colours come in shades of brown, green and purple [31-34]. However, significant progress has recently been made in this area as growers in Australia have genetically modified cotton to produce dyed cotton in black and other dark colours that are durable [35]. Since the introduction of the first genetically modified cotton, biotechnology has progressed, and new generations of GM cotton have been developed with the aim of improving fibre properties (length, strength, colour, resistance to burning, etc.), resistance to diseases and pests, and adaptation to different climatic conditions. Possibilities for reducing the consumption of water and nutrients during cultivation, and thus reducing the negative impact on the environment [36, 37], are also being explored.

Although genetically modified cotton offers many advantages, it also carries certain challenges and controversies. Some of these challenges include potential health and environmental risks associated with genetic modification, as well as ethical issues and regulations that limit its use and distribution [28, 38], such as GOTS (Global Organic Textile Standards) norms and EU directives [39, 40].

Flax, a genus of annual plants from the *Linaceae* family, with more than 200 once yearly and perennial species. The flax fibre is mainly obtained from the stem of the blue flax plant (*Linum usitatissimum* L.), and in addition to being one of the oldest textile fibres, it should be noted that by the end of the 18th century, along with wool and hemp, was the most important textile raw material [36, 41]. Today, when the use of renewable textile raw materials is imperative, flax is gaining in importance once again [42-44]. As a natural fibre, flax is extremely strong, absorbs moisture well and shows resistance to bacteria and fungi [36]. Despite these advantages, conventional flax production faces numerous challenges, including high production costs and limitations in terms of fibre quality, as well as unsustainable maceration processes [45]. Genetic modifications of flax were started at the end of the last century, primarily with the aim of increasing crop yields and flax resistance to herbicides and their residues in the soil [46]. The first flax transgenic plants/fibres on the market were engineered for glyphosate (Roundup®) [30] tolerance. Further study focused on genetic modifications of flax with the goal of improving fibre properties. One example is the introduction of transgenes that encode enzymes involved in lignin synthesis, which, according to some studies, facilitates the extraction of fibres from the stem without impairing their quality [46, 47].

The following step in engineering flax fibre [48] was aimed at generating transgenic flax plants that could be retted more efficiently. The constitutive expression of *Aspergillus aculeatus* genes resulted in a significant reduction in the pectin content in tissue-cultured and field-grown plants. This pectin content reduction was accompanied by a significantly higher retting efficiency of the transgenic flax fibres. Despite the good indicators, there are no genetically modified flax currently grown in the EU, primarily because of the EU regulations and a fact that European importers refused to buy it due to the health and environmental safety issues.

The study of genetic cotton and flax modification has prompted the genetic modification of other plants that generate textile fibres, such as nettle, hemp, and jute. The aim of these researches is to improve fibre properties, including strength, formability and the resistance to diseases and pests, as well as improving the adaptability of plants to different climatic conditions in order to ensure sufficient yields of textile raw materials of plant origin, due to the increased interest in the production of biocomposites [49-54].

Advances in the field of biotechnology and its use for the needs of the textile and fashion industries have recently led to the innovative and creative cultivation of cotton fibres from stem cells in laboratory conditions (**Fig. 5.**) [55]. Various cultivars of cotton plants are grown in greenhouses in order to isolate the stem cells from them in the laboratory. The stem cells, which have the potential to transform into any part of the plant, are placed in enormous bioreactors and their development is aided by the supply of nutrients. Once the cells begin to multiply, they are transferred to a bioreactor where they are differentiated into fibres. Instead of growing the whole plant, this approach merely produces cotton fibres. The process itself is significantly faster than traditional cotton growing - it only takes 18 days compared to the 180 days needed

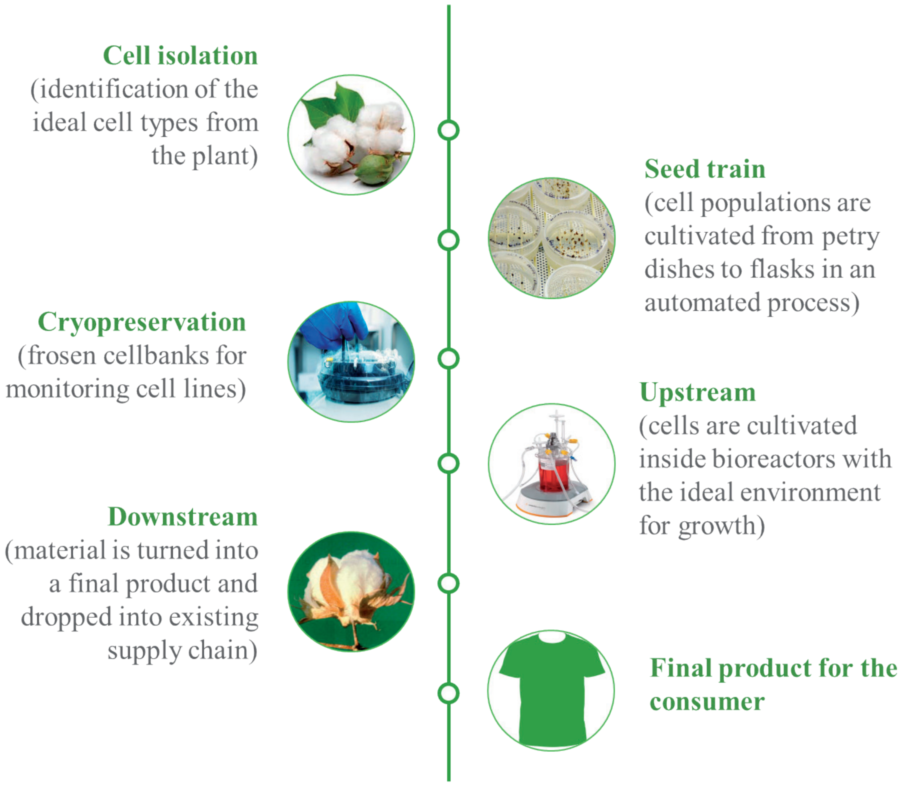


Fig. 5. Production of Bt cotton

for traditional growing. Additionally, this method uses less than 80% of water and land compared to traditional cotton cultivation. However, despite all these advantages, the quality of the fibres themselves is questionable and still unknown. Currently, the project is still in the research and development phase. The plan is to produce cotton, under reasonable price on the market, for ecologically and ethically conscious fashion brands [55, 56].

2.2. Genetically engineered/modified animal fibres

Animal or natural protein fibres is a common name for fibres that represent the hair covering of certain animals (so-called keratin fibres, e.g. wool) and fibres that are secretions of certain animals (so-called fibroin fibres, e.g. mulberry silk) [58].

Wool has been an integral part of human life for millennia, and as such, it has been and continues to be the focus of much research. In particular, wool, thanks to its structure and resulting properties, is considered one of the most complicated fibres whose secrets have not yet been completely discovered. Numerous improvements in the fleece covering of today's sheep compared to their ancestors are the result of sheep domestication, long-term efforts to select the best ones and care for their adequate safe and sound breeding, considering the climatic and vegetation conditions in which they are bred. For generations, genetic selection has been used to improve the existing phenotypic traits of sheep through the breeding of sheep most likely carrying the optimum gene combinations [59, 60]. However, while steady gains have been made, the progress is relatively slow, taking multiple generations. In the process, selective breeding relies solely on genes already within the sheep genome, a factor that clearly sets a biological limit for genetic gain. With respect to the main drivers of profitability in the wool industry, selective breeding has made great progress in the achievement of both higher clean fleece weights and lower fibre diameters. However, that was not enough considering the contemporary requirements of the global textile and fashion industries and their end users. Unlike artificial fibres, wool, as a textile raw material, is extremely non-uniform, not only among individual breeds of sheep (e.g. merino wool and domestic pramenka wool), but also within the breed (different sub-breed), due to the climatic and vegetation conditions in which it is grown (e.g. Australian *vs.* New Zealand or Spanish merino; Istrian vs. Lika pramenka). Additionally, the non-uniformity of wool is also contributed through the fact that wool of the same breed and sub-breed differs according to the gender of the sheep (i.e. ram *vs.* ewe), the part of the body from which it originates (e.g. back wool *vs*. belly wool), but also along the fibre itself (e.g. root *vs.* fibre tip) [61, 62]. Careful on-farm management of nutrition and minimization of environmental stresses contributes to the production of fibres with quite uniform protein compositions as well as properties like fineness, crimpness, length, strength, etc. However, such treatments come at a high cost, in terms of energy, used chemicals and human labour. Traditionally, post-farm processing treatments (starting with sorting and classifying, followed by industrial pre-treatments) have been the primary tool for the improvement or uniformity of wool fibre properties, necessary for its processing into a finished product [63, 64].

It is not unexpected that biotechnology and genetic engineering (especially transgenesis) have emerged as potential alternatives to selective breeding for modifying sheep genetics and achieving fibre modification and unification [65]. Complete decoding of keratin intermediate filaments (KIFs) and keratin-associated proteins (KAPs) present in wool follicles (**Fig. 6.**) has still not been accomplished and is under research. It is partially due to the fact that wool fibre represents the most sophisticated biological composite material and partially because wool fibre characteristics change during fibre formation by the activity of the follicles from which it grows [65-71].

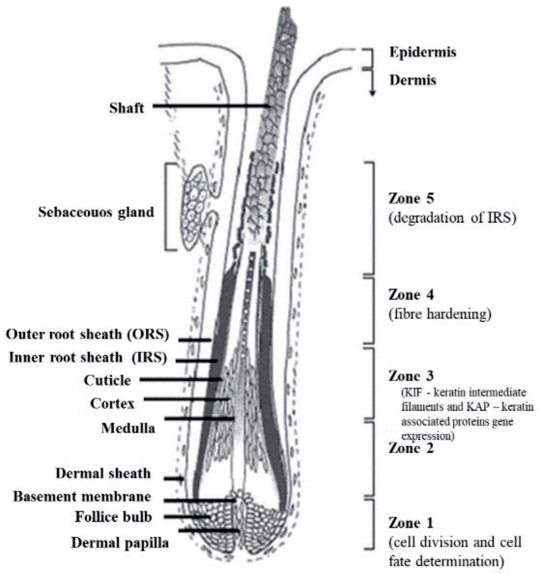


Fig. 6. Sketch of a mature wool follicle and summary of the gene expression that takes place in the wool follicle to produce the KIF and KAP [65, 69]

Numerous attempts have been made to modify wool fibre properties through enzymatically assisted CRISP/Cas9 genetic modification technology. New transgene DNA fragment for adding to sheep has been prepared through this work. In the case of the transgenic sheep made via the cortical-specific K2.10 transgene base vector, sometimes it is possible to see visible difference in the appearance of sheep fleeces depending upon the level of transgene expression, (**Fig. 7.**) [65]. The wool fibres of the high expressor have no crimp but rather a moderate wave, and high lustre. Since waviness is a consequence of cortex bilateral structure, it is obvious that such genetic modification can impact the fibre ultrastructure as well as properties like density, strength and stretchability, dye uptake and moisture sorption [72].

Such genetic sheep modification can offer chances for sustainable, faster and cheaper production of more uniform fibres or functionalized wool of different qualities [73, 74], but it also opens up numerous ethical and safety dilemmas [74], which is illustrated by the news that sheep have already been bred in laboratories with different fleece colours [75].

Silk is the common name for all-natural protein fibres that are created by the secretion of silkworms, spiders and/or shellfish [76, 77]. Due to its exclusivity and exceptional properties (fineness, strength, softness, lustre, biocompatibility, etc.), silk is often called the queen of fibres. Still, most commonly, this name is associated with mulberry silk that is obtained by pulling threads from cocoons made by silk moth larvae (silkworms). Historically, it has been cultivated and used not only for making luxury clothes and fashion accessories, but also for making tapestries, wall coverings, floor coverings, parachutes, surgical suture, etc. [78-80]. Advances in the field of biotechnology have opened up possibilities

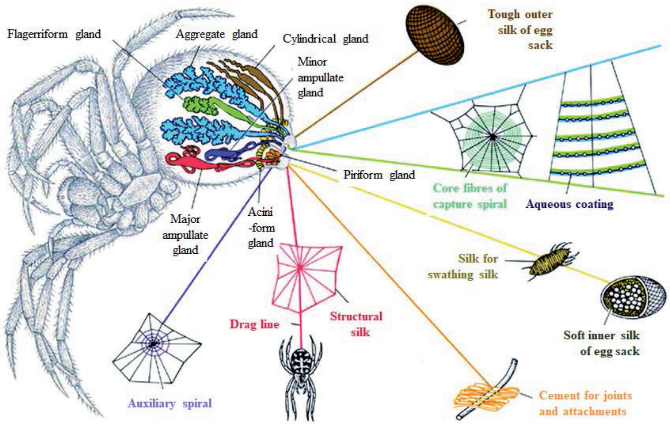
Fig. 7. Differences between the fibres / fleece depending on the level of expression of the added transgene [65]

for genetic engineering of silk in order to modify and/or improve its original properties and expand its application in e.g. the field of fibre-reinforced composites, the pharmaceutical and cosmetic industries or, to increase its use in the textile and fashion industries through the creation of smart as well as sustainable textiles [78, 80-85]. Genetic modification involves altering the silkworm genome to create improved or entirely new types of silk [83, 86]. After the world's first genetic modification of silkworms in Japan at the National Institute of Agrobiological Sciences (NIAS) in 2002, they managed to develop three lines of transgenic silkworms in 2009 [87]. The first line produced silk threads that emit green, red, or orange fluorescent light. These threads were created by introducing genes into silkworm eggs that promote the generation of fluorescent proteins. Green fluorescence was achieved using genes extracted from jellyfish, while red and orange fluorescence was achieved using genes extracted from corals [88, 89]. The cocoons were smaller and the quality of such genetically modified silk was slightly lower compared to traditional silk. However, fluorescent silk threads have attracted the attention of high-end apparel producers and fashion designers (**Fig. 8.**) [90, 91].The second line of transgenic silkworm yielded an ultra-fine silk thread. By introducing genes for producing especially fine thread into "Haugen silkworms" (a stable crossbreeds for fine silk creation), NARO (Japan National Agriculture and Food Research Organization) [91] developed a silkworm line that produced a thread even finer than that of ordinary "Haugen silkworms" [91-93]. The unique look and feel of fabric made from this type of ultra-fine silk makes it highly attractive to designers and producers of Haute Couture clothing and other fashion products. The third line of transgenic silkworm was realised by introducing genes that bolster cell adhesion and resulted in silk that exhibited high level of cell adhesion. The thread produced by these silkworms is expected to have applications in the field of medicine, e.g. for artificial blood vessels or as a cell culture substrate in the production of artificial cornea and artificial cartilage [83, 93, 94].

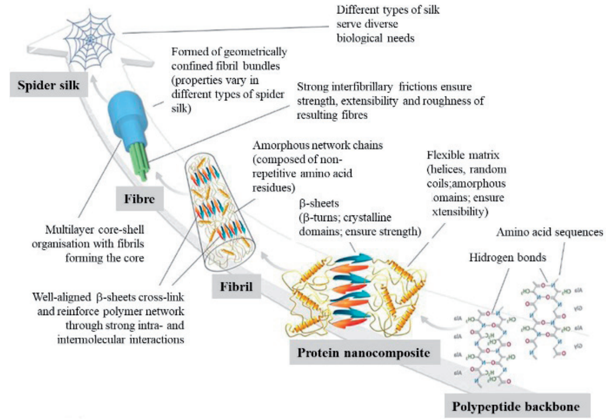
Wedding dress produced of the coloured fluorescent silks [90]

Twelve-layered dance costume designed using fluorescent silk [91]

Fig. 8. Clothes from fluorescent silk



Different types of spider` silk [103]



Structural hierarchy in spider silk [98]

Fig. 9. Spider silk

After many years of effort, the silkworm *Bombyx Mori* has been developed into insect systems for which the most advanced genetic technologies are available [83]. The application of these technologies has enabled the sophisticated genetic modification of silkworms to improve their commercial value. One significant step in this direction has been the recombinant production of protein spider silk [95-98].

Spider silk fibres are one of outstanding fibrous biomaterials [99-103]. Due to their remarkable protein sequence and ultramolecular structure (**Fig. 9**. [102]) they possess nature's most exceptional mechanical properties, along with biocompatibility and biodegradability [103]

Spider silk fibres have tensile strength comparable to steel and some silks are nearly as elastic as rubber on a weight-to-weight basis. Through the combination of these properties, silks reveals toughness that is several times higher than that of synthetic fibres like Nylon® or Kevlar® [10, 25, 58, 104, 105]. With such unrivalled combination of strength and toughness, spider silk is the model for creating high performance materials in the area of technical textiles, as well as in the area of sustainable fashion [104, 106-108]. Unfortunately, spiders cannot be farmed at a large scale to meet the commercial demand for spider silks, because of their territorial and cannibalistic behaviours [101, 109, 110]. In order to produce the purified spider silk proteins a variety of heterologous hosts have been explored like e.g. *Escherichia coli*, yeast, alfalfa, potatoes, goats etc. [111]. The purified spider silk proteins can artificially be spun into fibres, but the process is too complex, unpractical, and not so sustainable and, above all, such artificial spider silk fibres can not reach similar mechanical properties as natural spider silk fibres [110-112]. The questions – Why? and What is wrong? arises within scientific community. The answer appears to be in particular conditions of silkworm spinning that, in the case of natural silk, is responsible for finalising ultrastructure of fibres and corresponding properties [113-115]. CRISPR/Cas9 initiated fixed-point strategy used to successfully incorporate spider silk protein genes into the *Bombyx Mori* genome [111]. Using transgenic silkworms with their natural spinning apparatus has proven to be a promising way to spin spider silk-like fibres. The resulting fibres were 100% spider silk, as strong as native spider silks (1.2 GPa tensile strength), could withstand a stretching force of 1299 MPa without breaking, making them several times stronger than nylon. The energy that these fibers could absorb from an impact (toughness) was 319 MJ/m^3, which is six times stronger than Kevlar® [106].This strategy shows the feasibility of using silkworms as a natural spider silk spinner for industrial production of high-performance fibres, the more so transgenic silkworms. If realised in this way, they exhibit normal inheritance of the transgenes.

3. Fibres obtained by genetically modifying microorganisms

BioSteel fibres are genetically modified fibres that imitate the properties of spider silk. They are created using genetically modified microorganisms [117]. Using recombinant DNA methods, researchers managed to produce spider silk proteins through genetic modification of bacteria and yeast, thereby creating the possibility for the production of a large amount of this valuable material [14, 95, 96, 118]. *Escherichia coli*, mostly known as *E. coli*, is widely used bacterium in biotechnology since it exhibits fast growth and a large capacity for the production of foreign proteins. Modified *E. coli* can produce silk proteins that can be used for silk production [14, 119]. The researchers cloned the relevant genes from the spider *Nephila clavipes* and introduced them into the bacteria. Using small and large-scale bioreactors, they were able to produce synthetic spider silk proteins (spidrones). The final product is a silk fibre similar to natural silk [15, 119], and can be used in the textile and fashion industry [96, 98,120] or, more broadly, in the field of biomedicine [82, 119, 121]. The advantage of silk production through *E. coli* is that it can be carried out in laboratory conditions, without the necessity for large amounts of space and resources [14, 119], which contributes to global sustainable development [117, 122].

The term "Biosteel" was first used to describe a recombinant protein material similar to spider silk that was obtained from the milk of transgenic goats and produced by Nexia Biotechnologies [123]. Since the company ceased to exist in 2009, the name was taken over and registered by the company AMsilk, which produced fibres obtained from bacteria through an industrially proven fermentation process [124, 125]. In cooperation with Adidas, AMSilk developed the world's first sports shoes (**Fig. 10.**) made of Biosteel® fibres [125-127]. The Adidas Futurecraft Biofabric prototype shoe features an upper made of 100% Biosteel® fibres. The material offers a unique combination of properties, such as being 15% lighter than conventional synthetic fibres, and has the potential to be the strongest all-natural material. In addition, Biosteel® fibres are 100% biodegradable in a completely natural process [124].

Bacterial cellulose (BC) represents a significant part of the research in the context of genetically engineered/modified fibres for the textile and fashion industries. It is recognized as a new material suitable for a wide range of applications, due to its unique structure, high purity, outstanding mechanical properties and biocompatibility [128]. Various types of bacteria, including the genera *Acetobacter*, *Gluconobacter*, *Komagataeibacter*, *Rhizobium*, *Agrobacterium*, and *Sarcina* [129, 130], can synthesize BC from a wide variety of substrate through fermentation [117, 130]. During this process, bacteria produce and secrete extracellular polymers, which form a cellulose structure with unique properties [130]. The structure and properties of BC can be controlled by varying fermentation conditions, including substrate concentration, fermentation time, temperature, and pH [131] (**Fig. 11.**).

Bacterial cellulose has a wide range of potential applications. Biocompatibility and ability to be formed into different shapes and sizes makes BC an ideal material to be used in the sustainable fashion production [128, 130]. Bacterial cellulose is biodegradable, which further encourages its use as an environmentally friendly material for the textile and fashion industries. Due to its outstanding ability to absorb water, it can also be used in the production of highly absorbent products, such as diapers [131].

Fig. 10. Adidas shoe from Biosteel® fibre [124-127]

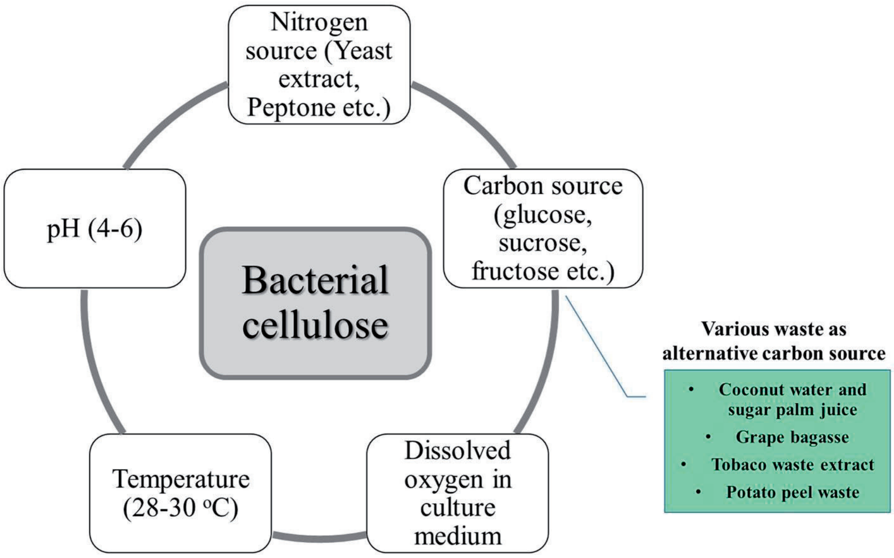


Fig. 11. Factors influencing the production of bacterial cellulose [131]

In addition, properties such as high strength and flexibility, together with excellent wear resistance, make it suitable for the use in the production of various types of textiles and composite materials. Bacterial cellulose also plays a significant role in biomedical applications. Due to its biocompatibility, BC can be used in the production of medical implants, tissue engineering, wound and skin dressings, as well as in drug delivery control [128].

4. Benefits and risks of genetically engineered/modified textiles: Current controversies and perspective

Today, there are already numerous innovative companies and projects [117, 120, 122, 131-137] that have dedicated themselves to the development and commercialization of genetically engineered/modified textiles in advanced biotechnological procedures (**Fig, 12.**) [117, 132].

Such projects offer an alternative to traditional, often resource-intensive, fiber manufacturing processes, promoting the shift to greener and more sustainable textile and fashion industries. Over time, more and more of these pioneering projects have appeared on the market (**Fig. 13.**), bringing with them new materials and technologies that have the potential to radically reshape the textile industry as we know it today [133-136]. At the same time, they not only open up new possibilities in the production of functionalized textiles (designed for use), but also contribute to sustainability and environmental preservation. However, every progress in science and technology, as history has shown, is accompanied by controversies and shortcomings that we unfortunately become aware of after the initial euphoria. Some of the advantages and disadvantages of genetic textiles are summarised in Table 1.

Genetically modified textile fibres and their applications will continue to evolve as technology advances. Collaboration between researchers, industry and regulatory authorities will be the key to successful dissemination of these innovations and their application across various sectors.

Fig. 12. Bio-couture clothes (The first research on bacterial cellulose inside the fashion domain was performed by the British fashion designer Suzanne Lee, for her research project "Biocouture, an initiative on sustainable material") [117, 132]

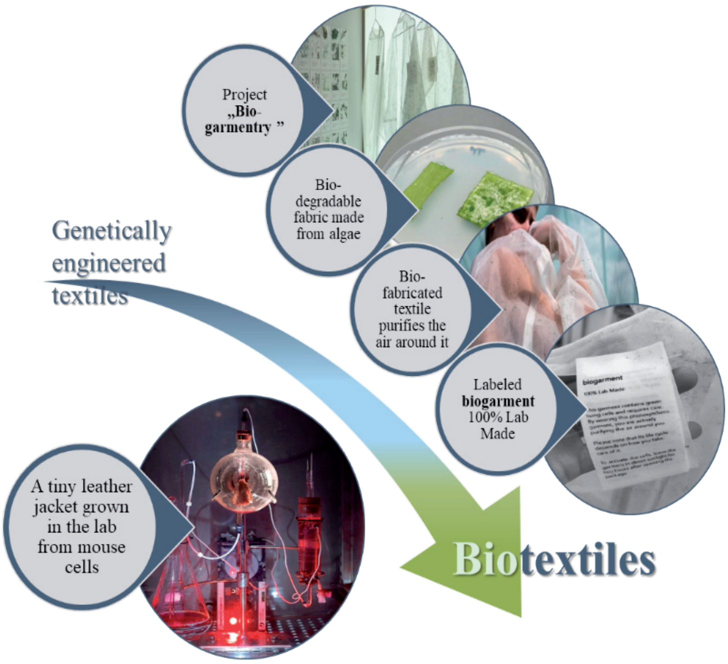


Fig. 13. Textiles for the future

Table 1. Genetically engineered/modified textiles - *pro at contra*

Advantages (*pro*)	Disadvantages (*contra*)
• Increasing fibre yield - genetic modification (GM) of fibre-forming plants can increase fibre yield per unit area of cultivation resulting in: reduction of resources/lands needed for fibre production, reduction of the need to expand agricultural areas, which helps preserve natural habitats and biodiversity. • Improving fibre quality - GM can improve fibre quality, including strength, elasticity, softness, air and water permeability and resistance to abrasion.	• Danger to human health - GM fibres can affect human health, especially if they are used to make clothing and textile products that come into contact, with the skin. • Environmental risks - GM plants can have environmental impacts on non-target organisms such as fish, worms, bees and insects, loss of biodiversity and gene instability. The release of such products and their possible impacts on the environment asks for high environmental biosecurity surveillance in order to reduce or completely eradicate the risk they cause.

Advantages (*pro*)	Disadvantages (*contra*)
• Resistance to diseases and pests - GM fibres can be more resistant to diseases and pests, which reduces the need for pesticides and other chemical means to protect plants. • Resistance to abiotic stress - GM can improve the resistance of plants to stressful conditions, such as drought or high salt concentrations in the soil, thus enabling the production of fibres in different climatic and geographical areas, reducing the need for irrigation and helping to conserve water resources, thus reducing emission of greenhouse gases. • Potential functionalization of fibres - GM fibres can be engineered to incorporate new properties such as resistance to moisture, fire, bacteria or UV radiation. • Potential increase in durability - GM can be used to develop fibres that are even more sustainable than now, thus reducing resource consumption, waste and negative impact on the environment. • Possibly personalized textile products - GM materials can be used to create personalized textile products, such as clothing that adapts to body temperature or the environment.	• Legislation - different laws and regulations in countries around the world regulate the way how genetically modified fibres can be used and traded. There is controversy over how products containing genetically modified fibres should be regulated and labelled. • Monopolization - several large companies hold patents on GMO technology, which can lead to monopolization in the industry and potentially disadvantage small farmers. • Gene flow - The most serious problem associated with gene flow is the loss of biodiversity, and it is often cited as a potential risk. Chances of accidental cross-pollination between GM crops and their wild relatives are very high, making them super-weeds that could be resistant to various herbicides and become difficult to control. There are several examples of gene flow from crops to related weeds, such as *Beta vulgaris, Avena strigose, Brassica napus*, etc. • Increased resistance to antibiotics - GM products might enter the human body through food, vaccines, bacteria or viruses. There is a concern that GM plants with bacterial resistance genes in their genome could act as a source of drug resistance genes for clinically important bacteria. • Allergies - introducing new genes into plants can cause allergies by creating unexpected products (proteins and metabolites) in plants. For example, Bt bacteria can effectively control insects that attack crops. However, the probability of consuming Bt toxins and reacting to mammals that cause allergies is equally high. • Starvation - insects, birds and other animals that feed on certain crops may not consume genetically modified crops due to allergic reactions or toxic products. As a result, large numbers of fauna may face starvation, affecting entire food chains and causing serious threats to ecosystems.

Public opinion and perception are significant barriers to the widespread use of genetically engineered textile fibers. The negative perception of GMOs can in some cases lead to opposition to their use, despite potential benefits. Educating and communicating with the public about the benefits, risks and safety of genetically modified textile fibres can help overcome this challenge.

Complex regulatory and legal frameworks can also be an obstacle to the spread of genetically modified textile fibres. It is necessary to establish clear and comprehensive regulations that enable the research, development and commercialization of genetically modified fibres, while at the same time ensuring the safety and protection of people and the environment.

Ethical concerns about genetic alteration may potentially influence the acceptability of genetically modified textile fibers. The ethical implications of genetic modification need to be carefully considered, including issues of genetic material ownership, potential risks to biodiversity and the environment, and potential social and economic impacts.

Future research and development in the field of genetically modified textile fibres should include an interdisciplinary approach that must combine knowledge and skills from different disciplines, such as biotechnology, genetics, textile technology and engineering, ecology, ethics and sociology.

5. Some final remarks

When studying genetically engineered/modified textiles, it becomes evident that it is still an insufficiently known area of progress, novelties, patents, innovations and creative designs, striving to overcome the deficiency of raw materials, improve the functionality or multifunctionality of textiles and clothing through rapidly renewable raw materials, eco - design and production, with a significant reduction of environmental load and impact on climate change. At the same time, it should be emphasized that along with rapid and often legally and regulatory unsupported progress, there are also controversies and problems that we will become aware later, such as the problem of fast fashion and the desire to fulfil the wishes of customers through a profitable and exclusive product that exist now. Having perceived the advantages and disadvantages of genetic textiles and the positive and negative implications on our life and the environment, instead of a conclusion, it is left to each and every reader to make his/her own judgment and decide, whether he/she will in the future support well-promoted marketing brands and designers that use genetically modified clothing or, perhaps ask himself/herself - What am I wearing? (**Fig. 14.**) or Have we crossed the line?

In ethical reflection, crossing the border implies the ability to deal with the content beyond the boundary. The technological power of today is greater than man's

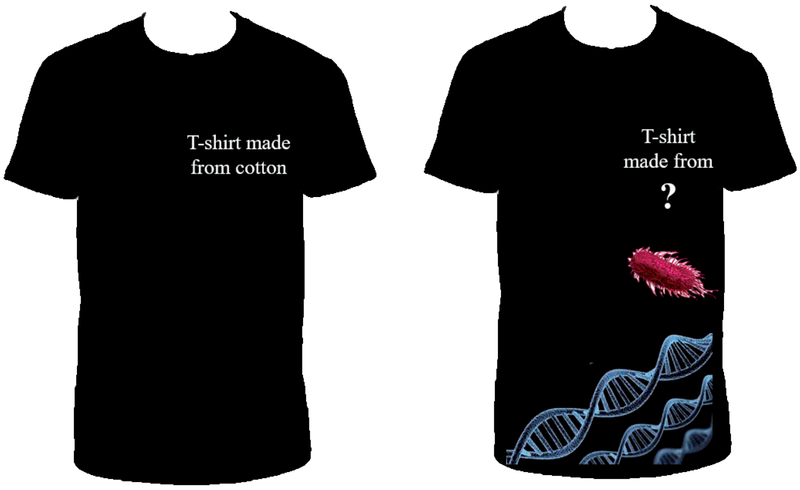


Fig. 14. Simple T-shirt heretofore and these days

reflective power [152], which means that we have to take into account - bioethics. Bioethical situation can be reconstructed and followed in its changes within various forms of social and cultural life as well as at different levels of collective existence. At the same time, it should be kept in mind that all formats of bioethical situation are resulting not only in awareness, but could also historically determine the change in the world-historical situation, which we call an epoch [153]. In other words, genetically engineered/modified textiles become a key point and a sign in which a new epoch appears - the epoch of biotextiles, which will be achieved through synthetic biology in addition to genetic design.

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6. References

[1] Isaacson, W. Steve Jobs. Simon & Schuster, US, 2011, pp. 132-298

[2] Cumo,C. Science and Technology in 20th-Century American Life. Greenwood press, Westport, US, 2007

[3] Renneberg, R., Süßbier, D., Berkling, V., Loroch, V. Biotechnology for beginners. Elsevier Academic Press, London, 2023, pp. 72-125

[4] Rani, S. Biotechnology: A review on its role in textile applications. International Journal of Home Science 5(2019) 270-274

[5] URL:https://www.britannica.com/technology/biotechnology (29.9.2023.)

[6] Directive 98/44/EC of the European Parliament and of the Council of 6 July 1998 on the legal protection of biotechnological inventions

[7] Swarup Verma, A., Agrahari, S., Rastogi, S., Singhl, A. Biotechnology in the Realm of History. Pharm Bioallied Sci. (2011) 321–323

[8] Batista, R., Margarida Oliveira, Facts and fiction of genetically engineered food, M. Trends Biotechnol. 27(2009) 277-186

[9] URL:https://www.techtarget.com/whatis/definition/biotechnology (27.9.2023.)

[10] Nierstrasz, V.A., Cavaco-Paulo, A. Advances in textile biotechnology. Woodhead Publishing Limited, Philadelphia, 2010, pp. 3-22

[11] URL: https://www.labiotech.eu/ in-depth/biofabrication-fashion-industry/ (6.5.2022.)

[12] Reddy, N., Yang, Y. Innovative Biofibers from Renewable Resources. Springer Berlin, Heilderberg, 2015

[13] Watson, J.D., Crick, F.H.C. Molecular Structure of Nucleic Acids: A Structure for Deoxyribose Nucleic Acid. Nature 171 (1953) 737-738

[14] Xia Xia, X., Qian, Z.G., Ki, C. S., Park, Y. H., Kaplan, D. L, Lee, S.Y. Native-sized recombinant spider silk protein produced in metabolically engineered Escherichia coli results in a strong fiber. Proc Natl Acad Sci 107(2010) 14059-63.

[15] Xuemei, Z. Wenrong, L., Chenxi, L., Xinrong, P., Jiapeng, L., Sangang, H., Xuejiao, L., Bing, H., Ning, Z., Yangsheng, W., Lei, C., Liqin, W., MaYila, Juncheng, H., Mingjun, L. Alteration of Sheep Coat Color Pattern by Disruption of ASIP Gene via CRISPR Cas9. Scientific Reports 7 (2017) 8149

[16] Alberts, B., Johnson, A., lewis, J., Raff, M., Roberts, K., Walter, P. Molecular Biology of the Cell. 4th ed, Garland Science, New York, 2002

[17] Doudna, J.A., Charpentier, E. The New Frontier of Genome Engineering with CRISPR-Cas9. Science, 346 (2014), pp. 1258096-1258096-9

[18] Fletcher, G.L., Peter, L.D. Transgenic Fish for Aquaculture. In: Setlow, J.K. (ed) Genetic Engineering, Plenum Press, New York, 1991, pp. 331–370

[19] Russell, D. Cotton – Biotechological Advances. In: Biotechnology in Agriculture and Forestry. Zehr, U.B. (ed), Heidelberg: Springer-Verlag, Berlin, 2010

[20] Khalid, A., Zahid, K. Breeding cotton for international Trade. In: Zulqurnain, K., Zulfiqar, A., Asif, A.K. (eds) Cotton

Breeding and Biotechnology: Challenges and Opportunities. First edition, CRC Press, Boca Raton, 2022

[21] Kelly, C. M., Osorio-Marin, J., Kothari, N., Hague, S., Dever, J. K. Genetic improvement in cotton fiber elongation can impact yarn quality. Industrial Crops and Products 129 (2019) 1–9

[22] Zhang, B. Transgenic Cotton: From Biotransformation Methods to Agricultural Application. Transgenic Cotton (2012) 3–15

[23] Karthik, K., Nandiganti, M., Thangaraj, A., Singh, S., Mishra, P., Rathinam, M., Sreevathsa, R. Transgenic Cotton (Gossypium hirsutum L.) to Combat Weed Vagaries: Utility of an Apical Meristem-Targeted in planta Transformation Strategy to Introgress a Modified CP4-EPSPS Gene for Glyphosate Tolerance. Frontiers in Plant Science (2020) 1-11

[24] Gordon, S., Hsieh, Y.L. Cotton: Science and Technology. Woodhead Publishing, Cambridge, 2007

[25] Čunko R., Andrassy M. Vlakna, Zrinski, Čakovec, 2005

[26] Čunko, R. Genetski modificirani Bt pamuk i globalne promjene u proizvodnji pamučnih vlakana. Tekstil 62 (2013) 14-30

[27] Dhivya, K., Sathish, S., Natarajan, B, Varathalajau, U., Duraialagaraja, S. Genetic Engineering of Cotton with a Novel Cry2AX1 Gene to Impart Insect Resistance against Helicoverpa Armigera. Crop Breeding and Applied Biotechnology 16 (2016) 205–212

[28] Smyth, S. J. The Human Health Benefits from GM Crops. Plant Biotechnology Journal 18 (2019) 887-888

[29] James, C. Global Status of Transgenic Crops in 1997. The International Service for the Acquisition of Agri-biotech Applications (ISAAA), Ithaca, 1997

[30] O Duke, S., Powles S.B. Glyphosate: a once-in-a-century herbicide. Pest Manag Sci. 64 (2008) 319-325

[31] Rathinamoorthy, R., Parthiban, M. Colored Cotton: Novel Eco-friendly Textile Material for the Future. In: Myriam, L., Martinez, O., Kharissova V., Ildusovich Kharisov, B. (eds) Handbook of Ecomaterials. Springer International Publishing, New York, 2019, pp. 1499–1519

[32] Keshamma, E., Manjula. A.C., Prathibha, K.Y., Geethanjali, R., Nalini, T.J. Colour cotton research: current and future perspectives, International Journal of Engineering Development and Research 9 (2021) 384-a388

[33] Chhabra, J., Suril, M., Parmar, M.S. Naturally colored cotton. Asian Textile Journal 18 (2010) 25-29

[34] Zhou, L., Ye, Y. A genetic pathway for naturally colored cotton production. Plant Physiology 189 (2022) 1190–1191

[35] URL:https://www.abc.net.au/news/2020-06-27/csiro-scientists-grow-coloured-cotton/12395250 (27.4.2022.)

[36] Dochia, M., Sirghie, C. Cotton fibres. In: Kozłowski, M.R. (ed). Handbook of Natural Fibres – Volume I. Woodhead Pub, Cambridge, 2012, pp. 11-23

[37] Militky, J., Aneja, A., Kremenakova, D. Future view on fibres. World Journal of Engineering 10 (2013) 411-418

[38] Kouser, S., Spielman, D. J., Qaim, M. Transgenic cotton and farmers' health in Pakistan. PLOS ONE, 14 (2019) 1-19

[39] GOTS Annual report 2022, Global Standard gemeinnützige GmbH, Stuttgart, 2023

[40] EU Directive 2001/18/EC on the deliberate release into the environment of genetically modified organisms and repealing Council Directive 90/220/EEC - Commission Declaration, the Publications Office of the European Union on the, Brussels, 2001

[41] URL:https://tehnika.lzmk.hr/lan/ (19.9.2023.)

[42] Šurina, R., Andrassy, M., Vujasinović, E. Lan – biljka i vlakno kroz stoljeća, Tekstil 58 (2009)12, 625-639

[43] Šurina, R., Andrassy, M., Vujasinović, E. Renewal of flax fibres production in Croatia. Wilson, C.A., Laing, R.M. (eds) Proceedings: Natural Fibres in Australasia, UN Food and Agriculture Organization - International Year of Natural Fibres. University of Otago, Dunedin, 2009, pp. 72-76,

[44] URL:https://allianceflaxlinenhemp.eu/en/all-about-european-linen (30.9.2023.)

[45] Ludvíkova, M., Griga, M. Transgenic flax/linseed (Linum usitatissimum L.) – expectations and reality. Czech Journal of Genetics and Plant Breeding 51 (2016) 123–141

[46] McHughen, A., Holm, F.A. Transgenic flax with environmentally and agronomically sustainable attributes. Transgenic Research 4 (1995) 3-11

[47] Roach, M. J., & Deyholos, M. K. Microarray analysis of developing flax hypocotyls identifies novel transcripts correlated with specific stages of phloem fiber differentiation. Annals of Botany 100 (2007) 931-940

[48] Musialak M., Wrobel-Kwiatkowska M., Kulma A., Starzycka E., Szopa J. Improving retting of fiber through genetic modification of flax to express pectinases. Transgenic Research 17 (2008) 133–147

[49] Van den Broeck, H.C., Maliepaard, C., Ebskamp, M.J., Toonen, M.A., Koops, A.J. Differential expression of genes involved in C1 metabolism and lignin biosynthesis in wooden core and bast tissues of fiber hemp (Cannabis sativa L.). Plant Science 174 (2008) 205-220

[50] Li, Y., Sun, J., Xia, G., Peng, L. Agrobacterium tumefaciens-mediated transformation of ramie (Boehmeria nivea Gaud.) with a bacterial phytase gene. Plant cell, tissue and organ culture 108 (2012) 471-479

[51] Frolich, N., Schoppler, A., Lehmann, S. Genetic variation of European nettle (Urtica dioica L.) in Central Europe inferred from AFLP markers. Plant Systematics and Evolution, 302 (2016) 1089-1097

[52] Lewandowski, I. The Increasing Demand for Biomass in a Growing Bioeconomy. In: Barth, S., Murphy-Bokern, D., Kalinina, O., Taylor, G., Jones, M. (eds) Proceedings: Perennial Biomass Crops for a Resource-Constrained World. Springer International Publishing, CH, 2018, pp. 3–13. The role of perennial biomass crops in a growing bioeconomy. Agronomy, 8(9), 167).

[53] Sarkar, D., Mahato, A.K., Satya, P., Kundu, A., Singh, S., Jayaswal, P.K., Chattopadhyay, K. Understanding the molecular basis of plant growth promotional effect of Pseudomonas fluorescens on rice through protein profiling. Proteome Science 15 (2017) 17

[54] De Oliveira, L.M., Torres, T.T., Freitas, R.M. Gene expression analysis in sisal (Agave sisalana) during acclimatization of in vitro plants. Crop Breeding and Applied Biotechnology 13 (2013) 251-257

[55] URL:https://www.forbes.com/sites/jeffkart/2023/07/08/lab-grown-cotton-enters-the-market-with-galy-suzuran-partnership/ (14.4.2023.)

[56] URL:https://unreasonablegroup.com/ventures/galy (12.4.2023.)

[57] URL:https://galy.co/ (14.10.2023.)

[58] Von Bergen, W. Wool / Specialty hair fibers. In: Matthews, J.M., Mauersberger. H.R. Matthews› Textile Fibers: their Physical, Microscopical and Chemical Properties. John Wiley and Sons, Inc., New York, 1954, 484-784

[59] Rogers, G.E. Improvement of wool production through genetic engineering. Trends Biotechnol 8 (1990) 6-11

[60] Swan, A.A, Purvis, I.W., Piper, L.R., Lamb, P.R., Robinson, G.A. The CSIRO fine wool project – background and objectives. In: Swan, A.A, Piper, L.R. (eds) Finewool 2000 breeding for customer needs. The Woolmark Company, Melbourne, 2000, pp. 65–73.

[61] Vujasinović, E. Prilog istraživanju kvalitete domaćih vuna – finoća i medulacija. Magistarski rad, Sveučilište u Zagrebu Tekstilno-tehnološki fakultet, Zagreb, 1996

[62] Hearle, J. Physical properties of wool. In: Simpson, W.S., Crawshaw, G.H. (Eds.) Wool: Science and technology. CRC Press, Cambridge, 2002, 80-120

[63] Vujasinović, E., Raffaelli, D. Priprema domaće vune za prodaju – vuna cresko-lošinjskog područja. Tekstil 43 (1994) 57-64

[64] Cottle, D.J. International sheep and wool handbook. Nottingham University Press, Nottingham, 2010

[65] Bawden, S. WOOLA472/572 Wool Biology and Metrology: Genetic engineering. The Australian Wool Education Trust, AU, 2009

[66] Yu, Z., Gordon, S.W., Nixon, A.J., Bawden, C.S., Rogers, M.A., Wildermoth, J.E., Maqbool, N.J., Pearson, A.J. Expression patterns of keratin intermediate filament and keratin associated protein genes in wool follicles. Differentiation 77 (2009) 307-316

[67] Makar, I.A., Havryliak, V.V., Sedilo, H,M. Genetic and biochemical aspects of keratin synthesis by hair follicles. Tsitol Genet. 41 (2007) 75-79

[68] Popescu, C., Hocker, H. Hair—the most sophisticated biological composite material. Chem. Soc. Rev. 36 (2007 1282–1291

[69] Purvis, I.W., Franklin, I.R. Major genes and QTL influencing wool production and quality: a review. Genet. Sel. Evol. 37 (2005) S97–S107

[70] Gong, H., Zhou, H., Forrest, J.H.R., Li, S., Wang, J., Dyer, J.M., Lou, Y., Hickford, J.G.H. Wool Keratin-Associated Protein Genes in Sheep—A Review. Genes 24 (2016) 1-16

[71] Zhao, H., Guo, T., Lu, Z., Zhu, j., Qiao, G., Han, M., Yuan, C., Wang, T., Li, F., Zhang, Y., Hou, F., Yue, Y., Yang, B. Genome-wide association studies detects candidate genes for wool traits by resequencing in Chinese fine-wool sheep. BMC Genomics 22:127 (2021) 1-13

[72] Wang, J., Cui, K., Yang, Z., Li, t., Hua, G., Han, D., Yao, Y., Chen, J., Deng, X., Yang, X., Deng, X. Transcriptome Analysis of Improved Wool Production in Skin-Specific Transgenic Sheep Overexpressing Ovine β-Catenin. International Journal of Molecular Sciences, 20 (2019) 620-646

[73] Kalds, P., Zhou, S., Cai, B., Liu, J., Wang, Y., Petersen, B., Sonstegard, T., Wang, X., Chen, Y. Sheep and Goat Genome Engineering: From Random Transgenesis to the CRISPR Era. Frontiers in Genetics 10 (2019) 750-773

[74] Zhao, H., Zhu, S., Guo, T., Han, M., Chen, B., Qiao, G., Wu, Y., Yuan, C., Liu, J., Lu, Z., Sun, W., Wang, T., Li, F., Zhang, Y., Hou, F., Yue, Y., Yang, B. Whole-Genome Re-Sequencing Association Study on Yearling Wool Traits in Chinese Fine-Wool Sheep. Journal of Animal Science 99 (2021) 210-245

[75] URL: http://www.xinhuanet.com//english/2016-06/06/c_135417312.htm (1.10.2023.)

[76] Strgačić, S., Vujasinović, E. Sea silk – myth or reality. In: Dragčević, Z., Hursa Šajatović, A. Vujasinović, E. (eds) The Book of Proceedings of the 10th International Textile, Clothing & Design Conference Magic World of Textiles, University of Zagreb, Faculty of Textile Technology, Dubrovnik, 2022

[77] Paponja, D.: Paukova svila. završni rad, Sveučilište u Zagrebu, Tekstilno-tehnološki fakultet, 2017

[78] Murugesh Babu, K. Silk – processing, properties and application, Woodhead Pub.Ltd., Cambridge, 2013

[79] Currie, R. Silk. In: Franck. R.R. (ed) Silk, mohair, cashmere and other luxury fibres. Woodhead Pub.Ltd., Cambridge, 2001, pp. 1-67

[80] Pedaki, N.V., Das, B., Basu, A. Advances in understanding the properties of silk. In: Basu, A. (ed) Advances in Silk Science and Technology, Woodhead Pub.Ltd., Cambridge, 2015, pp. 1-16

[81] Liu, X., Zhang, K. Silk Fiber — Molecular Formation Mechanism, Structure-Property Relationship and Advanced Applications. IntechOpen (https://www.intechopen.com/chapters/46460), 2013

[82] Kundu, S.C. (ed) Silk Biomaterials for Tissue Engineering and Regenerative Medicine, Woodhead Pub.Ltd., Cambridge, 2014

[83] Park, E.Y., Maenaka, K. (eds) Silkworm Biofactory - Silk to Biology, CRC Press, Boca Raton, 2019

[84] Deng, H. Optimized Design of Modern Silk Clothing Based on Material Matches. Advanced Materials Research 627 (2015) 577-580

[85] Moorhouse, D., Moorhouse, D. Sustainable Design: Circular Economy in Fashion and Textiles. The Design Journal 20 (2017) 948-959

[86] Xu, H., O`Brochta, D.A. Advanced technologies for genetically manipulating the silkworm Bombyx mori, a model Lepidopteran insect. Proc. R. Soc. B 282 (2015) 1-8

[87] URL:https://web-japan.org/trends/08_sci-tech/sci090227.html (30.10.2023.)

[88] URL:https://fashiontechnews.zozo.com/en/features/features006/naro_tomioka_silkbrand (8.10.2023.)

[89] Tamura ,T., Iizuka, T., Sezutsu, H., Tatematsu, K., Kobayashi, I., Yonemura, N., Uchino, K., Kojima, K., Machii, H., Takabayashi, C., Yamada, K., Kurihara, H., Asakura, T., Nakazawa, Y., Miyawaki, A., Karasawa, T., Kobayashi, H., Yamaguchi, J., Kuwabara, N., Nakamura, T., Yoshii, K. Production of high quality silks having different fluorescent colors using transgenic silkworms. AFF Research Journal 32 (2009) 7-10

[90] Iizuka, T., Sezutsu, T., Tatematsu, K., Kobayashi, I., Yonemura, N., Uchino, K., Nakajima, K., Kojima, K., Takabayashi, C., Machii, C., Yamada, K., Kurihara, H., Asakura, T., Nakazawa, Y., Miyawaki, A., Karasawa, S., Kobayashi, H., Yamaguchi, J., Kuwabara. N., Nakamura, T., Yoshii, T., Tamura, T. Colored Fluorescent Silk Made by Transgenic Silkworms. Adv. Funct. Mater. (2013) 1-8

[91] URL:https://asia.nikkei.com/Business/Technology/Transgenic-silkworms-changing-world-of-sericulture (20.9.2023.)

[92] URL:https://www.naro.go.jp/english/laboratory/nias/database/index.html (20.9.2023.)

[93] Yamamoto, T., Mase, Y., Nagasaka, K., Itsubo, T., Miyajima, T., Enoshima, M., Kumai, M., Izumi, S. Cultivation of ultra-fine silkworm variety "Hakugin". Japanese Seriology Journal 68 (1999) 2-16

[94] Hazra, S., Nandi, S., Naskar, D., Guha, R., Chowdhury, S., Pradhan, N., Kundu, S.C., Konar, A. Non-mulberry Silk Fibroin Biomaterial for Corneal Regeneration. Scientific Reports (2016) 1-13

[95] Tokareva, O., Michalczechen-Lacerda, V.A., Rech, E.L., Kaplan, D.L. Recombinant DNA production of spider silk proteins. Microbial Biotechnology 6 (2013) 651–663

[96] Heidebrecht, A., Eisoldt, L., Diehl, J., Schmidt, A., Geffers, M., Lang, G., Scheibel, T. Biomimetic Fibers Made of Recombinant Spidroins with the Same Toughness as Natural Spider Silk. Advanced Materials 27 (2015) 2189–2194

[97] Teule, F., Miao, Y.G., Sohn, B.H., Kim, Y.S., Hull, J. J., Fraser, M.J., Jarvis, D.L. Silkworms transformed with chimeric silkworm/spider silk genes spin composite silk fibers with improved mechanical properties. Proceedings of the National Academy of Sciences 109 (2012) 923–928

[98] Kiseleva, A.P., Krivoshapkin, P.V., Krivoshapkina, E.F. Recent Advances in Development of Functional Spider Silk-Based Hybrid Materials. Frontiers in Chemistry 8 (2020) 1-20

[99] Saravanan, D. Spider Silk - Structure, Properties and Spinning. JTATM 5 (2006) 1-20

[100] Blackledge, T.A. Spider silk: a brief review and prospectus on research linking biomechanics and ecology in draglines and orb webs. The Journal of Arachnology 40 (2012) 1-12

[101] Brunetta, L., Craig, C.L. Spider Silk – Evolution and 400 million years of spinning, waiting, snagging and mating. Yale University Press, New Haven, 2010

[102] URL:http://news.bbc.co.uk/2/hi/science/nature/7709435.stm (10.10.2023.)

[103] Karan, K.S., Maiti, S., Kwon, O., Paria, S. Nature driven spider silk as high energy conversion efficient bio-piezoelectric nanogenerator, Nano Energy 49 (2018) 655-666

[104] Woo, H.G., Li, H. Advanced functional materials. Zhejiang University Press, Hangzhou, 2011

[105] Bunsell, A.R. Handbook of Properties of Textile and Technical Fibres. Woodhead Publishing, Cambridge, 2018

[106] Mi,J., Zhou,Y., Ma, S., Zhou, X., Xu, S., Yang, Y., Sun, Y., Xia, Q., Zhu, X., Wang, S., Tian, L., Mengl, Q. High-strength and ultra-tough whole spider silk fibers spun from transgenic silkworms. Matter. 6 (2023) 3661-3683

[107] Arndt, T., Greco, G., Schmuck, B., Bunz, J., Shilkova, O., Francis, J., Pugno, N.M., Jaudzems, K., Barth, A., Johansson, J., Rising, A. Engineered Spider Silk Proteins for Biomimetic Spinning of Fibers with Toughness Equal to Dragline Silks. Advanced functional materials 32 (2022) 1-11

[108] Hansell, H. BIOmatters. Master Project, University of Brighton, 2017

[109] URL:https://www.ancient-origins.net/artifacts-other-artifacts/world-s-rarest-textile-made-silk-one-million-spiders-009010 (10.2.2020.)

[110] Ramezeniaghdam, M., Nahdi, N.D, Reski, R. Recombinant Spider Silk: Promises and Bottlenecks. Front. Bioeng. Biotechnol. 10 (2022) 1-18

[111] Zhang, X., Xia, L., Day, B.A., Harris, T.I., Oliveira, P., Knittel, C., Licon, A.L., Gong, C., Dion, G., Lewis, R.V., Jones, J.A. CRISPR/Cas9 Initiated Transgenic Silkworms as a Natural Spinner of Spider Silk. Biomacromolecules 20 (2019) 2252−2264

[112] Teulee, F., Cooper, A.R., Furin, W.A., Bittencourt, D., Rech, E.L., Brooks, A., Lewis, R.V. A Protocol for the Production of Recombinant Spider Silk-like Proteins for Artificial Fiber Spinning. Nat. Protoc. 4 (2009) 341−355

[113] Teule F, Miao YG, Sohn BH, Kim YS, Hull JJ, Fraser MJ, Jr, Lewis RV, Jarvis DL. Silkworms transformed with chimeric silkworm/spider silk genes spin composite silk fibers with improved mechanical properties. Proc. Natl. Acad. Sci. U. S. A. 2012;109:923–928. doi: 10.1073/pnas.1109420109. [PMC free article] [PubMed] [CrossRef] [Google Scholar]

[114] Xu J, Dong QL, Yu Y, Niu BL, Ji DF, Li MW, Huang YP, Chen X, Tan AJ. Mass spider silk production through targeted gene replacement in Bombyx mori. Proc. Natl. Acad. Sci. U. S. A. 2018;115:8757–8762. doi: 10.1073/pnas.1806805115. [PMC free article] [PubMed] [CrossRef] [Google Scholar]

[115] Tang, X., Ye, X., Wang, X., Zhao, S., Wu, M., Ruan, J., Zhong, B. High mechanical property silk produced by transgenic silkworms expressing the spidroins PySp1 and ASG1. Scientific Reports 11 (2021) 21-29

[116] URL: https://newatlas.com/materials/silkworms-spider-genes-spin-fibers/ (30.10.2023.)

[117] … Genetically Engineered Clothes: Synthetic Biology's New Spin on Fast Fashion. ETC Group, Montreal, 2018

[118] Hauptmann, V., Weichert, N., Rakhimova, M., Conrad, U. Spider silks from plants - a challenge to create native-sized spidroins. Biotechnology Journal 8 ((2013) 1183–1192

[119] Bhattacharyya, G., Oliveira, P., Krishnaji, S. T., Chen, D., Hinman, M., Bell, B., … Jones, J. A. (2021). Large scale production of synthetic spider silk proteins in Escherichia coli. Protein Expression and Purification, 183, 105839. doi:10.1016/j.pep.2021.105839

[120] Fletcher, K. Sustainable Fashion and Textiles: Design Journeys. New York, 2008

[121] Salehi, S., Koeck, K., Scheibel, T. Spider Silk for Tissue Engineering Applications. Molecules 25 (2020) 737-757

[122] URL:https://news.adidas.com/running/adidas-unveils-futurecraft-biofabric---world-s-first-performance Circular Fiber Iniciative. A new textiles economy: redesigning fashion's future. Ellen MacArthur Foundation, Cowes, 2017

[123] Service, R.F. Mammalian Cells Spin a Spidery New Yarn. Science 295 (2002) 419-421

[124] URL:https://www.amsilk.com/business-units/fiber/ (2010.2023.)

[125] URL:https://www.worldbiomarkets.com/wp-content/uploads/2023/07/World_Bio_Markets_Presentation_AMSilk_final_190423.pdf (20.10.2023.)

[126] URL:https://www.labiotech.eu/interview/amsilk-adidas-biodegradable-shoes/ (20.10.2023.)

[127] URL:-shoe-made-from-biosteel-fiber/s/1c2ea0f1-abcf-4f88-a528-ef82e6ea348c (20.10.2023.)

[128] Swingler, S., Gupta, A., Gibson, H., Kowalczuk, M., Healsegrave, W., Radecka, I. Recent Advances and Applications of Bacterial Cellulose in Biomedicine. Polymers 13 (2021) 412-438

[129] Cannazza, P., Rissanen, A.J., Sarlin, E., Guizelini, D., Mirandi, C., Losoi, P., Molinari, F., Romano, D., Mangayil, R. Characterization, Genome Analysis and Genetic Tractability Studies of a New Nanocellulose Producing Komagataeibacter Intermedius Isolate. Scientific Reports 12 (2022) 20520-20532

[130] Choi, S.M., Rao, K.M., Zo, S.M., Shin, E.J., Han, S.S. Bacterial Cellulose and Its Applications. Polymers 14 (2022) 1080-1122

[131] Rathinamoorthy, R., Kiruba, T. Bacterial cellulose-A potential material for sustainable eco-friendly fashion products. Journal of natural fibres 19 (2022) 3275-3287

[132] Gyde, C., McIntosh, C., Rosin, K., Melin, L., Gotsch, W. GUCCI: Luxury Biologically Redefined. KEA Copenhagen School of Design & Technology, Copenhagen, 2012

[133] URL:https://www.popsci.com/technology/article/2011-05/future-your-clothes-will-clean-air-generate-power-and-save-your-life/ (13.9.2022.)

[134] Rees, J. Cultures in the capital. Nature 451 (2008) 891

[135] URL: https://edition.cnn.com/style/article/living-textiles-algae -future-sept/index.html (5.9.2020.)

[136] URL: https://theindexproject.org/award/nominees/5319 (10.9.2023.)

[137] King, A. Bio-art. EMBO Reports 20 (2019) 1-6

[138] Klumper, W., Qaim, M. A meta-analysis of the impacts of genetically modified crops. PloS one 9 (2014) 1-28

[139] Maiti, R., Kumari,C.A., Kalam, A., Huda, A.K.S., Mandal, D., Begum, S. Advances in Cotton Science Botany, Production, and Crop Improvement. CRC Press, New York, 2020

[140] Ghimire, B.K., Yu, C.Y., Kim, W.R., Moon, H.S., Lee, J., Kim, S.H., Chung, I.M. *Assessment* of Benefits and Risk of Genetically Modified Plants and Products: Current Controversies and Perspective. Sustainability 15 (2023) 1-25

[141] Mittler, R., Blumwald, E. Genetic engineering for modern agriculture: challenges and perspectives. Annual Review of Plant Biology, 61 (2010) 443-462

[142] Carnegie, R. Genetic modification of fibres for enhanced performance. In: Tobler-Rohr, M.I. (ed) Handbook of Sustainable Textile Production, Woodhead Publishing, Sawston, 2016, pp. 49-80

[143] Meyer, H., Stamminger, R. The environmental impact of textiles and clothes. In Life Cycle Assessment. Springer, Dordrecht, 2012, pp. 225-246

[144] Hustvedt, G., Dickson, M. A. Consumer likelihood of purchasing organic cotton apparel: Influence of attitudes and self-identity. Journal of Fashion Marketing and Management 13 (2009) 49-65)

[145] Brouk, M., Calsamiglia, S. The effects of genetically modified plants on human health. CAB Reviews: Perspectives in Agriculture, Veterinary Science, Nutrition and Natural Resources 5 (2010) 1-8

[146] Paarlberg, R. Starved for science: How biotechnology is being kept out of Africa. Harvard University Press, Cambridge, 2008

[147] Glover, D. Is Bt cotton a pro-poor technology? A review and critique of the empirical record. Journal of Agrarian Change 10 (2010) 482-509

[148] Jhala, A., Weselake, R.J., Hall, L.M. Genetically Engineered Flax: Potential Benefits, Risks, Regulations, and Mitigation of Transgene Movement. Crop Science 49 (2009) 1943-1954

[149] Rocha-Munive, M.G., Soberon, M., Casteneda, S., Niaves, E., Scheinvar, E., Eguiarte, L.E., Mota-Sanchez, D., Rosales-Robies, E., nava-Camberos, U., Martinez-Carrillo, J.L., Blanco, C.A., Bravo, A., Souza, V. Evaluation of the Impact of Genetically Modified Cotton After 20 Years of Cultivation in Mexico. Front. Bioeng. Biotechnol. 6 (2018) 1-12

[150] URL: https://efsa.onlinelibrary.wiley.com/doi/epdf/10.2903/j.efsa.2013.3200 (17.9.2023.)

[151] Turnbull, C., Lillemo, M., Hvoslef-Eide, T.A.K. Global Regulation of Genetically Modified Crops Amid the Gene Edited Crop Boom – A Review. Front. Plant Sci. 12 (2020) 1-19

[152] Krznar, T. Private communication. Zagreb, October 2023

[153] Čović, *A*. Integrativna bioetika i pluriperspektivizam. In: Šošić, Z., Ajduković, M. (eds) Javno zdravstvo, etika i ljudska prava. Javno zdravstvo, etika i ljudska prava. Manualia Universitatis Studiorum Zagrabiensis. Škola narodnog zdravlja „Andrija Štampar“, Medicinski fakultet u Zagrebu, HR, 2010., pp. 20-27