Chapter

Characterization, Modeling and the Production Processes of Biopolymers in the Textiles Industry

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Abstract

The current chapter is focused on biopolymers and Bionanocomposite as environmentally friendly materials, modeling of the production processes, and coating of bio-textiles. Different industries use biopolymers and Bionanocomposite in for the current environmental applications. Furthermore, composition and classification of biopolymers, the theoretical methods, and factorial experimental designs (FED) for optimization and modeling processes of the environmentally friendly textiles used as an alternative to traditional chemical textile products with zero to low environmental footprint are studied at acceptable cost. This chapter will also describe the novel optimization, experimental factorial design, and how the novel modeling methods will help less experienced polymer designers in taking the best experimental decision controlled by the design factors. It also discusses how the fully biodegradable polymers support the industry by decreasing the processing energy, material and manufacturing costs. Finally there are an overview of the current and future developments of biodegradable polymers applications in modern bio-textiles industries.

Keywords: biodegradable textiles, biopolymers, coating, textiles industry

1. Introduction

The worldwide production of non-renewable textiles has increased, and textile producer are searching for solutions to overcome the waste problem [1]. There is a new generation of bio- textile materials based on petroleum, animal sources or agricultural [2] with a reasonable solution [3]. Micro-organisms (such as fungi and bacteria) broke down the biopolymers in the environment; such as a cotton fiber [4].

Table 1 [5] illustrates how degradation results are dependent on biodegradation type, the converted substrate, and residue makeup, with full degradation. Biodegradation happens within the biosphere, the organic chemicals are changed to simpler compounds and mineralized.

Researchers have established many standardized testing procedures for the evaluation of the compost-ability and biodegradability of polymers using mixed cultures [6–11]. Others have studied the effects of blend ratios on the degradation process on biopolymers [12–14]. The life cycle analysis is one of the methods simulating the development of biopolymers, with green fibers having a shorter life cycle than those that are oil-based. A green life cycle is given in **Figure 1** [15].

Original substrate	Biodegradation Type	Converted into
Polymer	Aerobic	CO2& H2O & (Biomass & Residue)
	Anaerobic	CH4& CO2& H2O & (Biomass & Residue)

Table 1.
Degradation results depending on biodegradation type [5].

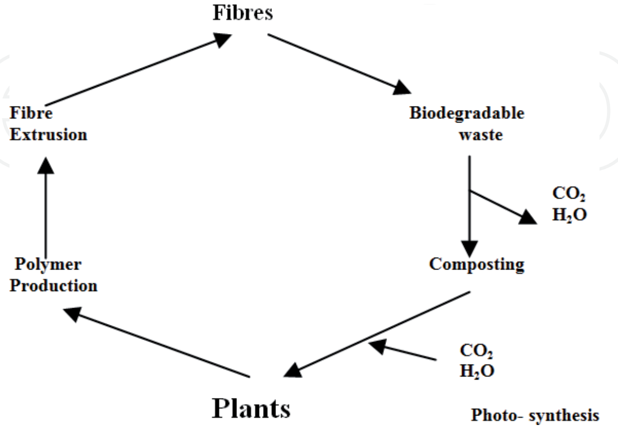


Figure 1.
Life cycle of compos-table biodegradable fibers [15].

Biodegradable polymers are smart polymers which are currently being used in many fields such as tissue culturing, biomedical, agriculture, food and intelligent textiles [16, 17]. Considering environmental hazards [18], the main factors controlling the market scope and size of biodegradable polymers are material properties and cost [19]. Plasticizers are added to biopolymers during the extrusion process to decrease the intermolecular hydrogen bonds, to limit microbial growth, and to stabilize product properties [20]. The degradation rate of blended bio-polymers set the degradability of the produced mix [21]. Bio-materials take a key role in the of nanotechnology improvement as friendly materials. Nanomaterials have attracted considerable attention in medical delivery applications [22]. Classification and composition of biodegradable polymers will be briefly discussed; their applications in modern bio-textiles as well as textiles. Furthermore, modeling of biopolymers' melt spinning process and factorial experimental design, optimization of the production processes for intelligent bio-fibers via statistical experimental design (SED), forecasting program for the fiber extrusion, as well as the future applications of biodegradable polymers in the modern textiles industry are also presented.

Electro-spinning of biopolymers has gained substantial attention in the last two decades, triggered mainly by the potential applications of electro-spun nanofibers in nanoscience and nanotechnology for tissue engineering [23]. Tissue engineering is a advanced technology, electrically conductive biodegradable composites are used in tissue engineering and bioelectronics [24].

2. Biodegradable polymers, classification and composition

Biopolymers are made from the agro-polymers (starch and cellulose), or are obtained by microbial production such as the polyhydroxyalkanoates. In polyhydroxybutyrate production, sugarcane, mustard, switch grass and corn have been recognized as candidates for genetic modification. Some polyhydroxybutyrate types polymerized chemically from agro-resources or chemical synthesis [25]. Classification of biopolymers and their origins are listed in **Table 2** [3].

Biodegradable polymers are produced from aliphatic (linear) highly amorphous, flexible polymers and aromatic rings semi-crystalline, rigid polymers. The classification, development and synthesis of the main bio-based polymer types from biomass and microbial production, or from renewable resources are listed in **Figure 2** [26, 27]. Aliphatic-aromatic copolymers can be synthesized and used in biomedical and agricultural applications by employing non-woven technology to produce products such as disposable wipes, refuse bags, seed mats and erosion control items [28, 29].

Biopolymers classification			
Natural		**Synthetic**	
Proteins	Gelatine, casein, silk and wool	Aromatic Polyesters	Polybutylene succinate terephthalate
Polysaccharides	Starch, cellulose, lignin and chitin	Aliphatic Polyesters	Polyglycolic acid, Polybutylene succinate and polycaprolactone
Lipids	Castor Oil,Plate Oil and animal fats	Aliphatic-Aromatic co-Polyesters	
Polyesters 1- micro-organism or plants	1-polyhydroxyalcanoates, poly-3-hydroxybutyrate	Polyvinyl-alcohols	
2- bio derived monomers	2- polylactic acid	Modified Polyolefin	Polyethylene or polypropylene & specific agents

Table 2.
Classification of biopolymers [3].

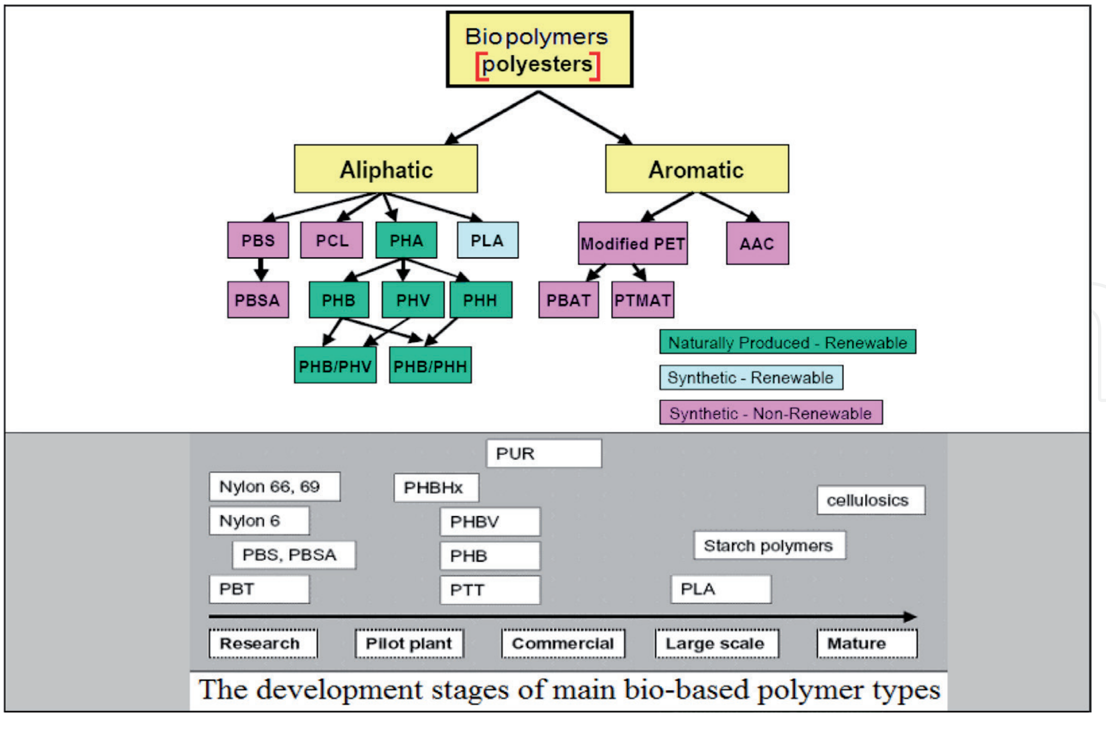


Figure 2.
*Classification and development of bio-based polymers [26, 27]. **PCL – polycaprolactone; PBS – polybutylene succinate; PTT– polytrimethyleneterephthalate; PBSA – polybutylene succinate adipate; PHH – polyhydroxyhexanoate; AAC – Aliphatic-Aromatic Co-polyesters; PHV – polyhydroxyvalerate; PET – polyethylene terephthalate; PLA – polylactic acid; PBAT – polybutylene adipate/terephthalate; PHA – polyhydroxyalkanoates; PTMAT– polyethylene adipate/terephthalate; PHB – polyhydroxybutyrate (type of PHA); PBT– polybutylene succinate; PHBV, PHBHx- types of PHA; PUR– polyurethanes.***

3. Techniques for the preparation and synthesis of biopolymers

Due to biopolymers' biodegradability and substantially, their applications are environmentally friendly [30]. Biopolymers properties influence the shelf-life and the product's biodegradability. The possibility of increasing the strength of bio-polymers and bio-composites have been studied without decreasing the biodegradability [31].

Poly (butylene succinate-co-butylene terephthalate) co-polyesters have much better thermal stabilities in nitrogen compare to air [32]. It was reported that "Poly(butylene succinateco- ethylene succinate-co-ethylene terephthalate)"can be polymerized from three pre-polymers of ethylene succinate, butylene succinate, and ethylene terephthalate by direct poly-condensation [33]. An ideal random copolymer (Poly(butylene terephthalate-succinate-adipate) from aliphatic units (BA and BS) has a rubber-like tenacity curve [34]. Aliphatic aromatic copolyester (AAC) could potentially modify the basic BTA (1,4-butanediol, adipic acid, and terephthalic acid) structure and may become commercialized [35, 36]. Development of biodegradable aliphatic-aromatic co-polyesters began with the study of different modes of degradation [37, 38]. Aliphatic biopolymers are biodegradable and sensitive to hydrolysis; their flexible chain fits easily into the active site of an enzyme [39]. Aromatic biopolymers have favorable physical properties such as resistance to bacterial, fungal and hydrolysis attack [40] but degrade if they are co-polymerized with aliphatic bio-polymers [41]; breaking down by means of hydrolytic or/and enzyme degradation [42]. It was reported that inclusion and/or incorporation of aromatic monomer groups in the aliphatic polyesters' main chain, can potentially enhance their mechanical properties [43]. The randomness and the length of the polymer chains aid in understanding the biodegradation behavior for aliphatic-aromatic co-polyesters [44]. Polyester-based nano-particulates could be easily prepared by solvents diffusion or evaporation methods. The degradability of the oligomers would decrease by increasing chain length [45], thus the amorphous part of the polymer would become that which is degraded [46].

4. Biopolymer and industrial applications

Biodegradable polymers used widely in industries such as textiles, packaging, fast-food container and packaging, paper coating, agriculture mulch films, medical products, tubes, lawn and garden waste bags, disposable wipes, erosion control, biologically-based resins, car parts, glass fibers agents, as well as coatings and adhesives [3, 47, 48]. Various blending ratios of regular and waxy corn starches with co-polyester were extruded into loose-fill foams [49]. PCL (polycaprolactone) are used to made spun fibers, scaffold fibroblasts and myoblasts for soft tissue engineering [15]. Natural biopolymer-based films and the packaging materials have been studied [50, 51]. Ochratoxin-A as well as amycotoxinis a common food contaminant that enters the human body through the consumption of improperly stored food products and can be used as a electrochemical biosensor [52]. Polysaccharide and protein based biopolymers can be utilized as coatings to enhance the fruits and vegetables quality; The medical biopolymers applications are [53] include extracorporeal (i.e., artificial kidneys, fluid lines, dialysis membranes, catheters, wound dressings, artificial skin, etc), temporary implants (i.e., degradable sutures, as well as arterial stents, tissue/cell transplants' scaffolds, temporary vascular grafts, etc), and permanently implanted devices. Biopolymer fibers with typical morphology find applications in bone tissue engineering [54] and as a degradable nano-fiber [55]. Wound dressing materials must be biocompatible, anti-bacterial, prevent infection, and provide a suitable moist environment [56, 57]. Chitosan complexed with gelatin has been useful as a surgical dressing at a ratio of 3:1 (chitosan:gelatin), as it stimulates hemostasis and accelerates tissue regeneration [58, 59]. Their fabrication provides appropriate biodegradability and excellent cell adhesion activity, both useful in making a novel and elastomeric bioactive vascular tissue scaffold [60]. A fiber based on chitosan and starch which was loaded with drug has had successful applications in drug delivery [61]. Various fabrication methods have been employed in the preparation of bio-polymeric membranes and a film-casting process [62, 63].

5. Biopolymers and biodegradable textiles industry

The textile industry has played a important role in the exchanging of goods and impacted by novel techniques through the development of more environmentally friendly processes [64–67]. Many biodegradable fibers may be natural, regenerated or synthetic such as Ingeo (Natureworks), LLC produced from corn, a biodegradable thermoplastic polyatide (PLA); Lenpur produced from wood pulp of harvested white pine tree clippings; and Modal and Tencel/Lyocell produced by Lenzing from wood pulp of beech and eucalyptus trees, and biodegradable aliphatic/aromatic multi-block co-polyesters. The largest application of alginates in textiles can be found in textile printing, the spinning and weaving of temporary fibers from calcium alginate [15]. Bio-based fibers like X-Static, Meryl Skinlife, Diolen Care, Trevira Bioactive are enriched with innovative antimicrobial products such as technical products, working uniforms, sportswear [68].

5.1 Fibers industry and biodegradable polymers

The melt spinning processing technologies with availability of biodegradable materials along have aided in qualitative and quantitative improvements [69]. The fibers reinforcing improve the relationship between the process parameters and the material properties [70]. Many natural fibers added to biopolymers as reinforcements (flax, cellulose acetate, bamboo, pineapple, ramie, kenaf, henequen, jute, sisal, and hemp); improving the strength without affecting the biodegradability [71]. Fibers of the poly(β-hydroxybutyrate) were produced via multistage melt-extrusion as well as gel-spinning [72]. The dry-jet wet spinning method was used to extrude the cellulose/NH3/NH4SCN solution [15]. By "dry-jet wet spinning" and using a cellulose/hydrolyzed starch-grafted-polyacrylonitrile solution, the mechanical properties of Lyocell fibers were improved [73]. An extruded Lyocell fibers were reported have potential uses in filters, geo-textiles, surgical gauze [74]. Cellulose fibers are used for the design of intelligent, bioactive, and biocompatible composites [75]. Preparing sol–gel derived biodegradable SiO2 gel fibers [76] for drug release consists of three steps: an initial burst, followed by a diffusion-controlled release behavior, and finally a step with a slower release rate. By incorporating responsive hydrogels in textiles, the surface energy switches between hydrophilic/hydrophobic, with the results listed in **Table 3** [77].

There is good compatibility between the chitosan obtained from shrimp shells and starch-based polymers when forming a chitosan/starch fiber. Some researchers have made fiber from starch and biodegradable glycerine-based polymers with/without PLA and glucitol, while others extrude high strength PLLA fibers. The type LA 0200 K of PLA is processed at a high speed spinning (draw ratio = 6)in a spin drawing [78]. A fiber from soya bean protein is crafted by forcing a globular protein to become a fiber forming protein; the fiber has to be cross-linked if fibrous products are to be obtained [79]. Fibrous materials are segregated into two basic groups, the first can be placed on the surface of materials (i.e., surgical covers, gauzes, diapers and tampons), and the second can be placed inside an organic tissue (i.e., surgical threads, tendons and ligament implants, meshes, stents, and vascular grafts).

Biopolymer	Monomer	Natural origin	Production Micro-organism	Hydrogel	Fiber	Commercialized
Cellulose	glucose	Plants, Micro-organism	A. xylinum	—	Yes	Wound covering
Hyaluronic acid	N-acetyl-glucosamin	Vertebrats, Streptococci	Streptococci, *B. subtilis*	Yes	No	Dermal fillers, Visco supplementation
γ-PGA	Glutamic acid	Bacillus spp., Micro-organism	Bacillus spp.	—	No	Cosmetics, fertilizer, flocculant
Silk	protein	Bomby-xmorii, spider, bee	*E. coli*,	Yes	Yes	Cosmetics, cell adhesion scaffolds
Collagen	protein	Vertebrates	Yeasts	Yes	Yes	Scaffolds, Cosmetics
Chitosan	N-aeetyl-glucosamin (partly deacylated)	fungi	Yeast, bacteria	Yes	Yes	Flocculant, Filter membranes, Cosmetics, wound covering

Table 3.
Monomers, origin and fiber formation of smart biopolymers [77].

5.2 Fabric industry and biodegradable polymers

Weaving, knitting, nonwoven web forming (carding, spun-bond and wet-laid) and nonwoven-bonding (stitch-bonding, needling, calendaring and hot air bonding) are fabric forming technologies. Biodegradable non-woven webs and disposable articles contain fibers such as cotton, hemp, milkweed floss, flax fiber, wool, silk, chitin and chicken feathers [80]. There are many examples in biodegradable nonwoven such as biodegradable cotton-based nonwovens (cotton/cellulose, or cotton/ biodegradable co-polyester) and (PTAT co-polyester and PLA). Cotton/(co-polyester/PP) nonwovens along with absorbency and flexural rigidity have suitable mechanical properties and they are better than that of cotton/co-polyester nonwovens [81–83].

Sanitary and medical textiles, geotextiles, filtration media, within the automotive industry, PLA based hair caps, Bionolle 3001 nonwovens, Landlok biodegradable erosion control coconut fibers mats, Kenaf fiber nonwovens, refuse bags, drain filters made from fine denier PLA nonwovens, and biodegradable filter materials are used for both air and liquids. A biodegradable thermoplastic polymer and a plasticizer could be used to produce a starch matrix of the finely attenuated fibers which could have applications as environmentally degradable nonwoven webs and articles [84].

Researchers have produced biodegradable cotton-based, nonwovens by using blends of cotton, flax and biodegradable thermoplastic fibers that act as binders [85]; Biodegradability was monitored, with 40% of the initial weight lost after 8 weeks composting [86]. To reduce the cost, researchers have made a pure nonwoven material from co-polyester by a direct melt-blowing process [87]. Woven tubes (3 to 6.5) mm are developed using Polyglactin 910 biodegradable yarn on a narrow width loom [88].

Biodegradable poly (L-lactide-co-caprolactone) fabrics of nano/micro- structured can be made Using CH_2Cl_2 as a solvent in electro-spinning. The electro-spun elastomeric nano-fiber fabric is used as a functional scaffold in tissue engineering (i.e., cardiovascular, muscular) [89]. The Belgian Textile Research Centre's projects include: Noterefiga for bio-based comfort textiles, Bioagrotex for agro-textiles (agriculture, horticulture, gardening and construction), Green-Nano-Mesh for medical areas, Dura cover for woven PLA taped ground covers, Hortaflex and Weed Control for PLA based nonwovens, and the BiobasedFilbio project for knitted PLA insect screens for climate control.

There are various commercialized fabrics made from naturally derived biopolymers such as those found in the Ethical Fashion Forum in London: POLY Acid Ingeo bio fibers; QMilchfibers, Lenzing's Modal fiber, Micro Modal fiber, Lyocell fiber, POLARTEC polyester, unique corn-based PLA fleece; and Cork shell made from cork to form high quality textiles for lightweight spring and summer jackets. Biopolymers based in intelligent and/or stimuli responsive polymeric systems have been developed and reported by researchers for the functional finishing of textiles [90]. Scientists proposed changes of the polymer backbone in a reversible formation of PLA-dye complexes [91]. Sorona is used in the coat fabric for jackets, trench coats and outerwear with its 37% renewably sourced plant-based components; they lose their wrinkles with one quick snapping motion. Bio-based fabrics made of wool and "BIOPHYL" or "TENCEL". Some commercial products are made from spider silk [92] and could be used in the bullet-proof vests industry [15].

5.3 Fiber and fabric coatings and biodegradable polymers

Modification techniques of the biopolymer's surface includes coating, oxidation by low-temperature plasma, and surfactant addition blending with various derivatives [93]. Cyclodextrins or linear carbohydrate biopolymers were attached to the textile to allow frequent use and washing [94]. Regenerated cellulose fibers were treated by plasma activation using a chitosan solution [95]. Cellulose was coated by chitosan nano-particles to reduce the cost and non-toxic methodology [75]. While studying their development as well as characterization, both the organic cotton based bandages and cotton were coated separately on the gauze structure using chitosan-sodium alginate polymer, calcium-sodium alginate polymer and subsequent mixtures of the two, thereby improving its antibacterial and wound healing properties [96]. For dyeing and printing, the dextrin derivative surfactant improves the whiteness and wetting properties of cotton fabrics [97]. The chemical surface treatments of jute fabrics involve bleaching, dewaxing, cyanoethylation, alkali treatment and vinyl grafting are used as reinforcing components in biodegradable matrix composites, which are environmentally friendly materials [98]. A Knitted Dacron graft made of polyethylene oxidepolylactic acid were coated with a polymeric biodegradable sealant [99]. Layer-by-layer electrostatic deposition is used to coat the material by adding dextran sulphate and chitosan to a soybean based polymer [100]. The functional finishing of the micro- and nano-sized hydrogels improve response times [101].

Nano-composites and nano-structured coatings improve mechanical strength and flexibility, temperature and moisture stability, as well as durability. "Metal Rubber"(Nano Sonic Inc.) combines the rubber and metal properties, and it is used in artificial muscles, electrically charged aircraft wings, and protective biopolymer clothing [102]. Hydrogel-based biopolymers are used for the functional finishing of textiles by surface modifying systems [103].

6. Case study: modeling of biopolymers' melt spinning process

All the production process parameters must be controlled to ensure the quality and then the significant main factors must be analyzed [104]. Commercially, it is a challenge to develop a new competitive product [105]. Some research is based on statistical analysis, mathematical simulation and modeling of the processes of fiber formation, and examples of their post-processes have been reported in literature [106–116]. The practical software-based approach has improved the confidence benefits of experimental design and simulation [117]. **Figure 3** shows a flow chart for the methodologies used for obtaining the program, starting from the data and statistical modeling methods and SED. Online quality control tools were utilized for prediction, measurement, correction as well as adjustment and feedback [118].

The aliphatic aromatic co-polyester fibers extrusion process was investigated in this work, and statistically modeled [119]. A linear biodegradable oil-based polymer (LAAC-flexibility component of Solanyl) and branched aliphatic-aromatic co-polyester (BAAC-Ecoflex F BX 7011) were used to study the effects of the extrusion process and the properties of fibers. The study describes the melt spinning of aromatic-aliphatic co-polyester depending on the extrusion thermal profile effect on as-spun fiber properties. The molten material flowed easily when the viscosity decreased and smoother extrudates were obtained at shear rates greater than 4.5 s-1 [120].

6.1 Factorial experimental design for melt spinning of biodegradable fibers

Factorial experimental design provides data about the optimization of the average response values in regards to the factor levels [121]. The STATGRAPHICS program is used to design the experiment random order matrix and to simulate the main data in one block experiments.

The studied factors for the fiber extrusion process include: speed of spin finish, quenching air speed, metering pump speed, and winding speed, as well as, melt-spinning or extrusion temperature. The analyzed levels of each parameter were listed in **Table 4**; the thirty-two trials matrix for the five control factors was applied for as-spun fibers analysis. **Figure 4** shows an SEM photomicrograph of the cross-section and surface of the fibers; fibers had an acceptable uniform surface and possessed a uniform circular cross section.

In this case study [122–124], several statistical tools were utilized for statistical analysis including the surface plot, normal probability plot, the main effect plot, pareto chart, interaction plot, as well as analysis of variance (ANOVA). Implementation of forecasting statistical methods plays a major role in creating a planning program and

Figure 3.
The flow chart of the statistical method.

Factor abbreviation	Factor name	Level	
		Low	**High**
T	Melt-Spinning Temperature, °C (LAAC)	130	145
	Melt-Spinning Temperature, °C (BAAC)	145	160
MPS	Speed of Metering Pump, rpm (2.4 cc/rev))	6	12
QA	Speed of Quench Air, % (velocity m/sec)	35	50
SF	Speed of Spin Finish Pump, rpm (0.15 cc/rev)	0.35	0.50
WS	Winding Speed, m/min	50	100

Table 4.
Factors and the selected levels for the spinning experiments of as-spun fibers.

a plan for the production process regression. A detailed experimental arrangement of the calculated results of spin draw ratio, birefringence, drawability, die head pressure, crystallographic order as full-width half-maximum (FWHM), filament temperature averages, count, tensile properties, diameter, and thermal shrinkage was completed. According to the drawability characterization, biodegradable fibers (i.e., as-spun) should consist of a drawn construction and be conducive to orient along the fiber axis of the chain [125]. There is a clear relationship between the draw down ratio and the orientation of the fibers and having a significant effect on the drawability. In other words, the overall orientation of fibers was increased and the draw ratio decreased as the spin draw ratio increased. Temperature significantly influenced the spin (down) draw ratio and fiber drawability that affects the flow rate and tension value. To study the effects of the factors as well as their statistical significance an ANOVA study was conducted. A factor was considered to have a significant effect if the F ratio (an ANOVA statistic) was shown to be more than the statistical value (F /4.49/at the appropriate level $\alpha = 0.05$) or had P-value smaller than 0.05. The ANOVA results from the experiments are presented in **Table 5**.

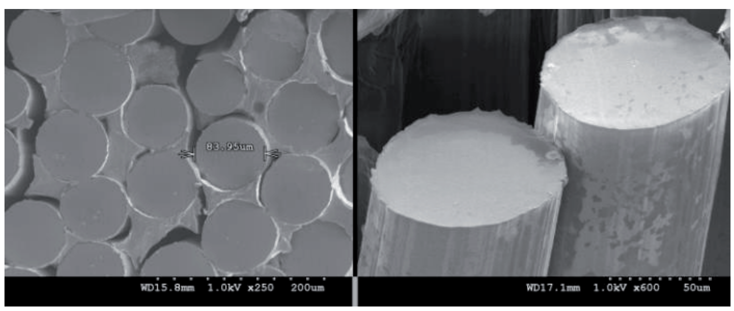
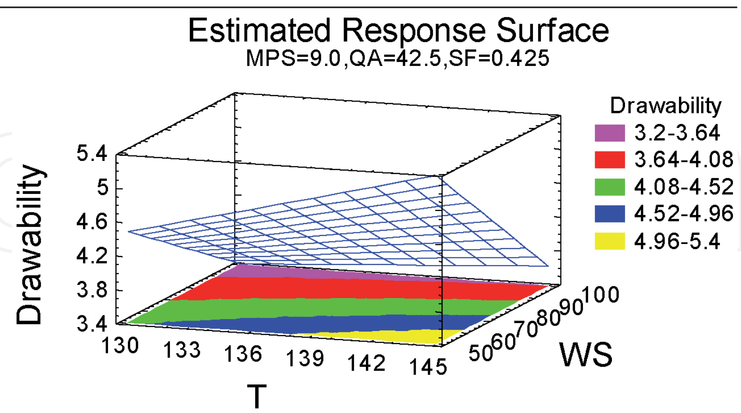


Figure 4.
The surface and cross section of the biodegradable fibers [119].

Source	Drawability	
	F	P
T	19.7	0.000
MPS	112.1	0.000
QA	0.2	0.666
SF	0.3	0.599
WS	120.5	0.000
T &MPS	0.1	0.737
T & QA	0.2	0.666
T& SF	0.1	0.810
T& WS	7.2	0.016
MPS& QA	2.0	0.176
MPS& SF	0.2	0.666
MPS& WS	1.5	0.240
QA & SF	0.0	0.885
QA & WS	0.0	0.962
SF& WS	0.3	0.599



Estimated response surface for the drawability
(T& WS)

Estimated response surface for the drawability
(T& WS)

Table 5.
ANOVA results of factor effects on the drawability.

The significance of factors were PWS > PMPS> PT in the drawability analysis, while no significant effect was observed due to other factors. The P-value (0.016) of T&WS is lower than 0.05 and therefore is significant. The most significant factors were T, MPS and WS. Metering pump speed was observed to have interaction with winding speed; the speeds' relationship oriented the fiber chains as well as added different spin draw ratio, having an effect on drawability later. Multiple and individual regressions optimized for the quality required for various applications and identified the factors' effects and interactions to determine the direction of those that are significant by using the estimated response surfaces. A twist was observed in the 3D surface response diagrams for T and WS (**Table 5**), thus the interaction is significant and agrees with the previous statistical results. This interaction will affect the structure of the as-spun fibers and help to extend the chains to achieve high orientation along the axis of fiber. The regression Eq. (1) was obtained from the analysis and forms the simplified models of the experimental data (coded values in **Table 4**). The regression equations forecast the fiber properties and accurately predict the properties in the final fibers produced. The mathematical regression model forms one of the basic source codes in the designed forecasting application, which will present the extrusion of aromatic-aliphatic co-polyester fiber.

$$\begin{aligned}\text{Drawability} = {} & a + b*T + c*MPS - d*QA - e*SF + f*WS \\ & + b1*T*MPS + b2*T*QA + b3*T*SF - b4*T*WS \\ & - b5*MPS*QA - b6*MPS*SF - b7*MPS*WS \\ & - b8*QA*SF + b9*QA*WS - b10*SF*WS\end{aligned} \tag{1}$$

Where: a, b, c, d, e, f b1–10, are statistical constants for the drawability calculated by the **STATGRAPHICS** program.

They were also affected by high extrusion speed at which the shear rate affects the morphological structure [126]. Employing the same technique, the overall orientation, spin draw ratio, crystallographic order, die head pressure, diameter, tensile properties, thermo-graphic measurement and thermal shrinkage were also analyzed and modeled. The statistical analysis models simulated the significant factors, their interactions, and gave useful results with some expected outliers which could be due to experimental and/or testing errors.

6.2 Forecasting program for the fiber extrusion

In the programming process, the relationship between the key inputs (factors) and the performance measures (responses) using factorial statistical experimental design technology are reported. The statistical data and regression formulas are represented as a computer application. Microsoft Visual Basic was used to write a forecasting program that could be utilized for the as-spun AAC fibers' extrusion process. The program offers the management of regression models for responses based on statistical factorial design, design analysis and process simulation. Conversion and summarization of the C++ source code into a simple flow chart was completed (**Figure 5**).

After selecting the polymer grade, the program requests the parameters' values, calculates the values' responses by using regression equations and then gives the results. The data from the input conditions was used to obtain the structural, mechanical and physical data. The program was designed as two windows. The first window is the input window for process conditions (**Figure 6**); the second interface is the output result window (**Figure 7**).

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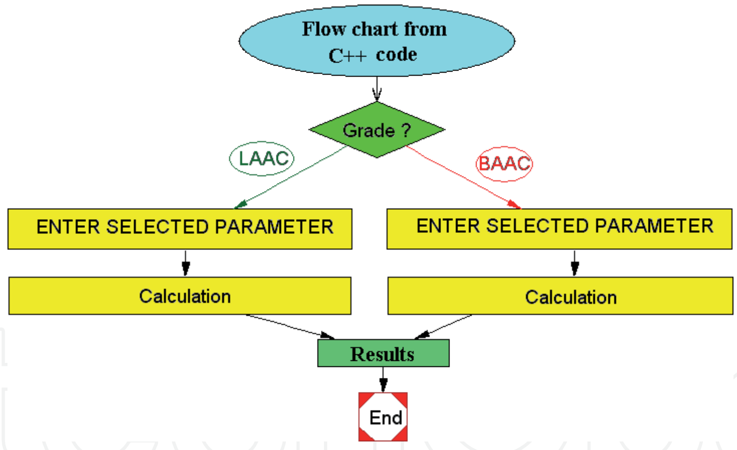

Figure 5.
Schematic program process.

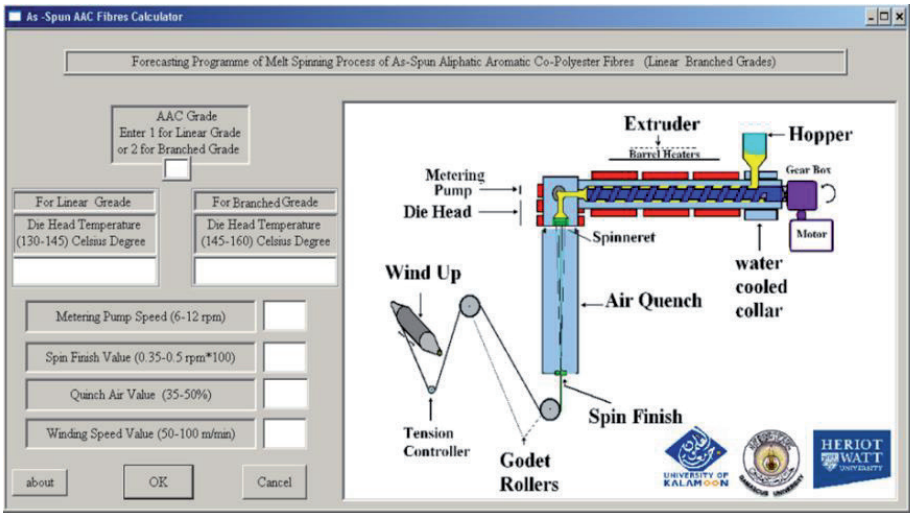

Figure 6.
The main input interface/window for process conditions input.

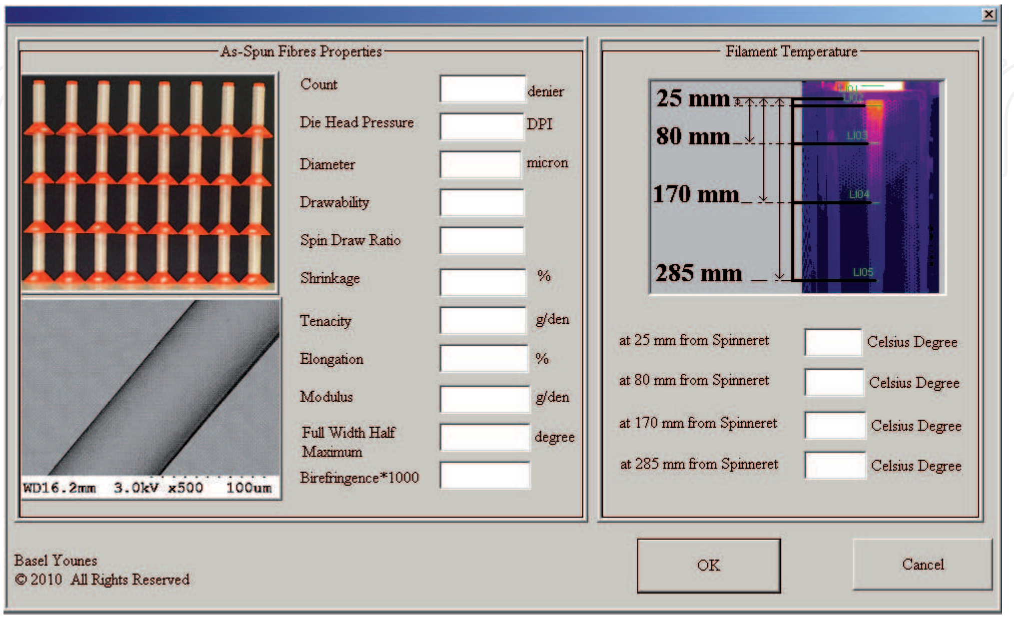

Figure 7.
The output interface/window for filament temperature in the machine's cooling window and the fiber's structural, mechanical and physical properties.

Each factor is represented as a record and it may be owned by more than one record, leading to a network-like structure. The multiple regression analysis and previous forecasting models provide a basis for identifying the relationship between process-input and process-output data; and formation of a source code to be used in the forecasting program. The 30 hole spinneret (diameter is 0.4 mm, l/d ratio is 1.2) was used. The programmed application powerfully supports product development, design process control, quality assurance and product performance evaluation; it displays data on the screen or sends data to a file or other devices. **Figure 7** shows the output interface/window for filament temperature in the machine's cooling window and the fiber's structural, mechanical and physical properties. Each factor is represented as a record and relationships between other factors through a matrix design.

7. Textiles industry future and biodegradable polymers

Reusing and recycling properties are the main goals for the environmentally friendly textile industry [127]; saving time, cost, and materials. There are various methods in which bio-polymers are processed, such as polymerization, crystallization and manufacturing depending on the polymer's nature and application [128]. Biomechanical engineering design of clothing products is still at the development stage. Biological health and psychological happiness are critical indexes reflecting quality of life. Bio-material processing and bio-garment simulation has grown from basic shape modeling to the modeling of cloth with complex physics and behaviors. Bio-textile engineering approach offers precise details of modeling cloth at a micro, the graphics software simulate the fabric to form the final deformation and animation. The acceptance of biopolymer materials as commonplace in textile industry require the passage of time. Biopolymers boast greater environmental consciousness than most modern technologies, as they have the potential to significantly reducing cost, energy and materials for future generations. Modeling crosses the boundaries of academia, science and industry [129].

8. Conclusion

This chapter reviewed the relationship between the bio-polymers and the modeling of the production processes in textile industry. The theoretical techniques and factorial experimental design together with the biopolymers' classification and preparation methods open new field of the modern textiles, from fiber to fabric forming and coating technologies. Biopolymer use in the textile industry is an exciting and innovative area of research for scientists and researchers alongside textile and polymer engineers.

In the case study, results obtained should answer the fairly complex demands posed by multi-applications running concurrently with the application programs (or processes) in the computer. It is limited by the regions of the studied factors between the factor levels. The program's results help in achieving a balance between the enhanced properties and the fiber cost while saving processing cost, material and the power required for enhancing fibers. After finishing the processes for modeled biodegradable fibers, the process conditions (process-input data) selected depends upon the user. The produced environmentally friendly, economical, energy saving fibers can be potentially utilized in textiles, agricultural, as well as horticultural applications.

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