13
Soya bean protein fibres – past, present and future

M M BROOKS, University of Southampton, UK

13.1 Introduction

Creating a warm, soft, comfortable and economically viable man-made fibre equivalent to wool, a natural protein fibre, has long been a goal for textile scientists and manufacturers. Developments in biodegradable fibres from renewable resources in the late twentieth century have revived interest in these fibres. The development of a wool-like fibre from soya beans is a story of technological innovation (and failure) interlinked with changing political and ecological priorities. Soya bean protein fibres were one of several innovative and pioneering regenerated protein fibres which were developed in the mid-twentieth century. However, technical problems meant that the resulting fibres could not compete with either natural fibres or the newly developed synthetic fibres and so having limited commercial application failed to become mainstream fibres and were almost totally forgotten. Spasmodic interest continued, but these fibres have only recently become the focus of renewed interest and commercial activity with research taking off again in the last decades of the twentieth century with the development of new processing methods and fibre structures. This chapter explores the two phases of the development of soya bean fibre using contemporaneous documentary evidence such as patents, technical journals, research papers and home economics literature. Technical data about the different fibres is presented where this is available. Samples of the mid-twentieth century soya bean protein fibres have not yet been located so textual evidence cannot be confirmed through analysis. Conversely, contemporary fibres can be acquired, but relatively little data is yet available in this rapidly developing area.

13.2 The soya bean plant

The soya bean plant (genus *Glycine*; species *Max*; family *Leguminosae*; sub-family *Papilionoideae*) is a bush-like annual, growing about 1.8 m tall and bearing pods which each contain several smooth seeds – the soya beans. It was grown in the Yellow River valley, North China as early as 3000 BC and remains an important crop in China and Japan. Missionaries brought seeds to Europe in the eighteenth century and soya beans were first cultivated in the USA in the nineteenth century. By the late 1990s, 70 million hectares worldwide were being used for soya bean cultivation, mainly in Argentina, Brazil, China, India and the USA. Thousands of varieties of soya bean are known and intensive research has been undertaken into soya bean breeding for a variety of applications. For example, research in Australia has explored the development of improved soya bean genotypes suitable for use in poultry diets.[1]

Soya beans became a significant crop in the USA in the early twentieth century in a linked producer/processor development known as the 'American soya complex' and were well established by the 1930s. Thousands of new varieties were introduced,[2] and by 1933 over 1,400,000 hectares were being used for soya bean production, producing over 600,000 kg of soya bean oil and equally large quantities of soya bean meal.[3] In 2002, 29.6 million hectares were planted with soya beans producing about 110 million metric tonnes annually; USA soya beans have an export value of $7.2 billion, the major markets being Europe, China, Mexico and Japan.[4]

Research into improving plant and bean characteristics has been undertaken in America since the 1930s. For example, two bulletins published by the Agricultural Experiment Station, Kansas State College of Agriculture & Applied Science[5,6] explored methods of soya bean cultivation and reported on tests on over 60 varieties of soya beans. The US Regional Soybean Industrial Products Laboratory (now the National Soybean Research Laboratory) was established at Urbana, Illinois in 1936, developing soya bean varieties, disease management and different end uses. Since the 1980s, the US Department of Agricultural Research Service has developed 66 different soya bean types. Genetic modification techniques are now being used to produce beans for very specific needs, but concern has been expressed that soya bean breeding has led to 'a dangerously narrow genetic base' and US gene banks have sought to introduce Chinese soya bean genetic materials into American strains.[7] Du Pont researchers have been experimenting with modifying soya beans to give beans with a higher oil or protein content.[8] Monsanto have produced a genetically modified soya bean cultivar, Roundup Ready™. This variety has been designed to be resistant to their Roundup© herbicide although the implications of the development of patented seeds is causing concern to Chinese farmers.[9]

Soya beans contain oil (180–220 g kg^{-1}) and approximately 35–45% protein (370–420 g kg^{-1}). The amino acid content differs significantly from that of wool and silk protein (see Table 13.1). Soya bean protein content is higher than that of peanuts (approximately 25% protein) and maize (approximately 10% protein).[10] The principal components of this protein are

13.1 Soya bean fibres made by the Ford Motor Company, early 1940s. From: *America's Fabrics* reproduced in Kiplinger, J. 2003. *Meet the Azlons from A–Z: Regenerated & Rejuvenated.* www.fabrics.net/joan103.asp. Accessed 16 November 2004.

β-conglycinin (trimeric structure) and glycinin (six subunits, each a basic polypeptide and an acid polypeptide connected with a disulphide bond) with other proteins in lesser quantities such as trypsin inhibitors, lipoxygenases and pectins. The complex association–dissociation behaviours of β-conglycinin and glycinin, resulting in the formation of soluble aggregates, are a critical factor in the processing of soya bean protein for the formation of fibres.[11,12]

13.3 Naming regenerated protein fibres

In the 1940s, there was considerable uncertainty over how to categorise and name regenerated protein fibres. Researchers were experimenting with a variety of animal and vegetable protein sources to create a wool-like fibre

Table 13.1 Percentage of amino acid content in soya bean protein compared with that of wool and silk

Amino Acid	Soya	Wool	Silk
Alanine	4.12 (1.7)	4.10	26.40
Arginine	5.80 (8.3)	3.60	1.05
Aspartic acid	3.86 (5.7)	7.27	2.00
Cystine (sulphur containing)	1.00 (1.1)	11.30	–
Glutamic Acid	19.46 (19)	16.00	2.03
Glycine	0.23 (0.7)	6.50	43.80
Histidine	2.30 (2.2)	0.70	0.47
Isoleucine	4.00 (2.4)	–	1.37
Leucine	8.40	9.70	0.80
Lysine	5.40 (5.4)	2.50	0.88
Methionine (sulphur containing)	2.00 (1.8)	0.35	–
Phenylalanine	5.30 (4.3)	1.60	1.50
Proline	3.04 (4.3)	7.20	1.50
Serine	6.00	9.50	12.60
Threonine	4.00 (2.1)	6.60	1.50
Tryptophan	1.50 (1.7)	0.70	–
Tyrosine	4.30 (3.9)	6.10	10.60
Valine	4.50 (1.6)	5.50	3.20
Ammonia	–	1.18	–
Hydroxylysine	–	0.10	–

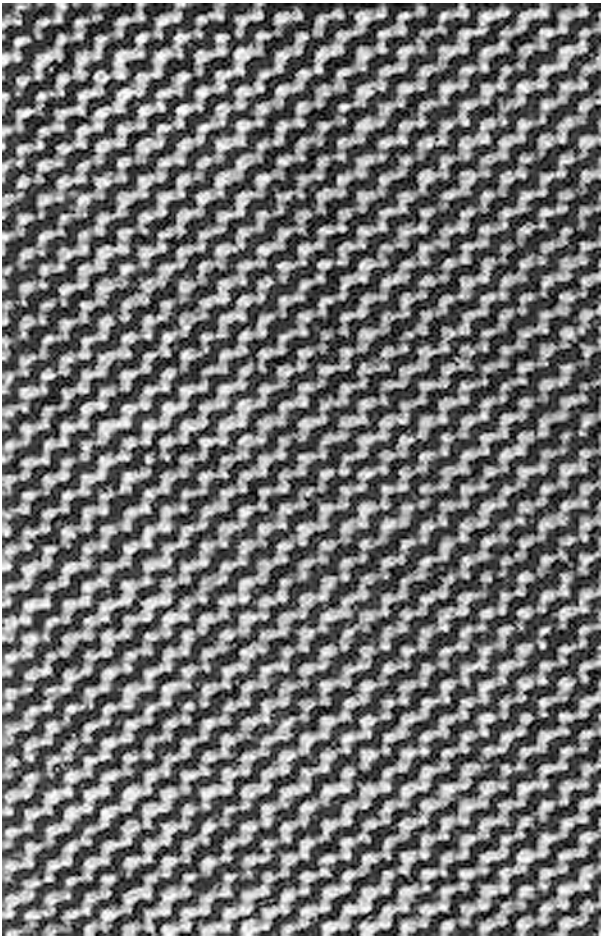
Data from Traill 1951, 258 with comparative data (in brackets) from www.nnfcc.co.uk/crops/info/soya.htm

which would parallel the silk-like fibres derived from regenerated cellulosic sources. Francis Atwood gave a paper in 1941 to the American Chemical Society and proposed the term ‘prolon’, combining ‘pro’ from protein and ‘on’ from nylon and cotton;[13] this had brief currency, but the term ‘azlon’ was eventually proposed and accepted; its derivation is unclear. The American Federal Trade Commission and the Textile Fibre Products Identification Act define azlon as ‘A manufactured fibre in which the fibre forming substance is composed of any regenerated, naturally occurring protein’, although other definitions extend this to include both regenerated protein and cellulosic fibres.[14]

13.4 The need for new fibre sources

13.4.1 The context for mid-twentieth century research into alternative protein fibre sources

The impetus behind research into alternative fibre sources in the 1930s and 1940s was fuelled by the desire to produce economically viable wool-like fibres which could compete with, or complement, natural wool fibres. It is clear that a fear of shortages of natural fibres during wartime was an increasingly strong factor in encouraging this research in America. By the mid-1930s, almost half of USA's wool requirement was imported; over 112 million kg in 1936. This dependence on overseas wool sources, particularly from Australasia, meant the textile industry was subjected to the effect of considerable price fluctuations. Increasing domestic production of a wool substitute had obvious benefits, particularly as preparations for war intensified; wool was needed in large quantities for military uniforms and equipment.



13.2 Blended regenerated protein fibres. This is an upholstery fabric containing soya bean fibre. (Photograph courtesy of Kansas State University Agricultural Experiment Station and Cooperative Extension Service, from the publication *Synthetic Fibers and Textiles* (Bulletin 300), Fletcher H.M., 1942.)

American textile manufacturers were clearly aware of the impact of war on both the supply of unprocessed fibres and the type of textiles required. Wickliffe Rose of the American Viscose Corporation made a speech to the 1944 American Association of Textile Chemists and Colorists (AATCC) convention in which he identified three aspects of this process: substitution of man-made for natural fibres, modification of industrial practice as a result of shortages of natural fibres and intense research into new fibres to satisfy military requirements, which had the effect of restricting supplies available for the civilian market.[15] What was available was of poorer quality. A 1944 survey undertaken by the Bureau of Human Nutrition and Home Economics showed 'how essential fabrics were downgraded during the war'.[16]

In the 1930s and 1940s, American, European and Japanese researchers and textile specialists were exploring the possibilities of making fibres from a variety of novel protein sources. O'Brian lists the range of sources being considered: 'Textile fibres from the redwoods and from yuccas are being studied. Fibres from milk casein, from soybeans, and many other sources are making their appearance'.[17] Regenerated protein fibres from animal sources which were produced commercially included 'Aralac' (USA) and 'Lanital' (Italy) made of milk. The American military experimented with the use of chicken feathers for blankets and some ladies' suits, seemingly of a rough tweed-like fabric, are said to have been made with feathers. Other researchers explored the possibility of making fibres from egg white and slaughter-house waste such as horns, hooves and gelatine. Research into fibres made from vegetable protein sources resulted in the commercial development of 'Ardil' (UK) and 'Sarelon' (USA) from peanuts and 'Vicara' (USA) from zein protein in maize. Lundgren and O'Connell, two researchers at the US Department of Agriculture's Western Regional Research Laboratory (Albany, California), noted that 'Interest in the formation of artificial fibres from proteins has been stimulated by the war emergency'.[18] An anonymous writer in *Rayon Textile Monthly* echoed this view: 'The nation's war effort has greatly accelerated the tempo of American skill and ingenuity in fibre and fabric creation'.[19]

13.4.2 The context for mid-twentieth century research into soya bean fibres

To be suitable for use as source for fibres, a vegetable protein needs to be either colour free or bleachable and readily available in large quantities at an economic cost. Soya beans were produced in large quantities because of their established uses in agriculture. Methods for extracting soya bean protein were already established, together with a tradition of exploring its potential in industrial contexts; it made sense to see whether it could also be used to create an effective fibre. Nevertheless, it is worth noting that soya bean

13.3 Henry Ford wearing his suit made from fabric containing soya bean protein, *circa* 1941. From the collections of Henry Ford (P.188.29410).

protein was considered as the source for a viable regenerated protein fibre for a relatively brief period during the mid-twentieth century. By 1942, Fletcher noted that technical problems were preventing the production of 'firm, tough protein filaments which will resist wear and deterioration like the natural and other synthetic fibres', although she implies that soya bean fibre is being manufactured.[20] Sherman and Sherman's comparisons of soya bean fibres manufactured between 1939 and 1944 indicate that the fibre was still in development and that quality was still being improved.[21] They note that 'the new protein fibre [soya bean protein fibre] should sell at around the same price level as casein fibre and find its principal market in blends with cotton, wool, and rayon';[22] however, there is no indication that any trade name was registered. It is unclear whether soya bean fibre was made into commercially available woven fabrics in the 1940s. One company, Drackett, produced the fibre in considerable quantities but its main commercial use seems to have been by hat manufacturers in unwoven felt (Fig. 13.4). There is no evidence for a marketing campaign to introduce soya bean fibre to the public comparable to that run by Atlantic Research Associates for their milk protein fibre 'Aralac'. Examples of surviving garments or hats have yet to be identified.

Need stimulated by war was affected by the arrival of peace and by 1945 the US government held over 1,800 million kg of wool suitable for clothing stockpiled during the war. It was initially expected that disposal of these stocks would take up to thirteen years; however, high home demand, reconstruction requirements in Europe and a drop in world wool production coupled with a slump in wool prices meant this stockpile was consumed in about ten years. This demand for wool was expected to stimulate research and production of regenerated protein fibres. However, their technological weaknesses meant that they failed to compete effectively with natural or synthetic fibres, even when used as a blend. It seemed that the regenerated protein fibres had no place in a world supplied with an increasingly wide range of effective and well-priced synthetic fibres. Some patents for soya bean fibres were filed in the 1950s but interest seems to have faded more quickly in this fibre source than in other possible protein fibre sources. Patents often list a range of protein sources. For example, patent GB 634,812 for improving 'the properties of protein spinning products' focuses primarily on fibres from milk casein but also cites soya bean or peanut protein as alternative sources (see Table 13.2). Specific commercial applications for soya bean fibres do not seem to have developed and research interests shifted fairly rapidly to fibres that appeared to have greater potential. For example, Wormell, a researcher closely involved in the development of regenerated protein fibres, does not include soya bean protein fibre in his 1954 X-ray diffraction studies. Post-war, there was also concern about using scarce resources for fibres: 'Why use good food to make poor wool?'[23] By 1966, such fibres only merited a fleeting comment in standard textile textbooks.

Traill acknowledges the technical problems, but, drawing inspiration from the improved quality of the regenerated cellulose fibres, he expresses the hope that 'regenerated protein fibres may become different from those we now know'.[24] Nevertheless, the general reduction in interest suggests that few researchers retained Moncreiff's belief that this generation of regenerated protein fibres were 'the pioneers of those man-made, probably scientific, protein fibres that will one day surely come, and in this sense they have played a part in the advance of fibre science'.[25]

Table 13.2 Selected patents for regenerated protein fibres using soya bean protein

Patent number	Date	Title	Patentee/s	Summary
China				
CN 141, 5646	Specification published 7 May 2003 Application date 10 December 2002	Spinning dope of synthetic fibre of phytoprotein and its producing method	Hu Zongshan and Song Huiyuan	Method for making spinning solution from plant protein copolymerised with an aqueous solution of poly-(vinyl alcohol) with sodium or potassium sulphite
WO 030, 56076	Specification published 10 July 2003 Application date 31 December 2002	Phytoprotein synthetic fibre and the method of making the same	Li Guanqi	Method for making a phytoprotein synthetic fibre made from vegetable protein and poly(vinyl alcohol)
France				
827,992	6 May 1938	Textile fibres made from soya bean protein	Nippon Kari Kogyo K K Japan	Method proposed is similar to that of manufacture of Lanital from milk casein
828, 075	10 May 1938	Textile fibres made from soya bean protein	Nippon Kari Kogyo K K Japan	Method proposed is similar to that of manufacture of Lanital from milk casein
Germany				
H 153,501 .IV c/12p	Filed 1 August 1939			Sulfurized protein. After treatment with Igepon and Stocko
Great Britain				
GB 525, 577	Application 23 Feb 1939 Specification published 30 August 1940	Improvements in and relating to the production of textile threads	Donald Leonard Wilson and Courtaulds Ltd, UK	Method for partial hardening using formaldehyde and heat treatment for fibres from casein, soya bean and peanut protein solutions

Table 13.2 Continued

Patent number	Date	Title	Patentee/s	Summary
GB 536,841	Application 24 November 1939 Specification published 29 May 1941	A process of treating a product synthetically formed from protein material to improve or modify the dyeing affinities, resistance to water and chemicals, and other properties	Atlantic Research Associates, USA	Method for stabilising fibres formed from milk or soya bean protein using an acylating agent such as acetic anhydride and ketenes which may be in gaseous form
GB 543,586	Application 29 August 1940 Specification published 4 March 1942	Improvements in or relating to the manufacture of filaments from vegetable globulin	ICI Ltd, David Traill, UK	Method for using sodium chloride solutions to harden fibres formed from peanuts, hemp-seed, castor oil seed or soya beans
GB 539,985	Application 30 March 1940 Specification published 1 October 1941	Improvements in or relating to the manufacture of wet spun protein fibres	Antonio Ferretti	Method for using chromium salt and formaldehyde to harden and insolubilise fibres formed from milk or soya casein
GB 605,830	Application 7 Jan 1946 Specification published 30 July 1948	Improvements in or relating to the insolubilising treatment of films, filaments, fibres and like-shaped articles made from protein solutions	Andrew Mclean, ICI Ltd, David Traill	Method for improving the dyeing of protein fibres of either peanut or soya bean fibres with acid wool dyes using alkali metal sulphate solutions acidified with sulphuric acid as the coagulating bath

Table 13.2 Continued

Patent number	Date	Title	Patentee/s	Summary
GB 634,812	Application 23 July 1947 Specification published 29 March 1950	Process for improving the properties of protein spinning products	Onderzoekings Instituut Research, Holland	Method for using pre-condensation products of formaldehyde and resorcin to improve resistant to hot dilute acid liquids such as acid dye baths without loss of flexibility
GB 638,356	Application 7 October 1946 Specification published 7 June 1950	Improvements in regenerated protein fibres and process for preparation thereof	Jack Jay Press, New York, USA	Method to produce a regenerated protein fibre with improved resistance to aqueous processing by forming insoluble condensation bodies within the fibre. Protein sources cited include casein, soya beans, peanuts, zein, silk waste and fish albumen
GB 665,462	Application 3 August 1948 Specification published 23 January 1952	Improvements in or relating to a method for improving the strength of artificial insolubilised protein filaments or fibres	George Kirkwood Simpson, ICI Ltd.	Method for metallic salt solutions, usually with formaldehyde, to improve the processing strength of fibres produced from 'alkaline solutions of casein and vegetable globulins such as peanut and soya bean globulin'

Table 13.2 Continued

Patent number	Date	Title	Patentee/s	Summary
GB 667,115	Application 13 April 1949 Specification published 27 Feb 1952	Improvements in and relating to the production of artificial protein threads, fibres, filaments, yarns and the like	Courtaulds Ltd, Robert Louis Wormell	Method for producing fibres using a solution of keratin from wool waste, horn or hoof with casein derived from milk, peanuts, castor beans or soya beans. The resulting fibres were formed in a coagulating bath of sodium sulphate before hardening and stretching
GB 673,676	Application 31 May 1949 Completed specification filed 30 May 1950 Specification published June 11, 1952	Improvements in and relating to the production of artificial protein threads, filaments and the like	Courtaulds Ltd, Frank Happey and Robert Louis Wormell	Method for producing fibres from 'solutions of proteins such as lactic casein and vegetable seed proteins, otherwise known as vegetable casein, such as soya bean protein and peanut protein' and improving tenacity by denaturing and stretching the fibre at high temperature
GB 674,755	Application 4 August 1949 Completed specification filed 8 Aug 1950 Specification published 2 July 1952	Improvements in and relating to the production of artificial protein fibres	Courtaulds Ltd, and Robert Louis Wormell	Method for producing 'a cheap soluble protein fibre having the requisite strength for use in protein processes'. This patent is intentionally seeking to design a soluble fibre which could be dissolved

Table 13.2 Continued

Patent number	Date	Title	Patentee/s	Summary
				out of a constructed fabric. The protein source could be casein (milk-based protein) or soya bean, peanut or castor bean proteins
GB 862,428	Application 30 May 1957 Specification published 8 March 1961	Method and apparatus for forming fibres	American Viscose Corp.	Method for forming fibres from thermoplastic macromolecular substances by discharging molten material into stream of high velocity gas to form fibres
United States of America				
US 2,191, 194	Application 8 Sept 1937 Patented 5 March 1940	Process for manufacturing artificial fiber from protein contained in soya bean	Assigned to Showa Sgangyo KK, Yokohama	Application applied for by Toshiji Kajita and Ryohei Inoue of Japan
US 2,342, 634	Application 23 August 1939 Patented 29 February 1944	Method of treating fibrous material and produce resulting therefrom	Francis Clarke Atwood, Newton, Mass., assignor to National Dairy Products Corporation, New York,	Method of forming fibres from casein and soya bean proteins using acylation to improve fibre stability
US 2,309, 113	Application 13 May 1940 Patented 26 January 1943	Treatment of artificial protein films and filaments	Oskar Huppert, Chicago, Ill., assignor to the Glidden Company, Cleveland, Ohio	After treatment using polyhydric alcohols (glycerol, glycol, glycol ethers), thiogelatine, controlled drying and heat setting. Twenty-two

Table 13.2 Continued

Patent number	Date	Title	Patentee/s	Summary
				variations listed, including versions for casein (milk-based protein) and zein (maize-based protein)
US 2,342, 634	Application 23 August 1939 Patented 29 February 1944	Method of treating fibrous material and produce resulting therefrom	Francis Clarke Atwood, MA, assignor to National Dairy Products Corp, New York	Acylation of synthetic protein materials to make them more resistant to water, acids and alkaline solutions
US 2,372, 622	Application 18 November 1942 Patented 27 March 1945 (in Great Britain 28 January 1943)	Manufacture and production of artificial threads, filaments and the like	Robert Louis Wormell, Coventry, England, assignor to Courtaulds Ltd, London, England	Method for improving resistance of threads from milk casein or vegetable seed caseins such as soya beans or peanuts to hot water and hot dilute acid by the use of formaldehyde and dilute sulphuric acid sufficient to form sodium bisulphate
US 2,377, 853	Application 10 May 1941 Patent 12 June 1945	Protein manufacture	Robert A. Boyer, Joseph Crupi, and William T. Atkinson, assignors to Ford Motor Co., Dearborn, Michigan	Method for improved protein manufacturing to produce 'a purer, more economical and more usable product' using a slow-freezing process, to dehydrate the protein and thus improve physical characteristics of fibres and paints, glues, sizes, etc.

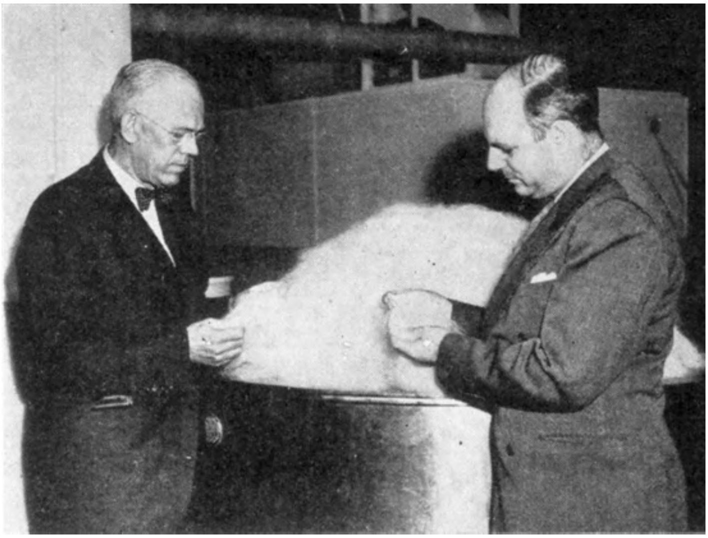
Table 13.2 Continued

Patent number	Date	Title	Patentee/s	Summary
US 2,377, 854	Application 7 June 1941 Patented 12 June 1945	Artificial fibres and manufacture thereof	Robert A. Boyer, William T. Atkinson and Charles F. Robinette, assignors to Ford Motor Co., Dearborn, Michigan	Method of spinning fibres from soya bean protein
US 2,377, 885	Application 20 December 1939 Patented 12 June 1945	Process of manufacture of synthetic wool from soya bean protein	Oskar Huppert, Chicago, Ill., assignor to the Glidden Company, Cleveland, Ohio	Process for spinning an alkaline solution of soya protein into an acid coagulating bath improved by hydrolysing the soya protein with pepsin in a hydrochloric acid solution so producing a controlled ageing of the alkaline solution

13.5 Generalised method for producing soya bean fibre in the mid-twentieth century

The fundamental requirement in creating a fibre from soya bean protein is forcing a globular protein to become a fibre-forming protein. Wormell noted that in contrast to 'cellulosic fibres [which] are regenerated immediately on coagulation … protein filaments have to be cross-linked if fibrous products are to be obtained'.[26] Five main production stages can be identified:

1. Separation: 'clarifying' the soya bean meal and precipitating out the protein.
2. Solubilisation: dissolving the resulting washed and dried curd to form the 'spinning' solution.
3. Hardening: forcing this solution, when sufficiently ripened, through spinneretes into a coagulating bath resulting in the formation of fibres.
4. Insolubilising: stretching and hardening this fibres, often using formaldehyde.
5. Controlled washing and drying followed by cutting into staple lengths.

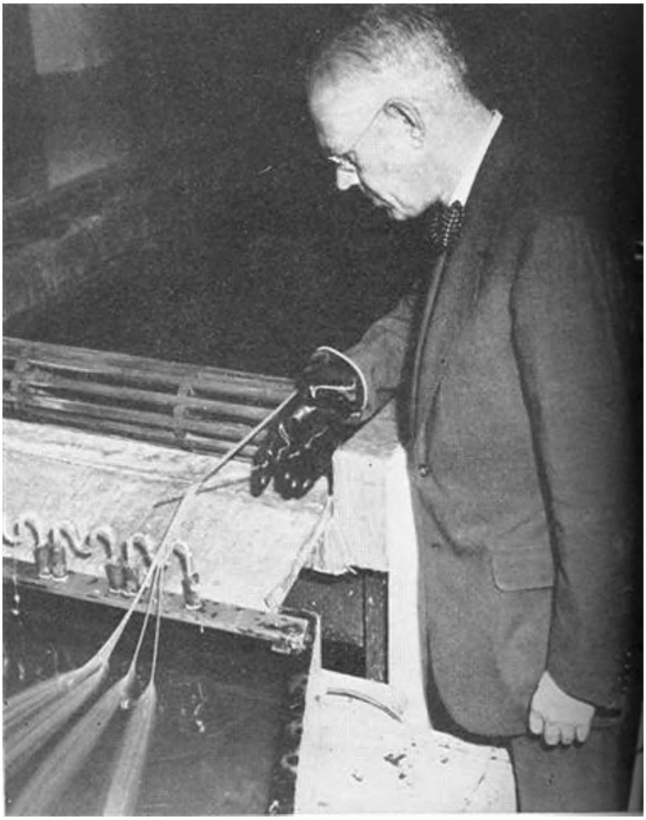


13.4 Robert Boyer and H.R. Drackett with soya bean protein fibre tow. From: Anon. 1944. Drackett Co. produces new soy bean textile fiber. *Rayon Textile Monthly*, 85 (37).

Each stage of the fibre manufacturing process presented a variety of complex technical challenges. The numerous patents filed by researchers such as Atwood, Boyer, Huppert and Wormell amongst others reveal both the problems experienced in processing these fibres as well as the techniques explored in attempts to resolve them.

13.5.1 Producing the soya bean protein curd

The production of a suitable oil-free soya bean protein was generally agreed to be critical to the success of the resulting fibres. An unpublished Ford Motor Company typescript notes that extracting the protein from the soya was 'the most difficult' stage.[27] The normal procedure was to flake the soya beans and then extract the oils and other fatty substances by mechanical or solvent extraction. Traill argues that the choice of solvent influenced the degree of denaturation; hexane resulted in 87% peptisation of nitrogen while ethyl alcohol only resulted in 57% peptisation.[28] Heat was also a critical factor, influencing the degree of denaturation obtained; exposure to incorrect temperatures could result in less soluble or darkened proteins.[29] Bergen notes that lower temperatures were used when preparing soya for use in fibres.[30] The protein was then extracted by dissolving the resulting oil-free substance in weak aqueous solutions of alkali with a pH ranging between 7



13.5 H.R. Drackett inspecting a batch of soya bean fibre as it emerges from the spinnerets. From: Anon. 1944. Drackett Co. produces new soy bean textile fiber. *Rayon Textile Monthly*, 85 (37).

and 12. Reducing agents such as sodium sulphide or sodium sulphite (0.1%) could be added to prevent oxidation during this extraction process.[31] After clarification by centrifuging or filtering, an acid was added to precipitate the protein in the form of a soft curd, which was washed to remove soluble salts and excess acids. The curd was then drained through filtering cloths to obtain a protein cake with a solids content of at least 60%; it could then be grated and dried, either at room temperature or under vacuum. Great care had to be taken in controlling the temperature and pH in order to obtain a curd that could be handled. Wormell[32] notes that both the solid and liquid by-products of this process could be treated for use as animal fodder or yeast extract so they too had an economic value.

Considerable research was undertaken into methods of improving the quality of the protein curd. Denatured soya bean protein tends to aggregate rather than crystallise so many of the modifications were intended to overcome this adhesive-like behaviour which gave rise to a variety of technical problems.[33] US Patent 2,112,210 describes a process in which the protein was solubilised in sodium hydroxide, treated with carbon disulphide and oxidised with air. It was hoped that this method would result in a fibre with better spinning viscosity, stability and tensile strength.

13.5.2 Producing the spinning solution

The soya protein was then dissolved again to form a viscous solution, often referred to as 'dope', with the consistency of molasses. A high viscosity spinning solution was needed to obtain a fibre, ideally with a high solids content of up to 20%. Proteins tend to gel in high concentrations so problems were experienced with forming fibres from the spinning solution. Atwood experimented with dissolving the protein in caustic soda (US 142,574; see Table 13.2). Astbury and his co-workers also explored the potential of using aqueous urea solutions to solubilise 'corpuscular' proteins (GB 467, 704 and GB 467,812). Lundgren, arguing that neither was effective, recommended the use of synthetic detergents.[34] The resulting soya protein was then slightly hydrolysed by pepsin or more fully hydrolysed by alkalis (US 2,309,113; see Table 13.2). Huppert observed that it was more difficult to form a spinnable solution from soya bean protein than from casein protein because the spherical soya protein 'particles', despite having larger molecules, form tri-dimensional peptide chains with low viscosity. He recommended treating soya protein with pepsin in hydrochloric acid to form long folded peptide chains running parallel with the length of the micelles (US 2,377,685). However obtained, the solution was then allowed to age or 'ripen' to achieve the required high viscosity and 'stringiness'. The nature of the changes undergone by the soya bean protein during denaturation was studied by a number of researchers including Traill[35] and Wormell.[36] Traill notes this vital denaturation process, in which the long-chain molecules opened out into an extended form, could be monitored by measuring the quantity of thiol (-SH) groups.[37] The control of enzymes and bacteria in the solution was also a concern. This process is now seen as consisting of two stages: degradation in which peptide bonds break down and denaturation in which the conformation of the molecules changes, in this case from the original folded and globular state to a random state. Later researchers have studied different factors influencing the viscosity of this solution, including pH levels and the effect of sodium sulfite and sodium hydroxide.[38,39]

13.5.3 Extruding and insolubilising fibres

Once sufficiently mature, this solution was 'wet spun' (actually extruded) into filaments, sometimes called 'tow', by extruding it through fine spinnerets into a precipitation bath (also termed a coagulation bath) (Fig. 13.5). The next stage was to 'set' or insolublise the fibres, sometimes termed 'tanning' or 'hardening'. Wormell notes that tanning methods using chromium and aluminium salts were relevant for developing processes to form regenerated protein fibres.[40] As a result of Ferretti's innovative work into the formation of milk casein fibres, the coagulation bath was usually a salt and acid bath such as sodium, aluminium or magnesium sulphate and sulphuric acid.[41] The salt had multiple functions. The osmotic pressure created by its presence caused the diameter of the newly extruded filaments to shrink, strengthening them and minimising their tendency to clump together. Insolubilisation was usually achieved by immersing the newly coagulated fibres in a formaldehyde

13.6 Soya beans and soya bean fibre. Harvester SPF Textile Co. Ltd.

bath under acid conditions. Traill summarises research into the processes going on during this treatment, but considered these were not clearly understood.[42] The formaldehyde reacts with lysine side chain amino acids while cyclic methylene complexes connect other side-chain amino groups through a secondary condensation reaction. The aim was to enable the formation of a complex network between the protein chains with sufficient cross-links to improve the wet strength of the resulting fibre but not so many as to create an over-rigid structure.[43]

Organic acids such as formic, acetic or lactic acids, all of which are solvents for proteins, could be added to the bath to improve the flow of the solution. Formaldehyde, synthetic tanning agents ('syntans') or other spinning aids, such as cation-active agents or anion-active soaps, could be used to reduce the potential for the newly formed fibres to stick to each other or to the processing equipment.[44] Wormell also notes that DDT could be added to control behaviour during extrusion.[45] Atwood recommends using a softening agent, such as a soap solution, during the neutralisation of the fibre after coagulation in an acid solution (US 2,342,634; see Table 13.2).

Lack of strength in the hot baths required for processing was a persistent problem. One patent noted that the filaments 'tend to stick together, or even to dissolve' in boiling water or hot dilute acids (US 2,372,622; see Table 13.2).

Numerous modifications were developed to try to overcome these technical challenges. A delicate balance of acidity level and temperature was required to improve fibre resistance to boiling water without damaging the fibre's physical appearance or properties. Methods for improving stability during processing included the use of different stabilising baths. Solutions proposed included formaldehyde and sulphuric acid, formaldehyde, formaldehyde and chromium salt (Ferretti GB 539,985; see Table 13.2), alkali metal bisulphate or sulphate and sulphuric acid sufficient to form a bisulphate (Wormell and Knight US 440,116) or aldehyde and sulphuric acid (US 2,293,986). Wormell's 1945 patent sought to improve stability by using a strong sulphuric acid solution with formaldehyde and sufficient sodium sulphate to form sodium bisulphate (US 2,372,622; see Table 13.2). Press's patent explored the potential of forming insoluble condensation products within the regenerated protein fibre itself in order to improve aqueous processing abilities (GB 638,356; see Table 13.2).

Others explored techniques to improve the elasticity and flexibility of the fibre after washing (US 2,309, 113; see Table 13.2). Acetylation, sometimes using acetic anhydride at temperatures of 80°C or above, could be used to improve colour, handle and dyeing performance.[46] Atlantic Research Associates used this approach to stabilising fibres formed from either milk or soya bean protein. The acylating agent, which could be in gaseous form, was used to make the newly formed fibres more resistant to water, acids and alkalis (GB

13.7 Bleached soya bean fibre top. Harvester SPF Textile Co. Ltd.

536,841; see Table 13.2). Atwood also explored the use of acetylating agents, such as acetic anhydride, ketene, keto-ketenes or ketenes of the lower fatty acids (butyl, proponyl and amyl), applied after the fibre had been partially dried. He considered this made the protein 'more resistant to oxidation and less reactive chemically' as well as being more economical (US 2,342,634; see Table 13.2). Although such an acetylation process removed the need to treat the fibre with formaldehyde to improve fibre characteristics, some treatment was still needed to avoid fibres sticking together and embrittling during drying. Atwood proposed using a dehydrating agent such as acetone rather than formaldehyde (US 2,342,634; see Table 13.2). Wormell reported on an alternative method of insolubilising protein fibres using nitrous acid, although he acknowledged that this added a stage to the process.[47]

13.5.4 Orientation of the fibres through tensioning

At this stage the tow, although slightly hardened, was still plastic, vividly described by Traill as 'flabby' when wet, soluble in saline solutions, acid and alkali and then becoming brittle when dry.[48] Bobbins or reels were used to collect the filaments which were then pulled through a bath over two glass pulleys or wheels, sometimes referred to as godet wheels.[49] One of these pulleys revolved faster than the other so the filaments were tensioned or stretched. This process aimed to improve the orientation of the molecules parallel to the fibre length resulting in 'greater wet and dry strength, and a greater wet–dry strength ratio' (Atwood US 2,342,634; see Table 13.2).

13.5.5 Washing, drying and crimping

The fibres were then washed and dried, a complex process requiring careful control of temperature and humidity, but which could be modified to create straight or crimped effects. Crimp frequency could vary from 0–4.7 per cm. Different after-treatments, including bleaching, could be applied before the fibre was subjected to controlled drying. Many patents registered techniques to improve the elasticity and flexibility of protein fibres after washing (e.g. US 2, 309, 113; see Table 13.2). Soya bean protein fibre was manufactured as continuous filaments with a fibre width between 13–27 μm but was normally cut into staple fibres ranging from 0.64–15.2 cm long.[50]

13.5.6 Dyeing

Soya bean fibres had an affinity for the acid and chrome dyes used on wool, but became very harsh and brittle if dyed at below pH 3.[51] Atwood discussed dyeing synthetic protein fibres in US patent 2,342,634 (see Table 13.2). He noted that achieving even dyeing of blended fibres requires the regenerated protein fibre to behave in the same way as a natural protein fibre. As wool and silk dyeing then required hot processing, either in acid or aqueous baths, the ability of regenerated protein fibres to withstand such processing was crucial. An alternative, proposed by Boyer, was to add dyestuff directly to the spinning solution.[52]

13.5.7 Manufacturing requirements: spinning, blending and weaving

Once a relatively stable thread was formed, standard textile manufacturing methods and machinery could be used. The threads could be plied, passed through a picker and blender, carded, and then twisted on a normal warping machine. The soya bean protein yarn could be blended with wool, rayon or silk yarn at this point. The yarns were then ready for weaving. Ramseyer[53] reported that equipment designed for spinning rayon (regenerated cellulose) could be used while Wormell[54] noted that regenerated proteins could be processed on cotton spinning machinery. Boyer stated the fibre blended well with wool, cotton and rayon and could be processed using either cotton or worsted wool fibre equipment.[55] Blending regenerated protein fibres with poorer quality woollen-spun wool yarns improved the qualities of both (Fig. 13.2 and Fig. 13.3).

13.5.8 After care

The fibres were said to be stable to dry cleaning solvents but shrank in boiling water.

13.8 Soya bean protein fibre yarns. Meedoo Textile Co. Ltd.

13.6 Contemporary research into alternative protein fibre sources

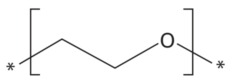
Soya bean protein fibre, now often referred to as SPF, is again being explored as a source for commercially viable fibres. This is a rapidly developing area with research being undertaken in several countries, primarily America and China (Fig. 13.6). The impetus behind the late twentieth and early twentieth-first century research into regenerated protein fibres is to do with reducing the ecological impact of large-scale production and consumption rather than seeking substitute fibres in a time of shortages. Wormell had raised the issue of ecological damage caused by merino sheep as early as 1954, arguing that animals were poor converters of food into protein fibre.[56] Regenerated protein fibres, probably produced in combination with synthetic polymers, could become technically and economically viable fibres which have less environmental impact than purely oil-based synthetic fibres. The use of renewable resources, reduced environmental impact of processing chemicals and the biodegradability of the resulting fibre all needed to be considered in looking at the life-cycle impact of these new regenerated protein fibres. SPF is being promoted as a healthy and comfortable fibre which also has ecological

13.9 Soya bean protein fabric. Meedoo Textile Co. Ltd.

benefits. However, serious issues have been raised for some time about the impact of large-scale intensive soya bean farming on the environment. Argentina, for example, is suffering deforestation, estimated at the rate of 10,000 hectares per year, with a consequent impact on the lives of indigenous communities. There are also concerns about environmental and economic effects of large-scale use of patented or licensed genetically-engineered soya bean seeds and related herbicides supported by bio-technology companies.[57,58] Conversely, the Chinese are arguing that the development of soya fibre could be environmentally beneficial. Throughout the 1990s Chinese researchers, supported by the State Economic & Trade Commission's national technology innovation programme, were exploring methods of developing fibres from soya bean protein. New bioengineering approaches using enzymes seem to have been the key to renewing the potential of soya bean protein as a fibre source. The aim is to produce soya bean fibres with a soft handle and attractive lustre which could become a replacement for cashmere fibres. China is a world leader in the production of cashmere, producing 80% of the world's annual production (10,000 tons/9,071.8 metric tons). However, the cashmere goats are highly destructive of grassland on which they graze and have been accelerating the process of desertification. A move to a commercially viable soya-based fibre could help preserve the environment.[59,60] Alternative methods of producing soya bean protein fibres have also been researched in America, partly funded by the United Soybean Board and the US Department of Agriculture. Their research has tended to focus on the development of bi-component fibres combining soya protein with synthetics.

13.7 Contemporary methods for producing fibres from soya bean protein

Two innovations appear central to the development of the soya protein fibres (SPF). Biochemistry is being used in the production process to modify the structure of soya bean protein while strength is added to the fibre by incorporating polyvinyl alcohol (PVA; Fig. 13.10) although methods for achieving this vary. PVA offers the benefits of higher strength and modulus and, like SPF, is soluble in water and exhibits hydrogen bonding so the same processing methods can be used. Fibres from water soluble PVA are said to be biodegradable in soil. In contrast with the mid-twentieth century producers, Chinese companies making soya bean fibres generally have expertise in fibre and textiles manufacture. In addition to producing a competitive fibre to compete or complement with wool and cashmere, SPF fibres are being promoted as having health benefits through their beneficial impact on skin.[61]



13.10

13.7.1 Generalised methods for producing SPF

Similar to the processes used by mid-twentieth century manufacturers, the protein is first isolated from soya bean meal from which the oil has been extracted. The Chinese method then uses bioengineering techniques to change the structure of the spherical soya bean protein using enzymes and an unidentified 'functional auxiliary'.[62] PVA may be incorporated into the heated spinning solution. The fibre is 'wet spun' (extruded) before stabilisation through acetylation, curling and thermoforming before cutting into short staple lengths. Careful pre-treatment, dyeing and finishing of SPF yarn appears to be necessary to obtain and retain the desired fibre characteristics. Yi-you describes the use of 'hydroformylation' to stabilise the fibres before they are wet spun, heat set and cut.[63] American researchers seem to be favouring an approach that modifies the fibre structure itself by creating a bi-component fibre with a PVA core surrounded by an outer sheath of soya protein. This is said to add strength and stability to the fibre whilst retaining lustre and soft hand, although problems have been experienced with the drawability of the fibre.[64]

Drying

Drying has to be carefully controlled to maintain a good hand. It should be carried out with as little tension as possible and at temperatures below 100°C.[65]

Bleaching and dyeing properties

SPF fibres are usually light yellow in colour. They are stable with both hydrogen peroxide and reduction bleaching. A whitening or brightening treatment may be necessary for purer whiteness (Fig. 13.7). When bleaching an SPF blended with another fibre, care must be taken to use a method suitable for both fibres. Either acid or reactive dyes may be used; dye fastness compares well with that of silk.[66]

13.11 Tee-shirt in 'Luxury Soy' 55% soy, 40% cotton, 5% Lycra®. Colorado Trading and Clothing. Photograph © Textile Conservation Centre, University of Southampton.

Finishes

A variety of finishes can be used to soften the fibre and give anti-wrinkle properties. The fibre is being promoted as health-giving with natural antibacterial properties. However, antibacterial finishes are also being applied. Yi-You notes that 'the addition of Chinese herbal medicine' with sterilising and anti-inflammatory properties can be added during the production of the fibre. He argues that this gives the resulting fibre medical properties which are more long-lasting than those obtained from after-treatments.[67]

Manufacturing requirements: spinning, weaving and blends

The resulting fibres can be spun on cotton or worsted machinery and blended with cashmere (80% soya to 20% cashmere) or in 50% blends with wool, silk, cotton (Fig. 13.8). It can be woven into high quality fabrics with high weave counts (Fig. 13.9).

After-care

SPF has a high modulus resulting in low shrinkage in hot water.[68] It is therefore said to have stable to normal washing requirements; it is also claimed to be a fast drying fibre. However, Colorado Trading recommends cold machine washing with low temperature ironing and non-chlorine bleach only for its SPF fibre blend tee-shirts.

13.7.2 Contemporary commercial availability

Soya bean fibre is being marketed commercially, sometimes as 'vegetable cashmere', as yarns and as garments including underwear as well as in bedding.[69] Some soya textiles are being marketed with organic certification although SPF is currently more expensive than other organic fibres, costing approximately 30% more than organic cotton.[70]

Yarns

The South West Trading Company (2004) is the North American distributor for a range of soya bean protein fibre yarns marketed under the trademark *Soy Silk*™. This is being sold to hand spinners, weavers and knitters as an 'environmentally friendly fibre' made from the waste of the tofu manufacturing process. Yarns available include worsted ribbon yarn, sport yarn, lace weight yarn, chenille and blends with wool or cashmere. Staple threads for spinning are also sold in natural or white which can be home-dyed using acid dyes. Staple fibres are also available in the UK and are similarly being marketed to spinners and feltmakers.

Garments

SPF is being used in an increasingly wide range of garments, tee-shirts and sweaters and underwear, sometimes in blends with bamboo fibre and silk. The Sichuan Silk Corporation exhibited knitted soya bean fibre shirts at the China Export Commodities Fair, Guangzhou, Guangdon Province in 2001. Over ten overseas importers were reported as signing letters of intent to promote these garments.[71] The Nanjing Textiles Import/Export Co. showed SPF underwear at the October 2002 New York International Fashion Fabric Exhibition.[72]

Soya fibre appears to have been introduced to the American market in 2003 at the MAGIC fashion trade show in Las Vegas. Colorado Trading and Clothing (Boulder, Colorado, USA) exhibited clothes made from soy fibre blends, including *SoyBu*™, a soya bean/bamboo mix, arguing that this makes an expensive new fibre more widely available to more people. Their marketing stresses that the fibre is 'eco-conscious' and 'naturally antimicrobial'.[73] They market tee-shirts which are a soya protein, cotton and Lycra® blend (Fig. 13.11) as well as robes and throws in soya protein fibre and polymicro chenille. Other companies, including Of The Earth and Under the Canopy, are also offering SPF clothing as part of a range of garments made from organic or renewable textile fibres.

13.8 Fibre characteristics

13.8.1 Mid-twentieth century soya bean protein fibres

Under magnification, these soya bean fibres were translucent with a smooth surface although some granulation and streakiness was often visible. The cross-section was almost circular.[74,75] Wormell noted that fibres from 'seed proteins' were brownish or yellowish[76] although Ford's process apparently resulted in a white fibre (Fig. 13.1) whereas Drackett's fibre was light tan to white. The staple fibre was described as 'a loose, fluffy mass with a resemblance to scoured wool', soft to touch and with good resiliency.[77] Its high moisture absorption and high heat of wetting made it warm and comfortable to wear. Under standard conditions (65% RH and 21°C), soya bean fibre showed a 16.1% regain when coming to equilibrium from the wet state and 12.9% regain from the dry state. This is similar to the hysteresis exhibited by wool.[78]

Despite this superficial resemblance, soya bean protein fibres had lower wet and dry strength and elasticity than wool (see Table 13.3). All mid-twentieth century manufacturers experienced problems with the low tensile strength and poor wet strength of soya bean fibres. Sherman and Sherman stated that 'its wet strength [was] so inferior as to constitute a distinct handicap'.[79] Dry soya bean fibre had a tensile strength of about 55% that of

Table 13.3 Tensile strength of soya bean fibre compared with wool of the same grade. Bundle test at 65% relative humidity and 21°C

Property	Soya bean staple 1944	Wool top 625
Dry tensile strength (kg cm^{-2})	805	1476
Wet tensile strength (kg cm^{-2})	298	1244
Strength, loss from dry (%)	63.0	15.8

Sherman, J.V. and Sherman, S.L. (1946) *The New Fibers,* New York, D. van Nostrand Company, 185

wool but, when wet, the tensile strength dropped to about 24% the strength of wool. Soya bean fibres' loss of strength when wet is particularly noticeable, being about 35–50% of its dry strength. This compared with wool which retains about 85% of its dry strength when wet.[80] When wet, soya bean protein fibres were 76% weaker than similar quality wool fibres. Boyer reports that the fibre produced at Ford had 80% of the strength of wool with greater wet and dry elongation.[81] Drackett claimed in 1944 that this weakness had been overcome, but this seems to have been over-optimistic; lower strength usually results in greater extensibility. Soya bean fibres, like wool and casein fibres, had high extensibility and similar moisture absorption (10–12%), heat-insulating characteristics, felting and dyeing characteristics to wool. In comparison with other regenerated protein fibres, soya bean fibres were 'intermediate in properties between peanut fibres and those from milk casein, reflecting intermediate values for basic amino-acid constituents and amide nitrogen'[82] (see Table 13.4). When blended with other fibres which provided much-needed strength, such as rayon or cotton, soya bean protein fibres provided warmth and softness.

13.8.2 Contemporary soya bean protein fibres

Contemporary SPF differs considerably from that of the mid-twentieth century fibres. The Chinese version has a grooved surface and a dumb-bell cross-section with a microporous structure. American versions tend to have a circular cross-section with a central synthetic core. The fibre is naturally coloured light yellow so requires bleaching prior to dying and has a soft lustre similar to that of silk. Like the mid-twentieth century soya bean protein fibre, woven SPF is said to be comfortable to wear with a soft hand and good drape, similar to that of silk; Chinese manufacturers compare it to cashmere.[83] The fibre is said to have good warmth retention and better moisture transmission than cotton, making it comfortable and healthy to wear. Huakangtianyarn Ltd state their fibre has 8.6% moisture regain, again similar to that of cotton. However, problems with tenacity and wet strength appear to remain. They

Table 13.4 Characteristics of soya bean fibre in comparison with other fibres

Property	Soya bean	Casein milk fibre	Wool	Silk (degummed)	Nylon
Specific gravity (g cm^3)	1.31	1.29	1.32	1.25	1.14
Dry tenacity (g den^{-1})	0.6–0.7	0.6–0.7	1.2–1.7	2.8–5.00	4.5–5.7
Wet tenacity (g den^{-1})	0.35–0.50	40–50	80–90	75–90	84–90
Tensile strength (kg cm^{-2})	700–840	700–910	1400–2000	3100–5600	4570–8220
Dry extensibility at break (%)	30–40	30–50	30–50	13–20	12–20
Wet extensibility at break (%)	60–70	85–120	30–60	–	13–26
Residual elongation, wet (%)	8.0	9.0	0.0	13.6%	Not tested
Residual elongation, dry (%)	Fibre broke before 20% extension reached	15.5	12.0	Fibre broke before 20% extension reached	Not tested
Young's modulus, wet (%)	0.006	0.016	0.10	0.26	Not tested
Young's modulus, dry (%)	0.28	0.24	0.22	0.74	Not tested
Load at 20% elongation, wet	0.05%	0.11%	0.32%	3.27	Not tested
Load at 20% elongation, dry	Fibre broke before 20% extension reached	0.44%	0.72%	Fibre broke before 20% extension reached	Not tested

Data derived from Harris and Brown, Natural and synthetic protein fibres, *Textile Research Journal*, XVII, 6, 323–330, 1947.
Harris and Brown note that soya bean fibre was an experimental fibre and that these are not representative figures as fibre properties change with different treatments.

also claim that the dry strength of their fibre is higher than that of wool, cotton and silk at 3.0 cN $dtex^{-1}$ while the wet strength is similar to cotton at 2.5–2.0 cN $dtex^{-1}$. Data about the characteristics of the Winshow SPF is available on their website.[84] The fibre is said to have a higher breaking strength than wool, cotton and silk (over 3.0 cN $dtex^{-1}$) and a high modulus with low shrinkage in boiling water making it stable to normal domestic washing. Results of published tests indicate that SPF has reasonable wet permeability, better moisture transmission properties than silk and is better than silk in retaining warmth although less well than wool. Its low friction coefficient results in a good hand which is combined with low pilling. Additionally, it is said to have 'natural bacteria resistance' to *coli* bacillus, *Staph. aureus* and *Candida albicans*.[85]

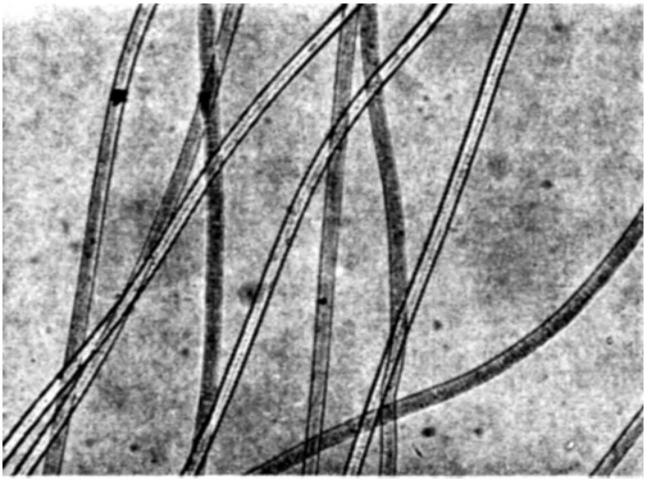
13.9 Identifying soya bean protein fibres

13.9.1 Mid-twentieth century fibres

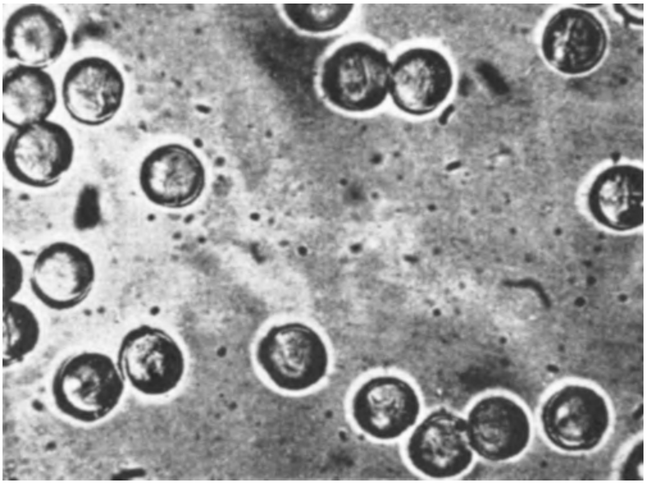
These fibres have few surface features and a circular cross-section – see Fig. 13.12(a) and (b). However, these features cannot be used as the sole basis for identification. In common with other man-made fibres, such characteristics may be influenced by the temperature of extrusion, the viscosity of the spinning solution or pressure exerted by processing equipment, depending upon the degree of plasticity in different stages of production. Fine marks and striations may therefore be visible on the surface of all such fibres.[86]

Fletcher reports that soya bean fibres responded like wool to chemical and burning tests.[87] Press describes their behaviour in burn tests: soya bean protein fibres melt away from the flame before touching the flame and melt and burn in the flame with a smell of burning feathers although they do not combust easily, tending to melt before burning.[88] The black ash is said to be brittle, puffy and easily crushable.

Williams and Tonn applied a range of standard stain methods to enable soya bean fibres to be distinguished from other regenerated or natural protein fibres (see Table 13.5).[89] They used soya bean fibre samples from Ford Motor Company, the Glidden Company, Cleveland, and the United States Soybean Laboratory, Urbana, Illinois (see Table 13.5). Although unsuccessful in distinguishing between different soya bean protein fibres, these tests did distinguish regenerated protein fibres from natural fibres. Wormell outlines a method to estimate the amount of a regenerated protein fibre in blends with natural protein fibres dependent upon establishing the relative amounts of phosphorus while also noting that the soya bean fibres test positive for tryptophan when soaked in concentrated hydrochloric acid.[90]



(a)



(b)

13.12 (a) Longitudinal view (×75) of mid-twentieth century soya bean protein fibre. From: Harris, M. (1954). *Handbook of Textile Fibers*. Washington: Harris Research Laboratories, 82. (b) Cross-sectional view (×380) of mid-twentieth century soya bean protein fibre. From: Harris, M. (1954). *Handbook of Textile Fibers*. Washington: Harris Research Laboratories, 82.

13.9.2 Late twentieth and early twenty-first century fibres

SPF has irregular striations running longitudinally along the surface which are said to contribute to the fibre's moisture-absorbing properties (Fig. 13.13).

Table 13.5 Stain tests

Fibres	α-napthol hypobromite test for arginine	Ninhydrin test for β-alanine	Adamciewicz test for tryptophane	Vanilla test for tryptophane	Morse test for hydroxy-proline	Solubility in 18% NaOH (1 hr hot)	Sulphur test for cystine
Ford soya bean	Deep red	Colourless	Deep wine purple	Purple	Colourless	Soluble	Black
Glidden soya bean	Deep red	Colourless	Brown purple	Purple	Colourless	Soluble	Black
USDA soya bean*	Deep red	Colourless	Deep wine purple	Purple	Colourless	Soluble	Black
Non-pigmented Aralac (USA milk-based fibre)	Orange	Blue purple	Colourless	Light brown	Rose-red	Disintegrated but not dissolved	Black
Pigmented Aralac (USA milk-based fibre)	Faintly orange	Colourless	Colourless to faint lavender	Light brown	Rose-red	Undissolved	Black
Lanital (Italian milk-based fibre)	Orange	Blue purple	Colourless	Light brown	Rose-red	Disintegrated but not dissolved	Black
Wool	Deep red	Blue purple	Colourless	Light purple	Colourless	Soluble	Black
Silk	Deep red	Colourless	Slightly yellowed	Purple (disintegrates)	Colourless	Soluble	Colourless
Nylon	Yellowed	Blue purple	Dissolves	Dissolves	Colourless	Soluble	Colourless

From: Williams S. and Tonn W.H., Qualitative methods of identifying soybean fibres in mixtures of casein fibre, wool or other textile fibre, *Rayon Textile Monthly* September, 63–64 (523–524), 1941.
* Soya bean protein fibre from the United States Soybean Laboratory, Urbana, Illinois obtained through A.E. Stanley Manufacturing Company

The cross-section of the Chinese fibre takes the form of irregular dumb-bells with micro-pores sometimes described as ‘islands-in-a-sea’. This makes the fibre permeable to air and moisture.[91] Spectral analysis of several samples of modern soya fibre showed the presence of protein (two small peaks at 1640 and 1530 cm^{-1}, the amide I and II bands) along with a larger quantity of cellulose or polysaccharide material (Fig. 13.14).

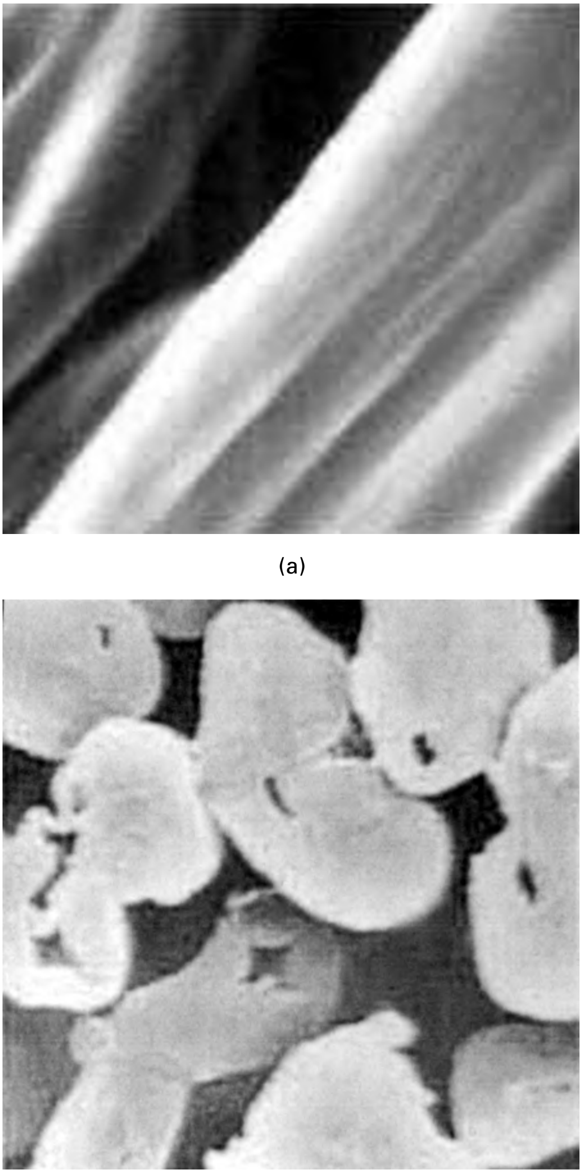
13.10 Degradation behaviour

13.10.1 Mid-twentieth century fibres

Soya bean fibre was easily degraded by alkali and yellowed considerably when placed in a conditioning oven and exposed to a temperature of 220°F. This is comparable to the behaviour by casein fibres.[92] Fletcher reports that soya bean fibres mildewed less easily than natural and casein fibres but more easily than the synthetic fibres.[93] Views diverge on the susceptibility of regenerated protein fibres to biological attack. Wormell argues that ‘the more a protein molecule is changed by chemical and tanning [hardening] processes, the less likely is it to suffer biological attack’.[94] Others contended that regenerated protein fibres, including soya bean fibres, were subject to attack by moths.[95] An anonymous writer in *Rayon Textile Monthly* notes that preventing such damage is a major issue ‘when fibre conservation is of such primary concern on both military and civilian fronts’.[96] It should be noted, however, that the author recommends the use of Merck & Co.’s anti-moth treatment ‘Amuno’ and the nature of the article is such that it seems possible that it is a promotional piece. However, the fibre’s lack of strength when wet appears to have been the major route for degradation.

13.10.2 Late twentieth and early twenty-first century fibres

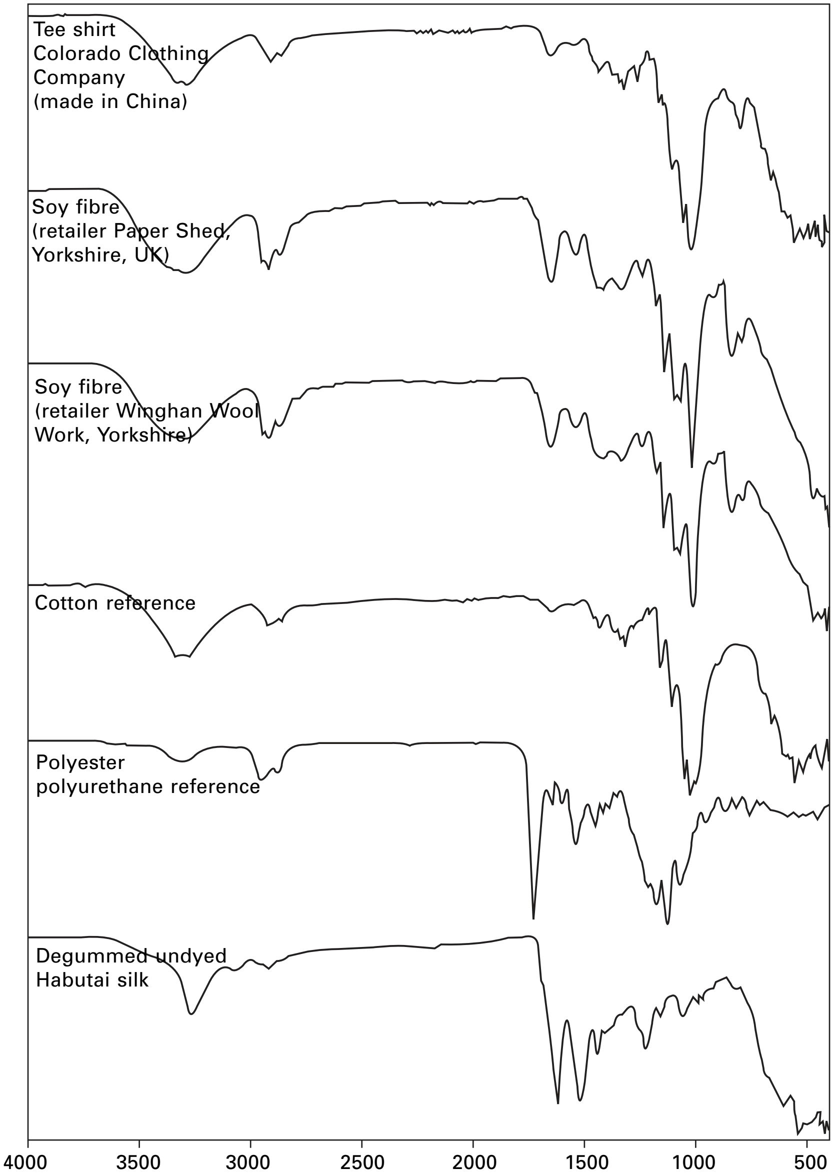
SPF is being actively promoted as a biodegradable fibre. It is said to wear well, being resistant to acid, alkali, perspiration and light, including UV light, although little reliable quantitative data appears to be available.[97] Two months’ outdoor exposure of the Huakangtianyuan SPF fibre resulted in little fading, 11% strength loss and no fungal formation. Exposure to UV for 120 hours resulted in a 9.8% strength loss.[98] It has good acid and alkali resistance. Exposure to dry heat caused the fibre to become yellow and sticky.[99] The fibre itself is said to be biodegradable in landfill[100] and it seems likely that biodegradation processes would be initiated through exposure to water.



(a)

(b)

13.13 (a) Longitudinal SEM view of contemporary soya bean protein fibre. Note the irregular grooves. From: Senshoku Keizai Shimbun, 2004, *Physical characteristics and processing method of Chinese soybean fiber.* Textileinfo.com. (b) Cross-sectional SEM view of contemporary soya bean protein fibre. Note the irregular dumbbell shape with the so-called 'islands-in-the-sea' structure. From: Senshoku Keizai Shimbun, 2004, *Physical characteristics and processing method of Chinese soybean fiber*. Textileinfo.com.



13.14 Comparative ATR spectra of soya bean protein fibres and natural and synthetic fibres. © Textile Conservation Centre, University of Southampton.

13.11 A truly biodegradable and ecological fibre?

Biodegradable fibres degrade safely and relatively quickly through biological processes, returning to their source materials. The mid-twentieth century fibre appears to have been all too successful in achieving this goal. The status of modern fibres is rather more complex. Pure SPF is being promoted as being as a biodegradable fibre; however, the impact of finishes on this process need to be considered as does the biodegradability of the PVA used in bi-component fibres. Whether or not it can be considered as an ecological fibre is not straightforward. Soya beans are a renewable resource although the environmental impact of their production is increasingly being questioned; the production method is said not to be environmentally damaging. Manufacturers such as Huakangtianyarn Ltd[101] stress the ecological acceptability of the process: the agents used in production are said to be non-toxic while other auxiliaries can be recycled; the residues of the soya beans may be used as animal fodder once the protein has been extracted.[102,103] However, the wider environmental impact of large-scale soya bean farming needs to be factored into an overall evaluation of the environmental impact of SPF.

13.12 Conclusion

The future of soya protein fibres is related to the availability of soya bean protein, which is influenced by political, economic and ecological issues. Commandeur *et al.*[104] argue that sustainable development, with reduced animal production, less dependence on agrochemicals and diversification of the vegetable oil sector might act to reduce soya production. The future of genetically modified soya beans will also have an impact on production. However, the future of the fibre itself seems promising. Li Jinbao, Director of the Textile Science and Technology Centre, China Textile Industry Association is optimistic that problems with flexibility can be overcome.[105] The attraction of renewable and organic textiles is growing; Magruder, director of Fabrikology International notes 'The whole category of renewable resource-base fibres is going to be huge'.[106] Echoing Henry Ford, Yi-you argues that soya bean fibres have the potential to create a new range of products which additionally 'will be beneficial to the industrialisation of agriculture'.[107] Clearly, SPF is being continually improved with the focus on developing yarns, spinning technology and weaving methods and manufacturers are developing confidence in the properties of the new fibre. Introducing consumers to the fibre is as critical as the performance of the fibre. SPF could remain a niche fibre, marketed for ecologically conscious and probably better-off consumers, or could develop into a mainstream fibre, effectively competing with natural and synthetic fibres. Whether it achieves acceptability as an economically competitive fibre, capable of holding its own in the marketplace with natural and synthetic fibres and with the added benefit of being a biodegradable fibre, is an unfolding story.

13.13 Acknowledgements

Much of the initial research for this paper was undertaken at the Getty Conservation Institute (GCI), Los Angeles as a GCI Scholar in 2002. I am most grateful for the Institute's generous support and particularly for the input of their research librarians, especially Luke Swetland and Mitchel Bishop. I would also like to acknowledge the help of colleagues at the Textile Conservation Centre, University of Southampton, particularly Dinah Eastop, Leo Dokos, Paul Garside for analysis and Michael Halliwell for imaging. Denise Buhr (Research Librarian, Central Soya, Indiana) and Patricia Starrett (Archivist, ICI) kindly searched company archives on my behalf. Finally, I would like to thank Nell Hoare, Director, Textile Conservation Centre, University of Southampton for permission to publish.

13.14 References

1. Perez-Maldonado, R.A., Mannion, P.W., Farrell, D.J. and James, A.T. (1999), *Raw Soybeans Selected for Low Trypsin Inhibitor Activity for Poultry Diets*, Cleveland, Australia: Rural Industries Research & Development Corporation, www.rirdc.gov.au/reports, accessed 28 August 2004.
2. Anon. (1996), *50th Anniversary Edition of the Soya Blue Book,* http://66.201.71.163/soyindustry/research.htm, accessed 28 August 2004.
3. Horvath, A.A. (1933), The soy-bean industry in the United States, *Journal of Chemical Education*, 10 (1), 5–12, summarised in: Shurtleff, W. and Aoyagi, A. (1994) *Henry Ford and his Researchers' Work with Soybeans, Soyfoods, and Chemurgy – Bibliography and Sourcebook, 1921 to 1993*, Lafayette CA, Soyfoods Center, 17–18.
4. Soyabean Almanac (2002), www.unitedsoybean.org/soystats2002, accessed 28 August 2004.
5. Agricultural Experiment Station (1930), *Soybean Production in Kansas. Bulletin 249*, Manhattan, Kansas, Kansas State College Agriculture & Applied Science.
6. Agricultural Experiment Station (1939) *Soybean Production in Kansas. Bulletin 282 (Bulletin 249 revised)*, Manhattan, Kansas, Kansas State College Agriculture & Applied Science.
7. Grain (pseud.) (1997), 'Soybean: the hidden commodity', *Seedling*, June, www.grain.org/seedling/, accessed 28 August 2004.
8. Grain (pseud.) (1997), 'Soybean: the hidden commodity', *Seedling*, June, www.grain.org/seedling/, accessed 28 August 2004.
9. Kurtenbach, E. (2001), Monsanto soybean patent alarms Chinese farmers, *Associated Press*, 13 December, www.organicconsumers.org/monstanto/chinapatent121701.cfm, accessed 28 August 2004.
10. Press, J.J. (1959), *Man-made Textile Encyclopedia*, New York, Textile Book Publishers, 23.

11. Moncrieff, R.W. (1970), *Man-made Fibres* (5th edn), London, Haywood Books.
12. Zhang, Y. (1996), *Solution Studies on Soybean Protein for Fiber Spinning*, (MSc Polymer thesis), Georgia, Georgia Institute of Technology.
13. Dirks, K. (2000), 'Aralac: "The cow, the milkmaid and the chemist" ', *Ars Textrina. A Journal of Textiles and Costume*, 33, 79.
14. Kiplinger, J. (2003), *Meet the Azlons from A–Z: Regenerated & Rejuvenated*, www.fabrics.net/joan103.asp, accessed 3 March 2003.
15. Rose, H.W. (1944), 'Synthetic fibers in military and postwar fabrics', *Rayon Textile Monthly,* XXV, 11, 63–65.
16. Morrison, B.V., Fletcher, H.M., Beery, Mack. P., Chapman Morse, E., Phelps, E.L. and Stout, E.E. (1946), 'How the war affected civilian textiles', *Journal of Home Economics*, 38, 21.
17. O'Brien, R. (1942), 'Wartime textile adjustments', *Journal of Home Economics*, 34, 514.
18. Lundgren, H.P. and O'Connell, R.A. (1944), 'Artifical fibers from corpuscular and fibrous proteins', *Industrial & Engineering Chemistry*, 36 (4), 370.
19. Anon, (1942) 'Beetles and moths will attack all protein fibres', *Rayon Textile Monthly*, XXIII (9), 109.
20. Fletcher, H.M. (1942), *Synthetic Fibers and Textiles. Agricultural Experiment Station Bulletin 300*, Kansas, Kansas State College of Agriculture and Applied Science, 35–36.
21. Sherman, J.V. and Sherman, S.L. (1946), *The New Fibers*, New York, D van Nostrand Company, 32.
22. Sherman, J.V. and Sherman, S.L. (1946), *The New Fibers*, New York, D van Nostrand Company, 343–346.
23. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, xiii.
24. Traill, D. (1951), 'Some trials by ingenious inquisitive persons: regenerated protein fibres', *Journal of the Society of Dyers and Colourists*, 67, 270.
25. Moncrieff, R.W. (1970), *Man-made Fibres* (5th edn), London, Haywood Books, 306.
26. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 19.
27. Anon. (1942), 'Notes on some of the development work now under way at the Ford Motor Company', (unpublished typescript), summarised in Shurtleff, W. and Aoyagi, A. (1994), *Henry Ford and his Researchers' Work with Soybeans, Soyfoods, and Chemurgy – Bibliography and Sourcebook, 1921 to 1993*, Lafayette CA, Soyfoods Center, 7–72.
28. Traill, D. (1951), 'Some trials by ingenious inquisitive persons: regenerated protein fibres', *Journal of the Society of Dyers and Colourists*, 67, 264.
29. Traill, D. (1951), 'Some trials by ingenious inquisitive persons: regenerated protein fibres', *Journal of the Society of Dyers and Colourists*, 67, 264.
30. Bergen, W. von (1944), 'The soybean fiber as seen by a wool man', *Rayon Textile Monthly*, XXV (5) May, 57–58.
31. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 153.
32. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 3.
33. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 27.

34. Lundgren, H.P. and O'Connell, R.A. (1944), 'Artifical fibers from corpuscular and fibrous proteins', *Industrial & Engineering Chemistry*, 36 (4), 370.
35. Traill, D. (1951), 'Some trials by ingenious inquisitive persons: regenerated protein fibres', *Journal of the Society of Dyers and Colourists*, 67, 257–270.
36. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 51.
37. Traill, D. (1951), 'Some trials by ingenious inquisitive persons: regenerated protein fibres', *Journal of the Society of Dyers and Colourists*, 67, 265.
38. Kelly, J.J. and Pressey, R. (1966), *Cereal Chemistry*, 43 (2), 195.
39. Ishino, K. and Okamoto, S. (1975), 'Molecular interaction in alkali denatured soybean proteins', *Cereal Chemistry*, 52 (1), 9–20.
40. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 80.
41. Dirks, K. (2000), 'Aralac: "The cow, the milkmaid and the chemist"', *Ars Textrina. A Journal of Textiles and Costume*, 33, 75–85.
42. Traill, D. (1951), 'Some trials by ingenious inquisitive persons: regenerated protein fibres', *Journal of the Society of Dyers and Colourists*, 67, 266–267.
43. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 90.
44. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 59–62.
45. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 55.
46. Traill, D. (1951), 'Some trials by ingenious inquisitive persons: regenerated protein fibres', *Journal of the Society of Dyers and Colourists*, 67, 268.
47. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 97.
48. Traill, D. (1951), 'Some trials by ingenious inquisitive persons: regenerated protein fibres', *Journal of the Society of Dyers and Colourists*, 67, 265.
49. Ramseyer, D.R. (1941), 'Ford develops soybean upholstery fiber', *Soybean Digest*, 11, 12.
50. Harris, M. (1954), *Handbook of Textile Fibres*, Washington, Harris Research Laboratories, 82.
51. Sherman, J.V. and Sherman, S.L. (1946), *The New Fibers*, New York, D van Nostrand Company, 187.
52. Anon. (1939), 'Soy-bean textile is advanced by Ford: Crowds see new synthetic fiber made', *New York Times*, 17 May, 19, summarised in Shurtleff, W. and Aoyagi, A. (1994), *Henry Ford and his Researchers' Work with Soybeans, Soyfoods, and Chemurgy – Bibliography and Sourcebook, 1921 to 1993*, Lafayette CA, Soyfoods Center, 52.
53. Ramseyer, D.R. (1941), 'Ford develops soybean upholstery fiber', *Soybean Digest*, 11, 12.
54. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 183.
55. Boyer, R.A. (1940), 'Soybean protein fibers: Experimental production', *Industrial and Engineering Chemistry*, 32 (12), 1549–1551, summarised in Shurtleff, W. and Aoyagi, A. (1994), *Henry Ford and his Researchers' Work with Soybeans, Soyfoods, and Chemurgy – Bibliography and Sourcebook, 1921 to 1993*, Lafayette CA, Soyfoods Center, 53.

56. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, xvi.
57. Grain (pseud.) (1997), 'Soybean: the hidden commodity', *Seedling*, June, www.grain.org/seedling/, accessed 28 August 2004.
58. Barnett, A. (2004), 'They hailed it as a wonderfood. But soya not only destroys forests and small farmers – it can also be bad for your health', *The Observer Food Monthly*, 44, 31–39.
59. China Education and Research Network (2001), *China develops world's first 'soybean' garment*. http://www.edu.cn/20010101/22557.shtml, accessed 17 December 2004.
60. The Woolmark Company (2001), http://www.wool.com, accessed 26 June 2002.
61. Casselle, T. (2003), 'Making a meal of fashion: soybean fibre arrives', *Market News Express*, 10 Dec. www.tdctrade.com/mne/germent /clothing115.htm, accessed 16 November 2004.
62. Huakangtianyuan High-Tech Co. Ltd (n.d.), *Introduction to SPF*, www.soybeanfibre.com, accessed 28 August 2004.
63. Yi-you, L. (2004), 'The soybean protein fibre – a healthy and comfortable fibre for the 21st century', *Fibres and Textiles in Eastern Europe*, 12 (2), [46], 8.
64. Zhang, Y., Ghasemzadeh, S., Kotliar, A.M., Kumar, S., Presnell, S. and Williams, D.L. (1999), Fibres from soybean protein and poly(vinyl alcohol), *Journal of Applied Polymer Science*, 71 (1), 11–19.
65. Shimbun, S.K. (1999), *Physical Characteristics and Processing Method of Chinese Soybean Fiber*, www.Textileinfo.com, accessed 3 March 2004.
66. Yi-you, L. (2004), 'The soybean protein fibre – a healthy and comfortable fibre for the 21st century', *Fibres and Textiles in Eastern Europe*, 12 (2), [46], 9.
67. Yi-you, L. (2004), 'The soybean protein fibre – a healthy and comfortable fibre for the 21st century', *Fibres and Textiles in Eastern Europe*, 12 (2), [46], 8–9.
68. Yi-you, L. (2004), 'The soybean protein fibre – a healthy and comfortable fibre for the 21st century', *Fibres and Textiles in Eastern Europe*, 12 (2), [46], 9.
69. Swicofil, A.G. Textile Services (n.d.), *Soybean Protein Fiber*, www.swicofil, accessed 28 August 2004.
70. Casselle, T. (2003), 'Making a meal of fashion: soybean fibre arrives', *Market News Express*, 10 Dec. www.tdctrade.com/mne/garment/clothing115.htm, accessed 16 November 2004.
71. China Education and Research Network (2001), *China develops world's first 'soybean' garment*. http://www.edu.cn/20010101/22557.shtml, accessed 17 December 2004.
72. Casselle, T. (2003), 'Making a meal of fashion: soybean fibre arrives', *Market News Express*, 10 Dec. www.tdctrade.com/mne/garment/clothing115.htm, accessed 16 November 2004.
73. Colorado Clothing (2004), 'Colorado Clothing's Soybu™ makes global debut at the Magic Show', *Peak Exposure Colorado Trading & Clothing Company*, http: //www.peakexposure/com, accessed 28 August 2004.
74. Fletcher, H.M. (1942), *Synthetic Fibers and Textiles. Agricultural Experiment Station Bulletin 300*, Kansas, Kansas State College of Agriculture and Applied Science, 15.
75. Harris, M. (1954), *Handbook of Textile Fibres*, Washington, Harris Research Laboratories, 82 and Fig. 5.
76. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 168.
77. Sherman, J.V. and Sherman, S.L. (1946), *The New Fibers*, New York, D van Nostrand Company, 185.

78. Sherman, J.V. and Sherman, S.L. (1946), *The New Fibers*, New York, D van Nostrand Company, 186.
79. Sherman, J.V. and Sherman, S.L. (1946), *The New Fibers*, New York, D van Nostrand Company, 183.
80. Sherman, J.V. and Sherman, S.L. (1946), *The New Fibers*, New York, D van Nostrand Company, 22.
81. Boyer, R.A. (1940), 'Soybean protein fibers: Experimental production', *Industrial and Engineering Chemistry*, 32 (12), 1549–1551, summarised in Shurtleff, W. and Aoyagi, A. (1994), *Henry Ford and his Researchers' Work with Soybeans, Soyfoods, and Chemurgy – Bibliography and Sourcebook, 1921 to 1993*, Lafayette CA, Soyfoods Center, 53.
82. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 153.
83. Yi-you, L. (2004), 'The soybean protein fibre – a healthy and comfortable fibre for the 21st century', *Fibres and Textiles in Eastern Europe*, 12 (2), [46], 8–9.
84. Huakangtianyuan High-Tech Co. Ltd (n.d.), *Introduction to SPF*, www.soybeanfibre.com, accessed 28 August 2004.
85. Swicofil, A.G. Textile Services (n.d.), *Soybean Protein Fiber*, www.swicofil, accessed 28 August 2004.
86. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 170.
87. Fletcher, H.M. (1942), *Synthetic Fibers and Textiles. Agricultural Experiment Station Bulletin 300*, Kansas, Kansas State College of Agriculture and Applied Science, 16.
88. Press, J.J. (1959), *Man-made Textile Encyclopedia*, New York, Textile Book Publishers, 143.
89. Williams, S. and Tonn, W.H. (1941), 'Qualitative methods of identifying soybean fibers in mixtures of casein fiber, wool, or other textile fiber', *Rayon Textile Monthly*, XXII, 11, 63–64.
90. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 153 and 175–176.
91. Shimbun, S.K. (1999), *Physical Characteristics and Processing Method of Chinese Soybean Fiber*, www.Textileinfo.com, accessed 3 March 2004.
92. Sherman, J.V. and Sherman, S.L. (1946), *The New Fibers*, New York, D van Nostrand Company, 186.
93. Fletcher, H.M. (1942), *Synthetic Fibers and Textiles. Agricultural Experiment Station Bulletin 300*, Kansas, Kansas State College of Agriculture and Applied Science, 17.
94. Wormell, R.L. (1954), *New Fibres from Proteins*, London, Butterworths Scientific Publications, 145.
95. Dooley, W.H. (1943), *Textiles* (new revised edition with experiments), Boston, Heath & Co., 699.
96. Anon. (1942), 'Beetles and moths will attack all protein fibres', *Rayon Textile Monthly*, XXIII (9), 109.
97. Yi-you, L. (2004), 'The soybean protein fibre – a healthy and comfortable fibre for the 21st century', *Fibres and Textiles in Eastern Europe*, 12 (2), [46], 9.
98. Huakangtianyuan High-Tech Co. Ltd (n.d.), *Introduction to SPF,* www.soybeanfibre.com, accessed 28 August 2004.
99. Anon. (2003), 'China develops soyabean fibre', *Textiles Magazine*, 30 (2), 4.

100. Swicofil, A.G. Textile Services (n.d.), *Soybean Protein Fiber*, www.swicofil, accessed 28 August 2004.
101. Huakangtianyuan High-Tech Co. Ltd (n.d.), *Introduction to SPF*, www.soybeanfibre.com, accessed 28 August 2004, 4.
102. Shimbun, S.K. (1999), *Physical Characteristics and Processing Method of Chinese Soybean Fiber*, www.Textileinfo.com, accessed 3 March 2004.
103. Yi-you, L. (2004), 'The soybean protein fibre – a healthy and comfortable fibre for the 21st century', *Fibres and Textiles in Eastern Europe*, 12 (2), [46], 8.
104. Commandeur, P. *et al*. (1995), 'Impact of biotechnology on the world trade in vegetable oils 1 & 2', *Biotechnology and Development Monitor*, 23–24.
105. China Education and Research Network (2001), *China develops world's first 'soybean' garment.* http://www.edu.cn/20010101/22557.shtml, accessed 17 December 2004.
106. Casselle, T. (2003), 'Making a meal of fashion: soybean fibre arrives', *Market News Express*, 10 Dec. www.tdctrade.com/garment/clothing115.htm, accessed 16 November 2004.
107. Yi-you, L. (2004), 'The soybean protein fibre – a healthy and comfortable fibre for the 21st century', *Fibres and Textiles in Eastern Europe*, 12 (2), [46], 9.