

Review

The Potential for Regenerated Protein Fibres within a Circular Economy: Lessons from the Past Can Inform Sustainable Innovation in the Textiles Industry

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Abstract: Humanity is currently facing a crisis of excess, with a growing population and the trend towards disposable goods, and the world's resources are under tremendous pressure. This is especially evident in the textiles industry, with increasing consumer numbers and the trend of 'fast fashion' causing demand to be at an all-time high, with non-renewable feedstocks depleting and production of natural fibres also under strain. Considering the future of textile production, it can be beneficial to investigate our past for inspiration towards more sustainable approaches. Much of the research into regenerated protein fibres was performed out of necessity during wartime, and while this demonstrates the potential for food waste to be exploited as a resource, the manufacturing methods used at the time now present issues for a circular economy due to the high amounts of toxic waste produced. Using a range of historical and modern literature sources, including journal articles, patents and conference papers, this review presents the historical precedent and research performed into *azlons*, regenerated fibres produced from waste protein-rich materials. Historical evidence shows that the success of these *azlon* fibres was short-lived, partly due to negative associations with deprivation and hardship, alongside the emergence of alternative man-made fibres, which were devoid of these connotations with never-before-seen physical properties. The social and political climate leading to the creation, and ultimate demise, of *azlons* is explored along with the influence of evolving technologies and the marketing of these textile products to consumers. Although the creation of products from waste is not a new concept, the literature has identified that the synergy between the challenges faced in a time of resource scarcity and the current trend of problematic excess reveals an exciting opportunity to learn from our past to create a greener future. Lessons that could help with the current crisis within the textile industry are extracted and presented within the concept of a circular textiles economy. Our findings show that there is notable potential for one regenerated protein fibre, made from casein extracted from milk waste, to be manufactured within a localised, circular economy in conjunction with the principles of green chemistry and sustainable textiles technology.

Keywords: regenerated fibres; regenerated protein fibres; waste; circular economy; valorisation; garment industry; man-made fibres; textile processing; textile history



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1. Introduction

Global annual fibre production in 2017 was over 105 million tonnes (Mt) [1] with polyester (53.7 Mt) and cotton (25.8 Mt) making up 76% of the total; regenerated cellulose (e.g., lyocell, viscose; 6.7 Mt), other plant fibres (e.g., linen, hemp; 5.6 Mt), polyamides (5.7 Mt), other synthetics including polypropylene (6 Mt), wool (1.2 Mt) and other natural fibres (0.4 Mt) make up the remainder. The garment industry produces an estimated 3.3 billion tonnes of CO₂e on an annual basis, based on 2017 estimates [2]. The uncontrolled release of microfibres (MFs) from both natural and synthetic fibres at different life cycle

stages (processing, cleaning, washing) is a growing concern: plastic MFs account for over a third of all plastic reaching the open ocean [3] and are now pervasive in all ecosystems and potentially more damaging to biogeochemical processes, species and human health than other plastic waste; some recent studies show ~80% of ocean MFs are dyed/finished cellulosic fibres [4] whose impact is still not known. With apparel consumption set to rise from 62 million tons today to 102 million tons by 2030 (a 63% increase) [5], it is no surprise that we are in the midst of an ecological and environmental crisis; the needs to secure new sustainable approaches for the garment industry are identified as a matter of urgency.

The catastrophic environmental and ecological impact of plastics, including synthetic fibres, is well documented in the media. However, the impact of natural fibres such as cotton, silk and wool also have their impacts. For example, wool fibre production accounts for 36% of the total carbon footprint of fashion fibre production in the UK [6] proving that improvements in fibre production would have a significant impact on the overall ecological footprint of the UK's garment industry.

With growing public and consumer awareness, the environmental incentive for re-thinking alternative material resources could not be more pertinent. Although some fashion brands are said to be making changes in their supply chain and opting for more environmentally friendly fibres, sustainable impacts resulting from efforts in the fashion sector are difficult to measure. Today, it is not uncommon for brands to promote an 'eco' range via switching to the use of more purported sustainable fibres or manufacturing processes. Yet, few offer sufficient insight to prove their claims and can be accused of 'greenwashing', the act of using misleading marketing strategies to persuade customers that a product is environmentally friendly. As for the determination of genuine sustainable raw materials, this can be difficult for brands and consumers alike due to a lack of legislation or clear guidelines as to what constitutes as 'sustainable' [7].

The implementation of circular design principles could offer a solution to this conundrum. A circular economy is an industrial system that is regenerative by design, with the end of one product's lifetime becoming the beginning of another's [8]. In a circular economy, waste can be eliminated by shifting towards the use of renewable energy, ending the use of toxic chemicals and through the design of new materials, products and systems [9]. One of the core concepts of circular design is that waste can act as a feedstock, removing the end-of-life concept by transforming old products into new ones. In the context of regenerated fibres, especially regenerated protein fibres (RPFs) that were historically known as *azlons*, this waste is often organic in nature and poses an interesting opportunity.

The use of food production waste offers a huge opportunity with benefits to the environment and the UK economy. According to 2013 data, up to 2bn tonnes *p.a.* of all food produced in the world ends up as waste [10,11], a carbon footprint of 3.3bn tonnes CO₂e, ca. 8% of global greenhouse gas (GHG) emissions. Yet this waste is often unavoidable by-products that offer an exploitation opportunity, irrespective of the efficiencies of food production, with some notable examples that could be used for RPFs. A 2020 report by WRAP [12] highlights that the UK dairy industry produces ~14bn litres of milk *p.a.*, with ~555,000 tonnes *p.a.* of waste from production, which is either incinerated or spread on land; the chief by-product of cheese-making is whey (~228,000 tonnes *p.a.*), which contains a significant amount of casein. 82% of milk protein is casein with the remainder being comprised of whey; whey is already utilised in the dietary supplement industry, but the uses for casein are fewer, hence casein from food waste presents an attractive opportunity for valorisation, potentially for RPFs. Several other waste protein sources offer interesting resource potential for RPFs: World peanut production for edible oil generates 5.8 Mt *p.a.* of 'cake' by-product after oil extraction (2012 data [13]), which has a protein content of ~50%; over 885 Mt *p.a.* corn (maize) is produced (2013 data [11]), of which 25% is used for ethanol production, the major by-product of which is protein (~40% zein) [14]; and over 262 Mt *p.a.* soybeans are produced (2013 data [11]), processing of which generates ~12.7 Mt *p.a.* of by-product (known as okara) [15], of which the dry weight is 27.4% protein [16].

With the amount of waste being produced along with the advent of ‘fast fashion’ and other consumerism movements, the modern world is struggling with excess; this means that more research is going into what can be done with such waste. While most of this research investigates the future, it can be beneficial to investigate our past. Other times of struggle, albeit for a vastly different reasons, were during the two World Wars; the issue then was not one of excess, but rather one of limited availability of resources. The approach taken at the time, however, was similar and utilised waste as a feedstock to alleviate pressures on resources that were strained by military demand or simply unavailable due to the challenges of wartime trade. Textiles were especially important, with wool for uniforms being quoted as just as important as bullets during wartime [17]. Research and development during this period allowed for the creation of textiles from waste protein, but due to a variety of factors these RPFs were quickly forgotten once the wars had ended. The reasons for this and the lessons we could learn from our past for future development of sustainable fibres are explored within this review.

2. Methods

A review of literature from current and archive-based journal articles and patents has been applied to create a timeline, plotting protein-based fibre technological innovations against key social, technological, and political events around the globe (Figure 1). The concept of Thompson’s *Rubbish Theory* [18] is considered to help understand the evolution of RPFs from a cultural and social perspective. Brooks and Rose [19] explore *Rubbish Theory* as a useful model for realising changing attitudes towards artefacts and to gain insight into why these fibres, once available across the globe, have disappeared. *Rubbish Theory* also traces shifting attitudes to the value of objects ‘The relationship between status, the possession of objects, and the ability to discard objects’ [18]. This framework enables a systematic understanding that an item’s worth is not fixed but fluctuates over time. Thompson dissects these characteristics into three categories: Transient (‘here today, gone tomorrow’), durable (‘a joy forever’) and rubbish; this theory also explores the dynamics through which rubbish can re-enter circulation as a valued commodity, potentially exceeding its original value [18]. In terms of a contemporary fashion market, this regeneration of value supports a circular economy of goods including textile fibres through recycling and reuse.

As we seek to understand the rise and fall of these fibres, it is necessary to investigate the relevant influencing factors: (1) The socio-political landscape of the time; (2) advances in technology; and (3) the way in which each fibre was marketed and presented to consumers. Through her own historical investigation, Brooks [20] also identifies three possible generations of RPFs, each developed in response to varying economic, political and social factors. The first were created between the mid-19th century and early 20th century, the second in the mid-20th century, and the third in the late 20th and early 21st centuries. Building upon this concept, a fourth generation will be identified to focus on fibres created in the 21st century and analyse the potential for a new range of fibres, created in response to excessive consumption over economic hardship.

This review seeks to understand the potential for protein by-products from the food industry, especially casein, as raw materials for the UK garment industry within the framework of a circular economy. Historical learnings have been combined with the outcomes of Brooks’ framework, from the lens of a contemporary fashion market. Socio-political drivers influencing the journey of casein fibre technology are analysed to underpin the potential for a review of milk waste streams, as an approach to a circular strategy, therefore the literature has been reviewed with the circular economy and sustainability in mind. Approaching this historical research with a modern sustainability mindset allows an exciting opportunity to learn from the past while also utilising the knowledge and experience afforded from a modern perspective.

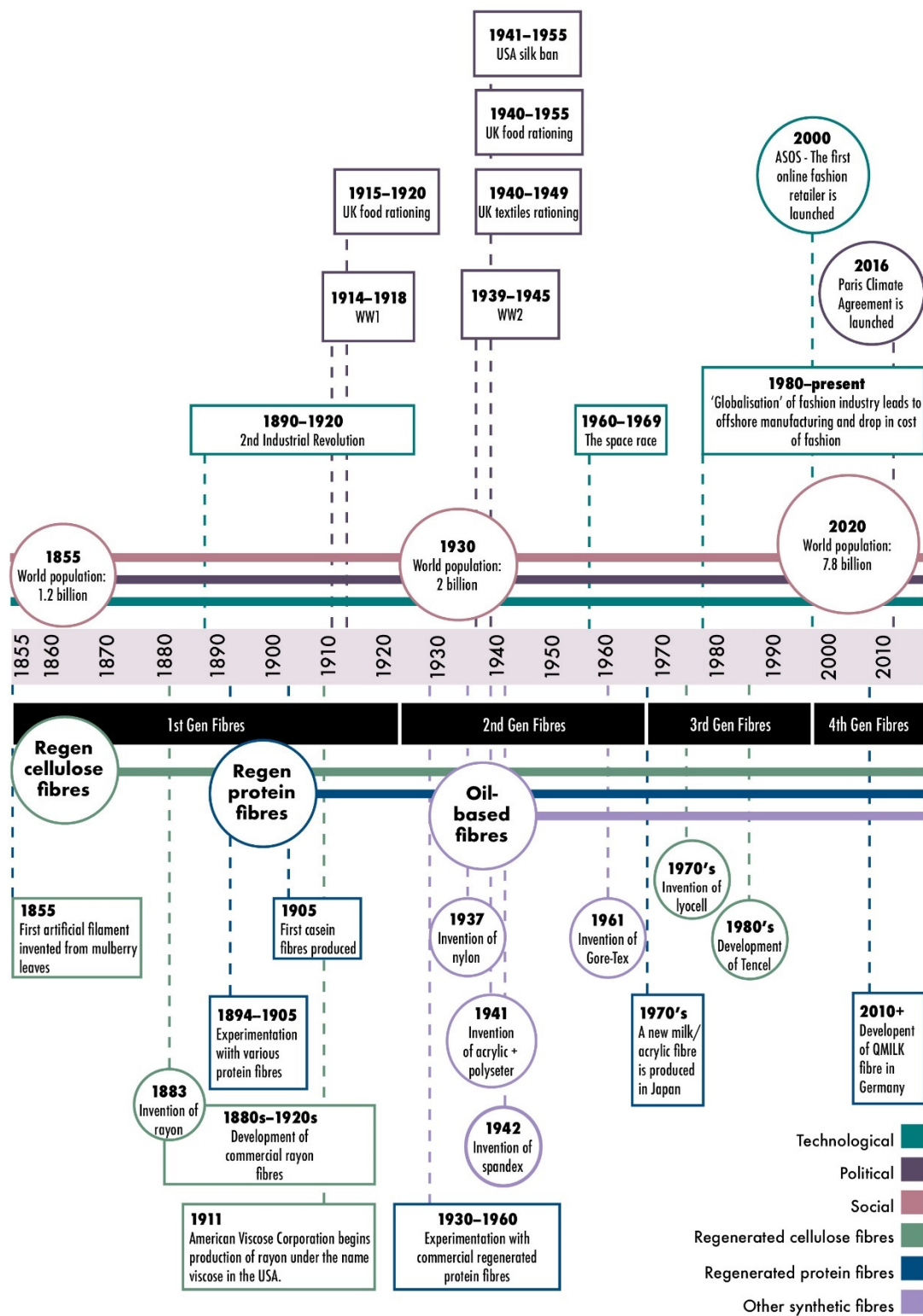


Figure 1. This timeline indicates the crucial events that might have influenced our fashion consumption choices, as well as demonstrating the shift in interest between three groups of synthetic fibres, from the first known man-made fibre in 1855, to present day.

3. Results

3.1. First Generation Fibres: 1855–1925

3.1.1. Socio-Political Context

The industrial revolution, the First World War (WW1) and the wider impact of globalization had significant effects on the development of RPFs. During WW1, many household products (from food to textile items) were replaced with substitutes known as ‘ersatz’, a term borrowed from the German language and often referred to because of the privations of war which came into prominence during WW1, with a resurgence in use due to the development of new, substitute products during the Second World War (WW2). Unlike regenerated cellulose fibres (notably viscose), which were invented some 25 years before WW1, RPFs were initially (and rather unsuccessfully) created as ersatz around the time of WW1. These initial fibres suffered from exceedingly poor strength and never reached the level of development needed to make them suitable for a commercial market, and by the 1920s industrial efforts had been largely abandoned.

3.1.2. Technology

The technology of natural fibres dates to pre-historic times where humans began to process biological materials such as animal skins to create garments and other textile products. Although the origin of man-made fibres as a concept is unclear, the link between observations of the silkworm’s method of producing silk with the concept for manufactured fibres can be found in Hooke’s *Micrographia* [21] where he describes the possibility of producing an “artificial glutinous composition” resembling the substance produced by the silkworm, which might be “drawn out into small wires for use”.

The original patent describing a manufactured fibre was filed by Swiss chemist, Georges Audemars [22] who discovered a process for creating artificial silk using cellulose derived from the wood of the mulberry tree. Thirty years later, Sir Joseph Swan discovered a more efficient process of producing an artificial thread while experimenting with the incandescent electric filament lamp. Swan invented a device for extruding fibres and describes a deoxidising agent that prevented the fibres from burning explosively [23]; in this process, a solution of nitrocellulose was dissolved in acetic acid and forced through small holes into alcohol, which carbonised and set the resulting filaments. This method paved the way for French industrial chemist Hilaire Bernigaud Chardonnet, who was the first to exploit the fibre for textile purposes, dominating the production of rayon for years to come [24].

Although early rayon was discovered in the 1880s, it was not until 1903 that a commercial way of making these filaments was discovered [25]. In 1905, British silk firm Samuel Courtauld & Company began manufacturing the fibre commercially, which then became known as viscose rayon, the term deriving from the viscous solution that comprised the spinning dope [26]. Soon after, the American Viscose Corporation began production in the USA. Many chemists across the globe used variations of this process to create their own versions of rayon, yet many were deemed unsafe for commercial production due to flammability and the use of toxic chemicals. In 1891, Chardonnet began production of an early type of rayon and the first commercially available man-made fibre, known as Chardonnet silk [27].

Although RPFs were invented in the 1890s, the vast majority of the 146 patents for producing fibres from protein sources were filed in the 1930s and 1940s [28]. The first on record is Adam Millar’s 1894 patent of a gelatine filament, produced by forcing a concentrated, hot gelatine solution through nozzles to form fine threads. These were supported by a series of traveling revolving cylinders used to wind the threads before leaving them to dry for weaving. These threads were known as vanduara silk and were highly promoted at the time, despite being unsuitable for commercial use due to their poor strength and water absorption [25].

Casein fibres were amongst the most successful RPFs despite their common issues of low tenacity and wet strength. Five years after patenting his gelatine threads, Millar

produced a 'proteids'-based fibre from egg albumen, blood albumen, vegetable albumen and casein [29]. This patent would largely inform the process for making casein fibres, patented by Todtenhaupt in the early 1900s [30] as a substitute for artificial silk and horsehair until his production company, Deutsche Kunstseidenfabrik, shut down [31].

3.1.3. Marketing

Major journals published statements regarding the threat of being burned by wearing rayon along with claims that it could dissolve in rainwater [32]. In 1905, *The Textile Mercury* described rayon to be 'stiff and wiry' and difficult to care for. Serious complaints were also being made that work in rayon factories was having a negative effect on the operatives, as well as reports of 'dreadful smells coming from rayon works' [32]. Today, rayon has survived the test of time, but early consumers were reluctant to accept rayon as a fashionable textile—and marketing the new fibre took large amounts of time and money. A 1930s report from the Women's Trade Union League of America reported that the use of carbon disulphide in the early manufacturing of rayon led to factory workers being poisoned, resulting in cases of carbon disulphate psychosis [33]; symptoms include skin burns and irritation, digestive issues, paralysis, pernicious anaemia and states of psychosis.

Unlike the persistent complaints of factory workers and the concerning articles written in home and textile magazines surrounding the dangers of rayon, there is little evidence to suggest that customers or workers were affected in such ways by RPFs. Although, first-generation RPFs were still under development and not yet suitable for any commercial market, and no promotional materials can be found. Rayon, however, was entering its first stage of commercial availability and appeared both under scrutiny and admiration by the press. Despite its faltering quality and safety concerns, some advertisers were quick to praise this new artificial fibre.

This early battle between chemists to create the first successful synthetic fibre, paved the way for larger companies such as the American Viscose Corporation and DuPont to form and play a large part in the commercialisation of man-made materials for years to come. By 1911 when the American Viscose Corporation had begun large-scale manufacturing of rayon (under the name viscose), RPFs were still in their infancy and needed much further work. During the start of the second generation of fibres, this development would pick up once again and RPFs were soon to become the unsung heroes of WW2.

3.2. *Second Generation Fibres: 1925–1970*

3.2.1. Socio-Political Context

During WW2, roughly 65% of the productive capacity of the textile industry was estimated to be on government fabrics [34]. As petrochemical-based synthetics had yet to reach a domestic textiles market, wool was used for uniforms and equipment, leaving mass shortages for civilian textiles. On top of this, fibres available for domestic textiles were of overall lower quality. In 1944, a survey undertaken by the Bureau of Human Nutrition and Home Economics discussed 'how essential fabrics were downgraded during the war' [35], which consequently had a positive impact in terms of encouraging innovation in fibre development. American and European manufacturers also feared that supplies of imported wool might become unavailable, which led to a race between countries trying to make their own technical progress in the production of alternative fibres, with the aim of creating a self-supporting textile industry [36]. RPFs were used to ease the substitution of natural fibres at this time of textile shortages and localisation. A range of home and fashion magazines would often promote them as wonder fibres, claiming that to accept them would help with the war effort; an editorial in the American fashion magazine *Harper's Bazaar* shows how these concerns were used to market the new fibres as a patriotic purchase: 'Now we will wear milk—dress in new milk-fed clothes based on discoveries that are rocking the fabric industry and taking the sting out of wool shortages' [37].

During the development of RPFs, many different sources of protein were explored depending on what the country of origin had a surplus of. The US explored RPFs from

soy protein and used zein (from corn waste) to produce the fibre *Vicara*; the UK evaluated peanut waste due to large amounts of peanuts being imported from the British Empire. Italy, however, proved to be the leader in RPFs before, during and after WW2; with their pedigree in the textile industry and the political and cultural climate within the country during this time, Italy became the world leader in RPFs, and indeed regenerated fibres in general. Italy was of particular interest in the context of RPFs with *Lanital*/*Merinova* fibre being adopted by the Italian fascist party to represent the country's independence and superiority in the textile world. Italy's obsession with RPFs was ignited by the advent of the Italian futurism movement, which started in 1909, and called for all areas of the arts to disregard the old and focus on new and exciting innovations. Fashion was no exception with new, innovative clothing being made from unconventional materials including glass, aluminium, rubber, paper and, of course, milk. Italy also led the way in the development of rayon and became the world's largest producer of the regenerated cellulose fibre in 1929, with the company SNIA Viscosa being the largest manufacturer. By 1935, the company was also producing the milk fibre *Lanital* (Figure 2), which was heralded by Mussolini as a key breakthrough, with 3.7 kg of fibre produced per 100 kg of waste milk [38].



Figure 2. (Left) Italian fascist party flag made from *Lanital*; (Right) SNIA Viscosa advertising for *Sniafiocco* (viscose) and RPF *Lanital* ('I tessili dell'Indipendenza', translation: 'The textiles of Independence').

3.2.2. Technology

The Italian government was keen on promoting *Lanital* on a global market, with patents being filed in multiple countries including the US where *Lanital* was produced under the name *Aralac*. This had a brief popularity in the high-end fashion market, before the advent of WW2 turned the use of *Aralac* into a substitute fibre, where its lack of tensile strength, especially when wet, led to a decrease in its popularity and eventually to the stopping of production in the US by 1948. SNIA Viscosa kept manufacturing *Lanital*, but under the name *Merinova* [39], until the mid-1960s, despite its popularity taking a severe hit after WW2 during which its mechanical shortcomings were shown during its use in the Italian military's uniforms (1944).

The technology used to produce RPFs changed rapidly during WW2, affording production of fibres to replace wool. Many of the changes aimed to improve the functional properties of the fibres, as opposed to making the manufacturing process more efficient. The number of patents filed over time by researchers and manufacturers seeking to improve

poor overall wet strength of RPFs indicates that this was a persistent problem. Table 1 shows a comparison of tensile properties of different RPFs compared to common textile fibres, where it is observed that dry tensile properties are comparable with wool, but a 40–80% reduction in strength is observed when RPFs are wet.

Table 1. Tensile strength of regenerated protein fibres and conventional textile fibres [40].

Fibre	Tensile Strength (MPa)	
	Dry	Wet
RPF from casein	126	40
RPF from peanut	115	34
RPF from zein	115	69
RPF from soybean	69	14
wool	184	126
cotton	413	459
PET	608	608

Looming technical issues and a rise in raw materials and production costs were met with the launch of petrochemical synthetic fibres including nylon, polyester and acrylic. These new synthetics provided a more consistent supply of materials and offered superior performance over RPFs (and other natural fibres) contributing to their downfall in the 1950s [41]. RPFs were closely guarded, mainly due to the fibres lack of success, and by 1955 the total output of protein fibres was well below half that of synthetics [42]. Not only had a new range of fibres taken over the factories, advances in crease-resist finishing of rayon, combined with improvements in its wet and dry strength, pushed rayon further ahead of RPFs in both industry and consumer opinions [32]. In the US, production of cellulosic fibres increased from nearly 16,000 tonnes in 1923 to nearly 6 Mt in 1951. In comparison, the output of all other man-made non-cellulosic fibres was roughly 95,000 tonnes [36].

After the war, the reputation of these abandoned fibres plummeted rapidly, and the industry had to consider whether adjustments to quality and cost could present it as a desirable fibre for commercial use [43]. Conversely, a new range of synthetic fibres had come into light and thrived in areas where RPFs had failed time and time again; they were cheaper to manufacture and far superior in terms of strength, durability and ease of care. Manufacturers began to question whether their efforts were worth it and the production of RPFs slowed to a halt. Brooks and Rose [19] believe that by this stage the changing status of RPFs fits the cycle of *Rubbish Theory* closely. WW2 ended in 1945, but textile rationing continued until 1949. Towards the end of the 1940s RPFs became perceived as inferior, substitute fibres associated with deprivation and hardship; ‘new’ synthetics (nylon, polyester and acrylic), on the other hand, were advertised as the textiles of a care-free, modern world, demonstrating their cultural value.

The period between 1914 and 1920 created a great expansion in the viscose rayon industry. Like the shortages of WW2, a lack of natural raw materials during WW1 led to extensive research and experimentation on artificial textiles placing viscose fibres in a ‘durable’ position [32]. Into the 1950s, synthetic fibres including rayon, polyester and nylon had been transformed from an expensive and luxurious novelty into a cheap and useful product; within 20 years synthetics would rival even established natural fibres in strength and popularity [36].

After reviewing the typical manufacturing process for casein-based fibres during the 1940s, it is evident that a range of undesirable and potentially harmful chemicals were employed throughout production. One of the most notable chemicals used to produce casein fibres at the time was formaldehyde (CH₂O) [44], which was used primarily as a crosslinking agent, creating bonds between the protein polymers within the fibre to increase both dry and wet tensile strength. Today, the safety issues around formaldehyde are much better known, with acute toxicity, suspected carcinogenicity and mutagenicity meaning that its use, and disposal, are subject to far more regulations [45]. Alongside formaldehyde,

high concentrations of sulphuric acid were used in the coagulation and hardening baths, and this would have resulted in problematic waste treatment or challenging regeneration of the acid medium along with issues regarding health and safety of workers and challenges in designing equipment capable of withstanding the acidic medium. High concentrations of salts (commonly aluminium or sodium salts) were used in both the coagulation and hardening baths to cause fibre shrinkage, which assists in aligning the protein molecules within the fibre and help prevent the fibres from sticking together within the spinning process [46]. While there is no recorded complaint of the use of these chemicals in the production of casein fibres, the use of concentrated acidic salt medium, combined with the use of formaldehyde throughout the production process would likely have posed more issues involving worker safety and environmental damage if the fibres had reached their full potential and were produced on a mass scale.

3.2.3. Marketing

Despite the quality of RPFs produced, efforts were put into their promotion and advertisers were likely to put a positive spin on their properties. This was especially the case after the war when their popularity was in decline and can be attributed to the initial expenditure that was put in by companies and governments. In 1945, The UK government invested £2.1 million to produce a new factory in Dumfries [47] for their RPF *Ardil* manufactured from waste peanuts, shortly after a marketing campaign was launched in effort to increase product popularity (Figure 3, left). Indeed, even Henry Ford attempted to increase the popularity of RPFs; the Ford motor company pushed for the inclusion of soy protein fabrics in their cars through research at the United States Soybean Laboratory and produced a patent detailing their work [48]—Ford even went so far as to model a soy-protein suit (Figure 3, right), although it was said to have been itchy and uncomfortable to wear. As with other RPFs, the end of WW2 in 1954, along with the accompanying reduction in international wool prices due to ease of trade, led to a loss of interest in soy fibres [40].



Figure 3. (Left) An example of advertising for Ardil with the tag line ‘Happy families—with Ardil ca. 1945; (Right) Henry Ford modelling a suit made of soy protein fibres circa 1941.

Once seen as the wonder fibres that helped fight the war, today few examples of RPFs remain in museum archives or textbooks. Brooks and Rose [19] believe this to be an intentional decision driven by the understanding that such were no longer of government interest and therefore would be needless to retain records of a failed project. On the other

hand, rayon, polyester, acrylic and nylon were making their mark worldwide, overtaking natural fibres in popularity. This second generation of fibres, best known for its innovation in difficult times, made possibly the most lasting and important contributions to the history of the textile industry. Today, these fibres are still widely used in all manner of textile items, making it difficult to imagine a world without them.

3.3. Third Generation Fibres: 1970–2000

3.3.1. Socio-Political Context

By 1970, the global population had reached 3.7 billion, a 2.6% increase from the previous decade and one of the fastest growing generations in history [49]. As population increased, with it came the increase in production of commodities, putting strain on non-renewable and renewable resources alike. Over several decades, globalisation of the fashion industry played a huge part in how we make and buy clothes, and offshore manufacturing meant that clothing could be produced faster, at lower quality and at a fraction of the price. This led to the birth of ‘fast fashion’, a linear business model encouraging over-consumption and generating excessive waste [50]. In 1976, the market for rayon fibre was poor, with plants operating at less than 45% capacity; the cost of cotton and polyester had fallen dramatically, whilst rayon prices continued to rise [51].

As growth of all kinds was increasing, a new group of environmentally aware consumers and businesses was beginning to form. Due to the rise in global communication and offshore manufacturing, concerns were raised surrounding unethical practices such as child labour and low wages. When, in the mid-20th century, eco-consciousness was reawakened in developed countries, such issues were largely ignored within the fashion and textile industries.

Falling within the concept of *Rubbish Theory*, McLeod [52] claims that environmentalism comes in waves, falling in and out of fashion over time. Aside from a brief uptake in environmental concern in the 1960s, there was little significant activity regarding the environmental impact of textile manufacturing until the 1980s and 1990s when the signpost for the eco-fashion movement was launched with Esprit’s Ecollection in November 1991 [53]. This collection was said to be revolutionary for its time and used a range of *Tencel* (regenerated cellulosic) fibres, organic and unbleached cotton, natural dyes and naturally coloured wools. They also used a carefully selected range of synthetic dyes that were free of heavy metals, achieved 75% less dyestuff in effluent, and used significantly less water and energy. Fabrics were mechanically pre-shrunk to avoid the use of resins and formaldehyde and biodegradable enzyme washes were developed to smooth fabrics and prevent pilling [54].

3.3.2. Technology

After a second dip in interest in RPFs, innovations in biotechnology and demand for more sustainable fibres sparked a flurry of activity in the late 20th century [20]. This combination of new technology and demand for fibres with a reduced ecological footprint meant that textile developers were once again looking to alternative sources for raw materials and advanced manufacturing methods. The milk/acrylic blended fibre *Chinon* was produced in 1970s Japan but is said to have been very expensive and quickly ceased production [55]. Interest lay primarily with milk and soybeans as a protein source, although chicken feathers were also said to have been researched. These new fibres aimed to exploit the soft hand and lustre of the protein while adding strength and durability by adding a synthetic resin and were also claimed to have an ecological benefit. Soybean fibres primarily became a substitute for cashmere, reducing the number of grazing cashmere goats and thus helping to minimise desertification in China [56]. This new generation of bioengineered fibres claimed to have biological health care functions and natural, long-lasting antibacterial effects, gaining international ecological textile certification. They were described as hygienic, flexible, smooth, sheen, renewable, biodegradable and eco-friendly, but with low durability and still very expensive [57].

Also driven by environmental concerns, a new regenerated cellulosic fibre lyocell (US/UK brand name *Tencel*) was developed in 1972 by a team at the American Enka fibres facility, before being commercialized by Courtaulds Fibers in the 1980s. Lyocell was developed and marketed as a sustainable alternative to viscose. Viscose is manufactured by soaking cellulose pulp in sodium hydroxide (NaOH) to produce alkali cellulose, followed by aging for 2 to 3 days, then mixing with liquid carbon disulphide (CS₂) to produce sodium cellulose xanthogenate, which is subsequently dissolved in alkali and used in a wet-spinning process, where the cellulose solution is precipitated as pure cellulose fibres in an acid coagulation bath [26,58]. However, CS₂ is hazardous [59], expensive and has a negative environmental impact [60]. In contrast, lyocell fibres are cellulosic fibres that are produced by regenerating cellulose into fibre form out of a solution in *N*-methylmorpholine-*N*-oxide (NMMO) hydrate [61], and have excellent environmental credentials [62,63]; the main environmental advantage to using NMMO is that it is easier to recapture, creating a closed-loop process where the chemicals are re-used rather than being disposed of with, typically, 98% of the solvent recovered [64].

Another European company involved in the production of lyocell fibre is Lenzing AG in Austria. Originally involved in the manufacture of viscose rayon, Lenzing established its first lyocell plant in 1990, and a full-scale production plant in 1997 running at a capacity of 12,000 tonnes *p.a.* of lyocell staple fibre, branded as *Lenzing Lyocell*. After acquiring the Tencel Group in 2004, in 2021 Lenzing is the world's largest lyocell fibre manufacturer, capable of supplying 130,000 tonnes *p.a.* for the global market [65].

3.3.3. Marketing

Marketing of green and sustainable textiles and clothing increased, however issues regarding the legitimacy of these claims must also be considered. Coined by environmentalist Jay Westervelt in 1986, the term 'greenwashing' refers to companies posing as sustainable through vague 'eco-friendly' policies and campaigns [66]. Another challenge regarding promoting behavioural changes towards and within the fashion industry was (and still is) the overall narrow understanding currently held by both the public and industry about what 'sustainable fashion' actually means. This inevitably makes it easier for companies to use words such as 'green', 'organic' or 'clean' with little questioning from consumers or stakeholders, and there is no consistent international standard that quantifies any of these terms.

Though there are many ways to achieve sustainability, what appears to be most readily promoted by brands with a desire to appear 'green' includes the use of naturally derived and organically produced raw materials. As discussed by Dempsey [67], 'While important, these efforts only touch the surface of a much deeper set of solutions, and in the case of material efficiencies, they can sometimes produce a paradoxical effect'. This is because the issue is not a single-faceted problem and therefore requires a multidimensional approach. Though feedstock for materials is of course a major issue, with many man-made polymers being derived from non-renewable resources such as crude oil, this is only one side of the issue. Manufacturing methods, efficiency, waste production and a host of other issues play into this as well. The matter of demand must also be considered; swapping all the world's textile needs to natural resources such as cotton would put huge amounts of strain on the production of such natural resources and would likely lead to further issues centred around the need to produce vast amounts of a single resource. This can be clearly seen in the case of cashmere: Research has been done that indicates that the increased production due to demand of cashmere is leading to desertification in Mongolia [68,69] and a life cycle assessment performed on silk production in Southern India indicates that the environmental impacts of this production process are higher than that of other natural fibres [70].

Unlike in the second generation of RPFs which saw huge levels of investment and government backing, new RPFs in the third generation were not as widely promoted. As many fashion campaigns moved away from quality, and advertisements became more

focused on price and garment aesthetics over fibre and functionality. As brands pushed more styles and more collections per year and relied on existing, oil-based fibres such as polyester and nylon, a dependency on cheap and low-quality fibres meant that consumer education in terms of fibres was not a priority. As the fast fashion market increased, the domestic textiles market decreased dramatically, and consumers started to know (and potentially care) less about the origins of their garments.

Although environmental preservation and sustainability was a rising topic of importance for some, the third generation of fibres appears to sit in an era of complacency. Following the innovation of the second generation, use of the most successful fibres was in full swing and there was little reason to explore or invest outside of these textile staples. In terms of priorities, increased speed, and reductions in the cost of manufacturing took precedence over quality. Based on this new economy, the third generation introduces us to the first fast fashion powerhouses and ultimately leads us into our fourth and final generation of RPFs.

3.4. Fourth Generation Fibres: 2000–2021+

3.4.1. Socio-Political Context

Twenty years into the rise of fast fashion, the first dedicated online fashion retailer, ASOS, allowed us to shop from anywhere in the world, at any time of day or night. As a result, the fashion industry opened up to a variety of new styles, influences and even faster production. The rise of mobile shopping and social media increased the pace once again [71], paving the way for even cheaper retailers such as Misguided and Boohoo. It could be argued that we have now passed ‘fast fashion’ and are in a new generation of ‘hyper speed fashion,’ with little intention of slowing down.

At the turn of the new millennium, an emergence of natural disasters and economic crises pushed us to question the integrity of businesses and create a demand for greater transparency in the age of online communication [72]. The year 2020 alone has seen a series of devastating climate disasters around the world such as the Australian wildfires, drought in east Africa and flooding in south-east Asia. Events such as these force over 20 million people a year from their homes, not to mention the loss of lives. In the past 30 years, the number of climate related disasters has tripled and The United Nations Environment Programme estimates that adapting to climate change and coping with damages will cost developing countries \$140–300 billion *p.a.* by 2030 [73]. Furthermore, we are currently facing the largest pandemic of the modern world, Covid-19, potentially caused by civilisations’ impact on nature and biodiversity. The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services (IPBES) states that our actions have “impacted more than three quarters of the Earth’s land surface, destroyed more than 85% of wetlands, and dedicated more than a third of all land and almost 75% of available freshwater to crops and livestock production . . . This rampant deforestation, uncontrolled expansion of agriculture, intensive farming, mining and infrastructure development, as well as the exploitation of wild species have created a ‘perfect storm’ for the spill over of diseases from wildlife to people” [74]. IPBES predicts that future pandemics are likely to happen more frequently with greater economic impact and causing more deaths if we are not extremely careful about our impending choices.

In 2017, 105 million tonnes (Mt) of fibre were produced globally [1], representing a ten-fold increase since 1950, with 62% of this being petrochemical-based fibres. The amount of clothing bought *per capita* in the EU has increased by 40% in the last few decades [75], and with global population set to increase by 40% by 2050, the environmental impact of the textile industry is set to increase rapidly accordingly [76]. In the first decade of the 21st century, a growing number of initiatives were developed by governments, trade unions, campaign groups and fashion brands, to tackle major environmental, social and economic sustainability issues [72]. The Changing Markets Foundation also held brands including Zara, H&M and ASOS accountable for using highly polluting viscose factories in China, India and Indonesia [77]; together, these countries account for over 83% of global viscose

fibre production. At production plants in China, investigators found evidence of water and air pollution, worker fatalities, and severe health impacts on local residents [78]; production of natural fibres including viscose also contributes to deforestation (including the depletion of endangered and ancient forests) and loss of biodiversity and animal habitats. The fashion industry is projected to use 35% more land for fibre production by 2030, an extra 115 million hectares that could be used to preserve forests to store carbon or grow crops for an increasing population [5]. This choice to produce a material object rather than produce food links into the ‘food versus fuel’ debate and leads to a potential new ‘food versus fashion’ issue if this trend continues.

Outside of the fashion industry, initiatives such as the Kyoto Protocol and the Paris Climate Agreement were put in place to reduce GHG emissions, a clear sign of a global recognition of the environmental destruction caused by industrialisation over the decades. Despite this positive step, there has been criticism surrounding the effectiveness of the regulations, claiming that they are not enough to keep global warming below 2 °C [79]. A total of 192 countries signed the Kyoto Protocol, yet by 2005 CO₂ emissions were still on the rise, and by 2009 global emissions had risen 40% since 1990.

The current trend of fast fashion is beginning to be challenged by both public perceptions; with more people demanding traceability and sustainability in their products, and by legislative and political agendas; with more legislation being put in place to reduce emissions, increase safety, reduce waste production and limit deforestation. This cultural shift will become increasingly evident in the coming years and allows a unique opportunity for novel research into new and innovative textiles to be performed, not only focussing on a fibre’s properties and ease of manufacture, but also incorporating circular economy and sustainability principles into its design. RPFs fit into this niche with their feedstock reducing current waste stream volumes while also potentially alleviating the pressure on current textile manufacturing. The challenge will be incorporating more green synthesis principles into the production of these fibres, and the area of green chemistry and sustainability has come far since invention of first and second generation RPFs and with it the opportunity to take the research done by those early pioneers and refine it with modern knowledge.

3.4.2. Technology

Although lower than other synthetic fibres and some natural fibres, the impact of some modern, regenerated cellulose fibres is still relatively high, notably some viscose that uses wood sourced using poorly managed forestry practices, energy, water and chemically intensive processes, which also have dramatic health implications on workers, local communities and the environment [80]. The fact that some regenerated cellulose fibres have excellent sustainability credentials (e.g., lyocell, sustainable viscose) and some are severely problematic does not help the general lack of understanding in the consumer population as to what sustainability truly means—how does one easily select a sustainable viscose garment? Education into the multi-faceted nature of sustainability including all the steps within the process from feedstock, to process efficiency, to waste generation and end of life will continue to improve and with it a more discerning consumer base that demands that its products be truly sustainable. Today, around 8000 different synthetic chemicals are used in the textile industry to turn raw materials into final products [81], the dangers and health hazards associated with CS₂ in viscose production have been an issue for over 100 years.

Following a brief revival of RPFs in the 1970s, German company QMILK developed the process to produce a quality, organic textile fibre from milk waste in 2010. This fibre is manufactured through a resource efficient, zero-waste process using no chemical additives. The resulting biopolymer fibre offers the potential for numerous high-value applications and can be modified for a range of markets including fashion, home textiles, automotive, medical and cosmetics [82]. Although extensive development of both QMILK fibres and product ranges has been carried out, none are yet commercially available.

Aside from a resurgence in interest of RPFs, a new range of bio-based synthetic textiles created from agricultural waste is beginning to emerge. One example is *Orange Fiber*, an

Italian company creating sustainable fabrics from citrus juice by-products. Their fabrics are formed from a cellulose yarn that can blend with other materials and when used in its purest form, it is reported that the resulting 100% citrus-based textile features a lightweight, silky texture [83]. Another example is *Piñatex*, a nonwoven textile made from cellulose fibres extracted from waste pineapple leaves, polylactic acid, and petroleum-based resin to create a natural leather alternative, with application opportunities in fashion and accessories, soft interiors and automotive industries [84].

The material science company, Circular Systems, is a social purpose corporation using new regenerative technologies to manufacture innovative materials. Their 'waste to fibre' platforms, *Texloop* and *Agralooop*, offer solutions to agricultural waste streams and textile management. The Agralooop Bio-Refinery transforms food crop waste into high-value natural fibre products in a cost competitive and scalable way, providing sustainable and regenerative benefits. The system can utilize a range of feed stocks including oilseed hemp and oilseed flax straw as well as pineapple leaves, banana trunks and sugar cane bark [85].

3.4.3. Marketing

Given the heightened awareness of climate change and depletion of natural resources, since the new millennium, a growing consensus has emerged that over-consumption via faster and faster fashion cycles must end. Sustainability is no longer a passing trend in fashion and a new body of conscious consumer is emerging; with this being the case, it can be predicted that future marketing of sustainable textiles will see a large increase, and hopefully alongside better consumer education, include more evidence of sustainability and traceability. Unlike the lack of evidence to support new fibres throughout the third generation, new and innovative fibres are once again making an appearance in the mainstream media. Although many are still in their development phase, companies such as Circular Systems are investigating ways to collaborate with brands, manufacturers and providers of agricultural waste, starting with small, collaborative collections and leading towards large scale changes to the traditional supply chain. With consumers now demanding more information on the origins of their clothing, it is the perfect time for developers of fibres—as well as fashion—to promote their technologies direct to consumers as well as business to business.

The rise of online journalism, as well as brands/manufacturers/developers having the ability to create their own websites and tell their own stories, allows businesses and consumers alike to seek further information and compare new technologies and fibres. Unlike the second generation of RPFs, where much innovation was funded by governments and happened behind the doors of large corporations (such as SNIA Viscosa and DuPont), much innovation is now crowdfunded or personally funded by small, independent start-ups. As competition in this sense is higher, the importance of transparency and having a more genuinely sustainable product to promote is greater than ever.

4. Discussion

Born from political crisis and material shortage, RPFs were once seen as the fibres of the future, yet, for the range of reasons discussed throughout this paper, were buried in the past. The modern climate of consumerism and fast fashion is providing a very different set of challenges involving excess and problematic waste generation. These challenges, while the antithesis of the original motivations for the development of RPFs, provide a similar opportunity for exploration into the synergy between reducing waste volumes while also alleviating the pressures of an increasing textile market.

First- and second-generation RPFs were plagued by issues regarding their properties, especially their wet tensile strength, but due to the demands of the time were still utilised as substitute fibres; the research performed into the development of these fibres was fast to make sure that the demands of wartime textile industry were met. After the end of hostilities, these fibres fell out of favour due to their lack of attractive mechanical properties and their association with substandard substituted materials, and after a brief push by

governing bodies to make use of the manufacturing sites invested in during wartime, these fibres were largely forgotten. Attempts have been made subsequently to research and even commercialise RPFs, however without the impetus of world-wide conflict to put pressure on the textile industry, these attempts were short-lived. Current trends towards a more sustainable and locally sourced economy have provided an interesting opportunity for RPFs to once again find their place in the textile world.

The area of biobased, biodegradable fibres from natural, renewable feedstock using green and sustainable methods is going to increase in importance if current trends continue. With fast fashion meaning that more clothing *per capita* is being purchased and with global population increasing, along with the increased awareness and concern over sustainability and traceability of commercial product, increasing impetus is going to be put on finding and developing novel methods for fibre production, while at the same time reducing excess waste created because of our expanding population, most notably in the food production industry. Creating products from waste is not a new concept but, differing from the direction taken during wartime in the 1940s, sustainability throughout the production of fibres will have to be a priority, utilising circular economy themes and considering the environmental and sustainability impact of everything, from the feedstock, to chemicals, energy and water usage and end of life for these fibres. The advancement in green and sustainable technology and chemistry gives opportunity to tackle the issue of producing truly sustainable RPFs fit for purpose for use in the textile industry.

Care would also have to be taken when considering the availability of the protein feedstock for textile products, which is especially important when waste (in this case from milk manufacture) could potentially be valorised back into the food industry. This poses environmental, societal and economic questions that must be analysed in depth to determine if the best routes for valorisation, in order to find a balance between valorisation for human nutrition or valorisation to reduce the environmental impact of 'fast fashion'. It may be that garment applications do not currently offer the best economic value for utilisation of milk waste compared to existing food products (e.g., animal feed, nutritional products); however, the unique properties casein fibres could potentially enable their use in high-value, non-apparel textile applications, such as medical textiles [86], which significantly changes the value proposition.

Localised industry was performed out of necessity during the World Wars, but modern trends are beginning to shift to a more localised economy, with the environmental impact of shipping products and feedstocks around the world no longer being ignored. Alongside this, unprecedented incidents such as the Covid-19 pandemic further highlight the benefits of self-sufficiency and utilisation of available local feedstocks. If, as the IPBES predicts, pandemics are going to occur increasingly in the future, locally sourced production would be beneficial from an environmental, economic and availability standpoint. Similarly, ethical and local sourcing of textiles and steering away from the typical outsourcing of production not only increases the ecological benefit of the textile, but also means that businesses have more control over production and worker welfare.

RPFs offer a unique opportunity to learn from our past for the betterment of our future, the needs of both past and future, although very different, potentially allow for the same solution. Production of fibres from waste is not a novel concept, but the production of fibres from waste protein sources has been largely forgotten. New research in this area utilising the advancements in technology and chemistry of the modern age is an exciting opportunity, and combined with the concept of a circular economy, a potential, truly sustainable textile fibre is possible.

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