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Review

Referencing Historical Practices and Emergent Technologies in the Future Development of Sustainable Textiles: A Case Study Exploring "Ardil", a UK-Based Regenerated Protein Fibre

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Abstract: We are currently experiencing a global environmental crisis. Our waste culture is leading to huge irreversible damage to our planet and ecosystems. This is particularly evident in both the textile and food sectors, with a system-wide restructuring as to how we consume and source materials becoming ever more urgent. By considering our waste as resource, we can access a vast source of raw materials that is now being recognised as such. Viable materials in the form of waste have the potential for conversion into textiles. However, this proposed solution to our contemporary crisis is not new technology. Throughout the 20th century, science and industry have researched and developed materials from food waste to meet global demand for textiles in times of need, with a major development during the world wars being the invention of regenerated protein fibres (RPFs). For various reasons, this research was abandoned, but much of the development work remains valid. This research critically analyses work that has previously been done in the sector to better our understanding of the historical hindrances to the progression of this technology. By applying modern thinking and scientific advances to historical challenges, there is the potential to overcome previous barriers to utilising food waste as a resource. One of the key influences in the discontinuation of RPFs was the rise of petrochemical textiles. Our current understanding of the detriment caused by petrochemicals warrants a further review of historical emergent technologies. This paper uses Ardil fibre as a case study, and shows that there is a clear disparity between the location of historic research and where the research would now be helpful. Ardil was a British-made product, using peanuts sourced from the British Empire as the source of protein. Techniques used in the processing of Ardil could be better utilised by countries and climates currently producing large amounts of peanut byproducts and waste. Through this research, another historical concern that thwarted Ardil's acceptance as a mainstream fibre was discovered to be its poor tensile strength. However, contemporary garment life cycles are far shorter than historical ones, with built-in obsolescence now being considered as a solution to fast fashion cycles by matching the longevity of the fibre to the expected use phase of the garment, but ensuring suitable disposal methods, such as composting. This research highlights the need for cross-disciplinary collaboration between sectors, with a specific focus on the wealth of valuable information available within historical archives for modern sustainability goals.

Keywords: regenerated fibres; regenerated protein fibres; waste; circular economy; valorisation; garment industry; manmade fibres; textile processing; textile history; Ardil

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1. Introduction

We are firmly in a period of environmental crisis, with humanity's impact on the planet becoming ever more evident, and the time before irreversible damage has been caused is rapidly dwindling. Two of the largest sectors contributing to this environmental crisis are the textile and food production industries. The size of the textiles sector has been increasing steadily in recent years, and the garment sector alone is estimated to produce 3.3 billion tonnes of CO_2e annually [1]. Globally, fibre production reached 109 million tonnes (Mt) in 2020, representing a 10-fold increase since 1950, of which synthetic fibres represent roughly 62% of production mass. Global fibre production is expected to increase by another 34% to 146 Mt by 2030. Worldwide fibre production per person increased from 8.4 kg per person in 1975 to 14 kg per person in 2020 [2]. With the global population simultaneously expected to increase by 40% by 2050, the environmental burden of the textile industry will increase rapidly in the coming decades [3]. The increase in clothing purchased can be attributed to several different factors, such as the comparably slow rise in clothing prices when compared to other consumer goods [4], and the advent of the phenomenon known as "fast fashion" [5,6]. With the turnover of fashion being so high, and the cost of clothing being comparably low, the amount of waste generated per annum is vastly increasing with this new model of textile consumerism.

Understanding the environmental impact of different textiles is complex, and the literature often provides conflicting data. For example, Moazzem et al. claim that a key contributing factor to the environmental impact of the textile supply chain is the consumer use phase in garment life cycles [7]. However, a 2017 report from WRAP cites the fibre production stage as the highest contributor to the carbon footprint of clothing, with roughly 11 Mt of CO_2e produced in 2016 (out of a total of 26.2 Mt of CO_2e across the whole supply chain) [8]. These conflicts often arise because the process of measuring and recording the environmental impact of a garment throughout its life cycle is highly complex, making any comparisons across fibre type subject to debate. Recently, a widely used tool for mapping the sustainability of fibre types and materials—the Higg Materials Sustainability Index (MSI)—has come under scrutiny, as it only considers the production phase in its assessment. [9].

The environmental issues and concerns with synthetic fibres are well documented, and have dominated the media headlines in recent years. It is often assumed that natural fibres are more sustainable when compared to synthetics. However, the environmental effect of the production of natural fibres cannot be ignored: the recent increase in the desirability of natural fibres in an attempt to be environmentally conscious has been shown to cause myriad issues. Cotton fibre is a vast industry estimated to employ nearly 7% of labour in developing countries [10]. Operating the cotton industry at this scale comes at a huge detriment to the environment. Cotton is very difficult to grow successfully, requiring huge amounts of water and pesticides to sustain the crop, which occupies only 2.4% of cultivated land but consumes 6% of pesticides and 16% of insecticides globally [11]. Production of cotton uses vast amounts of water; 69% of all water used in fibre production is attributed to cotton, with 1 kg of finished fabric taking about 20,000 litres to produce [12].

Protein fibres also have issues. Farming and harvesting silk also involves intensive and environmentally harmful processes, and is ranked higher than most other fibres on the Higg MSI [13]. Although silk fibre represents a much smaller proportion of the global fibre market than cotton, at just 0.1% of the global market, the value of silk was expected to be USD 16.94 billion in 2021 due to increased desire for this fibre [2]. Wool fibre production has an incredibly high carbon footprint, accounting for 36% of the total carbon footprint in fibre production for clothing in use in the UK in 2009 [14], and the desertification of Mongolia has been attributed to the farming of cashmere goats [15,16]. While, again, these statistics only consider the production phase of these fibres, this must be understood in the context of the renewed interest in natural fibres and the vast increase in demand. One hundred years ago, the quantity of textiles required to meet global demand was far less than today, due to the lower population and the different approach to clothing. A coat lasted a lifetime, as opposed to a fashion season, which meant that the pressure on the production of natural fibres was lower, and the associated environmental impact was limited. The synergistic effects of the increased demand for natural "sustainable" fibres from a more environmentally conscious consumer base, along with the evidenced increase in environmental impact resulting from overstrained natural fibre production routes, opens up an exciting opportunity for novel research into potential feedstocks for sustainable fibre production. However, there is potential not only in exploring "new" processes, but also in learning from historical precedent to draw inspiration for a more sustainable future.

There is a genuine need for sustainable fibres in contemporary society; however, the problems of overpopulation and lack of raw materials are not new. This was acutely felt during the first half of the 20th century, with the economic pressure created by two world wars and the growing global population. During the interwar period, in response to this hardship and strain on textile resources, government hopes turned to an emerging science—regenerated protein fibres (RPFs). Their revolutionary idea was to use regenerated protein fibres created in a lab to reduce their reliance on natural fibres grown in fields or on animals. In theory, RPFs could be made from an array of protein sources more simply and economically than traditional fibres such as wool, which requires farming livestock [17]. It was hoped that these new regenerated fibres would provide an economical and competitive alternative to natural fibre resources [18], and across Europe many companies began experimenting with RPFs on a commercial scale, in the hope that these fibres would be the future of the textile industry [19]. While there are some examples of contemporary RPFs in today's market, such as QMilch, this paper focuses on historical examples of RPFs.

The process developed during the interwar period to produce RPFs was as follows [20]:

1. Dissolution of the protein in a suitable solvent. This is typically an aqueous solution of a diluted alkali.
2. Denaturing and unfolding the protein molecules into a linear state. In the case of casein this is achieved via the introduction of NaOH which, when given enough time, breaks the proteins' secondary structure. This enables extrusion through small holes within a spinneret.
3. Extrusion of this protein "dope" through a spinneret directly into a coagulation bath in a wet spinning process. This involves controlled precipitation of the protein in the coagulation bath, forming continuous filaments. The coagulation bath usually consists of an anti-solvent—typically an aqueous solution of diluted acid—and other chemical additives. Salt is added to increase the osmotic pressure within the bath, causing fibre shrinkage to aid with protein molecule orientation and to prevent fibres from sticking together. A crosslinking agent (most commonly formaldehyde) is added to improve the tensile properties of the fibre. The filaments can then undergo further mechanical and chemical processes to increase their functional properties, including chemical hardening in a separate bath. The most common chemicals used historically for RPFs are sulphuric acid, sodium sulphate, magnesium sulphate, and formaldehyde.
4. Drawing filaments. A mechanical process of gradually stretching the fibre to aid in protein molecule alignment and increase fibre crystallinity, leading to an increase in tensile strength.

Despite showing early promise, this industry died out after World War II. Some of the key factors in the disappearance of these fibres included problems with tensile strength—particularly wet strength—and the availability of raw materials. RPFs were a revolutionary idea that promised to solve issues of supply and demand, but ultimately failed. However, this method of creating fibres has been shown to have potential in the realm of sustainable textiles, as the protein used can be upcycled from waste. There is renewed interest in this technology, as the need for more sustainable fibres grows ever stronger. It is also possible for regenerated fibres to be broken down post-use, creating a material with a circular economy. At present, further research into environmentally friendly methods of producing RPFs is required, as historically the process of crosslinking proteins uses harmful chemicals (e.g., formaldehyde). In particular, systems supporting the life cycle of these fibres, such as waste collection and composting of the garments, have previously been identified as key areas for further research [21]. This paper explores the reasons for the disappearance of RPFs, and asks what lessons can be applied to sustainable contemporary textile design. By reappraising historical examples of RPFs against contemporary scientific developments, it is hoped that a potential future sustainable method can be demonstrated.

Ardil fibre was chosen as a case study, with the aim of understanding the shift away from these promising early fibre developments and the potential lessons to be gained from past RPF research. Ardil is the brand name of a fibre first developed in the 1930s by the British company Imperial Chemical Industries (ICI). It was made from groundnuts, more commonly known as and hereafter referred to as peanuts (although the literature uses the names interchangeably). Ardil's development coincided with periods of shortage and austerity during the world wars—a time when manufacturers were seeking alternatives to natural fibres. During these wars, textiles were deemed to be of vital importance, with wool for uniforms being considered just as important as bullets [22]. Not only that, but the strain of the war effort on the textile industry was immense, with 65% of the production capacity being diverted to the creation of government fabrics [23]. This vastly reduced the available fibres and fabrics for the general consumer. There was also fear of disruption of the wool trade routes leading to material shortages. All of these factors combined resulted in the heavy investment in and rapid development of fibres that could be produced from alternative feedstocks, such as Ardil. However, Ardil production did not continue beyond the 1950s. By closely scrutinising the development, success, and subsequent downfall of this once highly promising RPF, and by employing modern techniques to critically analyse the sustainability of the process, we can begin a holistic approach to the development of contemporary RPFs.

2. Materials and Methods

This paper combines literature from design, science, and industry to investigate how textile materials can be created from food waste to elevate pressure on finite resources for textiles. The authors used Ardil as a specific example of an RPF as a case study, as it was one of the few examples of a British RPF to be put into commercial production with moderate success, providing useful insights for contemporary textiles. The authors first planned the paper, identifying Ardil as an appropriate case study before outlining the structure of the paper. Next, data were collected using literature searches and by identifying and visiting appropriate collections. This information was then critically analysed by the authors before reporting their findings and opinions on the subject. A detailed review of the RPF patents was used in order to understand the chronological progression of the technology. Using historical sources including newspaper articles, magazines, journals, and archival collections, this paper first outlines the story of Ardil, seeking to understand the nuances behind its development and, for the first time, the reasons for its subsequent failure. Secondly, this is contextualised through a contemporary lens, questioning what knowledge can be applied to the ongoing research and development of contemporary RPFs. A timeline illustrating the rise and fall of Ardil helps explain its place in history and the simultaneous shifts in the global textile market and the wider economy (Figure 1). Three main areas in the story of Ardil are considered:

1. Development of the historical technology;
2. Marketing and public reception of Ardil;
3. Social, political, and economic factors.

This research has been challenging, as there are very few recorded examples of Ardil in contemporary museum collections today. Brooks argues this may be a result of Ardil's poor longevity as a fibre and the difficulty in distinguishing fabrics made from Ardil from other fibres, such as wool [24]. As such, unless there is clear supporting evidence or labelling, many Ardil fabrics may sit in collections unnoticed. The lack of known examples of Ardil and the rarity of academic literature relating to it have previously hindered in-depth research into this fibre, as the material is not easily accessible. Whilst conducting the archival research for this paper, several little-known or previously unrecorded examples of Ardil were discovered. These discoveries have helped to shape further understanding of the prevalence and historical importance of this fibre.

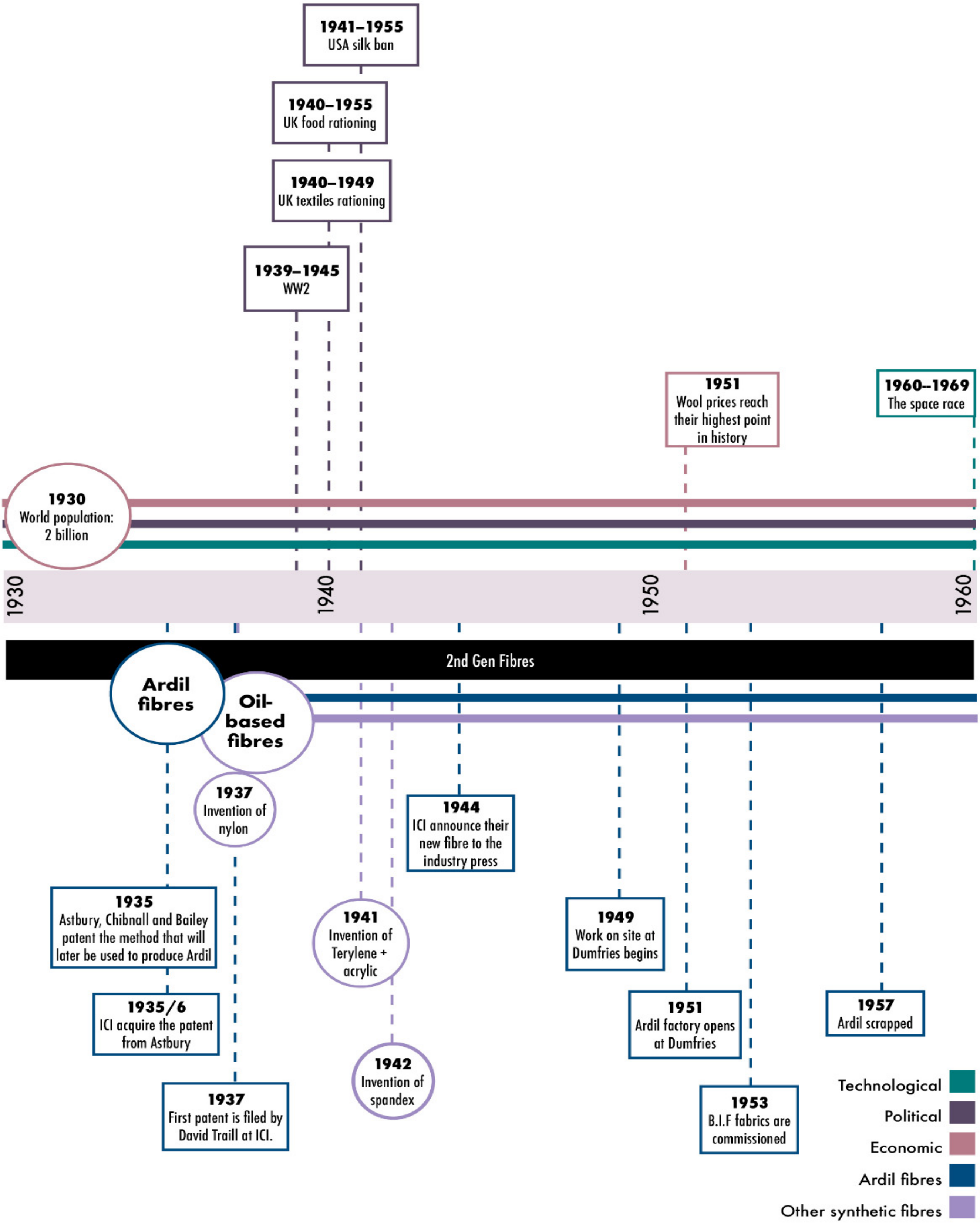


Figure 1. This timeline shows the key events in the development, marketing, and subsequent demise of Ardil fibre, as well as the social and economic events that influenced its trajectory.

3. Results

3.1. Historical Background

3.1.1. RPF Background

The development of RPFs stretches back to the 19th century, with the first known example being a fibre made from gelatine by the scientist Adam Millar in 1894. Following on from Millar's work, other scientists developed RPFs using sources of protein that included maize, soya beans, chicken feathers, albumin, and eggs. It was not until the 1930s that the technology sufficiently advanced to become scalable. In 1935, the Italian scientist Antonio Ferretti created a commercially viable casein fibre, which was marketed as Lanital. The Italians were so proud of their new fibre technology that it was used in the manufacture of Italian army uniforms, under Mussolini's rule. However, the army were not impressed by the poor quality of Lanital as compared to wool [25]. Lanital, like the majority of RPFs developed during the interwar period, proved unsuccessful, as it could not compete with natural fibres such as cotton and wool [26]. Although RPFs successfully mimicked desirable properties of natural fibres such as soft handle, they were easily damaged and became weak when damp [27].

3.1.2. Imperial Chemical Industries Background

ICI was one of the largest science and technology companies of the 20th century. They were responsible for creating well-known products such as Perspex, Polythene, Dulux paints, and hundreds more. Though predominantly a chemical company, ICI were acutely aware of the shifts within textiles, and of the potential role their chemical expertise could play in the sector. In the early 1900s, it was widely believed that the future of the textile industry lay in scientific development and the exciting properties that technology could imbue. Alongside RPFs, this was also the age of development for petrochemical-derived fibres such as nylon and polyester, which would eventually supersede RPFs to become the prevalent materials they are today, but for a time both technologies were equally feted. The work of ICI was a clear example of this, with involvement in developing several manmade fibres, including synthetic fibres from the petrochemical industry as well as RPFs [28].

3.2. Development of the Historical Technology

3.2.1. Invention of the Process

Though ICI were responsible for the development, marketing, and even naming of Ardil, the science behind the fibre originated from the work of William Astbury at The University of Leeds. Astbury worked in textile physics at Leeds from 1928, and held the Chair of Professor of Biomolecular Structure from 1946 until his death in 1961 [29]. He focused much of his work on using X-rays to study biological molecules—particularly wool and hair fibres. His work with Florence Bell on X-ray crystallography of biological molecules revealed the regular, ordered structure of DNA, which laid the foundations for the structural identification of DNA by Crick and Watson in 1953.

In addition to this work, in 1935 Astbury developed a technique for producing fibres from vegetable proteins with his colleagues Chibnall and Bailey at Imperial College London [30]. Their technique involved denaturing globular proteins—a process of chemically unfurling the molecules of protein in order to "refold" it into a fibrous form. These globular proteins are found in different sources of vegetable protein, including hemp seeds and peanuts.

3.2.2. The Role of ICI

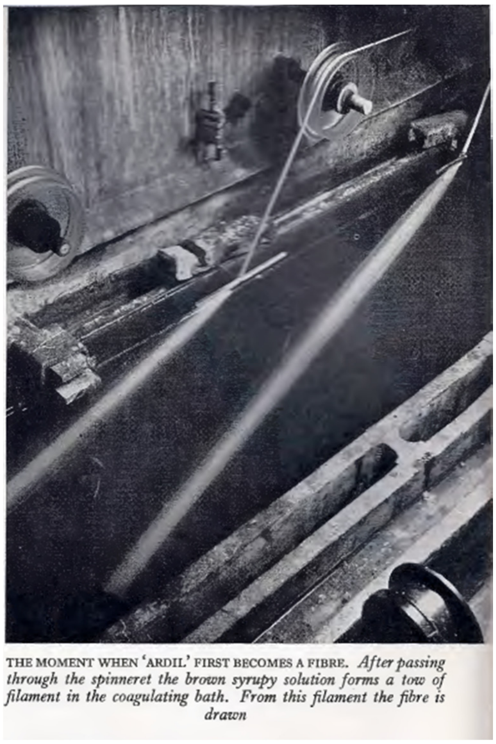
To understand why ICI were so interested in Astbury's work, it is important to understand where the technology was at this point in time. Analysis of patents filed relating to RPFs, from their invention in the 1870s onwards, shows that prior to Astbury's work RPFs were more commonly produced from animal proteins. Before Astbury and his colleagues filed their patent in October 1935, only three other researchers had filed patents for RPFs since Adam Millar in 1894. These were Dr Friedrich Todtenhaupt, Herman Timpe, and Antonio Ferretti, whose methods all focused predominantly on milk casein, gelatine, eggs, and albumin. In Astbury's patent, he specifies "Production of silk and wool-like threads from 'vegetable' proteins belonging to globulin group" [31]. This patent would have likely been of great interest to ICI, as it specifically worked with seeds and legumes, as vegetable proteins were in higher abundance throughout the world [26]. Importantly, using vegetable proteins would also cut out the additional and costly step of farming livestock that the previous patents for animal-protein-derived RPFs used.

Quickly realising the potential in Astbury's research, ICI formally purchased the patents the following year [32]. The responsibility of further developing Ardil for commercial use was handed to David Traill in ICI's Nobel Division [33], named after Alfred Nobel, who originally founded the factory at this site [34]. Traill set to work finding the most suitable source of protein to use with Astbury's methods. In patents filed by Traill between 1937 and 1939, he specifies peanuts as well as casein, until the 1940s onwards, where he focuses purely on peanuts [35,36]. Traill's experiments had found peanut protein to be the most suited to his purpose [37]. Peanuts were commonly imported to the UK as a foodstuff, and so could be relied upon as a regular source of protein to work with; the Gambia alone imported 10,275.6 tonnes to the UK in 1935 [38]. The main product produced from peanuts at this time was peanut oil, with the leftover meal used as animal feed or considered waste. As discussed, there were already several examples of casein regenerated protein fibres in commercial production [39], but none using peanut fibre yet (the only other historical example of a peanut fibre being developed commercially was Sarelon in the US, where peanuts can be grown [40,41]). With the parameters set for their new product, Ardil fibre was christened after the location where Traill worked—at an ICI plant in Ardrossan on the Ardeer Peninsula in Ayrshire.

3.2.3. The Chemical Process

The chemical process of creating Ardil was described in 1955 [19]: Peanuts are first crushed to extract the oil used as an ingredient in food manufacture (e.g., margarine) and personal care products (e.g., soap). The residue consists of approximately equal parts of carbohydrate and protein; the protein is extracted, and is washed and dried to obtain a white powder called Ardein, which is primarily composed of a protein called arachin. Ardein is dissolved in caustic soda and extruded through spinnerets into a coagulation bath, followed by hardening, washing, crimping, and cutting into staple fibres ready for spinning (Figure 2a). As discussed in the introduction, the hardening stage often employed the use of formaldehyde as a crosslinking agent; this posed serious environmental concerns with regards to wastewater. This, in combination with the fact that wet spinning as a process is very water-intensive, with large amounts of water being required for every stage of the process, means that even though this protein fibre utilised a "waste" feedstock, the actual environmental impact of the process was likely to be relatively harmful. The undissolved part of the peanut meal is recovered, and is valuable cattle food [42].

As Ardil was not produced as a continuous filament, it was very versatile for spinning into a variety of yarn weights. The fibres could be made into several different deniers to suit garments or interior textiles accordingly. In order to promote and explain their new fibre to potential customers, ICI produced a manual for manufacturers [26]. The manual explains that there were three main types: B, F, and K, each with slightly different properties and subsequent applications. Another important distinction between the types was the shade; Ardil was naturally a fawn colour, with the manual suggesting that to achieve a pure white shade, bleaching was required. This may have been seen as drawback by some manufacturers, as it would affect the shades that could be achieved through dyeing. The reasons for producing these different product specifications for Ardil are not immediately obvious, but the unusual product categories imply that ICI were compensating for shortcomings of Ardil.



(**a**)

(**b**)

Figure 2. (**a**) "The moment when 'Ardil' first becomes a fibre": Filaments of Ardil are drawn from fibres in the coagulating bath; Catalyst Science Discovery Centre and Museum. (**b**) "Ardil Protein Fibre Factory, Dumfries" by Henry Rushbury, with the Ardil Tower visible; Catalyst Science Discovery Centre and Museum.

3.2.4. Blends with Ardil

Despite high expectations, during initial testing, it became clear that Ardil was not particularly strong as a fibre; it had poor tensile strength when wet compared to other fibres, such as wool (Table 1) [26].

Table 1. Comparison of the principal physical properties of "Ardil" fibre and wool.

Property	"Ardil" Fibre	Wool
Specific gravity	1.31	1.31
Tensile strength (kg./sq.mm.)	8–10	12–20
Elongation at break (%)	40–60	30

It was therefore decided that Ardil would perform better when blended with wool and other fibres, such as rayon, which would stabilise it. The most notable incentive for using Ardil as a blend was the reduction in material costs when compared to a pure wool fabric [43]. However, there were also benefits to material properties when using Ardil as a blend, which *Silk & Rayon Magazine* reported on in 1945 [37]. Ardil was pitched to customers as a complimentary fibre that enhanced the properties of the other fibres it was blended with; it could be used to make lighter woollen fabrics, it was not subject to moth damage, and it was crease-resistant. Another key consideration in the production process highlighted by the *Silk & Rayon* article is that the variable length of fibres meant Ardil could be spun with existing machinery and, therefore, easily absorbed into company production lines [37]. Ardil was also found to be beneficial in hat making as, although it did not felt itself, it enhanced the felting process when used with wool [44].

In order to achieve the most from their new fibre, ICI encouraged industry partners to experiment with it. As a result, a wide array of Ardil blends were created, tested, and accessed [18]. It was suggested that blends with a higher percentage of Ardil would be better suited to dress fabrics, where washability was not as intensive or as frequent compared to shirting materials [43]. Ardil was blended in equal parts with wool, and just before the outbreak of war, sufficient fibre was produced on a laboratory scale to enable a number of suits to be made; a number of these suits were still being worn in the early 1950s [42]. Although *ICI Magazine* reported positively about the longevity of these early garments, anecdotal evidence suggests otherwise [45].

3.2.5. Ardil Factory

The ICI board approved Ardil for mass production in 1947. A GBP 2.1million budget for the project was agreed, and work began on the Ardil plant at the Dungan's site in Dumfries in 1949 [30]. The centrepiece of this site design was the Ardil Tower—a monolith to ICI's aspirations for their fibre (Figure 2b). The factory utilised a vertical assembly line, where all parts of the yarn-making process were conducted under one roof. The peanut protein meal was also stored onsite for ease of production. ICI were immensely proud of their new Nobel Division factory buildings, and boasted about the external "buff coloured" bricks and the "special acid-resisting floor" in an issue of *ICI Magazine* from 1950 [46]. Internally, the plant was fully tiled, as cleanliness was essential to the chemical processes of making Ardil. The description of the factory highlights the advancements made in contemporary RPF science, where the involvement of acid in the process would be highly controlled and minimised. When the plant was in full production, the output was around 9000 tonnes per year [42]. The site was ready for commercial production in 1951.

It took over 15 years from the initial idea developed by Astbury in his lab at the University of Leeds to the opening of Ardil's own dedicated plant. Throughout this time, numerous trials and testing of the material were carried out. Recommendations to blend Ardil were introduced to address flaws in its material strength, but despite this ICI still felt confident in the importance of the fibre they had invented.

3.3. Marketing and Public Reception of Ardil

3.3.1. General Public

Though ICI and textile manufacturers had great confidence in their product, they now faced a new challenge—marketing a new and unknown product to the public. After the Second World War, the public were keen to forget the hardship and rationing imposed on them, and to celebrate their post-war wealth. Although rationing of clothes continued until 1949, a desire for newness and convenience underpinned the marketing of many products, and the textile sector was no exception. Advances in science that had resulted from necessity during the war were now being applied to household products post-war. Textile journals from this period are filled with adverts for different coatings and finishes that ease the process of laundering [47]. The public were hungry for new materials and products that science could offer them, and the ease that they brought to their domestic lives. Ardil fit directly into this remit, with one advert declaring "Happy families—with 'Ardil'" (Figure 3a). Directly targeted at the housewife, this advert shows a domestic scene, and asserts that Ardil is a key ingredient to domestic bliss.

Though this was an era of new scientific ideas entering the domestic sphere, a textile made from peanuts was not easily accepted by the public. Many magazines and journals could not resist the humorous connotations of a fibre made from such an unlikely source. A headline from 1944 jubilantly declared that ICI had launched a "Monkey nut" fibre [34]. Another article reports that a wearer of an Ardil frock described it as "just nuts" [41]. Astbury was known to wear an overcoat made from Ardil during his lectures at the University of Leeds [48]; a cartoon published in the *Yorkshire Evening Post* in the same period [49] depicted the coat being pecked at by birds, further evidencing the humorous reception that this novel fibre would have had from the public (Figure 3b). It is notable that Astbury referred to the coat himself as made from "Monkey nuts", as he was not permitted to discuss ICI's new fibre by its brand name [32].

(**a**)

(**b**)

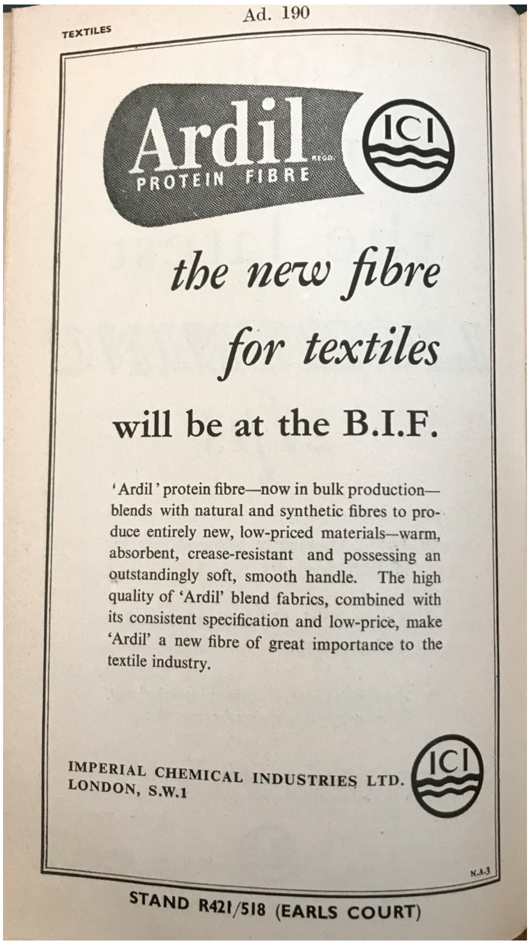
Figure 3. (**a**) Happy families—with "Ardil" advert circa 1955. (**b**) Cartoon of Astbury's "Monkey nut overcoat", *Yorkshire Evening Post*, 1944.

In fact, ICI were so concerned by these sardonic reviews from the press that they sold several garments made from Ardil to the public in secret [48]. Fearing that consumers would be put off by the origins of the yarn, they retailed several Ardil garments labelled as pure wool. This was part of wide-scale marketing test to see if the general public could notice the difference in the Ardil products.

3.3.2. The British Industries Fair

As well as advertising directly to consumers, ICI knew it was important to target the manufacturers who would use Ardil in their products. Established in 1915 by the Board of Trade, the British Industries Fair (BIF) was an esteemed showcase for British products and commerce. In 1953, ICI took a stand at the Earl's Court site of the BIF. ICI regularly showed their products at the BIF, but this was the first time they had shown a textile product, hoping to market it to manufacturers and the public alike. Stand No. R421/518 at the Earl's Court branch of the fair was an extremely large dual-aspect stand at the very centre of the exhibition [50]. ICI occupied more space than any other single exhibitor; the stand was designed by Hulme Chadwick, and was intended to show the fibre's "great versatility and exceptional properties" [51].

An advert for the upcoming show proudly declared Ardil to be "a new fibre of great importance to the textile industry" [52] (Figure 4a). The advert also hinted at several of the factors afflicting Ardil in its development so far. Ardil was referred to as a "new fibre" even though, as previously discussed, the development of Ardil had spanned nearly two decades already. Ardil was also described as "now available in bulk", alluding to the production and scaling problems faced at the plant. The BIF was so prestigious and the stand so intriguing that it was even visited by the new Queen, who was crowned the following month (Figure 4b) [53]. Tellingly, the Queen is reported to have asked "You tell us of all these remarkable properties. Surely there must be some snags?" [54].



(a)

(b)

Figure 4. (**a**) "Ardil a new fibre of great importance to the textile industry", 1953; Catalyst Science Discovery Centre and Museum. (**b**) "Her Majesty is seen here examining 'Ardil' protein fibre" at the British Industries Fair, 1953; Catalyst Science Discovery Centre and Museum.

3.3.3. Designers Working with Ardil

In order to showcase Ardil at its best, ICI had commissioned some of the UK's leading textile designers to create fabrics using Ardil blends [51]; the pioneering woven furnishings designer Tibor Reich was one of them. It is perhaps no coincidence that Reich was a graduate of The University of Leeds, where the method for making Ardil was invented. The University's reputation in industry was strong, and Tibor's link to the institution may well have led ICI to commission him for their stand. Tibor Ltd. produced several fabrics using Ardil—most notably a design called History of Shapes (Figure 5), described by one reviewer as a "A tour de force woven on the Jacquard loom in [A]rdil, spun silk, and a metallic thread, which was then screen-printed with a narrative pattern" [55]. Today, one of the same pieces that hung on the BIF stand can be seen in the Tibor Ltd. private archive. The piece is regularly described as being made of Ardil, silk, and Lurex. Upon closer examination of the piece, it appears that Ardil is spun with silk to produce a unique yarn. The Victoria and Albert Museum also holds History of Shapes in their collection, although it is not identified as being made from Ardil. As a result of this research, the catalogue at the V&A has been corrected to record this piece as being made from Ardil.

Figure 5. Furnishing fabric History of Shapes, designed by Tibor Reich, Hungarian, Stratford-upon-Avon, circa 1953. © Victoria and Albert Museum, London.

As a designer, Reich was always interested in working with new materials and concepts. He was already using another novel material called Lurex—a yarn made from thin aluminium foil—in many of his textiles. After his experience using Ardil in History of Shapes, he continued to work with ICI, producing several commercial ranges of fabrics using Ardil (Figure 6a). Tibor's typical yarn palette would include wool yarns in different specifications, combined with viscose and Lurex wefts woven on a cotton warp. Ardil blended well with all of these fibres, and would have been complimentary to his existing products. Designs produced by Tibor Ltd. in Ardil included the Jacquards *Movemento*, *Granite*, and *Gazelle*, as well as power-woven designs, including Ardil Prince, Henley, and one of Tibor's most popular designs, California. Tibor was so taken with Ardil that he created a distinctive design celebrating peanuts, entitled Harvest (Figure 6b). Using the unusual technique that he had developed with History of Shapes, Harvest has a woven Jacquard background, which it was screen-printed onto. The motifs in the design are based on the process of harvesting peanuts. Tibor produced a similar design, called "Aluminium story", depicting the process of smelting aluminium [56].

Many other important names from 20th century textile design were keen to develop products using Ardil fibres. During the course of this research, it was discovered that one of the most notable manufacturers of 20th century textiles, Warner & Sons, also worked with Ardil fibre. Warner & Sons' power-woven record books show an Ardil fabric being produced in 1953 (Figure 7). The piece described in the log was produced for ICI in February 1953, suggesting that the intention was to showcase it on the Ardil stand at the BIF. The fabric was described as being green in colour and made form a blend of Ardil and silk. Further research is required to determine whether the Warner Textile Archive still holds any examples of this Ardil fabric. Other noted designers who lent their signature designs to Ardil fabrics included Jaqueline Groag, John Piper, Lucienne Day, and the sculptor Nicholas Vergette [57].

(**a**) (**b**)

Figure 6. (**a**) "Tibor weaves new 'Ardil' blend textures" advert circa 1954. (**b**) Furnishing fabric, Harvest, depicting the process of harvesting peanuts, designed by Tibor Reich, Stratford-upon-Avon, circa 1953.

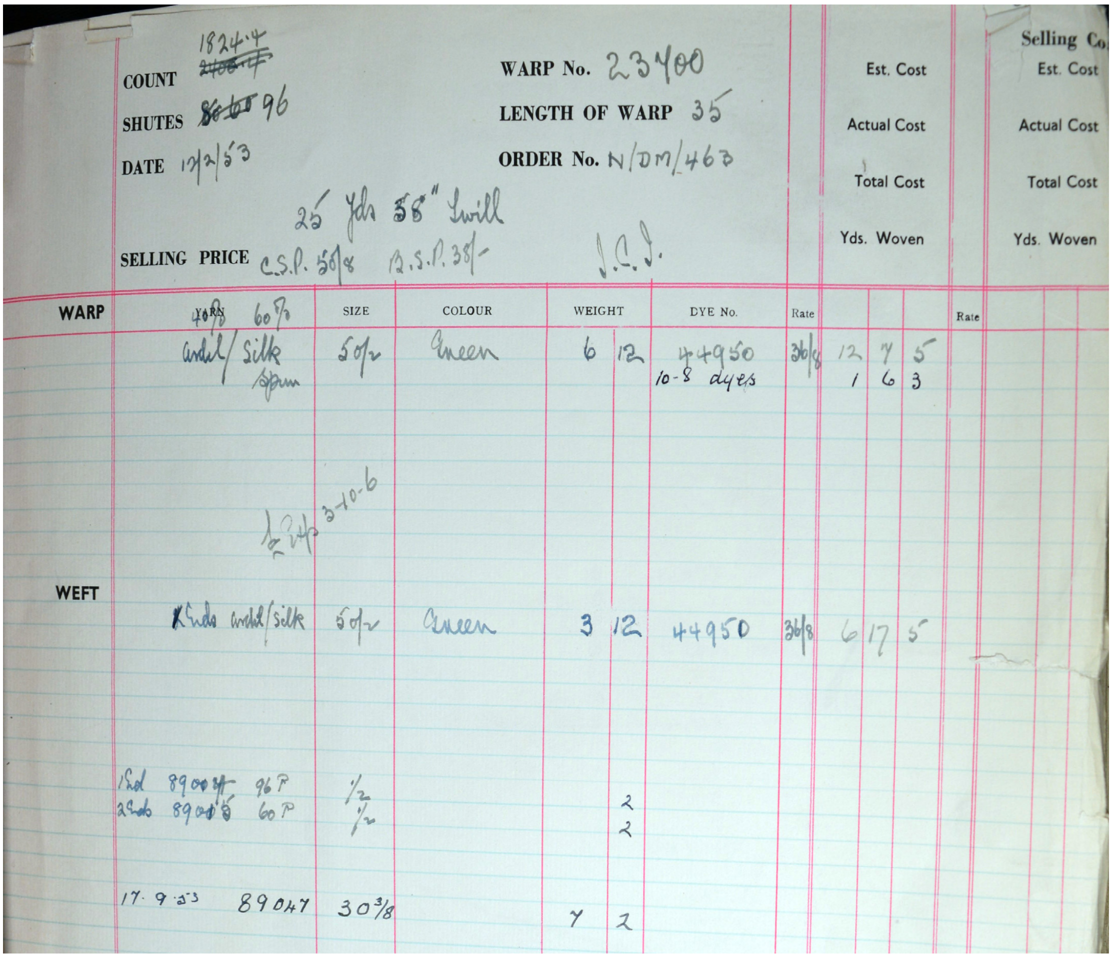


Figure 7. Power-woven fabric ledger, Warner & Sons, Warner Textile Archive, 1953. Reproduced with permission from the Warner Textile Archive, Braintree District Museum Trust.

3.4. Political and Economic Factors

Put simply, there are four main political and economic factors that governed the development of Ardil and can help to explain why it failed. These were the Second World War, the price of wool, the supply of peanuts, and the rise of petrochemical fibres. Whilst all of these are interlinked, each subject is tackled independently here to help understand the picture as a whole.

3.4.1. The Second World War

Although the Second World War was beneficial for development of many RPFs—most notably in Italy—the war actually postponed further development of Ardil, as much of ICI's technology was diverted towards the war effort. In fact, ICI's Drungans site in Dumfries, which would later become the Ardil plant, was originally created by ICI to produce munitions [58]. The peanut meal used to create Ardil was needed to supplement food supplies [39]. This significantly delayed the material developmental progress of Ardil. In contrast to the UK's postponement of Ardil, Italy doubled down on their output of RPFs during the war, clothing their army in Lanital uniforms. This may be in part due to the development of Ardil being several years behind that of Lanital; at the outbreak of war in 1939, Ardil was still only a lab creation. In 1944, development work on Ardil resumed, although ICI were still not able to produce Ardil in large quantities. "When the war ended, a small pilot plant was built and sufficient 'Ardil' produced to enable us to form some idea of its commercial possibilities" [42]. Slow development did not stop the press from eagerly reporting a 1944 press release from ICI. An article in *The Draper's Organiser* from January 1945 announced "New Wool-like Yarn from Nuts . . . ICI's important contribution to synthetic fibres" [18].

3.4.2. The Wool Price

The war impacted the supply of raw materials, and there was a notable strain on wool supplies. At first, this was promising for Ardil and other RPFs, as it indicated that wool stocks could not be solely relied upon to keep up with demand for clothing [59]. Even the wool industry felt that scientific enhancement would likely play a part in the future of wool [60]. When wool prices began to climb to their most expensive in history at the end of the 1940s, it is likely ICI felt vindicated in their decision to invest to so heavily in Ardil. The cost of wool reached the highest it had ever been at "125$\frac{1}{2}$ d. per lb. on 26 January 1951" [61], roughly equivalent to GBP 41.80 per kg in today's money [62,63]. This steep elevation in price was caused by the government commandeering the British Wool Clip during the war. They continued to pay a set price for wool based on a pre-war price. This price did not reflect the cost of sheep farming and wool production at the time, so when the price cap was lifted at the end of the war the cost of wool rose significantly [64]. The demand for wool during the war period was also steadily increasing while the global output of wool fell, further inflating the price [65,66].

Data gathered compiled using Kreglinger and Fernau market reports shows the prices for wool at the London sales between 1924 and 1954 (Figure 8) [66], demonstrating the lack of recorded prices during the war period and subsequent elevation in price post-war. Unfortunately for ICI, this seemingly exponential rise in the price of wool did not last. The drop in wool prices globally [67] from 1951 onwards doubtless took a toll on Ardil, as industry partners were not as likely to try a more expensive, unfamiliar fibre over a reliable material such as wool. The commercial success of their product relied upon the price being highly competitive compared to wool and other fibres.

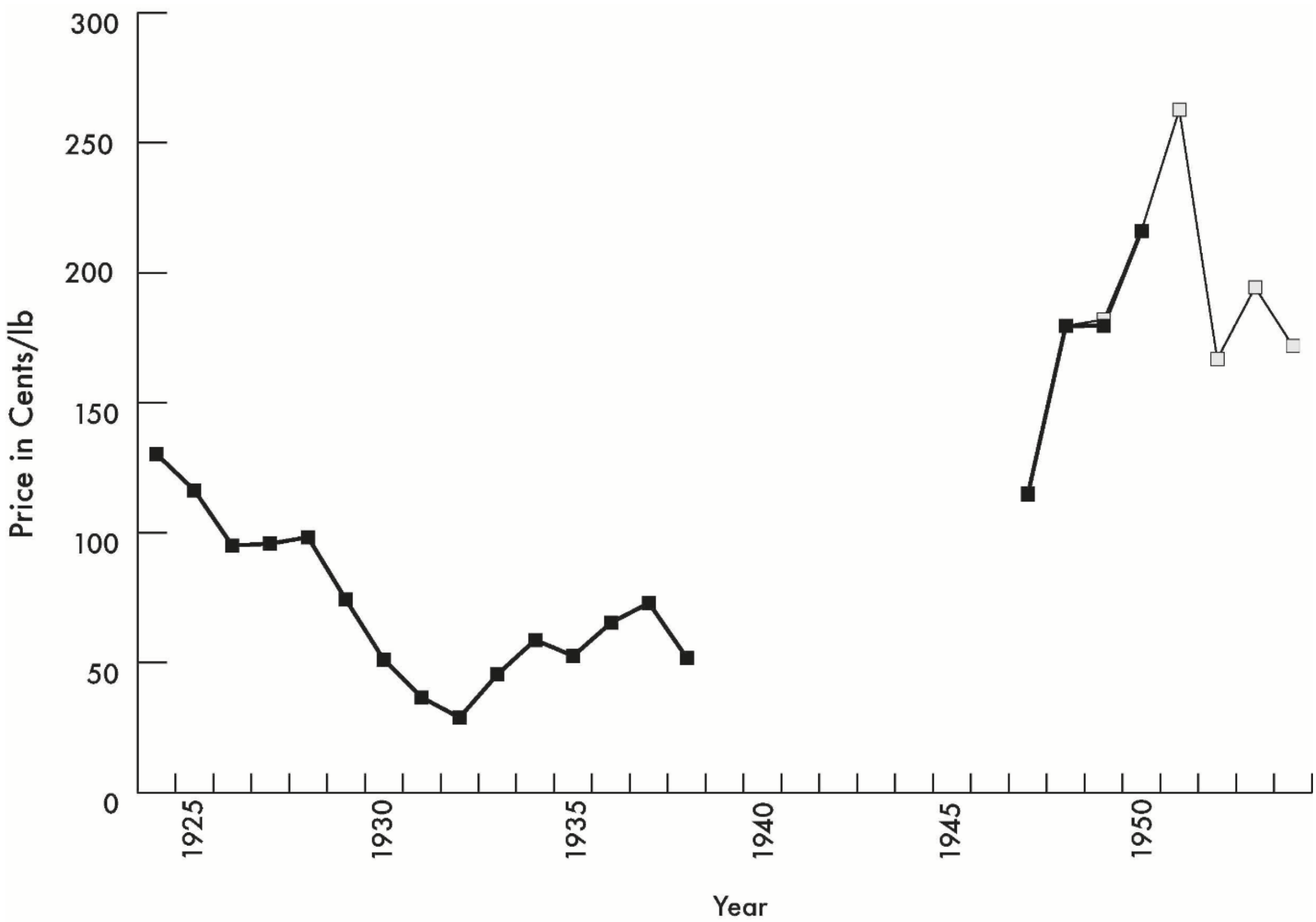


Figure 8. Graph showing the absence of a wool price during the war, and the initial spike and subsequent drop-off in wool prices post-war. Average price per pound and price differentials of fine wool at Boston and London markets, 1924–1954. N.B., Data taken from two separate sets, indicated by the colour change on the graph. Wool can be a difficult commodity to price, as it varies so much in quality, and is subject to fluctuations in yield. Data on the production and price of wool are therefore complicated to extrapolate, but the datasets used reflect the market trend as whole.

3.4.3. Supply of Peanuts

ICI had also not considered the difficulties they would face in finding the raw materials needed to scale up their production. At the same time as the peak in wool prices (July 1951), W Johnston at ICI wrote to Mr Greenhill of the Trades and Marketing Department of the Colonial Office, stating that he "would very much welcome any help or guidance which the Colonial office can give us in finding a source of consistent supply of good quality groundnuts . . . to be used for the production of Ardil Protein Fibre" [68]. The problems ICI were experiencing came from the quality of protein yielded from the peanuts. They had already experimented with several varieties of peanut, each giving different results; the quality of the fibre produced was closely linked to the quality of the protein that could be extracted from the peanut meal [68]. As such, ICI found that they had to be highly selective about the peanut meal they used for the development of their product, forcing them to seek more reliable and consistent sources whilst narrowing their options. Johnston had contacted the Colonial Office off the back of a report about the available protein supplies for Ardil published by the Ministry of Food [69]; the report expressed concern about the growing demand for peanut meal from the textile industry, and warned that this demand had already come at the expense of "feeding-stuffs supplies" [69].

3.4.4. East Africa Groundnut Scheme

The failure of the East African Groundnut Scheme (EAGS) was also making headlines in 1951. Started in 1947, the EAGS was a proposed solution to post-war food shortages. The scheme entailed cultivating large quantities of peanuts in the shrubland of Tanganyika, now known as Tanzania [70]. It would be easy to assume a causal link between the demise of the EAGS and the demise of Ardil, but a direct link between the two is not clear [42]. The work on developing Ardil had begun long before the conception of the EAGS; concurrently, the EAGS was developed as a response to food shortages, not textile shortages. Correspondence from ICI shows that they were working with peanuts sourced from around the world, including India and China, as well as several other African countries in addition to Tanzania [70]. There is further correspondence showing an interest from ICI in the progress of the EAGS in early 1952 [71], but the demise of the EAGS was already in motion [72]. Instead, it would be more accurate to suggest that the simultaneous rise and fall of both Ardil and the EAGS speak to the wider trend of peanuts as a commodity at the time, and the promise that they held as both a fibre resource and a foodstuff.

3.4.5. The Rise of Petrochemicals

As referenced in Figure 1, the development of Ardil and other regenerated protein fibres coincided with the development of new fibres from the petrochemical industry. The synchronicity of these emerging fibre technologies is perfectly encapsulated by ICI itself; at the same time as they were working on Ardil, they were developing another patented textile fibre—Terylene. Terylene is the ICI brand name for polyethylene terephthalate (PET)—a fibre derived from petrochemicals. These two textile products from ICI were developed concurrently; the 1953 BIF also served as a launch pad for Terylene, with one side of the dual-aspect stand being used for each fibre. While the Ardil factory at Ardeer was being built, a pilot plant was producing Terylene in Lancashire. A full-scale production facility dedicated to Terylene was completed at the end of 1954. It was capable of producing up to 10,000 tonnes of fibre a year, and was situated in Wilton, in what is now Teesside [73]. ICI invested heavily in and widely promoted both products; however, Terylene ultimately won, succinctly summarised by this 1957 headline in *The Outfitter* "Terylene output to be doubled—but it's the end of Ardil" [74].

4. Discussion

Ardil represents a unique and important case study in the development of RPFs. Its lifespan only lasted 22 years from conception to demise, but during that time Ardil was hugely prevalent. From the first experiments carried out by Astbury in his lab at the University of Leeds to the practically overnight closure of the Ardil factory in 1957, Ardil's story is full of Hollywood-like twists. The huge amounts of finance and time invested show how strongly Ardil's backers believed that this could be the future of material science. At its best, Ardil was a fibre that could simplify manufacturing techniques, address material shortages, and provide consistent and superior textile qualities such as drape and lustre. At its worst, Ardil was an expensive experiment that produced inconsistent results, was not scalable, could never be price-competitive with equivalent fibres such as wool, and lacked material longevity.

Unfortunately, the popularity and success of petrochemical textiles meant that RPFs were largely abandoned, and much of the information and research into them became obscured. In the 21st century, we are seeing a huge reversal in the popularity of petrochemical fibres as we discover more about their detrimental impact to the planet. Had we known then what we know now, research into RPFs might not have died out in favour of petrochemical fibres. RPFs hold huge potential for the future of sustainable textiles. A vast quantity of research into this field already exists, but is currently inaccessible for researchers wishing to build upon it. Archival research has provided more detail and clarity as to the reasons why Ardil failed, uncovering previously unseen or little-known material that has helped to build a clearer picture of the history of this once-celebrated fibre.

This methodology of reflecting on lessons from societies past has been mentioned by the Centre for Circular Design, Chelsea College of Arts, as part of their TED's TEN toolkit for sustainable design [75].

Ardil is a prime example of how and why RPFs met their untimely end as a result of myriad factors. Perhaps the most important of these was the poor performance of these fibres in comparison to others available on the market. It was clear that manufacturers were not always as keen to work with these new manmade fibres as the companies who promoted them. Another 1957 article in *The Outfitter* entitled "Test fibres for longer before we sell them" described how manmade fibres had "bedevilled the outfitting trade since the war" [76]. Customers were also not as keen to buy Ardil as ICI had hoped, with sales failing to grow. The struggle for new and experimental fibres to be accepted into a wider market is an important lesson to be taken forward into contemporary RPF development; the inherent poor fibre strength that plagued manufacturers at the time could now be seen as an opportunity, aligning RPFs with alternative, faster fashion cycles [77].

The issues Ardil faced with the supply of the peanut raw material are also relevant to contemporary RPF research. After the end of the hostilities in WW2 and the subsequent dissolving of the British Empire, the volume of peanuts imported to the UK reduced massively, meaning that the economics of utilising peanut waste for textile manufacturing were no longer favourable. While it was also hoped that Ardil would be cheap to manufacture, as it largely utilised byproducts from the food industry, it became clear that ICI needed to be more selective with the proteins they used in order to produce the best-quality fibre. Therefore, they began to move towards sourcing peanuts directly for producing Ardil, which was far less cost-effective than using peanut waste as they had initially planned. This highlights the need for robust future-proofing when designing a circular economy, ensuring that feedstocks are ideally locally sourced as well as actual waste streams.

Looking into the future of incorporating regenerated protein fibres into a circular economy, the environmental impact of the production process in terms of both the chemicals used and the volume of water consumed has to be considered; there has been a lot of contemporary research done into the replacement of formaldehyde as a crosslinking agent with more sustainable options, such as polycarboxylic acids; and methods for regenerating the water used within the process to try and "close the loop" could help alleviate issues with excessive water consumption. More research would have to be performed to determine the full environmental impact of these fibres through LCA, to identify which areas need to be improved and how they could be improved from an environmental perspective.

5. Conclusions

From a modern sustainability perspective, the prospect of importing vast quantities of produce from overseas is also problematic, with the correspondingly large environmental impact of transportation of the goods. It is much more attractive to look at processing the feedstock at a local level and utilising the waste as close to the production and processing as possible. Within the UK, there is no longer any potential for utilisation of large quantities of peanut waste, but the UK does have other forms of protein waste that could potentially be utilised. The majority of food consumed within the UK is actually dairy, accounting for roughly 27% of the food eaten [78]; therefore, a correspondingly large volume of waste is generated, with over 330,000 tonnes of milk being wasted every year, giving potential for RPFs from milk—such as casein fibres—to be explored. However, it should be noted that the majority of the milk being wasted in the UK is being generated in homes (90%), which would give rise to logistical problems for collection and ensuring that a uniform feedstock is obtained [79]. Casein-based RPFs were pioneered within Europe at roughly the same time as Ardil, with fibres such as Lanital having a similarly short-lived lifetime during and after WW2, although more contemporary research has been conducted into casein-based fibres [77].

While the demise of the UK-based RPF Ardil was marked by the sudden lack of peanuts being exported into England, this does not represent a reduction in the peanut waste being generated globally. Indeed, peanut production has seen a marked increase in recent years, due to an increase in the popularity of peanut oil. Global peanut production has increased from 31.4 Mt in 2000 to 48.1 Mt in the 2019/2020 season, representing a > 50% increase in the last 20 years [80]. Global peanut oil production has increased from 4.5 Mt in 2000 to 6.5 Mt in 2021/2022, representing a roughly 43% increase [81]. When processing peanuts for oil, the waste in the form of peanut meal can be as high as 70%; the global production of peanut meal in 2019–2020 was 7.7 Mt. As discussed previously, this peanut meal has a 53.3% average protein content, representing a raw waste protein mass of roughly 4.1 Mt; currently, the main use of this feedstock is animal feed. However, this is a low-value valorisation route for this waste feedstock, and also poses potential issues with contamination with aflatoxins. Peanuts are particularly susceptible to contamination by *Aspergillus flavus* and *Aspergillus parasiticus* fungi, which produce aflatoxins that in high enough doses are lethal to both humans and animals, and low doses can still cause myriad diseases, including cancer in humans, and have been shown to reduce weight gain and milk and egg production, as well as causing contamination of milk in animals. These issues do not stop peanut meal being a highly effective animal feed component, but they do highlight that it is not a perfect solution to this waste stream, and there is historical precedent to allow for this huge waste stream to help alleviate the modern world's reliance on non-renewable textiles [82].

For both of the feedstocks discussed, as well any waste utilised with the intention of replacing conventional fibres in the textile industry, care must be taken regarding the volumes of feedstock required. The textile industry is huge, and if regenerated protein fibres were to be accepted as a replacement for non-renewable fibres, the feedstock would need to be able to keep up with demand. This issue would require a collaborative effort across multiple disciplines to determine whether replacement with RPFs would be feasible, with potential future work being focused on the opportunities and drawbacks for theses fibres through SWOT analysis and LCA. It would also be important to learn from past mistakes and use the critical analysis of why Ardil failed during its initial conception, and what factors could be used to avoid such failure in the future.

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