Man-made Adaptations to Wool in the Anthropocene – Proposed Reference Framework for Fiber Comparison

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Abstract: This paper examines man-made adaptations to apparel wool in the Anthropocene and seeks to create a novel framework for mapping existing and novel fibre developments, treatments, and technologies. It aims to develop a methodology for comparing different types of fibres and technologies to better understand and guide the selection of future novel fibre developments. It describes and rates properties and characteristics of novel fibres and technologies as design tools to imagine, explore, and develop new material connections through a cross-disciplinary platform of knowledge. Several fibre novelties and functionalities are possible and can be mutually beneficial to wool and man-made fibres.

Keywords: Fibre Comparison Framework, Man-Made Fibres, Wool

1 Introduction

The Anthropocene, a proposed term to describe the geological, human-centered era that we are living in today (Hofstad and Delsett, 2023), was popularized by Dutch chemist Paul Crutzen around 2002 (Vetlesen, 2019). The term originates from ”anthropo-” which means human and “-cen” which means new (Hofstad and Delsett, 2023). The suggested starting point for the Anthropocene has been debated, ranging from the start of agricultural farming, the invention of the steam machine and the industrial revolution, to the invention of nuclear weapons. Alternative terms such as Capitalocene and Catastrophism have also been suggested to describe similar phenomena (Brooks et al., 2017). In 2016 the International Geological Congress recognized the Anthropocene as a geological era to replace the Holocene starting from the mid-20th century – coining it's '*raison d'être*' as a consequence of the effects human intervention has had on planet earth, its eco-systems and inhabitants (“International Geological Congress Archives,” 2016). The Anthropocene as a concept is firmly rooted in society today and used by scientists, researchers, politicians, other professionals, and the general public, to describe current and historical human-environment relationships (Carrington and editor, 2024) (Zhong, 2024).

The production of textile apparel is a complex industry with a vast number of challenges relating to sustainability and pollution, overproduction, and overconsumption. Research has shown that the share volume of clothing and textiles produced, represent the greatest environmental burdens and concerns, more so perhaps than a lack of long-lasting durable clothing (Klepp and Hvass, 2023). Synthetics and man-made fibres cause vast environmental problems due to their petrochemical origin, the release of microplastics and chemicals into waterways, their non-biodegradable and non-renewable nature and the imminent plasticization diffusion into living organisms (Klepp, 2023). Although sustainable in many aspects, the wool industry leads to deforestation and loss of biodiversity and carbon sequestration due to livestock fostering, releases greenhouse gases and causes water stress (Ozek, 2024). In this sense the trouble with textiles span across all types of fibres, and sustainable solutions can seem less tangible unless the problem of overproduction is addressed (Klepp et al., 2023). The first cradle-to-grave LCA report on wool reports that the more consumers use their garments, the more sustainable they become (Laitala et al., 2018). Although this might seem obvious, it is often forgotten when addressing the fashion and textiles industry in a sustainability context, especially where green washing is concerned.

The purpose of this paper seeks to investigate different types of man-made adaptations to wool and to create a framework, archive, and roadmap for investigating and assessing the overall performance and sustainability impact of novel fibres and textiles, textile treatments and finishings – from raw material, processing, and manufacturing through to the use phase and end phase. The scope of the investigation ranges from traditional to more novel and less travelled fibres and fibre combinations, treatments, and technologies that presently are – or that could potentially be – applied or used together with wool. The study includes new fibre technologies with a sustainable profile and others that may have a more questionable role in respect to humans, animals, nature, and sustainability, as a way of developing a better understanding of wool and man-made adaptations to wool. It aims to develop a methodology for comparing and rating different types of fibres and technologies to help understand and guide the selection of designed materials as well as design directions for future fibres, materials, and garment developments.

The target audience for this paper is mainly material researchers but can also extend to designers and artists working with novel fibres, materials, and textiles. The paper seeks to have an open, inquisitive, and critical approach to man-made adaptations to wool and attempts to look at fibre and textile developments from a cross-disciplinary design, innovation, and research perspective, to investigate how textiles might offer or introduce new services to society that do not yet exist and that could potentially replace existing unsustainable or unpractical practices. The sustainability aspect will be of great importance, and developments that could cause hazardous effects should not be taken further. Although of great importance and relevance, the framework of this study is not to be confused with Life Cycle Assessments (LCA) that traditionally tend to measure the carbon footprint of existing textiles (Laitala et al., 2018). LCA's traditionally tend to favor synthetic materials because they often focus on the cradle-to-gate footprint rather than the cradle-to-grave footprint, thereby favoring synthetic fabrics over wool because cradle-to-gate LCA's do not measure the use and end phase of textiles (Charter et al., 2024). LCA's have recently been performed on wool fibres and textiles that include the all-important use and end phase and demonstrates that wool performs well on the sustainability specter when a more holistic approach is taken. This is because wool is renewable, wool garments tend to be biodegradable and have a longer life than synthetic garments because wool garments are often taken better care of compared synthetic garments (Laitala et al., 2018). In this paper, renewability is understood as a resource that provides repeated or endless supply. In the case of wool fibres, healthy sheep will always grow back a new fleece, replenished naturally over time. Biodegradability is understood as the capacity for biological breakdown of organic materials by microorganisms in nature over time. The first LCA report on wool clothing found that the use phase of wool garments is essential when assessing their overall environmental impact ("Life Cycle Assessment of wool clothing," n.d.). The study also found that wool garments tend to be looked after better than other garments, requires less washing during the use phase and is more likely to be reused and recycled (Laitala et al., 2018). This again shows how consumers influence the carbon footprint of garments greatly through how they use and care for their garments (Laitala et al., 2018). The use phase of non-existent garments is of course difficult to assess, but knowledge derived through more holistic LCA's can help to assess and guide relevant future fibre development paths.

In this paper, Responsible Wool Standard (RWS) certified merino wool will act as a starting point to be compared with various man-made adaptations to wool. In the following section general wool properties and characteristics will be introduced and RWS merino wool and seven other textile groups will be explained. The groups that will be described, investigated, and assessed are the following: aerogel, Brewed Protein™, Dyneema®, graphene, Optim™, PPRMINT™ and WoolUp. The groups will then be rated, analyzed, and compared according to different criteria in three bar charts displayed in the analysis, data comparison and novel framework section. The criteria to be rated on a scale from -3 to +3 deal with various performance characteristics and properties and sustainability related issues. Finally, a discussion, conclusion and suggestions for future actions will be outlined to conclude the paper.

2 Fibre Groups, Properties and Characteristics

2.1 Wool and RWS Certified Merino Wool

Wool is a protein fibre and an animal fibre. Wool is a staple fibre, as opposed to synthetic fibres and natural silk fibres that are filament fibres, unless they have been cut into stable fibres to resemble the texture of wool or other natural fibres. Wool derives from different breeds of sheep but can also be understood in a broader sense to include animal hair from cashmere and angora goats (mohair), and animal fibres from other species such as the camel, vicuna, alpaca, angora rabbit and yak. The morphology of wool is also similar to human hair (Klepp and Køpke, 2023) (Simpson and Crawshaw, 2002). Depending on the breed, wool fibres have several unique properties and characteristics. Most notably they are excellent thermal insulators and regulators and can keep you warm in the cold and cool in warm weather. Due to wool's unique morphology, wet wool allows for permanent (or temporary) shaping when pressed with hot steam and shrinks irreversibly when exposed to hot water, detergents, and friction. Some wools shrink more than others. Wool has wrinkle resistance ("Wool Fibre - Properties, Facts & Benefits," n.d.), elastic recovery and can return to its original shape unless felting has occurred. Wool textiles have water repellence properties (hydrophobic) but can also absorb humidity (hydrophilic) up to 1/3 of its weight without feeling wet. Wool has great breathability properties because it continuously allows for humidity to evaporate. The combination of having the capacity to repel rainwater and the ability to absorb humidity, combined with great thermal insultation properties due to its porous fibres, makes wool an excellent apparel textile (Klepp and Køpke, 2023). Wool is also antistatic, provides sound insulation as well as UV and fire resistance (Kilinc et al., 2024). Wool has good odor control and can clean itself if left to hang in fresh air (Klepp and Køpke, 2023). For this reason it is often claimed that wool has antibacterial properties (Kilinc et al., 2024), but this is not verified (Klepp and Køpke, 2023) (Caven et al., 2019). Wool is both biodegradable and renewable which is preferable in terms of sustainability. Waste wool can be used as a fertilizer and because wool absorbs oil, it can assist the cleaning of ocean oil spills (Klepp and Køpke, 2023).

Wool only constitutes around 1,3 % of the annual global textile fibre production ("Life Cycle Assessment of wool clothing," n.d.). Merino wool from Merino sheep is the most widely used type of wool in the apparel industry (Klepp and Køpke, 2023) and is favored for apparel textiles due to its softness and long, fine, and curly fibres ("Wool Fibre - Properties, Facts & Benefits," n.d.) (Klepp and Køpke, 2023). Merino wool is therefore the focus of this paper, but other types of wool fleece will be included as the framework develops further. Merino wool is both applauded and criticized as a sustainable apparel textile. Although wool garments tend to be long-lasting (Laitala et al., 2018) and derive from both renewable, recyclable, and biodegradable fibres, ethical and environmental issues relating to water pollution, carbon footprint, biodiversity and animal welfare (mulesing in particular) have been scrutinized and criticized. High-end fashion brand Stella McCartney uses merino wool with sustainability certifications such as NATIVA™, ZQ Natural Regenerative Fibre, and RWS Wool (Responsible Wool Standard). RWS certified wool guarantees measures have been taken to minimize the carbon footprint and environmental impact of wool farming, processing, and manufacturing, and that humans, animals and nature have been respected and considered throughout the process. Confirming to specific requirements RWS certified merino wool follow strict animal welfare, land health preservation and social responsibility requirements from the farm through to the final products ("Wool," n.d.) ("Responsible Wool Standard (RWS)," n.d.).

2.2 Man-made fibres

Although initially inspired by silk, man-made and synthetic fibres have been vastly trying to imitate, modify and improve wool fibre properties and characteristics since their arrival in the 1920. Man-made adaptations, treatments, and finishes to wool commonly aim to add new capabilities, or alternatively enhance or minimize existing wool properties and characteristics (Klepp and Køpke, 2023) (Kilinc et al., 2024). Wool blends are yarns and fabrics where wool is mixed with other types of wool and other types of fibres, both natural and synthetic. Where wool is mixed with synthetic fibres this is often done to prevent shrinkage, optimize strength or permeability, or make textiles less expensive – as synthetic textiles tend to be cheaper to produce (Klepp and Køpke, 2023). The use of synthetic fibres is an environmental problem especially due to their petrochemical and non-renewable content, the release of microplastics and chemicals into waterways, and their non-biodegradable nature. Synthetic fabrics constitute around 65% of the annual global production of textile fibres (Klepp, 2023). It could be suggested that more sustainable and alternative new textile fibres are needed to mitigate this unfortunate trend, although others might claim that it is more important to first find and solve sustainable waste solutions that deal with existing textile waste before adding new innovations.

2.3 Aerogels

Aerogels are a group of fragile, ultra-porous, low density solid materials that look like a frozen cloud of smoke. Aerogels are excellent thermal insulators because air does not easily filter through the complex, twisted pores ("Smily Tex," 2024). Aerogels are made by replacing the liquid in the gel with air (Smedsrød, 2023). Traditionally aerogels derive from silica, cellulose, and various organic compounds. More recently research exploring recycled aerogels using different types of agricultural, industrial and municipal waste is emerging, and aerogels derived from wool waste show high oil absorption capacity (Nguyen et al., 2022). Primaloft® Gold insulation with Cross Core™ technology combines NASA developed aerogel particles with Primaloft® Gold fibres to achieve high insulation properties. The material is Bluesign® approved and contains 90% recycled material (Strafe Outerwear, 2023). Guide Aerogel Hybrid Pants 2.0 from sports apparel brand Stellar Equipment features Primaloft® Cross Core™ silica aerogel insulation, merino-wool blended fleece, and a PCF-free DWR-treated rip-stop shell (100% nylon) which is stretchable, ultralight, warm, fast-wicking, wind resistant, water-resistant and breathable ("Guide Aerogel Hybrid Pants | BluBlack," n.d.). Experimentation with textile-aerogels is ongoing and can be used to enhance textile properties such as thermal and acoustic insulation, improve fire and ballistic protection, chemical and infrared radiation resistance, and reduce compressibility of textiles (McNeil and Gupta, 2022). Aerogels do not seem to affect the air and water permeability of textiles. Graphene Oxide Aerogels have shown to increase protection from microwaves (McNeil and Gupta, 2022) and can have antibacterial properties (Kaya et al., 2021). McNeil and Gupta stress the importance of using fine particle aerogels with textiles rather than coatings derived from aerogels, because these can reduce flexibility and cause breakage due to the rigid nature of aerogels. Biobased aerogels derived from abundant, renewable, and non-petroleum resources are generally biodegradable and biocompatible and could potentially lead to future sustainable textiles and insulation options, although shrinking issues might need to be solved. They also mention carbon aerogels and magnetic aerogel as interesting areas to explore, and highlights that high costs and skin comfort will need to be improved for textile aerogels in general (McNeil and Gupta, 2022). A group of scientists newly developed an aerogel yarn inspired by polar bear fur. The aerogel fibre is encapsulated by a water-resistant synthetic polyurethane fibre preventing the aerogel from collapsing due to humidity exposure. A jumper was knitted from the yarn (picture 1), performing excellent thermal insulation and much greater thinness than a regular down jacket (Wu et al., 2023).

2.4 Brewed Protein™

Brewed Protein™ are lab-grown protein fibres, films and other polymer materials made from protein powder through a fermentation process using plant-based ingredients (sugarcane and corn) and microorganisms (Spiber, 2023). The technology which involves molecular engineering of nature-inspired protein polymers, began over a decade ago when Japanese Spiber started developing a biotech version of spider silk first coined Qmonos. Renamed Brewed Protein™, it has good strength, is non-reliant of petrochemicals and animal-derived raw materials and is proving to be biodegradable (Nguyen, 2024). Brewed Protein® can have a soft and luxurious touch, as well as other properties and characteristics similar to protein fibres like cashmere and wool ("Spiber," 2023). Great insulation and breathability properties are among these (Pavarini, 2023a). According to Spiber, the Brewed Protein™ filament yarn has a brilliant silk-like luster and finesse. The feel and texture of textiles made from yarn spun from Brewed Protein™ staple fibres can vary greatly depending on the porosity and degree of twisting of the Brewed Protein™ staple fibres. By changing the protein content and the fibre diameter, the feel and touch of Brewed Protein™ textiles can range from soft to a more bulky, fleece-like texture ("Spiber," n.d.). This diverse fibre can be used to produce a variety of apparel materials including woven and knitted fabrics, fur, and leather, and companies such as the North Face, Goldwin, Vollebak, and Woolrich have recently produced garments comprising Brewed Protein™ with wool and synthetic fibres (Spiber, n.d.). A similar technology called PlaX recently introduced by Bioworks, emphasizes the material's antibacterial, deodorizing, and quick-drying capabilities ("Bioworks," 2022) as well as other properties like high heat resistance, durability and dyeability ("J-GoodTech," 30.112023).

2.5 Dyneema®

Dyneema is an ultra-high-molecular-weight-polyethylene (UHMWPE) ("Hva er Dyneema®?," n.d.). Invented in 1963, and commercially introduced as Dynema® by DSM in 1990, it is described as the world's strongest fiber: 15 times as strong as steel, and light enough to float on water ("Dyneema," 2024a). It is typically used to make ropes and protective clothing and has proven to have good abrasion, great chemical and electrical resistance, high flexibility and durability, and UV and water resistance (Sabir, 2018). Polyethylene is biologically inert (Vlasblom, 2018). Although Dyneema® is a synthetic fibre, DSM has developed an ISCC certified Bio-based Dyneema® fiber made from a bio-based HMPE fiber, and described by Dyneema to derive from renewable feedstock ("Dyneema," 2024b). According to Dyneema® it has the same performance properties as their regular ultra-high-molecular-weight polyethylene Dyneema® fibre and a 90% lower carbon footprint than generic HMPE fibres. Dyneema® UD is described as having ballistic protection properties (Govarthanam et al., 2016). As reported by Vermeulen and Ferreira, ultrafine yarns made from wool and Dyneema have been developed, and similar developments show improved stability and abrasion resistance to knitted wool textiles comprising small amounts of Dyneema (Vermeulen and Ferreira, 2005). The Indestructible Puffer from Vollebak features a 100% Dyneema fabric and is marketed as being extremely durable and waterproof ("Indestructible Puffer," 2024). Commercialization of Dyneema® mixed with wool includes Chinese textiles company Shepherd Inc. who has developed a fabric comprising a blend of wool and Dyneema® to produce a super-tough material ("The Woolmark Company," n.d.) and fashion brand Zenga has introduced a high-performance jacket made from a ripstop wool fabric with Dyneema® fibres (main body: 60% polyamide, 28% wool, 12% polyethylene, lining: 100% polyamide) featuring high levels of strength, lightness and wind- and water resistance ("Zegna," n.d.).

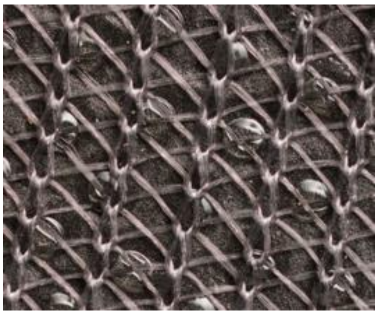

Figure 1 (right). Polar bear inspired aerogel knitted jumper (Conroy, 2023)

Figure 2 (middle). 100% Dyneema fabric ("Indestructible Puffer," 2024)

Figure 3 (left). 100% polyamide with graphene-coated polyurethane membrane ("Graphene Jacket," 2024)

2.6 Graphene

Graphene derives from graphite, consists of one single layer of carbon atoms arranged in a hexagonal lattice, and is claimed to be the thinnest material in nature. Resistex® Graphene yarn promises high mechanical tenacity, abrasion resistance, antistatic properties ("Graphene," n.d.) and good shrink stability (Lu et al., 2012). It is very light, strong, flexible, transparent, highly electrically and thermally conductive, and selectively permeable. Developments have shown that it can store and harvest energy ("What is graphene?," n.d.) ("Graphergia Project," 2023) ("Graphergia Project," 2023). It is highly elastic ("What is Graphene?," n.d.) and has shown to be waterproof and excellent at regulating heat, preserving heat when it is cold and getting rid of heat in warm weather ("Materials of the future," 2023). Graphene was first isolated and tested by two scientists at the University of Manchester in 2004 and won a Nobel Prize for their work in 2010. Graphene is featured in a jacket commercialized by Vollebak made from 100% polyamide with graphene-coated polyurethane membrane ("Graphene Jacket," 2024). However, the garment does not contain wool. Several sports and fashion companies are collaborating with graphene suppliers to produce fabrics containing graphene ("Materials of the future," 2023), and a study has shown that graphene can be biodegradable using a human enzyme ("Can graphene and layered materials biodegrade?," n.d.). Alfa Chemistry has developed a mature graphene composite wool process and claims that graphene can provide wool fabrics with added functionalities such as electrical and thermal conductivity and antibacterial properties ("Modified Wool," 2024). One study concluded that electrically conductive textiles made using waste wool fibres and graphene can be suitable for wearable textiles (Al Faruque et al., 2021). The Global Sources website shows a wool fabric comprising 16% graphene, 68% wool and 16% viscose that promises colorfastness, wrinkle and pilling resistance, good flexibility and moisture absorption, warmth and a soft, elegant and crisp feel, but the website cannot vouch for the accuracy of the information displayed because the supplier no longer advertise on the website ("Environmental Wool Fabric," n.d.). Some graphene-based materials may have self-healing properties (Jilani et al., 2020). Graphene-info highlights how scientists are concerned that graphene may be hazardous and toxic to humans, animals, and nature, and refers to a study from Singapore's A*STAR concluding that graphene-based materials kill more bacteria than graphite-based materials and that graphene oxide can be toxic ("Graphene Oxide may be toxic, kills bacteria," n.d.).

2.7 Optim™

Optim™ is a fibre stretching technology developed by the Woolmark company made from 100% Australian merino wool which they describe as a machine washable water and wind resistant fabric with enhanced wrinkle resistance and natural durability. To produce this fabric, merino wool fibres are pre-stretched and spun into yarn before being woven into a fabric. During Optim™ processing the tread density is very high during weaving using stretched yarns that have not been permanently set. Once the construction is complete and the fabric has been wet finished, the stretch is released causing the yarns to contract and creating an extremely tight construction with high density and low permeability. The technology allows for other unique wool properties like breathability to stay intact. No chemicals are used during the process ("Wind and waterproof wool," n.d.). In this study the assumption is that RWS merino wool is used for this process.

2.8 PPRMINT™

PPRMINT™ oil treatment is a lasting odor control finish and broad-spectrum antimicrobial treatment developed by American materials science apparel company Pangaia, to keep garments stay fresher for longer and thereby minimizing washing and use of water during the use phase. The company promises that peppermint oil treated garments keep the antibacterial effect for up to 50 washes, and guarantees that the material's texture, color, and other physical properties will stay unaltered for the same number of washes. The treatment is natural and non-harmful to wildlife, humans, and the planet, by avoiding the release of metals and chemicals into nature during production, the use-phase and end-of-life ("Pprmint Oil Treatment," n.d.). Pangaia uses PPRMINT™ in several products including a recycled and reversible wool jacket made from 75% recycled wool and 25% lyocell. The lining, made from 100% cotton is treated with Panagaia's trademark peppermint oil ("Recycled Wool Fleece Jacket," n.d.). They do not have garments where the peppermint oil treatments is applied directly onto wool, but this may be because wool inherently display a certain degree of odor control ("Wool reduces body odour," n.d.). A similar treatment is utilized in Polartec's Delta™, Power Dry® and Power Grid™ collections (Pavarini, 2023b) ("Polartec to switch to peppermint treatment," 2021). Power Wool™ by Polartec is marketed as naturally odor resistant and made from a soft, odor reducing, merino wool base, covered by a strong and highly durable synthetic outer-layer ("Power Wool™ Fabric," n.d.). The odor reducing merino wool may or may not have this treatment.

2.9 WoolUp

Superwash is a well-known chemical finishing used to prevent wool from shrinking, dating back to the 1970s (Klepp, 2021). The chlorine-Hercosett treatment has been the most widely used superwash method ("What is machine-washable wool?," 2023) and has also proven to be the most efficient shrink-prevention method (Hassan and Carr, 2019). The process does, however, have negative sustainability implications regarding usage of water, chemicals, and plastic polymers (Hassan and Carr, 2019). Various superwash treatments also reduce or remove desirable wool properties such as elasticity, moisture absorption, flame retardance, insulation ("What is machine-washable wool?," 2023) and breathability and can make the fibre weaker, stiffer and less supple ("Environmental Constraint," 2008). On the positive side, shrink prevention methods result in less garments having to be replaced due to shrinkage. Newer shrink-prevention methods include EXP by Schöller Spinning Group and Naturetexx Plasma® by Südwolle, and these are both OEKO-TEX 100, Bluesign and GOTS approved (Klepp, 2021). WoolUp is a shrink-prevention treatment recently commercialized by Jeanologia and the Woolmark Company that has proven to be more environmentally friendly than more traditional shrink-prevention treatments in the superwash category. WoolUp is an adaptation of existing science and claims to reduce the carbon footprint of shrink-preventing technologies. It is a dry ozone treatment that modifies the surface of wool fibres without using plastic polymers ("WoolUp machine washable wool," n.d.). Ozone treatments can be more sustainable than traditional methods because they use less water, energy and chemicals (Eren et al., 2020), and because ozone decomposes to oxygen, it does not release toxic by-products. Ozone treatment on cotton fibres have shown to increase biodegradability (Eren et al., 2020). Patagonia uses ozone and Hercosett treated wool in the Patagonia Base Layer collection (Hassan and Carr, 2019). According to Hassan and Carr, ozone-based treatments are costly and machinery corrosion might be problematic. They suggest that future developments should focus on polymerizing-gas-based continuous plasma treatments or plasma combined with biodegradable polymeric coating-based treatments (Hassan and Carr, 2019).

3 Analysis, data comparison and novel framework

The criteria addressed in this study deal with properties, characteristics, and issues relating to both textile and garment performance and sustainability. Figure 4 deals with properties relating to protection, strength, and durability performance: abrasion, strength, antibacterial properties, water resistance, wind resistance, and fire resistance. Figure 5 deals with properties relating to comfort and other functionalities: breathability, odor control, softness, thermal insulation, thermal regulation, and electrical conductivity. Figure 6 concerns environmental and economic aspects: biodegradability, microplastic pollution, renewability, shrink stability, FPP costs (farming, processing, production), and water usage. Several characteristics and properties could fit in to more than one category. Other capabilities could also have been included, but the size of this paper does not have room for further assessments. The textile groups have been rated according to criteria on a scale from absent (-3), very low (-2), low (-1), average (0), average + (1), high (2) to very high (3). The ratings have been estimated according to found knowledge and educated assumptions. Ratings marked in pink are educate guessed with higher uncertainty due to a lack of found and verifiable information at this stage, as well as some cases of contradicting facts or misleading marketing related information. Where these discrepancies are suspected or apparent, the ratings attempt to take this into consideration.

Looking at figure 4, Dyneema® and graphene combined with wool show great strength and abrasion and can likely add strength to wool, producing durable garments that could offer an extended lifetime. Brewed Protein™ also adds strength to merino wool due to its potential resemblance to silk ("Spiber," 2023), and Optim™ adds strength and durability to wool due to Optim™'s highly stretched and densifying construction technology ("Wind and waterproof wool," n.d.).

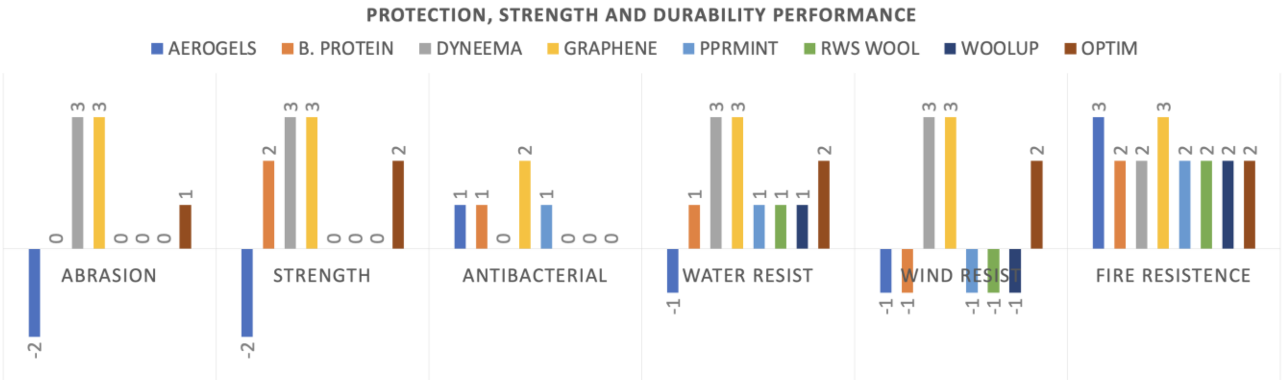

Figure 4. Bar chart showing properties relating to protection, strength, and durability performance.

Figure 5 shows that thermal insulation and regulation are generally high throughout the groups except for perhaps Dyneema®. Dyneema® is rated lower as little information regarding Dyneema® was found on thermal capacities. Figure 5 illustrates that aerogels have a very low score on softness compared to the other groups. Figure 5 shows that aerogels can likely reduce material softness and enhance insulation properties in wool, and graphene could potentially increase thermal regulation performance in wool materials. Because of the diverse properties of Brewed Protein™, it is unsure whether the presence of Brewed Protein™ will enhance or decrease thermal insulation and regulation in wool fabrics, but quite likely it may stay the same, as RWS merino wool due to its wool resemblance. In terms of how wool might benefit other fibres, it can be assumed that wool could strengthen breathability in textiles incorporating Dyneema® and graphene. Graphene, Optim™, and Dyneema® with wool stands out in terms of enhancing water and wind resistance. Only graphene stands out as being electrically conductive. Figure 4 shows that graphene and aerogel can enhance fire resistance in wool fabrics, although wool already has a high level of fire resistance (Klepp and Køpke, 2023).

In figure 4 graphene is rated as having high antibacterial properties because it supposedly can kill bacteria ("Modified Wool," 2024). PPRMINT™ is also rated higher than average due to its claimed antibacterial effect ("Pprmint Oil Treatment," n.d.), and has the highest odor control rating due to its peppermint oil treatment. Aerogels are rated above average regarding antibacterial properties (Kaya et al., 2021). PlaX, a similar technology to Brewed Protein™, promises antibacterial and deodorizing properties ("Bioworks," 2022), and Brewed Protein™ is therefore rated higher than average regarding antibacterial properties and odor control, although this information may be linked to marketing strategies. Wool has self-cleaning properties but is often wrongly claimed to harbor antibacterial properties and is therefore rated as average due to conflicting and incongruent information found about wool and antibacterial properties (Klepp and Køpke, 2023).

Figure 6 show that shrink stability in merino wool will likely increase in combination with WoolUp, Optim™, graphene, Dyneema® and Brewed Protein™. WoolUp, Optim™. Graphene has the highest estimated ratings for shrink stability (Lu et al., 2012), and in the case of Brewed Protein™ the rating is less certain due to its diverse character. In figure 6 costs are

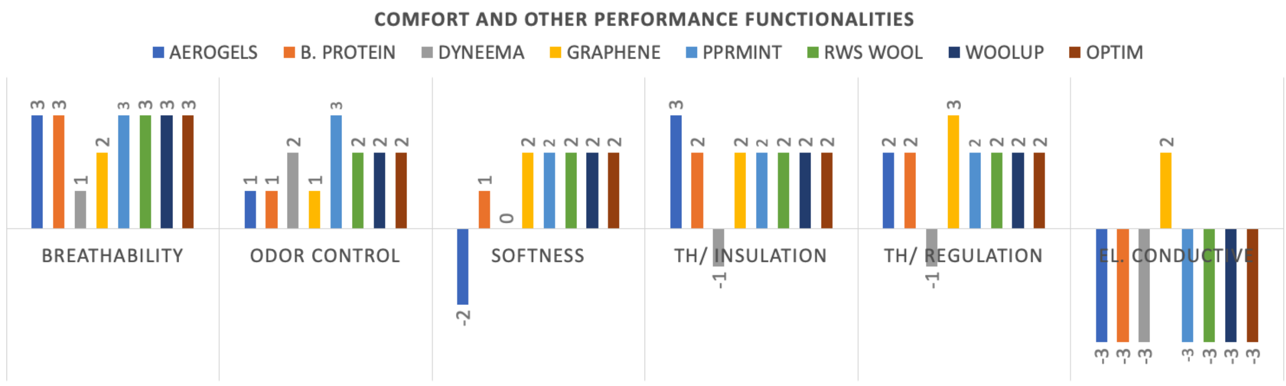

Figure 5. Bar charts showing properties relating to comfort and other performance functionalities.

rated high for all the groups. RWS merino wool is already expensive, and graphene and Dyneema® are rated as having especially high processing costs. WoolUp and Brewed Protein™ are also expensive to produce. Water usage is high for merino wool in general. Treatments like WoolUp and PPRMINT™ use little or no water ("WoolUp machine washable wool," n.d.) ("Pprmint Oil Treatment," n.d.) and therefore shows up positively with a low score on water use. The groups that rate high on biodegradability and renewability in figure 6 are Brewed Protein™, PPRMINT™, WoolUp, Optim™ and RWS merino wool. Figure 6 shows how groups with a high level of biodegradability tend to have a low score on microplastic release. The exception here is graphene because it is not made from polymers.

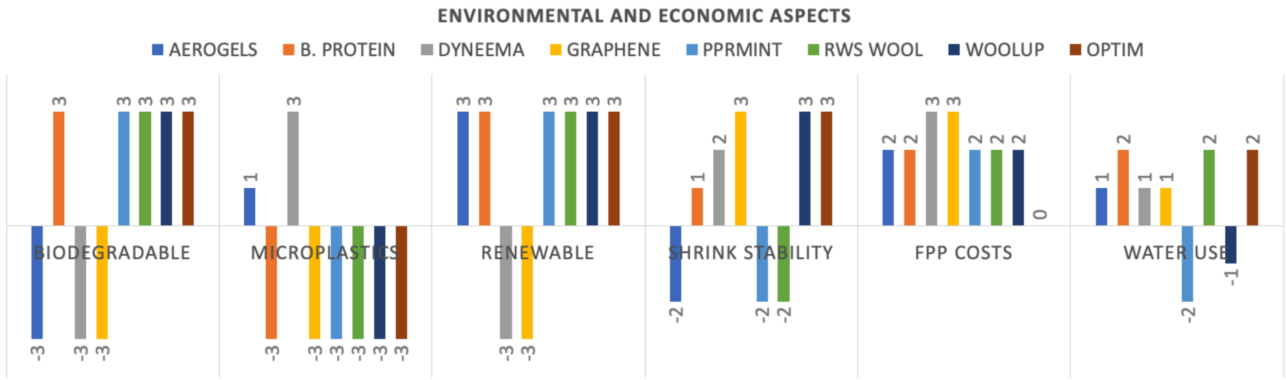

Figure 6. Bar chart showing properties relating to environmental and economic aspects.

4 Discussion, Conclusion and Future Works

The analysis shows that several man-made adaptations to wool can both enhance and reduce existing wool properties and characteristics, addressing various performance functionalities relating to durability, wearability, and comfort as well as issues relating to care, sustainability, and economy. For instance, several of the groups show great potential in adding strength and durability to wool such as Dyneema®, graphene, Optim™ and Brewed Protein™. On the one hand, durability is not necessarily a sign of sustainability (Klepp et al., 2023), as garments made from a combination of wool and synthetic materials like Dyneema® and graphene could become non-biodegradable. Wool garments are often taken better care of, as shown in the introduction. On the other hand, bio-based Dyneema® can be biodegradable ("Dyneema," 2024b) and a study has shown that graphene can be biodegradable using a human enzyme ("Can graphene and layered materials biodegrade?," n.d.). They could therefore potentially benefit wool textiles with strength and durability without removing biodegradability. As mentioned earlier there are concerns relating to graphene, because graphene and graphite can cause harm to humans, animals and nature, and future developments will have to be thoroughly investigated to prevent hazardous results and should proceed with great caution or left untouched ("Graphene Oxide may be toxic, kills bacteria," n.d.). Brewed Protein™ and Optim™ can become important material forces moving forward away from petrochemical synthetics due to their biodegradable nature. Brewed Protein™ could also replace wool if the focus is to replace animal-based textile fibres due to animal welfare concerns or resource scarcity.

Functionalities such as water and wind resistance in wool can be improved through man-made adaptations such as Optim™, Dyneema®, and graphene and could potentially replace existing technologies. Optim™ stands out because the technology does not require plastic polymers or chemicals to become less permeable ("Wind and waterproof wool," n.d.), thereby representing a sustainable alternative to other technologies due to a high level of biodegradability and a lack of microplastic release. In the case of the latter two groups, bio-based and biodegradable versions like bio-based Dyneema®

are preferable due to sustainability. Where graphene is concerned, extra caution is required due to its potentially hazardous content (“Graphene Oxide may be toxic, kills bacteria,” n.d.). Similarly, aerogels and graphene could potentially enhance thermal insulation and regulation where necessary. Aerogels have great insulation properties and could both enhance and replace animal-derived thermal insulation materials, if concerns regarding aerogels lack of comfort and softness in apparel textiles are solved (McNeil and Gupta, 2022). Aerogels derived from various types of waste could have great prospects turning waste into materials with thermal insulation, in particular to replace animal derived materials in puffer jackets but also for other insulation purposes. Only graphene stands out as being electrically conductive and can potentially be able to store and harvest energy (“Graphergia Project,” 2023), and could be a promising area to investigate further. Graphene also stands out in terms of being antibacterial. However, this capacity could potentially also cause harm to those wearing textiles containing graphene, and future developments will need to proceed with caution (“Graphene Oxide may be toxic, kills bacteria,” n.d.). In terms of textiles affecting human health in negative ways, developments concerning materials that could harbor health benefits and benevolent treatments have great potential. Interestingly, some graphene-based materials may have protective and self-healing properties (Jilani et al., 2020) which could be another capacity worth investigating in future works. Whether added odor-control from PPRMINT™ treatment could enhance odor-control and antibacterial properties in wool, will need to be examined further to conclude whether it could be a useful and necessary enhancement.

All the groups tend be costly. In terms of novel fibres and technologies, it is possible that once processing and productions costs, machinery, and facilities are properly in place, costs are estimated to stabilize. WoolUp and PPRMINT™ use little or no water and could therefore be preferable technologies from a sustainability perspective, although the environmental impact of ozone treatments might need to be investigated further. Regarding costs, the maintenance of ozone treatments can be difficult to stabilize due to the corrosion damage that ozone treatments may have on machinery and equipment, and some scientists recommend other shrink stability practices instead (Hassan and Carr, 2019). Brewed Protein™, PPRMINT™, WoolUp, Optim™ and RWS merino wool are biodegradable and due to their non-synthetic content, they do not contribute to microplastic pollution. Dyneema® has a bio-based version, and bio-based aerogels also exist (McNeil and Gupta, 2022), including wool waste aerogels, and these could potentially be biodegradable and renewable. As mentioned earlier, graphene can be biodegradable through a human enzyme.

Some limitations to this study are worth mentioning. More work and investigations including several experts and further improvements on material knowledge could lead to broader and more extensive analyses. Some estimates are partly based on incongruent facts derived from product marketing sources that might play down or exaggerate certain properties for promotional purposes and could influence results. Other apparent limitations to the study include how different choices of categories and criteria may have led to other results or conclusions. Lastly, it is unsure how the choice of RWS merino wool as a comparison point of reference has affected results, and how results would be different exploring other fibers.

A great number of man-made fibres, treatments and technologies exist, many of which are mixed and performed on or together with wool. Several fibre novelties and functionalities are possible and can be mutually beneficial to both wool and man-made fibres on functional as well as sustainable levels. Especially with regards to new developments, aspects concerning levels of usefulness, costs, and sustainability need to be further addressed, explored, and investigated. It could be claimed that future works developing – and examining the potential of – novel materials need to be both critical and explorative, engaging and spanning across disciplinary fields to develop new fibre technologies, in order to replace exiting unsustainable solutions. From a design perspective, the importance of choosing relevant and sustainable materials and technologies is perhaps more critical than ever due to current climatic challenges. An attempt to develop a novel framework seeking to address a cross-disciplinary professional audience is suggested as a beneficial tool, resource, and common ground for developing new and novel material directions and perspectives through a co-creative space of material and sustainability knowledge, critical possibilities, and novel connectivity. A vast territory of unexplored possibilities is likely ready to capture and ignite new and sophisticated scientific fibre and textile developments; guided by past, traditional, existing, and future material and sustainability knowledge.

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