sustainability

Review

Developing the Use of Wool Rope within Aquaculture—A Systematic Review

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Abstract: To date, wool is an underutilised sustainable resource that has the potential to reduce the use of plastic within the environment. Wool can be manufactured as rope, but is this a viable innovation? To gain a comprehensive understanding of the economic viability of utilising wool rope in seaweed aquaculture, a systematic literature review was undertaken. The review focuses on wool, rope, natural and man-made fibres and seaweed farming, and used bibliometric and content analysis of peer-reviewed papers, with no timeframe requirements. It is important to explore alternative materials to reduce marine rope pollution; ghost gear, microplastics from abrasion and plasticrusts are now believed to be significant ecological problems. To date, the production of wool rope is limited, and its strength and durability within the fishing industry remain untested. It is important to understand whether wool rope is a useful alternative: does it have the same tensile strength, and can it be used within the industry without the risk of damage to the environment? There is currently a lack of research on natural rope fibres, resulting in limited access to commercial rope alternatives being used within the industry. This systematic review shows that there has been a large gap in wool research, with limited publications in recent years; however, the drive to increase sustainability (particularly within the marine environment) has increased. This is the first paper that combines both topics within one research study. Further research is needed to identify whether wool rope will provide a feasible alternative to polypropylene in terms of strength and durability, and how wool rope will perform, the length of time it can provide optimum service and within which seaweed farming practice it can offer a practical alternative to polypropylene.

Keywords: wool; seaweed; rope; polypropylene; natural; man-made; fibre; microplastics; degradation; sustainable

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1. Introduction

The seaweed industry is an emerging market in the UK and Europe, enticing entrepreneurs and environmentalists looking for carbon capture solutions, requirements for fast-growing protein, reduced exposure to land competition and places to invest. The Scottish Government have recently calculated that the gross value added (GVA) from seaweed-based industries could be £45.1 million by 2040—an increase of 9000% from 2020 [1]. Naylor et al. [2], believe that the mollusc and seaweed industries are underexploited when it comes to addressing global nutritional food security. However, there is a need to address microplastics in the environment (including lochs, rivers, estuaries and oceans), and a consumer desire to see food production and practices being carried out more sustainably.

1.1. Micro- and Macro-Plastic Pollution

Oceanic sources of macro-plastics and micro-plastics can come from many human activities, including shipping, fishing, boating and farming, both inshore and offshore. Pollution from rope can come in several forms, either from abandoned, lost or discarded fishing gear (ALDFG), which is commonly called ghost gear, the abrasion of ropes and plasticrusts found on rocks. Synthetic rope can become embrittled with a reduction in mechanical properties, leading to the formation of microplastics [3] from formulations of non-biodegradable polyolefins and nylons [4]. Ghost gear is reported to make up 10% of the marine litter in our oceans [5]. In 2015, the Ghost Gear Initiative (GGI) was formed, consisting of over 100 organisations. It seeks to address the issue by restricting high-risk gear, making fishing gear visible and identifiable, improving recycling and disposal and developing mitigations by using more biodegradable components [5]. Plasticrusts are a relatively new type of plastic pollution that occur where plastic debris has begun to encrust the rocky surfaces of intertidal rocky shores [6]. They were discovered in 2019, on the volcanic coastline of Madeira, NE Atlantic Ocean [6]. Ehlers et al. [7] identified that plasticrusts were a result of maritime ropes being scoured across the raspy intertidal rocks and are composed of polypropylene (PP) and high-density polyethylene (HDPE). Ogunola et al. [8] describe plastic as ubiquitous in the marine environment, resistant to degradation and pose a complex risk to human and environmental health. Microplastics are commonly formed from the breakdown and weathering of macro-plastics, and can be ingested by biota, particularly filter feeders such as molluscs, mussels and oysters [8].

Napper et al. [9] assessed the impact of rope abrasion and how this leads to microplastic generation in the marine environment (Figure 1). They suggest that fragments that have been found in the marine environment, often reported to be from land-based sources, are likely to directly enter the marine environment due to in situ rope abrasion, thus masking the problem of poor plastic rope management. Rope age was also an important factor, with new and one-year old rope releasing significantly fewer microplastic fragments (and total mass) compared to two- or ten-year old rope [9]. This is of critical concern when discussing the longevity of polypropylene rope used in marine industries and how this may compare to natural fibres.

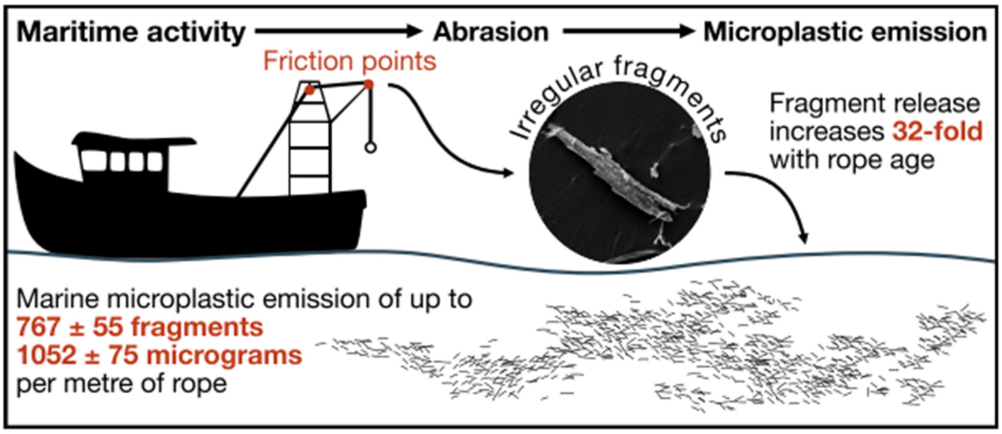

Figure 1. Marine micro-plastic from abrasion of rope. From Napper et al. [9].

1.2. Seaweed Industry in the UK and Northern Europe

Deemed to be the third-generation biofuel, seaweed farming is becoming an attractive off-land production area [10]. However, to date, Europe is only a minor player within the world market, which is dominated by Asian producers and processors [11]. Seaweed is now seen as a sustainable future feedstock, providing food for both animal and human consumption, food packaging, and higher-value product markets such as cosmetics and pharmaceuticals [12,13]. Seaweed aquaculture has a growth capacity that is several times higher than that of land-based crops, such as sugar beet and rapeseed [14], and also soaks up excess nitrogen from coastal waters and estuaries [15].

Two systems of seaweed farming are currently being deployed: (1) the direct seeding route and (2) a seeded pilot line [16]. Direct seeding requires the substrate rope that the seaweed will grow on to, be covered with seaweed seed, aided by a binder, and then deployed. The seeded twine is cultured in a nursery and then deployed by being wrapped around the substrate rope at sea.

The seaweed industry is a growing industry, with both environmental benefits (nutrient absorption and carbon capture) and environmental costs (Figure 2). Figure 2 demonstrates the additional, unintentional consequences of increased seaweed farming, including changing the habitat within the vicinity of the seaweed farm and increased amounts of discarded and lost equipment [16]. Drifting debris from increased infrastructure increases the risk of ghost gear appearing on shorelines, affecting communities and creating a burden for local authorities and tourism [17]. The unintended consequences of increased seaweed farming indicate the disconnect between the producers, deployers and potential recipients of plastic rope and the need for innovation within the industry.

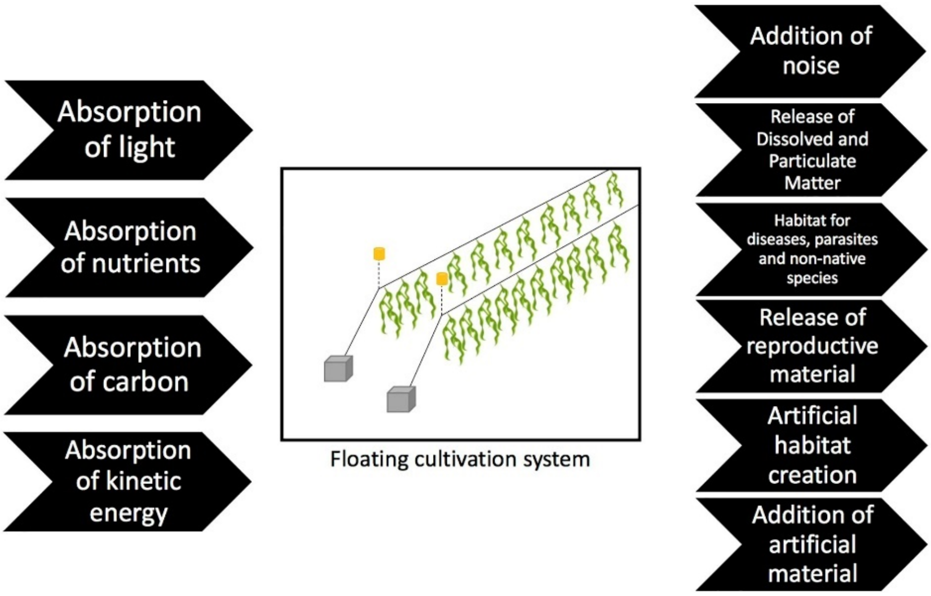

Figure 2. Drivers of environmental change in relation to seaweed farms. From Campbell et al. [16].

Oceans 2050 is a global project focusing on the recovery of the world's oceans through five strands (ocean forests, the future of seafood, coral reefs, regenerative ocean farming and blue carbon). Blue carbon (carbon sequestration) needs to be quantified for seaweed farmers to monetize the carbon impact of their activities [18]. They envisage achieving this through a carbon code or protocol, following the ground-breaking work of Duarte et al. [19] on ocean restoration.

1.3. Wool Properties

Figure 3 [20] shows the structure of wool fibre; however, when assessing the correct application for wool, the fibre length, diameter measured in micron and crimp, and its natural kink must be considered. Once the wool has grown, these are permanent attributes, and so selecting the right type of wool is important. There is a great deal of variation in wool characteristics, not only between breeds but also within breeds, as the sheep live in different environments. Of particular significance is the micron—the diameter of the wool fibre [21]. In the UK, there are over 60 sheep breeds that produce wool, which have been graded into 120 diverse types by the British Wool Marketing Board, now known as British Wool (BW). This infrastructure is globally unique and enables the only wool auction in the northern hemisphere. Every two weeks, merchants can buy greasy wool, wool that has not been scoured (washed) to the critical specifications required by the supply chain [22].

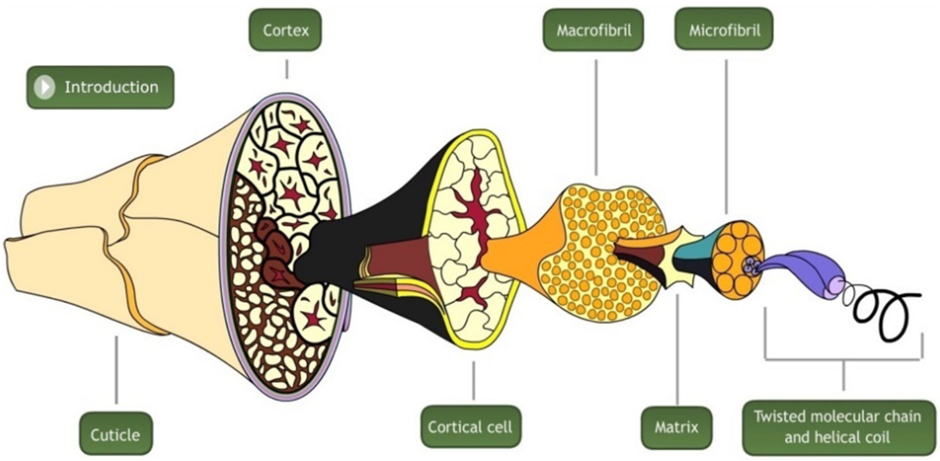

Figure 3. Wool fibre structure. © University of Walkato. [20].

Wool fibre does not sit in a uniform geometrical arrangement due to its crimp; however, the majority of fibres lie in one direction. This interdependent effect allows for individual strands to play their part when twisted into a rope, enabling the wool to take up the strain as a whole [23].

1.4. Wool Market

In 2020, the wool market closed down due to COVID-19, meaning that scouring plants and exports were put on hold. Wool prices fell (Figure 4), not only for the UK but also its comparative market in New Zealand, halving the auction price by 50% [22]. This drastic decrease in market value led to the creation of one of the most challenging times in wool history.

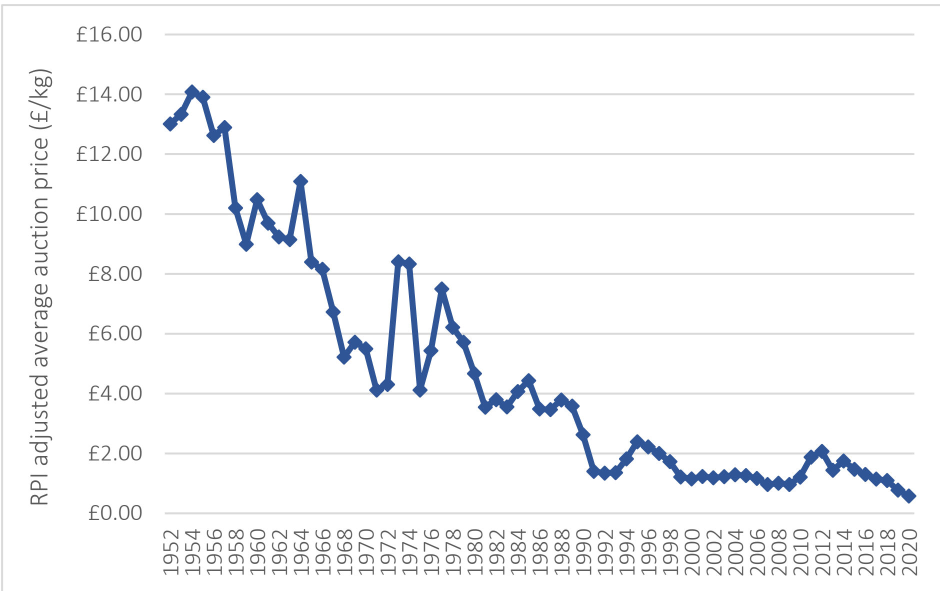

Figure 4. Long-term trends for cross-bred wool prices from 1952 to 2020. Source: British Wool [22].

The long-term trend for the price of wool in the UK has been declining for many years (Figure 4). In the 1950s, inflation-adjusted wool averaged at £12 per kg, with today's price averaging at 75p per kg. This reduction in sell-on value means that farmers are paying more than they are remunerated for shearing and the cost of transporting the fleeces to the wool depot. However, shearing sheep is a necessity for the animal's welfare, and thus must continue—making use of this bi-product is essential to improve the sustainability of the sheep industry. Coupled with the drive to reduce microplastics in our environment, wool is gaining the interest of innovators and engineers as a sustainable replacement for plastics [22].

In the late 1940s, the government and the National Farmers' Union wanted to ensure there was a secure supply for wool, efficient marketing and consumer protection. Therefore, in 1950, under the 1947 Agricultural Act, the British Wool Marketing Scheme was created to enable a guaranteed price for wool to farmers. The Agricultural Marketing Act required the scheme to be run by producers but was underwritten by the Treasury, (milk, eggs, and potatoes had similar schemes [24]). There has been a steady decline in demand over this time period; for example, Bowman [25] describes a declining demand for wool in the UK, going from 480 million lbs in the 1950s to 380 million lbs in 1970. Two significant reasons were presented for this: the growing competition of man-made (cheaper/mass-produced) fibres and the success of new and expanding markets in Hong Kong, Japan and Italy. The UK wool market was fighting on two fronts, both domestically (from these man-made fibres) and from cheaper imports. Exports of top (wool that has been scoured and combed) fell by half in the 1960s and imports of woven wool fabric doubled [25]. The guaranteed price was revoked in 1993. This potentially created a false price for wool, meaning that our domestic wool textile industry could not compete with cheaper imports, and exacerbating the problems we are experiencing at present. Only mills with traditional skills and knowledge, employed in the production of high-end products, such as apparel, could maintain an advantage [25]. While wool was expensive compared to man-made fibres, it was overlooked until the urgency and demand for more natural fibres was realised.

Ropes can be made out of any flexible fibre; drawings have shown ropes made from leather from circa 1450 BC [26]. Based on requirements, availability and economics, soft vegetables such as hemp were historically widely used [27]. The Industrial revolution led to steel wires being incorporated, which were then superseded by nylon, a synthesised polymer from the oil industry, in the 1950s. [27]. Until recently, wool was of too high a value to be considered as an alternative to synthetic rope, as shown in Figure 4. The drive for natural-fibre rope production has led to an increased interest in fibres such as wool and hemp. However, there is no commercial (hemp) flax-processing industry left within the UK; this leaves only wool, which still has a natural-fibre commercial supply chain and the potential to reduce the amount of plastic in the environment. Wool can be manufactured as rope, but is this a viable innovation? The overall objective of this review is to assess the current knowledge related to wool, wool degradation and its potential use within an aquatic environment and the seaweed industry.

2. Materials and Methods

2.1. Approach

A systematic literature review was carried out, which identified, selected and critically appraised research covering wool, rope, natural and man-made fibres, and the seaweed farming industry. A bibliometric and content analysis of peer-reviewed papers was conducted, with no timeframe requirements. This research was carried out following the ten-step systematic review process by Boland, Cherry and Dickson [28], to obtain a comprehension of the economic viability of utilising wool rope in seaweed aquaculture.

2.2. Search Strategy and Selection of Literature

By implementing a scoping strategy [28], keywords and phrases were identified, including Boolean operators, which could yield the most extensive result (Table 1).

Table 1. Keywords and search terms.

Keywords and Search Terms
Systematic review of wool
Systematic review of the environmental impact of sustainable fibres
Wool
Wool rope
Wool rope characteristics
Wool rope properties
Wool marine environment
Wool AND degradation
Natural AND degradation AND wool
Wool AND degradation AND Sea water
Environmental impact of sustainable fibres
Sustainable fibres for rope
Availability wool rope
Availability of production of wool rope
Supply chain wool rope
Viable alternatives for polypropylene rope
Environmental AND impact AND sustainable AND rope
Man-made vs natural fibre
Seaweed rope
Seaweed farming rope requirements
Marine AND industry AND rope
Sustainable rope in seaweed production
Sustainable rope in seaweed farming
Wool AND Rope AND seaweed
Financial margins for seaweed production in the UK

Two bibliographic databases were searched: Google Scholar (https://scholar.google.co.uk/ last accessed 14 March 2022) and the Web of Science (https://www.webofscience.com/wos/woscc/basic-search last accessed 14 March 2022). All references were recorded within EndNote. They were then screened according to title and abstract against the inclusion and exclusion criteria (Table 2), and any duplicate records were removed. Publications that referred to the inclusion criteria were retained (Table 2—see “include” column). Research into wool was historically served by grey material produced by organisations such as ‘The Wool Education Society’ [29] and companies such as ‘Ciba-Geigy’ [30]. Ciba-Geigy’s Review last edition was in 1975, which focused on dye and chemical applications in the textile industry [30]. There is no comprehensive digital archive for this grey material, and so it was discounted for the purpose of this research, as it could not be systematically evaluated.

Table 2. Inclusion and exclusion criteria for systematic review.

Inclusion and Exclusion Criteria		
Area	**Include**	**Exclude**
1. Locality	No location, UK, Europe and Scandinavia	Southern hemisphere, Outside of Europe
2. Applications	Rope for seaweed farming.	All other applications
3. Fish-farming rope requirements.	Seaweed—its environment and requirements of the rope.	All others
4. Characteristics: Incl. strength, durability, degradation, stretch, buoyancy	Wool rope, polypropylene rope	Aesthetic look, cellulosic fibres, non-protein, re-engineered fibres
5. Application methods of rope in seaweed farming	UK, inshore and outshore	Rest of the world.
6. Economics and accessibility wool	Common breeds to UK	All others including Merino
7. Study design	All	None

Inclusion and exclusion criteria were identified to screen the titles and abstracts. This was followed by a reductive process using abstracts and full papers (Figure 5). Overall, 436 records were screened against the inclusion and exclusion criteria. Those that contained only an abstract, or those where only the abstract was in English, were removed, and three grey material reports were considered but withdrawn due to their relevance. This yielded 40 articles, which were then screened based on their abstract. From these, 27 articles were then reviewed using the full text.

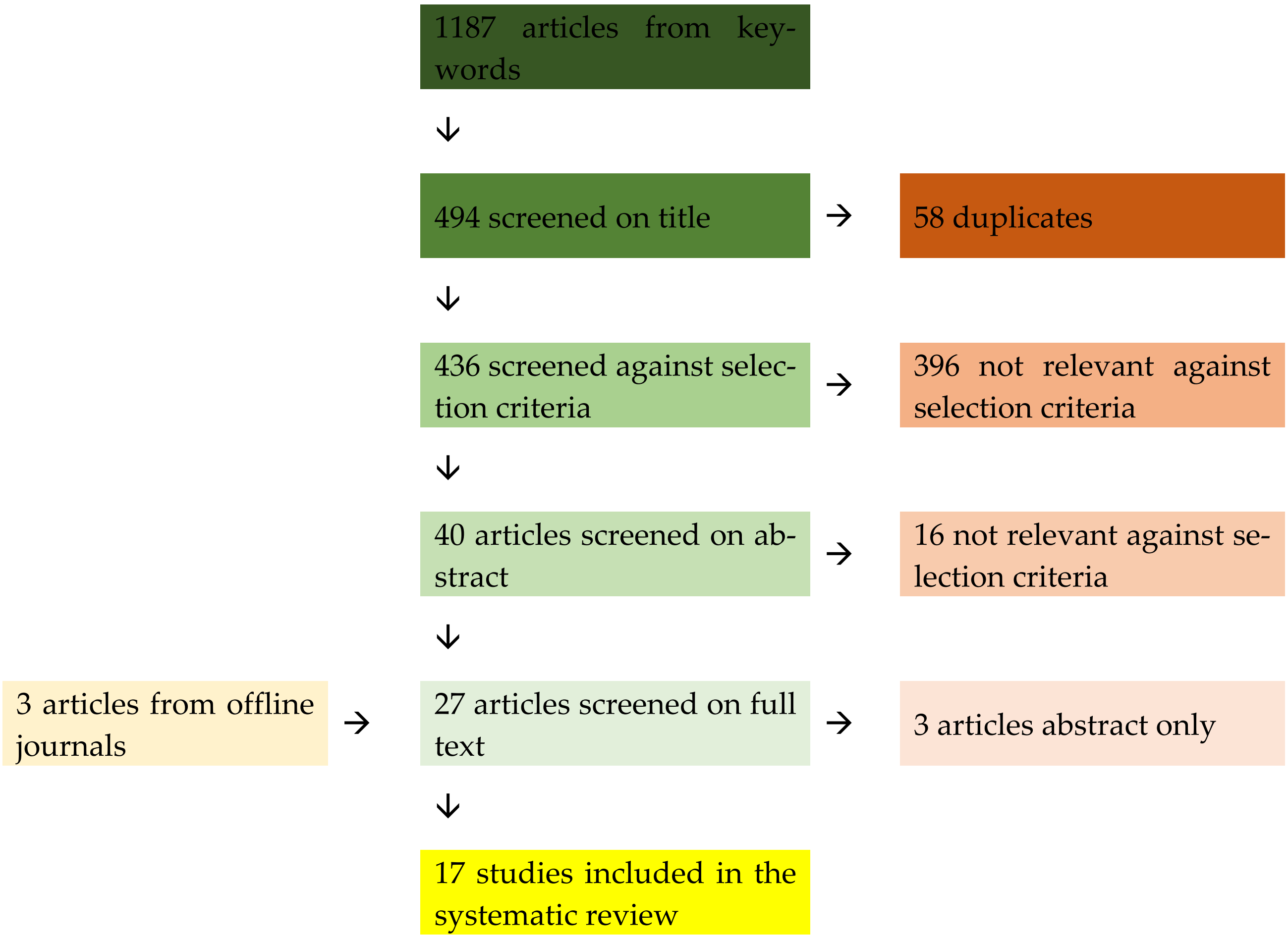

Figure 5. Flow diagram showing search and selection process to select studies for the systematic review.

3. Results

3.1. Findings

Overall, 1187 articles were initially identified from our database search. Following screening (for duplicates, title relevance, selection criteria, abstract and full-text review) Figure 5 shows the reductive process for the discussion on relevant research within this review. Overall, only 17 papers were relevant for this systematic review, ranging from 1946 to 2022 (Table 3).

Table 3. Factors that influence wool rope's viability as an alternative to polypropylene rope in the seaweed industry: systematic review.

	Author	Year	Reference	Title	Journal	Keywords:
1	Broda et al.	2016	[31]	Biodegradation of sheep wool geotextiles.	International Biodeterioration & Biodegradation, 115, 31–38.	Wool rope characteristics and degradation
2	Brown, R.M.	1994	[32]	The microbial degradation of wool in the marine environment.	Thesis—University of Canterbury, New Zealand	Degradation in a marine environment
3	Cassie, A.	1946	[33]	Natural fibres versus man-made fibres. Natural Fibres.	Journal of the Textile Institute Proceedings, 37(12), P556–P561.	Characteristics of natural and man-made fibre
4	Cheng et al.	2010	[34]	Discussion on the Natural Fiber Degradation Index.	Proceedings of the 12th international wool research conference, vols i and ii. 12th International Wool Research Conference (IWRC 2010), Shanghai, PEOPLES R CHINA.	Degradation
5	Chou et al.	2016	[35]	Synthetic lines for marine and other applications: Rope design, selection and best practice.	OCEANS 2016-Shanghai,	Rope characteristics and requirements
6	Collie et al.	2019	[36]	Microfibre pollution–what's the story for wool.	Proceedings of the AUTEX2019–19th World Textile Conference on Textiles at the Crossroads	Wool degradation
7	Collins et al.	2022	[37]	Economic and environmental sustainability analysis of seaweed farming: Monetizing carbon offsets of a brown algae cultivation system in Ireland.	Bioresource Technology, 346, 126637.	Life-cycle assessment and application in seaweed farming
8	Endresen et al.	2019	[38]	Current induced drag forces on cultivated sugar kelp	Proceedings of the ASME 38th International Conference on Ocean Offshore and Arctic Engineering, Univ Strathclyde, Glasgow, Scotland	Rope requirements and application in seaweed farming
9	Grosvenor et al.	2010	[39]	Protein Primary Level Degradation in Wool.	[Proceedings of the 12th international wool research conference, vols i and ii]. 12th International Wool Research Conference (IWRC 2010), Shanghai, PEOPLES R CHINA.	Degradation

Table 3. *Cont.*

	Author	Year	Reference	Title	Journal	Keywords:
10	Kozłowski, R.M. and Mackiewicz-Talarczyk, M.	2020	[40]	Introduction to natural textile fibres.	Handbook of Natural Fibres (pp. 1–13). Elsevier.	UV degradation. Economics and accessibility
11	Napper E. et al.	2022	[9]	Potential microplastic release from the maritime industry: Abrasion of rope.	Science of The Total Environment, 804, Article 150155.	Rope abrasion, age and maintenance
12	Prakash et al.	2019	[41]	Effect of Sea-water environment on the tensile and fatigue properties of synthetic yarn	Proceedings of the ASME International Mechanical Engineering Congress and Exposition	Rope requirements and construction in sea water. Degradation
13	Ryszard et al.	2012	[42]	Future of natural fibers, their coexistence and competition with man-made fibers in 21st century.	Molecular Crystals and Liquid Crystals, 556(1), 200–222.	Characteristics of wool. Economics and accessibility
14	Sebok et al.	2020	[43]	Growth of marine macroalgae Ectocarpus sp on various textile substrates.	Environmental Technology, 12.	Rope design
15	Sørensen et al.	2021	[44]	UV degradation of natural and synthetic microfibers causes fragmentation and release of polymer degradation products and chemical additives.	Science of The Total Environment, 755, 143170.	UV degradation
16	Sun et al.	2013	[45]	Study on biodegradability of wool and PLA fibers in natural soil and aqueous medium.	Advanced Materials Research,	Degradation
17	van Oirschot et al.	2017	[12]	Explorative environmental life cycle assessment for system design of seaweed cultivation and drying.	Algal Research-Biomass Biofuels and Bioproducts,	Rope requirements and application in seaweed farming

3.2. Analysis

The review took an inductive approach, synthesising the results obtained from database searches with the aim of developing a connection between the main concepts (wool, rope and the seaweed industry) to realise the purpose of this review [28]. No other systematic reviews were found to combine these concepts within the literature to date. In total, 17 papers (Table 3) were identified from the 1187 as being relevant to the inclusion and exclusion criteria (Table 2). Those 17 papers were then classified according to the topic covered within the research contribution (Table 4).

Table 4. Review of findings.

Study	Year	Country	Funding
Fibres—Natural and Synthetic			
Cassie, A. [33]	1946	UK	Textile Institute
Cheng et al. [34]	2010	China	International Wool Research
Ryszard et al. [42]	2012	Poland	Ins. Of Natural Fibres & Medical Plants
Wool degradation			
Broda et al. [31]	2016	Poland	University of Bielsko-Biaol, Poland
Grosvenor et al. [39]	2010	China	International Wool Research
Kozłowski et al. [40]	2020	Poland	Ins. Of Natural Fibres & Medical Plants
Sørensen et al. [44]	2021	Norway	SINTEF Ocean AS
Sun et al. [45]	2013	China	Ministry of Education, PRofC
Rope consideration in a marine environment			
Chou et al. [35]	2016	USA	Samson Rope Technologies
Collins et al. [37]	2022	Ireland	University College, Dublin
Endresen et al. [38]	2019	Norway	ASME Int Conf. OMAE
Napper et al. [9]	2022	UK	University of Plymouth
Prakash et al. [41]	2019	USA	ASME Int Mechanical Engineer CE
Sebok et al. [43]	2020	Germany	Uni of Applied Sciences, Bielefeld
van Oirschot et al. [12]	2017	Netherlands	Wageningen University, Netherlands
Wool in the marine environment			
Brown, R.M. [32]	1994	New Zealand	Wool Research of NZ
Collie et al. [36]	2019	New Zealand	Ag Research Ltd., New Zealand

3.3. Review of Findings

The timeframe that the selected research studies cover is extensive (Tables 3 and 4); however, there is a distinct academic research gap between 1946 and the early 2000s (over 50 years). This gap occurs between the 1940s, when wool was a considered a significant fibre (Figure 4), and recent times, when microplastic pollution, rope used in the marine industry and the sustainability of fibres has become important within academic research and the public consciousness. The only paper that was relevant between these two eras was Brown's [32] thesis on wool degradation. Fibre research specific to rope has been sporadic over time. Research on marine rope can be attributed to those nations who have a sea border and has featured quite prominently over the last 5 years. Wool degradation has been a focus for Poland and China, and wool in a marine environment seems to be specific to New Zealand.

4. Synthesis

4.1. Natural Fibres

The debate over man-made fibres versus natural fibres had already started in 1946 (although it was only significant within clothing apparel, with the development of rayon and nylon in the 1930s). However, as Cassie [33] importantly states, you can only assess a fibre's quality and effectiveness when considering the application in which it is to be used. A characteristic of wool that was of particular importance at the time was its thermal conductivity, which was reported to be ten times greater than air [33]. This demonstrated that reducing air and increasing wool fibre increases the thermal conductivity. Despite limited knowledge regarding artificial fibres, as they were so newly developed, artificial fibres were deemed to be closer to cellulose fibres, regarding thermal conductivity compared to protein fibres. Cassie [33] goes on to report that fibre form is important when comparing natural fibres such as wool, with man-made fibres. Wool yarns may appear to be solid, but actually contain many air pockets due to the crimp in the wool, resulting in the fibre lying irregularly (Figure 3), as opposed to man-made fibres, which are packed closer together with more uniformity. Cheng et al. [34] compared natural and synthetic fibres against a degradation index. They concluded that cellulose degraded faster than protein-based natural fibres, and synthetic fibres resulted in an extremely low degradation index and would, therefore, have the potential to be linked with future environmental problems, depending on the requirements and the nature of the fibres used.

Ryszard et al. [42] highlighted new trends in sustainable development by raising awareness of renewable, biodegradable natural materials. The low homogeneity and more heterogeneous composition of natural fibres, as well as present-day issues around their economic viability compared to man-made fibres, hampered production. They believed that coexistence needs to be found. Calls for ecological legislation to effectively resolve the ecological problems that were being reported by the textile authorities in 2012, according to Ryszard et al. [42], would create a competitive edge for natural fibres and be determined by their ability to address such problems. The distinctive characteristics of natural fibres are important and need to be considered based on their deployment or application.

4.2. Wool Degradation

There has been limited research on wool degradation to date, and the research discussed here has mainly been carried out by two nations—Poland and China. Grosvenor et al. [39] assessed the value-loss caused by wool degradation due to protein damage affecting strength and elasticity. However, there is no timescale for the loss of strength and elasticity, which could be significant when considering its application. Sun et al. [45] compared wool and poly-lactic acid (PLA) in both soil and aqueous mediums (AM), measuring their degradation rates, using cotton as a control. Biodegradability tests ISO 14851 and 846 were used, with the conclusion that using fibres within soil was more efficient than AM in terms of biodegradation. The different samples produced different behaviours. Of note was the percentage difference in weight loss (only 8.8% loss in AM compared to an 83.2% loss within soil) for wool. This demonstrated that wool degradation rates for soil do not equate to those within an aqueous medium.

Broda et al. [31] also investigated wool degradation but used a different wool composite. Whilst Sun et al. [45] used carded wool, Broda et al. [31] used wool that was wrapped in woollen non-woven ropes. The rope degraded more slowly; this was thought to be due to the actions of microorganisms that were hampered by the unevenness of the rope surface and the absorption of water. Water absorption also changes the microclimate around the fibres, which Broda et al. [31] believe is less favourable for the growth of microorganisms. However, surface roughness has been found to regularly increase bacterial attachment and provides protection against shear forces [46]. Although the study described the wool as "ropes", they comprised a centre of coarse wool fibres and woollen needle-punched nonwoven sheath. This is significantly different to the braided or laid rope used by the seaweed industry.

4.3. Rope Specification within the Seaweed Industry

For seaweed to grow, they need to have nutrients and to be at a depth that the sun can penetrate. Therefore, the effects of UV are an important consideration for rope longevity and sustainability. Sørensen et al. [44] analyse the effect of accelerated UV degradation on microfibres made of polyester (PET) and polyamide (PA). These are two of the main groups of microplastics found in high proportions in the marine environment. They investigated the effect of UV irradiance on the degradation of natural and synthetic yarns. This is an important consideration, as ghost rope will float on the surface of seawater and be exposed to UV. After 56 days, polyester and wool both exhibited changes in fragmentation and surface morphology, whilst the polyamide showed surface morphology changes but no significant fragmentation. It must be noted that benzoic acid was found in the wool leachates. It was hypothesised that this was due to the wool yarn being coated in a PET polymer (to increase durability), and thus it should not truly be classed as a natural product. Kazlowski et al. [40] believe that for natural fibres to compete with polymeric fibres, they must do so on two fronts, with those being price and technical specification. This must be considered when making comparisons between natural and man-made rope fibres.

Chou et al. [35] concentrate on identifying the key limitations and factors that need to be taken into consideration when selecting a rope for a specific application. Some parameters are general and necessary for all rope, e.g., cost, rope strength, elastic elongation, size and weight. However, some factors are application-specific, e.g., tensile and bending fatigue, abrasion resistance, spooling, surface characteristics and stiffness. Equally important are radius rigidity, spooling performance, coefficient of friction and post-process treatment. Many different types of rope are used in the UK seaweed farming industry and the construction of each rope is inherently different, from braided and laid ropes to jacketed and non-jacketed. Chou et al. [35] believe that there is a misconception equating rope and fibre technology and, ultimately, a balance needs to be found between the application needs and economic viability.

4.4. Environmental Impact of the Seaweed Industry

Van Oirschot et al. [12] report the results of an explorative environmental life-cycle assessment for seaweed cultivation, variations in the seaweed farming system and drying; this is crucial, considering the growing interest and growth in seaweed farming. The greatest environmental impact was found to be from the production of the chromium steel chains, polypropylene rope and drying the harvested seaweed during the production process. Figure 6 shows the infrastructure components (steel chromium chains), giving the highest environmental impact per ton of dried protein, showing that polypropylene rope has the second highest impact.

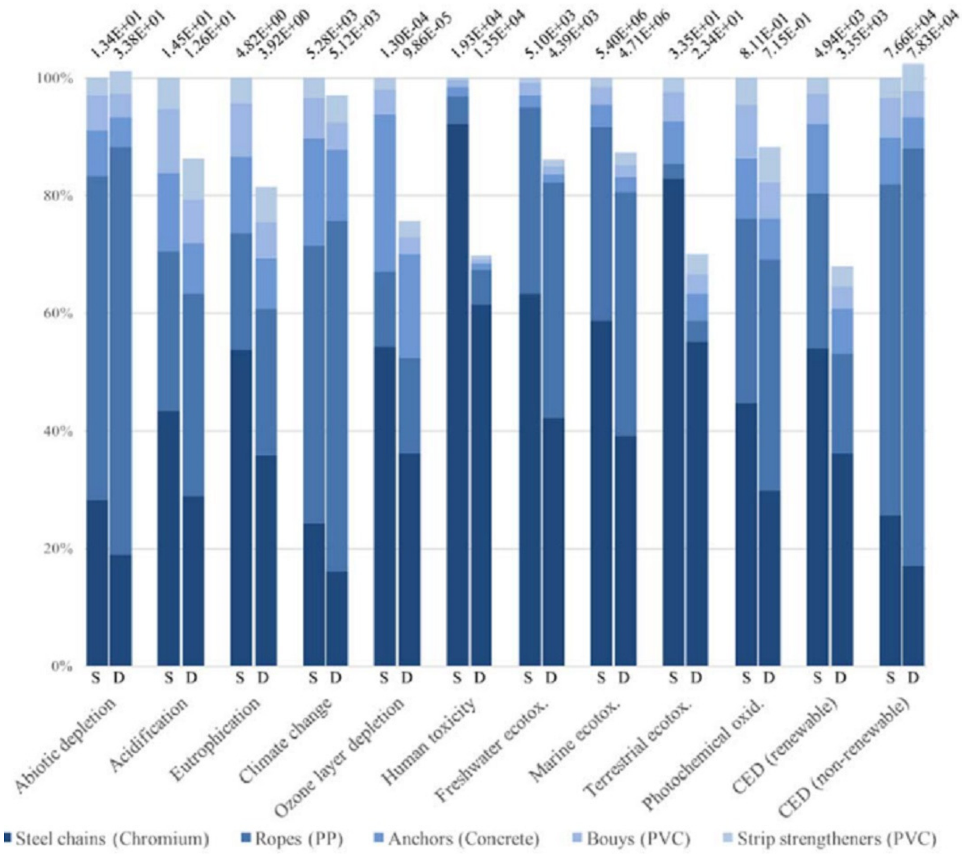

Figure 6. Impacts per ton of dried protein for the cultivation infrastructure components for the single-layer (S) and dual-layer (D) configurations. From van Oirschot et al. [12].

A significant portion of polypropylene ropes' environmental impact is due to crude oil consumption, as this is used within the rope manufacturing process. However, this environmental life-cycle assessment does not consider the degradation of plastics, the so-called plastic soup of the marine environment [12], making this a clear research gap that needs to be addressed for a complete environmental life-cycle assessment of seaweed farming. Prakash et al. [41], consider issues regarding the management of ropes and potential consequences that synthetic rope may have for marine environments. Ropes suffer from static and cyclical mechanical loading when present in corrosive sea water. If management of the rope does not consider tensile strength degradation and fatigue, unexpected and sudden failure could happen. Prakash et al. [41], carried out experiments to identify the effect of the marine environment on yarns, noting that twisted yarns had a better tensile strength and fatigue performance compared to parallel yarns. However, they did not reference the composition of the yarns. Another consideration when assessing rope for the seaweed industry is the deployment style and location. Endresen et al. [38] measure drag forces on sugar kelp, as they grow in vertical lines down from the growing rope. They identified that kelp plants can reconfigure themselves to adapt to the current flow, but that this could become limited. The demands on the rope relative to the location will change as the kelp grows heavier and drag force increases.

With the increased interest in seaweed farming comes innovation; Sebok et al. [43], focused on rope design for the growth of marine macroalgae *Ectocarpus* species and concluded that the best-suited design was knitted fabrics based on an open-pore structure made completely or partly from natural fibres. There were issues regarding floating of lightweight man-made fibres; also rougher surfaces led to greater seaweed adhesion, leading to an increased visible growth of macroalgae on natural woven fabrics. Collins et al. [37], carried out an economic and environmental sustainability analysis of seaweed cultivation in Ireland. They reached a similar conclusion to van Oirschot et al. [12]: that the cultivation equipment with polypropylene rope accounted for the highest share of the impact due to their replacement rate. The seaweed farm would need to have a long-term deployment policy to enhance its environmental sustainability, with average rope replacement rates of every 5 years. However, Collins et al. [37] recommend no management or maintenance of the infrastructure, nor do they discuss the impact from the abrasion of rope and the creation of microfibres, or the consequences of marine plastic pollution.

4.5. Rope Microplastic Pollution

Napper et al. [9] were concerned with microplastic pollution via rope abrasion and quantified microplastics and their characteristics, as they are produced through different rope types and applications. They compared both polypropylene and 'Polysteel' of varying ages and with previous applications, such as mooring, hauling and as a buoy line for nets rendered "at the end of their life" by previous owners. Ropes were either 12 mm or 16 mm in diameter and at varying stages of degradation, from new, one, or two, and up to ten years old. Using electron microscopy imaging, they obtained images of microplastics produced through rope abrasion. Napper et al. [9] concluded that standards need to be implemented for rope maintenance, replacement and recycling, including a focus on rope design, to reduce microplastic creation and thus pollution.

4.6. Wool in the Marine Environment

From this systematic review and selection of research, very little research was found on wool in a marine environment. Two papers were identified, written 25 years apart, which reaffirms that there has been little consideration of the use of wool in this industry. Brown [32] completed his master's thesis on behalf of the Wool Research Organisation of New Zealand, and evaluated 'Woolspill' and its application for the removal of oil from water, as the 'wool knops' were capable of absorbing 40 times their own weight. Brown [32], identified that bacteria played a vital role in the degradation of wool and that wool did degrade in a marine environment; however, no time values were stated. In 2019, Collie et al. [36], again from New Zealand, studied the comparative biodegradation of wool and man-made fibres in seawater. Collie et al. [36] concur with the findings of the systematic review that, despite there being research on the biodegradation of wool on land, there has been little research regarding the use of wool in a marine environment. After 90 days, the wool, which was made up of one apparel product and four interior products, namely, carpet pile, was compared against a polyester fleece, Triexta and polypropylene carpet pile. Collie et al. [36], identified that wool showed substantial biodegradation compared to synthetic fibres. However, it should be noted that Merino wool was used for this research. Merino wool is known for its fineness and low micron numbers. Merino wool has a smaller diameter fibre than the most common wools found in the northern hemisphere due to the different climates and breeds. Further research would have to be carried out to see if the results found in this study are similar to a UK grade of wool.

4.7. Rope Innovation within the Seaweed Industry

Significant factors are involved when considering fibre for rope-making and deployment in the sea for seaweed farming and, to be effective, its application needs to be considered. Factors include access to commercially made rope, its composition and providence, the location of the seaweed farm and the design and deployment of the infrastructure, growing periods and conditions of the water, in terms of both nutrient load and tidal energy. As seaweed farming is a young industry in Northern Europe, there appears to be no industry standard or consistency between seaweed farms. We still do not fully understand the requirements and supply chain for rope within the seaweed industry. However, to drive change and reduce polypropylene rope use and overall plastic pollution within the marine environment, many factors need to be considered: the ability to operate at scale, efficiently and cost-effectively, whilst addressing the environmental impact of ropes in life-cycle assessments is critical.

5. Conclusions

This systematic review shows that, although some research has been conducted within the wool and seaweed industries, this paper is the first to combine the two topics. The seaweed industry has the opportunity to provide answers to some of our pressing ecological problems, such as carbon capture, competition for land and the need for a fast-growing protein that requires fewer planetary resources to grow than animal protein and can be a source of all amino acids [47]. However, the problem of pollution from rope used in the marine industry needs to be addressed. A total of 10% of all marine litter is reported to have come from ghost gear, rope that has been abandoned, lost or discarded. Coupled with the creation of micro-plastics through rope abrasion and the creation of plasticrusts, there is an argument that these issues need to be addressed before the expansion of this emerging market in the UK and Northern Europe. Due to the rapidity of growth within the seaweed industry and the dual potential for both environmental benefits and costs (Figure 2), careful monitoring is needed to protect the environment during set-up. In addition, governments need to advocate for the environment by using incentives (for example, only using natural rope fibres within seaweed farms) to maximise the sustainability of the seaweed industry.

As we have seen from the wool market, wool has been overlooked in terms of its application as a sustainable alternative to man-made fibres. Wool has moved from a period in which it was of high value (through market support and limited competition) to become overlooked in the last 40 years. There is a growing interest in revisiting natural fibres, especially if they can provide solutions to present-day ecological problems. Significant factors are at play when considering the use of a fibre for rope-making and deployment in the sea for seaweed-farming. To ensure that it is effective, all aspects of the application of the rope need to be considered. As discussed by Kazlowski et al. [40], for natural fibres to compete with man-made fibres, they need to be competitive in terms of price and technical specification. However, this relies on an understanding of the needs of the industry—does wool rope need to be as strong as man-made rope for implementation in seaweed farming? If seaweed is going to be harvested for biofuel, could the wool rope become part of the harvest, thus reducing the issue of degradation? Factors that are currently being considered include access to commercially made rope, its composition, the materials used, the location of the seaweed farm, the farm design, deployment of the infrastructure, growing periods and water conditions, both nutritionally and in terms of the tidal currents. It is only by understanding these factors and how they affect each other that a conclusion can be reached as to whether wool can provide a viable alternative to polypropylene rope. There is a distinct academic research gap between 1946 and the early 2000s (over 50 years). In the 1940s wool was a considered a significant fibre and, can be again, with the prominence of microplastic pollution, rope's use in the marine industry and the sustainability of fibres has become important within academic research and the public consciousness.

Seaweed farmers are looking for innovation in the sector; using the manufacture of wool rope can provide an opportunity to lower the levels of plastic in the ropes they deploy. Smaller farms need the consumer to support more sustainable farming through their selection and the price they are prepared to pay. Seaweed farming in the UK is set to grow, and environmental and sustainable standards can be insisted upon by investors. Through a combination of these factors, seaweed farming can truly become a solution to the ecological problems being evidenced. Plastic pollution mitigation can be improved by switching to more environmentally benign products. Wool rope has the potential to substantially reduce plastic rope use and pollution within the seaweed industry and all sectors. However, further research is required to assess the viability and longevity of the rope and whether it can be commercially produced and become part of the supply chain.

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