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Reducing the Environmental Impacts of Garments through Industrially Scalable Closed-Loop Recycling: Life Cycle Assessment of a Recycled Wool Blend Sweater

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Abstract: Wool recycling has been practiced commercially for more than 200 years. This study used data from established, commercial processes with the aim of determining the environmental impacts of a recycled wool blend garment and the contribution of recycling to reducing impacts on the market for wool sweaters, in comparison to other emission reduction approaches relating to garment use. A cradle-to-grave life cycle assessment showed impacts of 0.05 kg CO_2-e, 0.63 MJ, 0.58 L H_2O-e and 0.95 L per wear of a recycled wool blend sweater for climate change, fossil energy demand, water stress and freshwater consumption, respectively. Impacts predominantly arose from garment manufacturing and consumer practices (retail and garment care). When a recycled wool blend sweater was maintained with best practice garment use and care, impacts were reduced by 66–90% relative to standard maintenance of a virgin pure wool sweater. Increasing the closed-loop recycling rate to 50% had the potential to reduce impacts for the wool sweater market 7–24%, depending on the impact category. Brands and consumers hold the key to increasing recycling rates and reducing environmental impacts via increased donation of garments for recycling and increased adoption of garments containing recycled wool.

Keywords: wool; recycling; LCA; closed-loop; energy; footprint

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1. Introduction

Circularity has been proposed as a major solution to the environmental impacts of consumerism [1]. The textiles sector has been criticised for increasing demand for garments, and consequently raw materials [2,3], leading to the exploration of circularity and recycling as means to reduce environmental impacts [4,5]. While this thought is primarily conceptual, as such recycling practices are seldom practiced [6], wool is an exception. For over two hundred years, the textile industry has used old wool garments, historically referred to as 'rags', as a raw material to manufacture new garments. Industrial-scale mechanical recycling of such post-consumer wool garments traces its roots back to 1813 and the beginning of the 'shoddy' industry in West Yorkshire, UK [7].

Fundamentally, the process of recycling provides a source of low-cost wool fibre for manufacturing new garments and other industrial products. In practice, the recycling and reuse of wool textiles relies on consumers donating old garments via recycling collection routes such as clothing banks, doorstep collections or return bins in stores, instead of disposing of them via municipal waste collection. After donation, if garments are not suitable to be sold for reuse, they are sorted into various recycling grades before mechanical pulling enables a loose fibrous material to be produced that is suitable for making new textiles [8]. In this process, recycled wool fibre is blended with virgin wool or other fibres (to aid processing efficiency and to meet the required performance specifications of the final product) and spun into yarn, before being woven or knitted into new fabrics suitable for clothing production [9]. Traditionally, clothing such as overcoats, military uniforms and jackets have been made in this way, and more recently an array of consumer garments including sweaters have also been made from recycled fibre [10]. Alternatively, in what has become the largest market for used wool, the recycling of wool fibre bypasses the traditional spinning, knitting and weaving processes and is used to make a variety of nonwoven fabrics for industrial products such as internal mattress components and automotive insulation because of the acoustic and flame resistant properties of the fibre [7]. In both the former (closed-loop) and latter (open-loop) recycling systems, used wool garments are diverted from end-of-life disposal (i.e., landfill or incineration) into new commercial products with service lives often extending to many years. Where these loops produce recyclate of lesser or greater quality and functionality than the original material, the recycling process may be referred to as downcycling or upcycling, respectively [11,12]. The latter is not applicable in the context of wool fibres, where minimizing downcycling and maximizing closed-loop recycling is partly dependent on maximizing fibre length during the mechanical recycling process [7].

Globally, as part of a shift towards circular economies, there is renewed interest in closing the loop for textiles [13], and significant scope exists to increase recycling rates for old wool garments and the utilisation of these well-established technologies and systems. Adopting attributes of a circular economy has been widely proposed as a solution to high environmental impacts from raw material and manufacturing [6,14]. To evaluate the impact and potential of this approach, a systematic approach such as life cycle assessment (LCA) is required. Recycling, at least in the context of natural fibres, is more appropriately considered as an adjunct to so-called 'virgin fibre' supply chains, as recycling is finite and relies on the ongoing supply of virgin fibre. Thus, recycling can complement the supply system by extending the services that can be supplied from a given volume of virgin fibre.

LCA is the most widely used tool for reporting the environmental impacts and resource use of products, and ideally should report on all major environmental impact and resource use categories affected by a product across the full supply chain. Recently, a detailed cradle-to-grave LCA study was completed for wool supply chains used to manufacture a Merino wool sweater [15] and the best practice use and care of such a garment was examined [16], though neither study considered recycling. The present study expands upon this research by conducting an LCA to evaluate the cradle-to-grave environmental impacts of a recycled wool blend sweater, investigating the contribution of this practice to reducing environmental impacts in the wool sweater market.

2. Materials and Methods

2.1. Goal and Scope

The study specifically aimed to (i) determine impacts and hotspots of a recycled wool blend sweater, (ii) identify the extent to which best practice garment use and care could reduce these impacts, (iii) compare the impacts of a recycled wool blend sweater to those of a virgin pure wool sweater, and (iv) quantify the effect of recycling on the impact of an average wool sweater in the market. An attributional (aLCA) approach was applied, consistent with ISO 14044 [17], ISO 14046 [18], and the wool LCA guidelines developed by the IWTO [19].

Impact assessment methods are described elsewhere [15]. Briefly, the impact assessment included greenhouse gas (GHG) emissions (in CO_2-e units using 100-year global warming potentials [20]) and water stress (water stress index) [21], and aggregated inventory results for fossil fuel energy use (in megajoules, using lower heating values) and freshwater consumption (in litres). Modelling was done using SimaPro 9.3 [22].

The functional unit was one garment over its lifetime, with impacts reported per wear event in Europe. Merino wool is used to make a large variety of garments, and knitted sweaters are a major product category. In the present work, a knitted wool sweater made from recycled wool fibre blended with polyester and weighing 300 g was selected as a specific example. Other recycled wool blends are possible; for example, virgin/recycled wool blends are commercially produced, although these are more likely to be used in woven rather than knitted fabrics (e.g., suiting cloths), and recycled wool may be blended with synthetic fibres other than polyester. The manufacturing phase of the supply chain included the fibre recovery, blending and treatment processes of two wool recycling companies. The system boundary was cradle-to-grave (Figure 1). The virgin wool supply chain (originating in the tablelands of New South Wales and south-western Western Australia) and inventory data were as described previously [15].

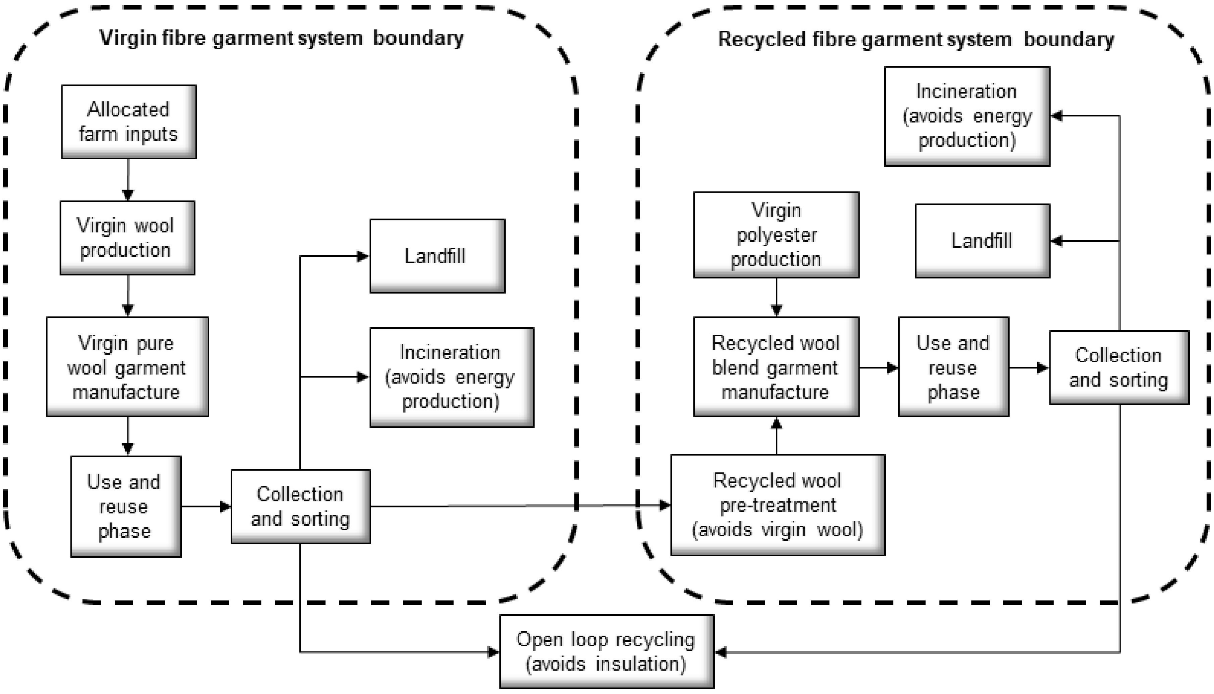

Figure 1. Processes within the system boundary of the life cycle of virgin pure wool and recycled wool blend garments, showing linkages between the life cycles.

2.2. Inventory Data

The inventory data for a recycled wool blend sweater began with the collection, sorting and transport of donated wool garments to recycling locations. Processing data for the mechanical recycling of wool sweaters were collected from a survey of industrial closed-loop recycled wool processors located in Italy and India, providing inventory for pre-treatment (Table 1), overdyeing (Table 2), spinning (Table 3), knitting (Table 4) and finishing (mechanical and chemical treatment of the fabric) (Table 5). Of the recycled wool fibre content, 17.5% was required to go through an over-dyeing process; the remaining 82.5% did not require dyeing. When spinning new yarn, the recycled wool processors used a blend (by weight) of 89.5% recycled wool and 10.5% polyester terephthalate (PET) fibres. For the PET fibre production, a global market process from the ecoinvent v3.6 database [23] was modified to include Chinese electricity and water consumption, reflective of China being the largest producer of PET globally.

Table 1. Pre-treatment process inventory (including shredding and frying) per tonne of pre-treated fibre from recycled wool.

Category	Material/Process	Unit	Value
Input	Wool rags	kg	1068.4
	Electricity, high voltage	kWh	1372.6
	Water	L	44.3
	HDPE, laminated	kg	2.3
	Steel wire	kg	0.9
	PET strap	kg	0.5
	Alkyl benzoate	kg	0.5
	Freight transport, lorry	tkm	987
	Freight transport, ship	tkm	6310
Output	Wool fibre	kg	1000.0
	Water, to wastewater treatment	L	44.3
	Short wool fibres, to municipal waste	kg	68.4

Table 2. Over-dyeing inventory process per tonne of over-dyed wool fibre from recycled wool.

Category	Material/Process	Unit	Value
Input	Wool fibre	kg	1005.1
	Electricity, high voltage	kWh	420.7
	Coal	kg	252.5
	Water	L	4970.6
	Water, steam	L	141.4
	Dyes	kg	13.6
	Acetic acid	kg	8.1
	Sodium chloride	kg	3.6
	Sodium sulphate	kg	7.4
	Formic acid (75%)	kg	3.7
	Ethoxylate amine	kg	3.7
	Packaging, undefined	kg	0.4
	Freight transport	tkm	31
Output	Over-dyed wool fibre	kg	1000.0
	Water, to wastewater treatment	L	4526.1
	Water, emissions to air	L	444.5
	Short wool fibres, to municipal waste	kg	5.1

Table 3. Yarn spinning process inventory (including carding, blending, spinning and spooling) per tonne of spun yarn from a recycled wool blend.

Category	Material/Process	Unit	Value
Input	Over-dyed wool fibre	kg	186.2
	Pre-dyed wool fibre	kg	875.6
	Over-dyed polyester	kg	124.4
	Electricity, high voltage	kWh	2447.0
	Electricity, self-generated solar	kWh	6.6
	Lubricating/antistatic oil	kg	166.1
	Water	L	512.6
	Water, steam	kg	430.5
	Cardboard cone	kg	40.2
	HDPE, film	kg	10.9
	Freight transport	tkm	27.1
Output	Spun yarn	kg	1000.0
	Water, emissions to air	L	512.6
	Wool fibre, to recovery	kg	111.3
	Short wool fibres, to municipal waste	kg	74.9

Table 4. Knitting process inventory per tonne of spun yarn from a recycled wool blend.

Category	Material/Process	Unit	Value
Input	Spun yarn	kg	1011.6
	Electricity, high voltage	kWh	3495.0
	Diesel	kg	6.6
	Petrol, unleaded	kg	6.9
Output	Woven fabric	kg	1000.0
	Wool fibre, to recovery	kg	6.5
	Short wool fibres, to municipal waste	kg	5.1

Table 5. Finishing process inventory (mechanical and chemical) per tonne of finished wool blend fabric.

Category	Material/Process	Unit	Value
Input	Woven fabric	kg	1035.7
	Electricity, high voltage	kWh	990.3
	Coal	kg	171.7
	Water	L	3092.6
	Water, steam	kg	56.0
	Washing detergent	kg	10.8
	Milling agent	kg	8.0
	Softener	kg	5.4
	Acetic acid	kg	1.9
	Ethoxylated alcohol	kg	8.3
	Silicone	kg	11.1
Output	Wool fabric	kg	1000.0
	Water, to wastewater treatment plant	L	3036.6
	Water, emissions to air	kg	56.0
	Short wool fibres, to municipal waste	kg	35.7

A pre-existing inventory [15] was used to model knitting (fabric manufacture), garment make-up, warehousing and use phase of the recycled garment, as these stages were considered to be equivalent to that of a virgin pure wool sweater. The freight distance to the point of retail was adjusted to reflect manufacturing steps taking place in India and Italy.

Impacts were modelled according to the PEF (European Union Product Environmental Footprint) circular footprint formula (CFF) and its associated application rules [24]:

$$\begin{aligned} P_i = (1-R_1)E_{\mathrm{v}} + R_1\left(AE_{recycled} + (1-A)E_{\mathrm{v}}.Q_{\mathrm{in}}\right) + (1-A)R_2\left(E_{recyclingEoL} - E_v^*.\ Q_{\mathrm{out}}\right) + \\ R_3(E_{ER} - \text{avoided heat and electricity}) + \\ (1-R_2-R_3)E_{\mathrm{D}}, \end{aligned} \tag{1}$$

where:

P_i = full life cycle impacts for indicator i, $E_{recycled}$ = emissions and resources associated with the recycling process (described above), and all other terms are described in the following paragraphs.

This approach required estimates of recycling rates at the start (R_1) and end (R_2) of the product life cycle as well as identification of avoided impacts (E_v^*). The first two terms of the CFF relate to the impacts of virgin and recycled inputs, respectively. Wool is over-represented in clothing donations [7] and in closed-loop mechanical recycling. Approximately 22,000 t. p.a. of wool rags are recycled in Prato, Italy [25]. If annual wool use in apparel is 460,000 t [26], then approximately 4.8% of wool is close-loop recycled annually in Prato; the global market rate would be higher considering the other regions which recycle wool. To reflect these considerations, a closed-loop recycling rate (R_1) of 5% on a garment mass basis was used as a conservative standard, and a sensitivity analysis was used to assess the effect of setting this value at 0.5, 10 or 50%.

The third term of the CFF relates to recycling of the product at hand. The rate of open-loop recycling at home (i.e., what would have been a specific R_2 value) was set to 0%, as wool garments are not normally used as cleaning rags and alternative home uses (e.g., stuffing, textile or fibre recovery) were considered immaterial. A recent grey literature source suggests the combined open- and closed-loop recycling of clothing, home textiles and footwear could be as high as 23.4% [27]. Taking a conservative approach, we estimated the open-loop recycling rate R_2 to be 10%, and assumed that this process avoided the primary production of mineral wool (fibrous inorganic material) used as insulation, in line with [28].

The final terms of the CFF relate to the impacts of incineration and landfill. To remain conservative, a 55:45 landfill:incineration ratio [Annex C of [24]] was applied to garments not recycled. Energy recovery from incineration (R_3) was modelled using an efficiency of 30%, textile energy content of 24 MJ kg^{-1}, heat:electricity production of 38:62, process input of 19.32 J kg^{-1} mass (E_{ER}), released biogenic 0.5 kg CO_2 kg^{-1} mass, and avoided the production of European low voltage electricity and central heat or small-scale natural gas [23]. Landfill (E_D) was modelled as municipal solid waste [23]. Impacts associated with the collection and sorting of textile waste ($E_{recyclingEoL}$) were allocated to the end of life processes on a mass basis.

Burdens were allocated between the source and destination of recycled materials using an A factor of 0.8 [24]. The quality ratios (Q, where subscripts 'in' and 'out' refer to incoming and outgoing recycled materials) for recycled wool and insulation were set at 0.895 (reflecting blending with PET described above) and 1.0, respectively [28]. The quality ratios are used in the circular footprint formula to modify the allocation of impacts between the source and destination of recycled materials. $Q < 1.0$ is consistent with downcycling.

2.3. Scenario Analyses

A scenario analysis was conducted in which cumulative best practice consumer behaviour was modelled [scenario S6B of [16]]. Briefly, this included best practice washing frequency (14 wears per wash), washing load (2.1 kg), washing machine efficiency (0.1 kWh/kg, 43 L per load), drying regimes (50% outdoors and 50% in unheated rooms), and 200 wears by the first user (and no reuse). The most important parameter change was the number of wears, which under the standard scenario was 109 wears across first and second users. However, the number of wears by the first user under the best practice use and care scenario were half those modelled previously [16] in order to reflect the limited information available on consumer behaviours pertaining to garments made of recycled fibres. The garment end of life fates were consistent with those described above for a recycled wool blend sweater.

For the purpose of comparison, the modelling choices described above, both with and without best practice use and care, were replicated on a virgin pure wool sweater.

To assess the sensitivity of impacts to the PEF circular footprint formula and its associated allocation rules, the life cycle of the recycled wool blend and virgin pure wool garments with and without best practice use and care were modelled using a simple cut-off approach. This approach assigned no impacts to R_2 pathways of open-loop recycling at home, recycling materials for insulation, or energy recovery. End of life impacts were included for the collection and sorting of textile waste, as well as for landfill.

Within the system boundary, there is a link between sweaters made of virgin and recycled wool fibres via closed-loop recycling (Figure 1) because recycling relies on an ongoing supply of virgin wool fibre. Comparing virgin fibre with recycled wool without taking this into account would overstate the potential for recycling to reduce impacts. More realistically, a reduction in environmental impacts resulting from closed-loop recycling will the reduce the impact of all wool sweaters in the market containing both virgin and recycled fibres. The environmental impact of an average market product (MP_i) was determined as follows:

$$MP_i = \frac{VP_{\frac{i}{FU}} + RP_{\frac{i}{FU}}.R_2}{1 + R_2}, \quad (2)$$

where $VP_{i/FU}$ = impact of the virgin pure wool product per functional unit and $RP_{i/FU}$ = impact of the recycled wool blend product per functional unit.

For simplicity, it was assumed that there was one recycling event, although multiple recycling events are possible. Values tested were R_2 = 0, 0.5, 5, 10 and 50%.

3. Results

3.1. Recycled Wool Blend Sweater Impacts

The environmental impact of a recycled wool blend sweater was 0.05 kg CO_2-e, 0.63 MJ, 0.58 L H_2O-e and 0.95 L per wear for GHG emissions, fossil energy demand, water stress and freshwater consumption, respectively (Figure 2). Manufacturing and the use phase were hotspots across all impact categories. Manufacturing accounted for 54% of GHG emissions, 58% of fossil energy demand, 29% of water stress and 20% of freshwater consumption. The use phase accounted for 43% of GHG emissions, 40% of fossil energy demand, 72% of water stress and 81% of freshwater consumption. The fibre production and end of life phases each accounted for $\leq$4% of full life cycle impacts. The impacts of a recycled wool blend sweater were consistently lower than those of a virgin pure wool sweater (Figure 2). This contrast was driven by much smaller raw material acquisition impacts (especially for climate change, water stress and freshwater consumption) and more moderate reductions in the manufacturing impacts of a recycled wool blend sweater. Manufacturing was the main source of fossil energy demand contrasts between the virgin pure wool and recycled wool blend sweaters.

Most GHG emissions were from energy production during the fibre processing and garment care phases, with smaller contributions from freight, consumer transport, virgin fibre polyester production, water supply, and waste disposal across the value chain. Fossil energy demand was minimised by the reduced energy requirements of processing recycled fibres and the short transport distance from the processors to retail in comparison to the long transport distances for virgin fibre. The water impacts of a recycled wool blend sweater were low primarily in comparison to virgin fibre because on-farm water use was allocated to previous product life cycles and because water consumption during manufacturing was low. In comparison to virgin fibre, scouring and shrink resistance treatments were not required, and not all recycled fibre required over-dyeing.

The results presented here for a virgin pure wool sweater are 3–4% lower than those previously reported [15,16]. The lower impacts are due to the inclusion of avoided products (insulation, clean wool, grid electricity), as per PEF methods.

3.2. Incorporating Best-Practice Garment Use and Care

When the best-practice garment use and care scenario was included, the full life cycle impacts of a recycled wool blend sweater were two to three times lower (55–66%) (Figure 2). Under this scenario, the environmental impact of a recycled wool blend sweater was 0.02 kg CO_2-e, 0.28 MJ, 0.21 L H_2O-e and 0.32 L per wear for GHG emissions, fossil energy demand, water stress and freshwater consumption, respectively. The impacts of a recycled wool blend sweater incorporating best-practice garment use and care were 66–90% lower than those of virgin pure wool sweater incorporating standard use and care practices (Figure 2).

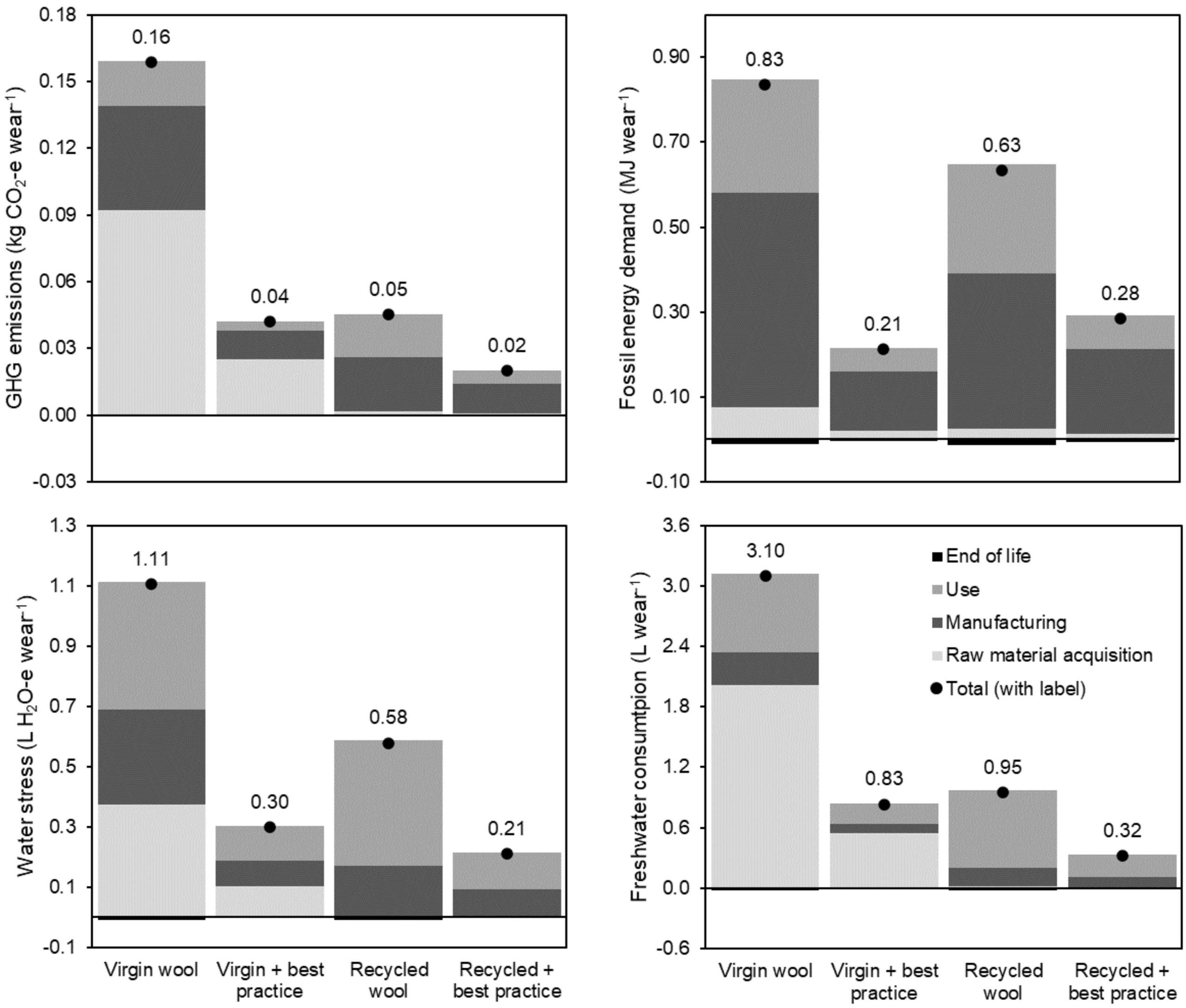

Figure 2. GHG emissions, fossil energy demand, water stress and freshwater consumption impacts per wear of a wool sweater in the European market under different recycling and use phase scenarios; virgin pure wool sweater [13], virgin pure wool sweater combined with best-practice garment use and care [14], recycled wool blend (this research), and the recycled wool blend sweater combined with the aforementioned best-practice garment use and care.

3.3. *Effect of End of Life Allocation Method*

Application of a cut-off rule had a larger effect on the impacts of a recycled wool blend sweater than a virgin pure wool sweater. However, the effects were consistently minor (Table 6). A cut-off rule reduced the impacts of a recycled wool blend sweater by 2–8% and of a virgin pure wool sweater by 3% (data not shown). The reduction in impacts upon applying a cut-off rule were greatest for fossil energy demand and climate change impacts (Table 6).

Table 6. Impact assessment upon application of a cut-off rule relative to impacts determined using the circular footprint formula.

Impact Category	Relative Impact by Treatment (%)			
	Virgin Pure Wool	Virgin Pure Wool + Best Practice Garment Care	Recycled Wool Blend	Recycled Wool Blend + Best Practice Garment Care
Climate change	99	99	94	93
Fossil energy demand	97	97	93	92
Water stress	99	99	98	96
Freshwater consumption	99	99	97	95

3.4. *Effect of Varying the Closed-Loop Recycling Rate*

The effect of setting the closed-loop recycling rate at 0.5, 10 or 50% had a minor effect on the impact of a virgin pure wool or recycled wool blend sweater (±1.5%, results not shown).

3.5. *Impacts of an Average Market Product*

Closed-loop recycling consistently showed a reduction in the impact of an average market sweater relative to a market comprised only of virgin pure wool sweaters (Figure 3). Closed-loop recycling was most effective at reducing the impacts of indicators that dominated the raw material acquisition impacts of a virgin pure wool garment life cycle (Figure 2). That is, closed-loop recycling was most effective at reducing the climate change and freshwater consumption impacts of an average market sweater, least effective at reducing fossil energy demand impacts, and the effect on water stress was intermediate (Figure 3). The effect of increasing the closed-loop recycling rate was parabolic, whereby the marginal reduction in impacts decreased as the closed-loop recycling rate increased. A second closed-loop recycling event (results not shown) increased the effectiveness of closed-loop recycling by increasing the linearity of the relationship between the recycling rate and reduction in impacts (for example, where R_2 = 50%, climate change impacts of an average market sweater were 30% lower than those of a virgin fibre sweater, rather than 24% as in Figure 3; results not shown).

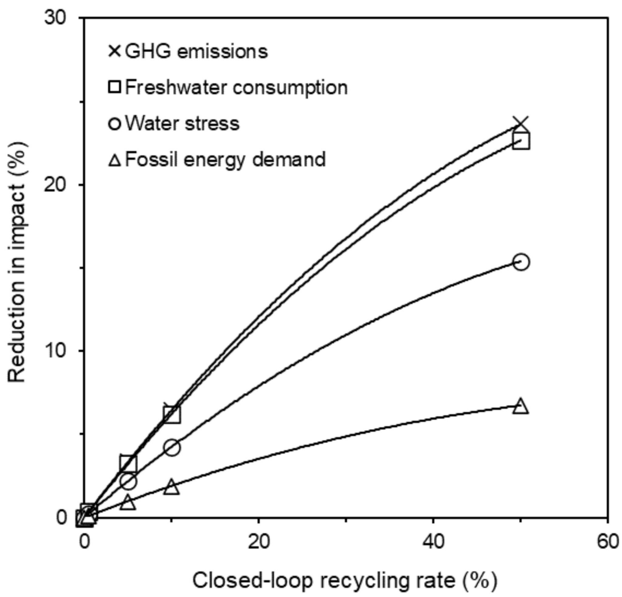

Figure 3. Reduction in GHG emissions, freshwater consumption, water stress and fossil energy demand per wear of an average market wool sweater in the European market relative to impacts of a

market comprised only of virgin pure wool sweater under contrasting closed-loop recycling rates. A parabolic curve (r^2 = 1.0) was fitted to each data series.

4. Discussion

4.1. Increasing the Circularity of Garment Life Cycles Reduces Environmental Impacts

The present work shows that strategies to increase the circularity of garment life cycles by using recycled material inputs and best-practice garment use and care are effective at reducing the environmental impacts of these garments (Figure 2). The GHG emissions and freshwater consumption associated with a recycled wool blend sweater were more than three times lower than the impacts of a virgin pure wool sweater. The comparatively low GHG emissions were largely the result of wool fibre production and the enteric methane emissions associated with sheep production being allocated completely to virgin fibre as opposed to recycled fibre. Similarly, the recycled wool blend garment avoided the large farm stage water impacts of a virgin fibre sweater; the water stress impacts of a recycled wool blend sweater were half those of a virgin pure wool sweater. In contrast, the fossil energy demand of a recycled wool blend sweater was only 25% lower than that of a virgin pure wool sweater. This was because manufacturing was a hotspot for fossil energy demand (~60% of impacts) for both garments. Manufacturing impacts were lower for the recycled wool blend garment because some virgin fibre processes were not required (scouring, shrink-resistance), or required to a lesser degree (over-dyeing). These results are consistent with research showing that the substitution of primary materials with recycled materials is effective at lowering the impacts of garment life cycles across a broad range of indicators [29,30]. Importantly, the results (Figure 3) show that closed-loop recycling can have benefits beyond recycled garments per se by effectively reducing the environmental impact of sweaters made of wool in the market. The greatest reductions are observed for those impacts that contrast between virgin pure wool and recycled wool blend sweaters, which are principally the farm stage impacts referred to above.

Recent research has shown best practice use and care of a wool sweater can reduce impacts by ~75% [16] (Figure 2). The most important aspect of garment use and care was the number of wear events per user, and the number of users of a garment was of secondary importance [15,16]. This is consistent with research that shows processes that avoid the production of virgin fibres, such as extended use and textile reuse, can be particularly effective at reducing environmental impacts [30–35]. In the present research, best practice garment use and care reduced impacts of a recycled wool blend sweater by 55–66%, which is consistent with the earlier findings. We note that, as a general trend, increasing the number of wears per garment lifetime is more effective than recycling at reducing impacts [4]. Thus, the implication of the previous research holds true here. That is, consumers have an important role to play in minimising the environmental footprint of the clothes in their wardrobe by maximising the effective lifetime use of garments prior to disposal. These behaviours can be fostered by garment design and marketing that maximises wears per garment life and low-impact care [16]. Importantly, the present research shows that the reduction in impacts achieved by using recycled fibres can be increased by using best practice garment care as well, as the two processes can be seen as complementary; however, a double-track fashion industry consisting of short-life fashion for recycling and long-life fashion for reuse [5] may capture the environmental benefits of recycling or reuse while failing to capitalise on the environmental benefits of combining both processes.

Increasing garment life and recycling deliver environmental improvements in fundamentally similar ways by increasing the active life of the fibre for its initial purpose. In contrast to extending garment life, recycling is a technical solution that allows the fibre to be manufactured into a brand-new product, which could be a different shape, size or style, potentially increasing its consumer appeal and generating new retail revenue. This comes at the cost of increased manufacturing impacts from transporting, processing and re-manufacturing the garment, though these are less than producing a new garment from virgin fibre (Figure 2). Provided manufacturing standards are high, recycled garments can provide equivalent service to virgin fibre garments. However, blending is typically required, and there are limits to the number of cycles that the same fibre can be mechanically recycled before the fibre length is reduced to the point where closed-loop recycling is unfeasible. Fibre of reduced quality could be redirected to open-loop applications, such as upholstery fillings, mattress padding and automobile insulation [7,36]. As in the present study, the use of recycled wool in these open-loop contexts would avoid the use of virgin materials and their associated environmental impacts.

Unlike emerging or prospective chemical recycling systems, recycling wool requires no new technology development to expand. However, at least two interventions are required to strengthen the market for recycled wool. First, there is a need for improved consumer education with respect to the disposal of garments. While the current rate of closed-loop recycling for wool garments is well below historical levels and potential capacity, it is relatively high for the textiles sector [37], where circularity is conceptually popular but much less frequently practiced. To maximise recycling rates the donation of old garments to charity is preferred, as this pathway promotes lifetime extension by either a second consumer use stage or by directing it into established recycling pathways. Retailers could contribute to circular supply chains via buy-back schemes or donation in-store. Embedding technology such as radio frequency identification or trace markers within wool garments to facilitate ease of sorting could be advantageous in terms of reducing sorting costs as well as connecting supply and demand for textile waste [38]. However, the full life cycle of any such embedded technology should be considered in order to avoid increasing environmental impacts or impairing the recycling process. The second shift needed in consumer perception is around the purchase of recycled garments; poor demand impairs the realisation of economies of scale for established brands, and the availability of recycled materials for start-ups [39]. To date, there has been poor consumer demand for textile products marketed as recycled, in part because they are often perceived as lower quality (see [40] and references therein). There are perceptions that mechanically recycled fibres are not hygienic or clean, particularly for garments destined for recycling rather than reuse, which are not perceptions encountered when fibres are chemically recycled [10]. However, historically, recycled wool fibre has been routinely blended in different proportions with virgin wool, made into high quality garments, and sold successfully by not expressly marketing the composition as 'recycled'. Redirecting recycled wool fibre to closed-loop garment manufacturing would reduce its availability for use in industrial products outside clothing; however, other wool sources such as coarser wools from sheep bred for meat consumption could potentially meet this demand. The impediment to increased demand for garments containing recycled wool therefore appears to be cultural rather than technological.

4.2. Limitations

In the present study, it was assumed that the wool in a knitted wool sweater is manufactured into a second knitted wool sweater. In practice, the second garment is not always of the same basic type as the first. For example, recycled wool from sweaters is used as raw material to make woven rather than knitted fabrics, from which coats, jackets and suiting are made. Commercially, such products retain a relatively high economic value, and the recycling processes involved are similar. Such additional recycling scenarios could not be studied here because the functional unit of each garment is different. In the present study, the same use phase characteristics were assumed for both the virgin pure wool and recycled wool blend sweaters. While this was plausible, it relies on recycled garments being manufactured to a standard that enables use for at least 109 wear events. For this reason, the veracity of the findings would benefit from consumer research into the wear life of garments containing recycled wool to confirm this assumption.

5. Conclusions

Using the example of a current commercially operating textiles recycling system based on wool fibre, it was demonstrated that the full life cycle GHG emissions, fossil energy demand, water scarcity and freshwater consumption impacts of a recycled wool blend sweater were lower than those of a virgin pure wool sweater. The research showed that the benefits of recycling could be combined with best practice garment use and care to further lower impacts. These findings were consistent with previous research that showed extending the number of wears per garment life by the first and subsequent users is highly effective at reducing impacts across diverse indicators. Because the benefits of recycling and best practice garment use and care were additive, this combination of treatments showed impacts much lower than those of a virgin pure wool sweater in a conventional use phase scenario. Promoting and incentivising increased collection of used wool garments would enable an increased supply of wool fibre for recycling and reduced environmental impacts from wool textiles. These opportunities are available with established technology, suggesting that garment designers, brands, and consumers hold the key to increasing recycling rates and reducing environmental impacts by increasing adoption of garment ranges containing a proportion of recycled wool.

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