IDENTIFYING LOW CARBON SOURCES OF

Sheep Wool, Hair, Alpaca Fiber, and Silk Fiber

Fashion for Climate

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Acronyms

AWI	Australian Wool Innovation
CH_4	Methane
CO_2	Carbon dioxide
Eq	Equivalent
dLUC	Direct Land Use Change
EU	European Union
FICCA	Fashion Industry Charter for Climate Action
GHG	Greenhouse gas
GWP	Global Warming Potential
IPCC	Intergovernmental Panel on Climate Change
IWTO	International Wool Trade Organization
ISO	International Organization of Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LU	Land Use
LUC	Land Use Change
m	metres
MJ	Megajoule
MMCF	Man-Made Cellulosic Fiber
N_2O	Nitrous oxide

Executive Summary

This report is developed by the Fashion Industry Charter for Climate Action (FICCA) Raw Material Working Group with the primary goal of identifying low carbon raw materials for wool, hair and silk. This work is carried out through engagement with industry experts, textile, and apparel organizations, and working group members with SCS Global Services (SCS) as the neutral technical lead.

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The report focuses on the initial life cycle stages of raw material sourcing in the textile supply chain. Greenhouse gas hotspots within the investigated processes are identified and recommendations are provided on practices to lower the carbon footprint in sourcing animal-based fibres (wool, hair, and silk). The report does not make comparisons between fibre types (e.g., sheep wool compared to cashmere hair). The Raw Materials Working Group would encourage anyone reading the report to avoid comparing one material to another as the report is intended to provide insight into how to reduce climate impact by a given material, for example by changing method of production, rather than promote use of one material over another.

A more detailed outline of the objectives can be found in the "Introduction" and "Collected Information" sections. The scope of the report covers raw material production starting with the cultivation or extraction of raw materials through to raw material processing and fibre creation. The report (a) analyses data on the climate change impacts of animal-based virgin wool and hair, recycled wool, and silk; (b) assesses the current level of scientific knowledge, data gaps, and methodological issues regarding the climate change impacts of wool, hair, and silk; (c) identifies the main hotspots for each fibre type and suggests potential strategies for addressing these hotspots; and (d) provides recommendations for future study.

The analysis of virgin wool and hair raw material sourcing revealed that: (a) methane from enteric fermentation[1] is the most significant contributor to climate impacts for virgin wool and hair production systems; and (b) the choice of allocation approach has a determining effect on final quantified results for virgin wool and hair. For recycled wool, analysis indicated high variability in impact from raw material sourcing (e.g., sorting, transportation, shredding) depending on: (1) the source of raw material (e.g., pre-consumer, post-consumer); (2) transportation requirements (e.g., country of origin and means of transportation); and (3) energy and material demand for shredding and fibre production. For raw silk, producing the leaves to feed the silkworms was the highest contributor of climate impacts, compared to the subsequent sericulture and reeling processes. Due to the relatively low value of co-products (other than perhaps firewood and unreelable silk), the yields achieved in the leaf production and sericulture stages significantly affect the overall greenhouse gas emissions from raw silk production.

Key gaps in the existing literature were identified. These, together with calls to action, are summarized in the conclusions section. Limited literature exists on life-cycle assessment (LCA) and greenhouse gas assessment of other animal-based fibres, such as cashmere, mohair, alpaca fibres, and tasar silk; by region, for example top-producing countries with respect to each fibre; and production system, for example smallholder and nomadic systems. Approaches to how greenhouse gases are allocated should be consistent with the International Wool Trade Organization guidelines. Methodologies and emission factors used in the calculation of enteric methane should be clearly reported to increase transparency in calculations of climate impact. Further study of recycled wool is needed, with focus on the initial stages of materials sourcing, such as sorting, transportation to processing facility and shredding, based on different scenarios and with disaggregated results. Further study is also essential into silk types and production systems in different regions.

1. Introduction

1.1 Overall perspective

The Raw Materials Working Group of the Fashion Industry Charter for Climate Action (FICCA), convened by UN Climate Change, is developing a roadmap for reducing greenhouse gas (GHG) emissions from raw material extraction, production and processing, which for some companies is the most carbon-intensive part of the fashion value chain. Work on the roadmap began with analyses of cotton, polyester and man-made cellulosic fibre (Phase I) and is progressing to other materials, to allow FICCA signatories to identify actions to reduce their GHG emissions in line with the 1.5°C global target, with the vision to achieve net-zero emissions by 2050.[2] As a practical step along that pathway, signatories to the Charter commit to setting Science Based Targets or adopt a 50% absolute emissions reductions accross scopes by 2030, and achieve net zero by 2050.

Recognizing the interconnected nature of the climate challenge and spurred by increasing evidence of the fashion and textile industry's impact on the environment, several other global sustainability campaigns have been founded and have developed ambitious goals to reduce emissions.

The Textile Exchange's Climate+ strategy, for example, is meant to help the global fashion and textile industry reduce its GHG emissions from fibre and raw material production by 45 per cent by 2030 compared to 2019. Adopting preferred fibres, closing the innovation gap, and enabling a reformed approach to growth can only be accelerated through strong partnerships.

The 2020 Circular Fashion System Commitment, introduced by the Global Fashion Agenda calls on the fashion industry to commit to: (1) implementing design strategies for cyclability; (2) increasing the volume of used garments and footwear collected; (3) increasing the volume of used garments and footwear resold; and (4) increasing the share of garments and footwear made from recycled post-consumer textile fibres.[3]

The Sustainable Clothing Action Plan 2020 Commitment, introduced by the Waste and Resources Action Programme,[4] seeks to facilitate industry-led reductions in carbon, water, and waste in the clothing industry by 15 per cent by: (1) reinventing how clothes are designed and produced; (2) rethinking how we value clothing by extending life of clothes; and redefining what is possible through reuse and recycling.[5]

The Science Based Targets initiative (SBTi) provides a detailed framework for apparel and footwear companies[6] to set their own science-based targets, a validation process for the targets, and a platform[7] for reporting the companies' targets. According to SBTi, targets are considered science-based if they are aligned with the latest climate science and deemed necessary to meet the Paris Agreement's goals to limit global warming well below 2∞C above pre-industrial levels and pursue efforts to limit warming to 1.5∞C. More than 100 apparel and footwear companies, including H&M and Levi Strauss & Co, had successfully set their science-based targets as of November 2021.[8]

The Fashion Industry Charter for Climate Action's roadmap will provide guidance on ways to reduce the GHG impact within a single fibre type and does not attempt to compare fibre types. Comparisons should not be made between regions for sourcing fibres, either. The aim of the fibres studies was to provide information to help guide decisions from among the various fibre options rather than to identify a single preferred or recommended fibre type. The focus of this study is on identifying areas and practices to improve over time on a regional basis for different fibre types rather than on comparing regions for sourcing purposes.

It is important to highlight that this study is focused on cradle-to-gate GHG emissions and does not address other sustainability issues (e.g., eutrophication, acidification, primary energy demand, water use, animal welfare, biodiversity, toxicities). As a result, choices of environmental preferability should not be solely based on cradle-to-gate carbon footprint and should consider other issues, including the full product life cycle (I.e., cradle-to-grave).

The Phase I focus materials, cotton, polyester, and man-made cellulosic fibres (MMCF),[9] made up over 82 per cent of the global fibre market in 2020[10] according to the Textile Exchange's Preferred Fiber & Materials Market Report 2021.[11] Phase II, this study, focuses on animal-based fibres including wool from sheep, alpaca fibres, recycled wool, hair from cashmere, mohair, and silk.

1.2 Animal fibre positions in the fashion and clothing industry

Animal fibres accounted for 1.62 per cent of global fibre production in 2021, up from 1.57 per cent in 2020 and 1.3 per cent in 2019, indicating a slightly upward trend in animal fibre market share over the past few years.[12,13,14] In 2021, sheep wool was the most used animal-based fibre, accounting for 1 per cent of global fibre production.[15] Global wool fibre production has been declining since 1992, with global wool fibre production reaching 1.03 million tonnes in 2021.[16] Despite the general decline, wool market share has been holding steady at around 1 per cent of global fibre production. It is also important to note that the decrease in global wool production in 2020 was led by a 6 per cent reduction in production in Australia due to an ongoing drought, which has since broken.[17]

Global fibre production has almost doubled in the past two decades (58 million tonnes in 2000 to 109 million tonnes in 2020). Despite the slight decrease in overall production in 2020 due to the COVID-19 pandemic, global fibre production is expected to increase long term, by 34 per cent in 2030 (146 million tonnes).[18] The increase is mainly due to increases in the production of polyester and other synthetic fibres. Still, animal-based fibres are expected to hold their share and see increased production in line with growing global fibre production.

1.3 Top regions of animal-based fiber production

1.3.1

Sheep

The annual production of wool sourced from sheep was 1.03 million tonnes in 2020. Sheep wool is the most used animal-based fibre, with an overall market share of about 1 per cent of global fibre production in 2020.[19] The top five wool producing countries are Australia, Argentina, New Zealand, South Africa, the United States of America, and Uruguay.[20]

1.3.2

Alpaca

The annual production of fibres from alpaca, a camelid native to Peru, was around 6,000 tonnes in 2020. Alpacas are mostly in Peru, with a small percentage in other countries, such as Bolivia, Australia, United Kingdom, and the United States of America.[21]

1.3.3

Cashmere

The annual production of hair sourced from cashmere goat was 25,200 tonnes of greasy cashmere in 2020. The top producing cashmere countries are China, with about 60 percent of production, and Mongolia, with about 20 percent.[22]

1.3.4

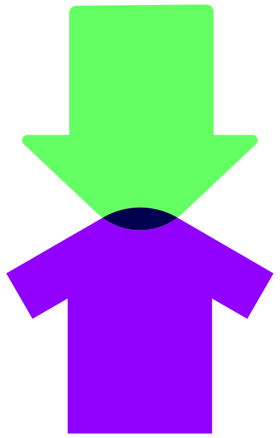
Mohair

The annual production of Mohair, the hair from the Angora goat, was 4,320 tonnes of raw fibre in 2020. The top mohair producing countries are South Africa (50%), Lesotho (17%), Turkey (11%), Argentina (8%), and USA (5%).[23]

1.3.5

Recycled Wool

The annual recycled wool production, sourced from pre-consumer and post-consumer recycled wool, was around 70,000 tonnes in 2020, about 6 per cent of total wool market. The top three production sites for recycled wool are: (1) Prato, Italy (about 22,000 tonnes annually); (2) Panipat, India; and (3) China.[24]



Globally

12%

of the material used for clothing ends up being recycled.

1.4 Countries with the highest production of silk

Raw silk production amounted to about 109,111 tonnes in 2020 (involving about 300,000 households in the production). The three top silk producing countries are China (63%), India (33%) and Uzbekistan (2%).[25]

1.5 Relative greenhouse gas contribution of animal-based fibres

Since 2012, world GHG emissions have amounted to more than 45 billion tonnes of CO_2e annually. The emissions increased from 44.76 Gt CO_2e in 2010 to 48.94 Gt CO_2e in 2018.[26]

In a 2021 study,[27] the United Nations assessed that the apparel and footwear industry as a whole was responsible for more than 8 per cent of annual GHG emissions in 2018.[28] This number can vary, from 3 per cent to 10 per cent of global emissions, depending on the scopes and methodologies applied in making an assessment.[29] Production of raw materials accounts for a significant part of this total: the Word Resource Institute (WRI) has assessed the contribution from raw materials production to be 24 per cent of the apparel industry's cradle-to-finished garments gate emissions in 2019,[30] while a study by McKinsey found that emissions from raw materials production accounted for 38 per cent of emissions (cradle-to-grave) in the apparel and footwear industry in 2018[31] Both studies used bottom-up methods (using data on the quantity of fibres or quantity of garments produced) and Higg MSI data to assess the impact of the life cycle stage. The WRI study focused on the apparel industry only (no footwear) and excluded consumer use (washing and drying of garments), end-of-life, downstream transportation, corporate offices, and buildings. It assumed that 66 per cent of fibre produced in the world is dedicated to the apparel and footwear industry. The McKinsey study assessed both the apparel and footwear industries, and included all cradle-to-grave emissions. The calculations were based on the quantity of all garments produced, used, and disposed of in a given year. Both studies demonstrate the significant share of GHG emissions from the production-of-raw-materials phase: it is the second most impactful life cycle stage, after the material (fabric) production phase, in the WRI study, and the most impactful phase in the McKinsey study.

Emissions from sheep and goats are assessed by the Food and Agriculture Organization of the United Nations (FAO).[32] The GHG emissions from enteric fermentation, manure management and manure left on pastures by sheep and goats in 2011 are shown in Table 1. The emissions described cover all products: meat, milk, and non-edible products including wool or hair. The emissions account for a significant part of the emissions from production of animal-based fibres).

Table 1.

2011 Greenhouse gas emissions related to sheep and goats husbandry. Extracted from the 1990-2011 FAO Analysis.

	SHEEP	GOATS
Enteric Fermentation (million tonnes CO_2e)	145	104
Manure Management (million tonnes CO_2e)	7.2	3.6
Manure Left on Pasture (million tonnes CO_2e)	99	99
Total (million tonnes CO_2e)	251	206

Compared with the total 2011 global GHG emissions,[33] the total emissions from sheep and goat husbandry represent 0.6 per cent and 0.5 per cent of global emissions, respectively.

In FAO's 2013 report on livestock emissions,[34] emissions from sheep and goat husbandry were estimated at 475 million tonnes of CO_2e[35] (6.5 per cent of all livestock emissions), including 299 million tonnes from meat production, 130 million tonnes from milk production and 46 million tonnes from other goods and services including wool (about 0.1 per cent of global emissions in 2011),[36 37]

The animals covered in the FAO report include cattle, swine, chickens, sheep, goats, and buffaloes. An additional category ("other category") includes turkeys, ducks, horses, asses, mules, llamas, and camels. Alpacas are not included. Similarly, GHG emissions from insects, including silkworms, are not included in the FAO report. The climate change impact of alpacas and silkworms are not assessed globally by the FAO.

1.6 Objectives of the study

In this roadmap, raw material production begins with cultivation or extraction of raw materials and proceeds through raw material processing and fibre creation. For virgin animal-based fibres, this includes animal farming, shearing and scouring/top making; for recycled wool, this includes collection, sorting, transportation, and shredding; for silk, this includes leaves production, cocoon production and reeling.

All raw materials have a carbon footprint, and raw materials can have significant environmental impacts. Many of the potential benefits of animal-based fibre products are found post-production, in consumer use or at the products' end of life. These benefits are difficult to quantify and usually subjective. However, estimates of animal-based raw materials' relative contribution to the overall cradle-to-grave impacts of animal-based and silk fibres are reported to be significant.[38 39 40]

To measure the carbon footprint of a raw material, all processes used to grow or manufacture the raw material should be considered. One of the most-used methodologies to measure environmental impacts is Life Cycle Assessment (LCA). Although these studies have produced credible and industry-recognized results, comparing studies poses challenges.

Among the challenges, results calculated using industry averages that are not applicable to specific regions, or use of inconsistent assumptions that limit comparability. LCA practitioners should consider the following factors before determining the comparability of the environmental profiles of multiple products:

- Scope of assessment and function of the products;
- Inclusions and exclusions of processes across the life cycle stages;
- Time period of data collection;
- Modelling assumptions across all the products; and
- Databases and data sources, LCA software, and metrics used for modelling processes.

To manage these challenges, the Raw Materials Working Group engaged SCS Global Services, experts in LCA development and research, and collaborated with industry organizations with pertinent tools and information.

This report summarizes a review of 94 studies: on animal-based fibre and silk, including 30 LCA and carbon footprinting studies; on modelling parameters used to develop LCA data analysis of the main contributors to climate change impacts; and results of the LCA. The report also highlights key findings. With the goal of identifying low-carbon raw materials for the fashion industry, this report:

- Analyses data on the climate change impacts of virgin animal-based fibres, recycled wool and silk;
- Assesses the level of scientific knowledge, data gaps and methodological issues regarding the climate change impacts of these fibres;
- Identifies the main hotspots for each fibre type and potential strategies for improvement; and
- Provides recommendations for future study.

2. Scope

2.1 Goal and Scope of Assessment

The goal of the study was to identify low-carbon sources of animal-based fibres (wool, hair, silk), based on a review of LCA and carbon footprint studies and reports, and to investigate approaches to sourcing animal-based fibres with potential for a lower carbon footprint. Table 2 outlines the scope of assessment for animal-based fibres and silk.

Table 2.

Summary of this report's scope of assessment for wool and silk.

Scope	Wool/Hair	Silk
Raw Material Sub-Type/Sources	Virgin animal-based fibre Sheep wool Alpaca fibres Cashmere goat hair (cashmere) Angora goat hair (Mohair) Recycled Wool	Silk from silkworm rearing
Geographic Regions Under Consideration	Australia, New Zealand, China, Argentina, Peru, Mongolia, India, South Africa, United States of America, Italy	India, China, Italy
System Boundary/Scope	Cradle-to-Gate (up to scouring/top making)	Cradle-to-Gate (up to reeling)
Climate Impact Results Reported	Kilogram CO2-equivalent per kg of wool/hair (greasy, scoured, or top)	Kilogram CO2-equivalent per kg of raw silk

2.2 Background on the different fibres

2.2.1 Virgin wool, fibres and hair

2.2.1.1 Wool from sheep

Sheep (Bovidae, Caprinae) are fleece-producing mammals believed descended from the wild mouflon of ancient Mesopotamia. Their domestication started at least 11,000 years ago, first for their meat and milk, and then wool. Traces of sheep wool being washed, woven and worn date back 10,000 years. Breeding created more than 1,000 sheep breeds. Merino sheep, a prominent breed, were introduced to the Dutch from Spain in the 1700s and expanded widely in proceeding centuries in Australia, South Africa, New Zealand, and South America with expansion of European empires.[41]

Sheep are now found worldwide. Depending on breed and country, they are raised in flocks for their meat, milk and/or fleece. The average weight of sheep varies from 35 kg in South Asia to 80 kg in North America for females, and 45 kg in South Asia to 108 kg in North America for males.[42] Depending on their breed, fleece fibre diameter varies from 9 microns to more than 30 microns, with production starting at 12 microns. Coarser fibres are used for home textiles (e.g., carpets) or insulation, while fine fibres (less than 21 microns) are used in the apparel industry. Finer fibres (17 microns and less) are targeted by high-end apparel manufacturers. Merino and Rambouillet are the main sheep breeds whose fleece is sought after by the luxury fashion industry. Romney or Scottish Blackface sheep produce more coarse fibres, which are used in interior textiles, décor, and carpets. Merino can be crossbred with meat breeds to produce good reproductive ewes and increase meat production while preserving the fineness of the Merino fibres.

In Australia, Merino is the most prevalent sheep breed. The Merino breed is also prevalent in New Zealand, together with the Romney and Corriedale breeds. In Argentina, Corriedale and Criollo are found together with a large Merino presence. In China, wool output is divided between fine, semi-fine and coarse fibres. In South Africa, wool is produced mostly by Merino, followed by dual-purpose Merino breeds (Dohne Merino, South African Mutton Merino and the Letelle).[43]

Sheep are shorn annually in the spring.[44] An average adult animal can produce between 3 kg and 5 kg of raw wool annually, with variation depending on breed, production system and husbandry conditions. In most countries, the sheep production system is extensive, meaning that sheep graze natural pastures, or is mixed, where more than 10 per cent of the dry matter fed to livestock comes from crop byproducts and/or crop stubble.[45] Sheep can subsist on rocky or high-altitude grasslands not suitable for crop cultivation.

Sheep raw wool is also called greasy wool, due to its natural greasy coating. After shearing, fleeces are scoured, or cleaned, to remove grease, dirt and vegetable matter. The wool grease isolated in the scouring process is refined into lanolin, which has value in the pharmaceutical and cosmetic industries. Lanolin represents about 3-4 per cent of the raw wool weight and 8-10 per cent of the clean weight. Depending on the farm, country and supply chain, scouring is done close to the farm or transported or exported for scouring and further processing.

2.2.1.2 Hair from goats

Goats (Bovidae, Caprinae) belong to the same tribe Caprini with sheep. Like sheep, the goat's domestication started about 11,000 years ago in the foothills of the Zagros Mountains in present-day Turkey, Iran and Iraq. Most domestic goats have a hairy outer coat, which lays over a short, fine underwool or "down". The outer hair provides protection, while the fine undercoat provides thermal insulation. This structure, with outer hair and fine undercoat, was inherited from the goat's wild ancestor and has not evolve significantly over time.[46]

Adult goats weigh an average between 29 kg in Sub-Saharan Africa and 64 kg in North America per female, and between 36 kg in Sub-Saharan Africa and 100 kg in Eastern Europe and Russia per male.[47] Cashmere goats weigh 45 kg per doe and 54 kg per buck on average.[48] Angora goats weigh between 30 kg and 50 kg per doe and between 80 kg and 100 kg per buck on average.[49] Goat production systems produce meat, milk and non-edible products including hair. Like sheep, goat production systems are either extensive or mixed systems. Unlike sheep, goats graze on grass but also shrubs.

Goat hair has been woven into textiles since prehistoric times, the outer hair mingled with the underwool or the outer hair used separately. Goat hair is coarse (from 35 to 90 microns), suitable for producing carpets, tents, ropes, sacking and sails. In the 1990s, there was still a small need for goat hair in the United Kingdom, for brushes, suit interlinings and binder manufacturing. The underwool is removed from the hair and the hair is prepared and spun.[50] However, two types of goat fibres, cashmere and mohair, are very different from other goat hair.

Cashmere fibres are the fine and soft underwool of the Cashmere goats, native to the Himalayas.[51] Their fibre diameter ranges from 13 to 18 microns and their length from 4 to 5 cm. Cashmere goats have long curling horns, and their hair colour varies from white to brown and black. Cashmere goats are raised mostly in China and Mongolia.[52,53] The cashmere underwool can be combed directly from the Cashmere goat, which has kept its ancestral ability to molt, or it can be combed from the shorn goat hair. Combing or shearing is done once a year, in spring. The average annual production of cashmere (i.e., underwool) fibre per goat amounts to 120-150 g in Kyrgyzstan[54] and between 185 g and 330 g in China, depending on province.[55] Their fineness and softness make them one of the most high-end natural animal fibres in the fashion industry, used for luxury knitwear.

Mohair fibres come from Angora goats, native to the Ankara region of Turkey. Like Cashmere goats they are mainly white with spiral horns. However, unlike other goats, Angora goats do not have outer hair, only long, lustrous and curly fibres. Their coats are comparable to sheep fleeces, with longer, coarser and denser fibres compared to the underwool of other goats. Angoras do not molt, so must be sheared, typically twice a year when their fibres are about 12 cm long. Each animal produces between 5 and 8 kg of fibre per year.[56] Those fibres are twice the diameter of cashmere. As an Angora goat ages, its fibre diameter increases. Mohair from Angora kids ranges from 23 to 29 microns; from young Angora, 30 to 36 microns; and from older adult Angora, 34 to 40 microns and more.[57] Kemp are short, bristly hairs that can be part of the Angora goat's fibres. Kemp can find their way into Angora fleece through cross breeding and reduce the quality of Mohair fibres.[58]

Angora goats reached South Africa from Turkey in 1838. Sixty years later there were already twice as many Angora goats in South Africa than in Turkey. In the same century, Angora goats also reached the state of Texas in the United States America, another site with high altitude plateaus and little rainfall.[59]

2.2.1.3 Fibres from alpacas

Alpacas are among the smallest animals in the camelid family,[60] which includes camels, llamas, vicunas and guanacos. Ancestors of the alpaca evolved in North America and migrated to South America 3 million years ago. The domestication of vicunas into alpacas[61] started in the Peruvian Andes about 6,000 years ago. Alpacas are still found mostly in South America, mainly in Peru, but have been brought to other countries, such as the United States of America, Australia and the United Kingdom. Most alpaca production systems are extensive: alpacas graze freely on grassland all year with minimal feed supplements. In Peru, more than 90 per cent of the produced alpaca fibres come from small farms comprising fewer than 45 animals.[62,63] Alpaca production systems can produce meat, live weight animals and fibres. Alpacas' average weight ranges from 54 kg to 90 kg.[64]

There are two breeds of alpacas, Huacaya and Suri, both suitable for wool production. Huacaya, comprising 95 per cent of all alpacas, have a compact, dense, soft, spongy and curly fleece. Suris have longer, silky fibres resembling pencil-like locks.[65] The alpaca fibre diameter averages 15 microns with a length of 12 cm to 20 cm.[66]

Alpacas produce between 2 kg and 5 kg of fleece per head annually. They are sheared once a year, yielding fibres in a range of white, beige, shades of fawn, brown, grey and black.[67] Unlike sheep fleece, Alpaca fleece is not naturally coated in grease. As a result, no lanolin is produced as a co-product of the scouring process, and alpaca wool is regarded as a hypoallergenic fibre.

2.2.1.4 Scouring

After shearing or combing, the raw fibres from sheep, alpacas and goats are cleaned and prepared for top making and spinning. This washing stage, called scouring, removes grease, dirt and vegetable matter. Sheep naturally produce a significant amount of grease covering the raw wool, which can be further processed into lanolin after the scouring. Alpacas and goats do not produce this extra co-product.

2.2.2 Recycled wool

Recycled wool can be sourced from (1) pre-consumer textile waste, which includes material diverted from the waste stream during the manufacturing process,[68] and (2) post-consumer textile waste, which includes material generated by households or by commercial, industrial and institutional facilities in their role as end-users of the product, including returns of materials from the distribution chain.[69] Recycled wool fibres can be made from one or both source types, and can be blended with other fibres (e.g., polyester and virgin wool)[70,71] at the subsequent stage of yarn spinning.

2.2.2.1 Sorting

Fibres coming from the recovery supply chain are first sorted based on type and colour (labels, seams, buttons and zippers might also be removed in this step, depending on the raw material source). With respect to impact, one must account for production (e.g., mixed fibre to selected fibre), energy use (e.g., electricity and natural gas, fuel for motor vehicles), waste (amount and mode of disposal), water and transport (type and distance). In the studies reviewed, the raw material is assumed to have no impact because it is recovered waste (garments no longer in use or process scraps). This is known as the recycled content allocation approach (the 100-0 cut off method),[72] whereby system inputs with recycled content do not receive any burden from the previous life cycle other than reprocessing of the waste material. Therefore, no environmental impacts are allocated to the pre-consumer and post-consumer waste that are used as recycled wool material.

2.2.2.2 Transportation

After being collected, pre-consumer and post-consumer textile wastes are transported, usually by truck and boat, to shredding centres where they are further processed.

2.2.2.3 Shredding/Fiber production

Textile scraps, sorted by colour and type, are passed through a series of blades (or guillotines) and cylinders, producing finely shredded fibres. One must account for energy use (e.g., electricity and natural gas, fuel for motor vehicles), waste (amount and mode of disposal), water, chemicals (anti-foam agent) and transport (type and distance). Cleaning, mixing and fibre dyeing are included in this stage, if applicable based on the supply chains. Depending on the fabric production process in the facility, additional chemical (e.g., hydrochloric acid, sodium chloride, dye) and energy inputs may be included in this stage. This is the last processing stage before recycled wool fibres are spun into recycled wool yarn, usually blended with other fibres.

2.2.3 Silk

Ninety-six per cent of all silk is produced by China and India,[73,74] the two largest producers followed by Uzbekistan, Thailand and Brazil.[75] Mulberry silk is the most common type of silk produced. Production of mulberry silk starts with the planting of mulberry trees, whose leaves are harvested to feed silkworms. The trees thrive in warm, humid conditions, with an ideal temperature range from 24∞C to 28∞C and annual rainfall from 600 mm to 2500 mm.[76]

Mulberry leaves are fed to the silkworms as they grow through five instars[77] lasting 28 days overall. The silkworm then slowly spins a tight cocoon around itself. The cocoon is made of sericin. This part of the process lasts about two days. The feeding of the worms and the production of the cocoons is called sericulture.

The cocoons are then treated to reel the raw silk filament onto standardized spools. This stage, called silk reeling, can comprise drying and boiling the cocoons in an alkaline solution. The diameter of the mulberry silk fibre ranges from 10 to 13 microns.[78]

Co-products can be produced at the different stages of raw silk production: co-products of the mulberry trees (e.g., uneaten leaves, branches and twigs, agricultural waste, firewood), co-products of the sericulture (pupae) and co-products of the silk reeling (silk of lesser quality).

Other types of silk include spider silk (from spider webs), tussar silk (by several species of silkworms living in wild forests), eri silk (from a caterpillar in northeast India), and muga silk (from the muga silk moth, Antheraea assamensis).[79] These silks occupy very small niches and are not the subject of any LCA or carbon footprint studies.

Table 3.

Summary of main characteristics of the animal fibres of the study.

Animal fibre	Animal producing the fibre	Fibre diameter
Wool	Sheep	17 to 21 microns for Merino sheep
Cashmere	Cashmere goats	14 to 17 microns
Mohair	Angora goats	25 to 45 microns
Recycled Wool	Pre-consumer and Post-consumer wool	Depends on the type of wool
Silk	Silkworms	10 to 13 microns

2.3 Functional unit

To identify low-carbon sources of animal-based fibres (wool, hair, silk) and to investigate approaches to sourcing animal-based fibres with potential for a lower carbon footprint, this report screened animal fibres' LCA and carbon footprint studies and articles. The report came across the following functional units: mass unit of greasy wool, mass unit of alpaca fibre, mass unit of goats' hair, mass unit of recycled wool/fibre, and mass unit of raw silk. It is important to mention that the results presented in this study are not intended for use in comparative assertions due to differences in system boundaries and differences in the characteristics of final products.

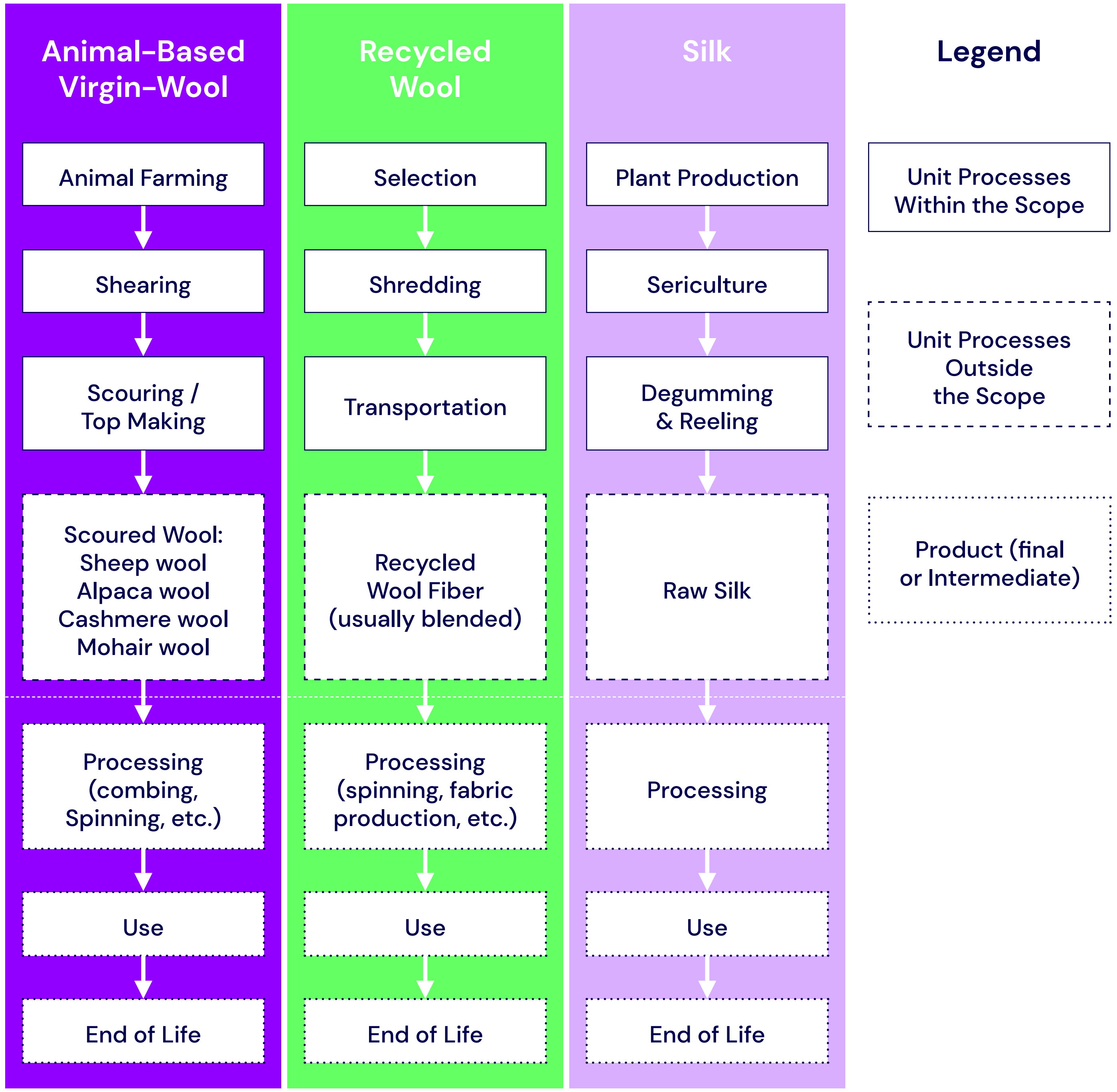
2.4 System Boundaries

According to ISO 14040, the system boundary is defined as the set of criteria specifying which unit processes are part of a product system.

The system boundary of the current assessment is illustrated for the fibre types (wool, hair, and silk) in Figure 1.

Figure 1.

System boundary of assessment for different types of animal fibres (wool, alpaca fibre, hair), recycled wool, and silk.



3. Collected Information

3.1 Datapoints overview from the literature review

This section provides an overview of the scope of the literature review conducted for wool, hair and silk. Table 4 outlines the criteria used to review existing and accessible LCA research and reports on wool, hair and silk, and to retrieve climate data to provide informed conclusions and guidance to the industry on sourcing raw materials.

Table 4.

Scope of literature review for wool, hair and silk.

Review Criteria	Wool/hair	Silk
Raw Material Sub-Type/Sources under consideration	Virgin Animal-Based Fibre Sheep wool Alpaca fibres Cashmere goat hair (cashmere) Angora goat hair (mohair) Recycled Wool	Silk from mulberry
Geographic Regions	Australia, New Zealand, China, Argentina, Peru, Mongolia, India, South Africa, USA, Italy	India, China, Italy
System Boundary/Scope	Cradle to farm gate (up to scouring/top making)	Cradle to gate (up to reeling)
Climate Impact Results Reported	Kilogram CO2-equivalent per kg of wool / hair (greasy, scoured, or top)	Kilogram CO2-equivalent per kg of raw silk
Key Processes Driving Climate Impacts	Enteric Fermentation Manure management Machinery use Fertilizer use Scouring/top making Feeding Transportation	Plant cultivation (e.g., mulberry) Egg production Sericulture Reeling Machinery use
Calculation Methodology	IPCC (2006), IPCC (2013), Impact 2002+, TRACI, CML, Ecopoints, EcoIndicator 95 & 99, EPS, EF2, ILCD 2011 midpoint, EU 27 2010	
Primary and Secondary Data	Proportion of primary and secondary data used for modelling and data sources used for filling data gaps	
Data Collection Period	Review data collection period of primary data for each process and fibre type	
LCA Software	SimaPro, GaBi, ecochain	
LCA Databases Used for Modelling	Ecoinvent (2.1, 2.2, 3.4, 3.5, 3.6, etc.), RMIT 2005, ILCD, AusLCI, Australian LCA database, USA input-output	
Key Modelling Assumptions/ Data Gaps/ Inconsistencies	Identify key processes and factors excluded from the assessment	
Limitations	Limitations of models and data sources applied in the studies	

3.2 Virgin animal-based fibres articles and reports repository

Virgin wool sourced from sheep, virgin alpaca fibres, and virgin hair from cashmere goats and Angora goats have the highest volume of global production among the investigated fibres in this report, with an annual market share of about 1.7 million tonnes (2020).[80] However, the largest share comes from sheep wool (1.03 million tonnes) followed by silk (about 109,000 tonnes), recycled wool (about 70,000 tonnes), cashmere (25,000 tonnes), alpaca (6,000 tonnes) and mohair (about 4,000).[81]

Articles were collected through search of public sources using Google Scholar, Science Direct and Google Search Engine (using key words: life cycle assessment, virgin wool, sheep, alpaca, cashmere, mohair, animal fiber, carbon footprint, CO2 emissions, greenhouse gas emissions, fiber production), and through industry partners on the task team. A call for input was put out through the Textile Exchange Animal Fibers Round Table to collect relevant resources. Among all reviewed resources on virgin animal-based fibres, 19 LCA and carbon footprint research articles and reports and three literature review reports were collected and analysed. The data sources comprise peer-reviewed papers, public reports and confidential reports accessed through the United Nations working group. Table 5 lists the reports collected and analysed, as well as information on geographic location, animal (breed), type of study, and life cycle stages covered in the source studies.

Among the 19 reports, two are specific to alpaca fibres and 17 focus on sheep wool. No LCA and carbon footprint reports using primary data on cashmere and angora goat hair were found.

Table 5.

Life cycle assessment and carbon footprint data resources on virgin wool and hair covered in this study, and corresponding life cycle stages in the source study.

Study author, Year	Title	Geographic Scope	Animal (Breed)	Type of Study	Life Cycle Stages					
					Farming	Shearing	Scouring	Processing	Use	End of Life
Wiedemann et al., 2015	Application of life cycle assessment to sheep production systems: investigating co-production of wool and meat using case studies from major global producers	Australia New Zealand UK	Sheep (Merino, Meat Merino, Romney dominant, Lleyn and Cheviot)	Peer-reviewed						
Wiedemann et al., 2016	Resource use and greenhouse gas emissions from three wool production regions in Australia	Australia: NSW, WA, SA	Sheep (Merino)	Peer-reviewed						
Wiedemann et al., 2020	Environmental impacts associated with the production, use, and end-of-life of a woolen garment	Australia	Sheep (Merino)	Peer-reviewed						
Barber & Pellow, 2006	LCA: New Zealand Merino wool total energy use	New Zealand	Sheep (Merino)	Conference Paper						
Brent & Hietkamp, 2003	Comparative evaluation of life cycle impact assessment methods with a South African case study	South Africa	Sheep (Merino (50%), Other)	Peer-reviewed						

Study author, Year	Title	Geographic Scope	Animal (Breed)	Type of Study	Life Cycle Stages					
					Far-ming	Shea-ring	Scou-ring	Pro-ces-sing	Use	End of Life
Brock et al., 2013	Greenhouse gas emissions profile for 1 kg of wool produced in the Yass Region, New South Wales: A Life Cycle Assessment approach	Australia: NSW	Sheep (Merino)	Peer-reviewed						
Van de Vreede & Sevenster, 2010	Lifecycle environmental impact assessment of textiles, For priority streams in Dutch lifecycle-based waste policy	Netherlands	Sheep	Peer-reviewed						
Laitala et al., 2018	Does Use Matter? Comparison of Environmental Impacts of Clothing Based on Fiber Type	Global	Not Applicable	Peer-reviewed						
Ecoinvent	sheep production, for wool | sheep fleece in the grease	USA	Sheep	Data-base						
Cardoso, 2013	Life cycle assessment of two textile products wool and cotton	Farming: New Zealand, Scouring: Italy, Spinning & Dyeing: China & Italy	Sheep	Thesis						
Peri et al., 2020	Carbon Footprint of Lamb and Wool Production at Farm Gate and the Regional Scale in Southern Patagonia	Argentina: Patagonia	Sheep (mainly Corriedale)	Peer-reviewed						

Study author, Year	Title	Geographic Scope	Animal (Breed)	Type of Study	Life Cycle Stages					
					Far-ming	Shea-ring	Scou-ring	Pro-ces-sing	Use	End of Life
Nolimal & Klimas, 2018	Life Cycle Assessment of Four Different Sweaters	USA	Sheep	Report						
Fishwick, 2012	A Carbon Footprint for UK Clothing and Opportunities for Savings	UK	Various	Report						
Emanuele, 2017	Application of Life Cycle Assessment to a Wool Sweater: A Case Study	Farming: South Africa; Fiber creation: Italy; fabric creation: Italy and Romania; Use: worldwide (Canada, USA, Australia, Japan, Germany)	Sheep (Merino)	Peer-reviewed						
Wiedemann et al., 2021	Reducing environmental impacts from garments through best practice garment use and care, using the example of a Merino wool sweater	Farming: Australia; Production: China & India; Use: West Europe	Sheep (Merino)	Peer-reviewed						
The Schneider Group	Environmental Benchmark Summary Report – 2019 and 2020	Farming: Argentina & Australia Mill processing: Argentina, China, Egypt, Italy	Varying	Report						

Study author, Year	Title	Geographic Scope	Animal (Breed)	Type of Study	Life Cycle Stages					
					Far-ming	Shea-ring	Scou-ring	Pro-ces-sing	Use	End of Life
Biswas et al., 2010	Global warming contributions from wheat, sheep meat and wool production	Australia	Not Specified	Peer-reviewed						
Pelcan, PUCP Dueñas et al., 2021 (a)	Analysis, Measurement, Interpretation of the environmental footprint of the alpaca value chain under life cycle analysis (a)	Peru: Arequipa; Pasco; Puno; Huancavelica	Alpaca	Report						
Pelcan, PUCP Dueñas et al., 2021 (b)	Analysis, Measurement, Interpretation of the environmental footprint of the alpaca value chain under life cycle analysis (a)	Peru	Alpaca	Report						
Devaux, 2019	Wool Production – Systematic review of Life Cycle Assessment studies	Global	Sheep	Report						
Henri, 2012	Understanding the environmental impacts of wool: A review of Life Cycle Assessment studies	Global with focus on large producing countries	Sheep	Report						
Turley et al., 2009	The role and business case for existing and emerging fibers in sustainable clothing	UK	Sheep	Report						

*** Processes include combing, spinning, weaving/knitting, dyeing and finishing (manufacturing).**

While trying to access all existing data about hair and virgin wool's life cycle assessment and carbon footprint, two studies identified in the literature review could not be accessed and so were not part of the analysis (Table 6).

Table 6.

Identified articles about virgin wool and hair which were not available to the working group.

Study author, Year	Title	Geographic Scope	Animal (Breed)	Type of Study	Life Cycle Stages					
					Far-ming	Shea-ring	Scou-ring	Pro-ces-sing	Use	End of Life
Eady & Ridoutt, 2009	Setting reporting periods, allocation methods and system boundaries for Australian agricultural life cycle assessment. Proceedings of the 6th Australian Conference on Life Cycle Assessment – Sustainability Tools for a New Climate, Melbourne.	Australia	Sheep	Confe-rence Paper						
Eady et al., 2010	Resource use and greenhouse gas emissions from three wool production regions in Australia	Australia	Australia	Confe-rence Paper						

Table 7 presents information about the virgin wool, fibre and hair production systems in the studies analysed for this report (listed in Table 5).

Table 7.

Information about wool, fibres and hair production systems in the studies analysed for this report.

Study author, year	Scope, and Functional Unit	Breed, average animal weight, and fibre diameter when specified	Wool Production Location	Type of data for wool production system	Production System Description	Climatic and Topographic Conditions when specified
Wiedemann et al., 2015	cradle to farm gate 1 kg greasy wool at farm gate	Merino 45 kg 17 µm	New South Wales, Australia	3 case study farms	Optimized production system for fine wool and meat. Grazing. 7.4 DSE* per ha	700-800 mm average annual rainfall
		Merino, Meat Merino 60 kg 21 µm	South Australia, Australia	4 case study farms	Optimized production system for fine wool and meat. Grazing. 0.4 DSE per ha	250-350 mm average annual rainfall (semi-arid)
		Mostly Romney 60 kg 32 µm	New Zealand	151 surveyed farms	Dual purpose production system (meat and coarse wool). Grazing. 0.4 DSE per ha	1420 mm average annual rainfall
		Lleyn and Cheviot 68 kg ~30 µm	United Kingdom	1 case study farm	System production focused on meat; coarse wool is a by-product. Grazing all year, except 1 month in winter when sheep are housed and fed pasture silage, hay and by-products from horticulture, such as surplus potatoes. 14.7 DSE per ha	Over 1200 mm average annual rainfall (high rainfall)
Wiedemann et al., 2016	cradle to farm gate 1 kg greasy wool at farm gate	Merino 50 kg 17 µm	New South Wales, Australia	3 case study farms, and 34 surveyed farms	Wool and meat production system. Grazing on native pastures with introduced clover or sown pastures (phosphate fertilizer application). Small amount of supplementary feed in lower rainfall years and annually during winter.	700-900 mm annual rainfall O in winter to 27∞C in summer 950-1000m above sea level
		Merino 60 kg 20 µm	Western Australia, Australia	4 case study farms, and 18 surveyed farms	Grazing on native pastures with introduced clover (phosphate fertilizer and lime application), with supplementary feeding and forage crops to manage annual feed deficiencies in summer.	400 to 550 mm annual rainfall (temperate) -6 in winter to 30∞C in summer 250-300 m above sea level
		Merino 60 kg 21 µm	South Australia, Australia	4 case study farms, and 18 surveyed farms	Only grazing, supplementary feed not typically provided.	around 250 mm annual rainfall (arid to semi-arid) -4 in winter to 34∞C in summer 300-350m above sea level
Wiedemann et al., 2020	cradle to grave 1 garment used for one wear event	NS	New South Wales and South Australia, Australia	data from Wiedemann et al., 2016	NS	NS

Study author, year	Scope, and Functional Unit	Breed, average animal weight, and fibre diameter when specified	Wool Production Location	Type of data for wool production system	Production System Description	Climatic and Topographic Conditions when specified
Barber & Pellow, 2006	cradle to wool top gate 1 tonne of dry wool top	Merino	South Island, New Zealand	24 case study farms	Mixed production systems (other farm products: cattle, deer, crops). Variable stocking rates from 0.9 to 7.4 sheep stock unit per ha (1 sheep stock unit is equal to one breeding ewe that weights 55 kg and bears one lamb)	NS
Brent & Hietkamp, 2003	cradle to yarn gate 1 kg of dyed wool yarn	varying (50% Merino)	South Africa	literature and publications	Model includes pastureland as well as maize and lucerne feed supplement. Model selected: 28500 m2 per sheep (unit and calculation not detailed)	less than 400 mm average annual rainfall
Brook et al., 2013	cradle to farm gate 1 kg greasy wool	Simulation: Merino 58 kg 19 µm	New South Wales, Australia	Data generated via simulation on software	Simulated – different scenarios for co-products, feed supplement, fibre diameter, market price, fleece yield. 13.2 dry sheep equivalents per ha	650 mm average annual rainfall monthly annual temperature varying from 7 to 27∞C
Van de Vreede & Sevenster, 2010	cradle to farm gate 1 kg wool	NS	USA	data from Ecoinvent	NS	NS
Laitala et al., 2018	use phase no FU	NA	Worldwide	NA	NA	NA
Ecoinvent	cradle to farm gate 1 kg sheep fleece in the grease	NS	USA	Data from statistics, literature, farm surveys and expert knowledge	Phosphate fertilizer and lime application. Wool and liveweight production. 80% extensive (grazing), 20% intensive (feed supplement in form of soybean and maize).	NS
Cardoso, 2013	cradle to textile gate 1 kg of greasy wool for the farming stage	NS	New Zealand	1 case study farm	Production system not described individually. Grazing on pasture, supplementary feed (silage or maize and hay), fertilizers and lime application. 1.2 stock unit** per ha	NS
		NS	Australia	1 case study farm	Production system not described individually. Grazing on pasture, supplementary feed, fertilizers, and lime application. 12 stock unit per ha	NS
		NS	Australia	1 case study farm	Production system not described individually. Grazing on pasture, no supplementary feed, no fertilizers application. 0.1 stock unit per ha	NS

Study author, year	Scope, and Functional Unit	Breed, average animal weight, and fibre diameter when specified	Wool Production Location	Type of data for wool production system	Production System Description	Climatic and Topographic Conditions when specified
Peri et al., 2020	cradle to farm gate 1 kg greasy wool	Mainly Corriedale	Santa Cruz, Argentina	63 farms	Rotational grazing in different paddocks all year, with different paddocks based on the sheep and climate seasonality and associated nutritional needs. Pasture made of short grasses and forbs among tussocks. No supplementary feed. 0.2-0.75 PSUE per ha (Patagonian Sheep Unit Equivalent, equivalent to one Corriedale ewe of 49 kg of live weight requiring 530 kg of DM per year)	200 mm annual average rainfall in the East 800 - 1000 mm in the Andes Mountains Mean annual temperatures between 5.5 and 8.2∞C. 166 - 454 m above sea level (subregion averages)
Nolimal & Klimas, 2018	cradle to use phase 1 sweater (28 laundry cycles)	NS	USA	Data from Ecoinvent	NS	NS
Fishwick, 2012	clothes produced for the UK, worn, and cleaned, as well as disposed of each year	NS	Australia for the wool	Data from Biswas et al., 2010	NS	NS
Emanuele, 2017	cradle to grave 1 sweater	Merino	South Africa for wool	NS	NS	NS
Wiedemann et al., 2021	cradle to grave 1 wear of a 300 g wool sweater	Merino	Australia for wool	data from Wiedemann et al., 2016	NS	NS

Study author, year	Scope, and Functional Unit	Breed, average animal weight, and fibre diameter when specified	Wool Production Location	Type of data for wool production system	Production System Description	Climatic and Topographic Conditions when specified
The schneider group	GHG Protocol scope 1, 2, partial 3 for scouring/ top making 1 kg wool top leaving the mill	Merino 45 kg 20-21 μm	Argentina	12 case study farms described in another report	No details given in the report. References other reports for details about the production systems (Wiedemann et al., 2019 – unpublished). Meat and wool production system. Grazing on pasture. Supplemental feed (hay).	NS
		Merino 50 kg 17-20 μm	New South Wales, Australia	data from Wiedemann et al., 2016	No details given in the report. References other reports for details about farming data (Wiedemann et al., 2016 and Wiedemann et al., 2019 – unpublished)	NS
Biswas et al., 2010	cradle to farm gate 1 kg of wheat, sheep meat and wool	NS	Victoria, Australia	Experimental data based on 12-month field study	Not a production system; simply three 5 m x 15 m plots producing different crops: mixed pasture (perennial ryegrass/ subterranean clover/grass and cape weed), wheat and sub-clover.	727 mm during the year of measurement, 685 mm annual average 205 m above sea level
Pelcan, PUCP Dueñas et al., 2021 (a)	cradle to garment gate 1 kg of alpaca fibre garment	alpaca	Puno, Arequipa, Pasco and Huancavelica, Peru	Directly from farms. No other description.	NS	NS

Study author, year	Scope, and Functional Unit	Breed, average animal weight, and fibre diameter when specified	Wool Production Location	Type of data for wool production system	Production System Description	Climatic and Topographic Conditions when specified
Pelcan, PUCP Dueñas et al., 2021 (b)	cradle to grave 1x400 g alpaca sweater (109 uses)	alpaca	Puno, Arequipa, Pasco and Huancavelica, Peru	data from cradle-to-gate Pelcan, PUCP Dueñas et al., 2021 (a)	NS	NS
Devaux, 2019	NA	NA	worldwide	13 LCA studies	NA	NA
Henri, 2012	NA	NA	worldwide	9 LCA studies	NA	NA
Turley et al., 2009	NA	NA	worldwide	1 LCA study, 2 carbon footprints, 1 communication	NA	NA

NS = Not specified, NA = Not applicable

***DSE = Dry Sheep Equivalent, equivalent to an annual feed consumption rate of 400 kg DMI (dry matter intake)**

****Stock Unit = the farmers calculate the Stock Unit using standard and official values for their countries. It represents the number of sheep equivalent. It has different conversion factors according to the metabolic system of the animals (breed and age) and country or region environment.**

Among the 19 studies (17 sheep wool, two alpaca fibres), only nine describe succinctly the livestock production system, seven refer to another study about the wool generation life cycle stage without any details on the production system, and three do not mention a production system at all.

Table 8.

Summary of production system descriptions and modelling data for virgin wool and hair in the collected studies.

	Description of the animal fibres production system		Source of modelling data		No Description of the production system
	Brief description	No description but refer to a study or database	Farm	Other	
Number of studies	9	7	5	11	3
Comment	All production systems described are for sheep wool and depict systems relying on pasture grazing. Depending on the natural geographic conditions, stocking rates, supplementary feed, phosphate fertilizer and lime application vary.	Studies and database used as reference for the greasy wool stage: -Wiedemann et al., 2016 and 2019 -Ecoinvent -Biswas et al., 2010 -Pelcan, PUCP Dueñas et al., 2021	Articles used data directly from farms, covering production systems in Australia, New Zealand, United Kingdom and Argentina.	Modelling data comes from referenced study or database (e.g., Wiedemann et al., 2016; Ecoinvent; Biswas et al., 2010; Pelcan, PUCP Dueñas et al., 2021) or software simulation, unreferenced publications and field experiment.	One study (Laitala et al., 2018) does not include the greasy wool stage in its scope of work. The two others (one for alpaca, the other for sheep wool) do not describe the production system.

As summarized in Table 8, only five studies use primary data from farms to measure the climate change impact of the fibres. The rest use data from previous studies, database, simulation, statistics, or other published sources.

Among the 19 studies analysed, a few studies use the terms “extensive” and “intensive” to describe the production system. Sheep wool production systems, both extensive and intensive, are pasture based. Intensive sheep systems have a higher stocking rate (animals per ha) than extensive systems.

3.3 Recycled Wool

Recycled wool, with an annual production of about 70,000 tonnes (2020), is a promising source of animal fibre in the fashion industry in terms of waste reduction and product reuse.[82] Raw material for recycled wool production can be sourced from either pre-consumer or post-consumer recycled materials. Recycled wool is normally blended with other fibres with a maximum recycled wool content generally around 70 per cent.[83,84] For example, the main part of recycled wool portion in Bi Bye TD fabric is sourced from a mix of pre-consumer and post-consumer wool (about 50 per cent post-consumer wool, 12 per cent pre-consumer wool, 38 per cent nylon).[85]

For this study, eight reports on the LCA or carbon footprint of recycled wool were collected through search of public sources using Google Scholar, Science Direct and Google Search Engine (using key words: life cycle assessment, recycled wool, regenerated wool, carbon footprint, CO2 emissions, greenhouse gas emissions, fiber production) and two through industry partners in the task team.

Table 9 lists and describes studies on recycled wool covered in this report.

Table 9.

Life cycle assessment and carbon footprint data resources on recycled wool covered in this study, and corresponding life cycle stages in the source study.

Study author, Year	Title	Geographic Scope	Type of Study	Life Cycle Stages				
				Sorting	Shredding	Processing	Use	End of Life
Fishwick, 2012	A Carbon Footprint for UK Clothing and Opportunities for Savings	UK	Report	■	■	■	■	■
Manteco, 2019	LCA analysis of Bi Bye TD fabric and of the main yarns and fabric classes	Italy	Report	■	■	■		
Made Green in Italy, 2021	Screening study for carded wool or fine hair fabrics	Italy	Report	■	■	■		
Next Technology, year unknown	Environmental footprint study for the production of 1 kg yarn made by Recycled Cashmere vs Virgin material	Italy (recycled raw materials from America)	Report	■	■	■		
Next Technology, year unknown	Environmental footprint study Yarn wool-polyamide	Italy (recycled raw materials from America)	Report	■	■	■		
Next Technology, year unknown	Environmental footprint study Yarn wool-polyester	Italy (recycled raw materials from America)	Report	■	■	■		
Ergo Srl, year unknown	Recycled Wool environmental footprint	Italy (Prato district)	Report	■	■	■		
Norden, 2016	Gaining benefits from discarded textiles LCA of different treatment pathways	Norway, Sweden, Finland, Denmark	Report	■	■			

LCA = life cycle assessment

One article identified in the literature review could not be accessed and so was not part of the analysis: The technical report of Life Cycle Assessment of "mechanical wool" by Riccadonna and Bruschi in 2015.

3.4 Silk

Silk, with an annual production volume of about 109,111 tonnes (2020), has a relatively low market share of the animal-based fibres. However, silk production is still a significant industry involving 300,000 households in raw silk production and generating some USD 215 million (2020[86] in raw silk export value. For this report, data from seven studies were analysed. Table lists and describes the studies, with respect to geographic scope, insect and plant on which it feeds, type of study and life cycle stages covered. Data were collected through search of public sources using Google Scholar, Science Direct and Google Search Engine (using key words: life cycle assessment, silk, sericulture, carbon footprint, CO2 emissions, greenhouse gas emissions, raw material, fiber production) and through industry partners in the task team.

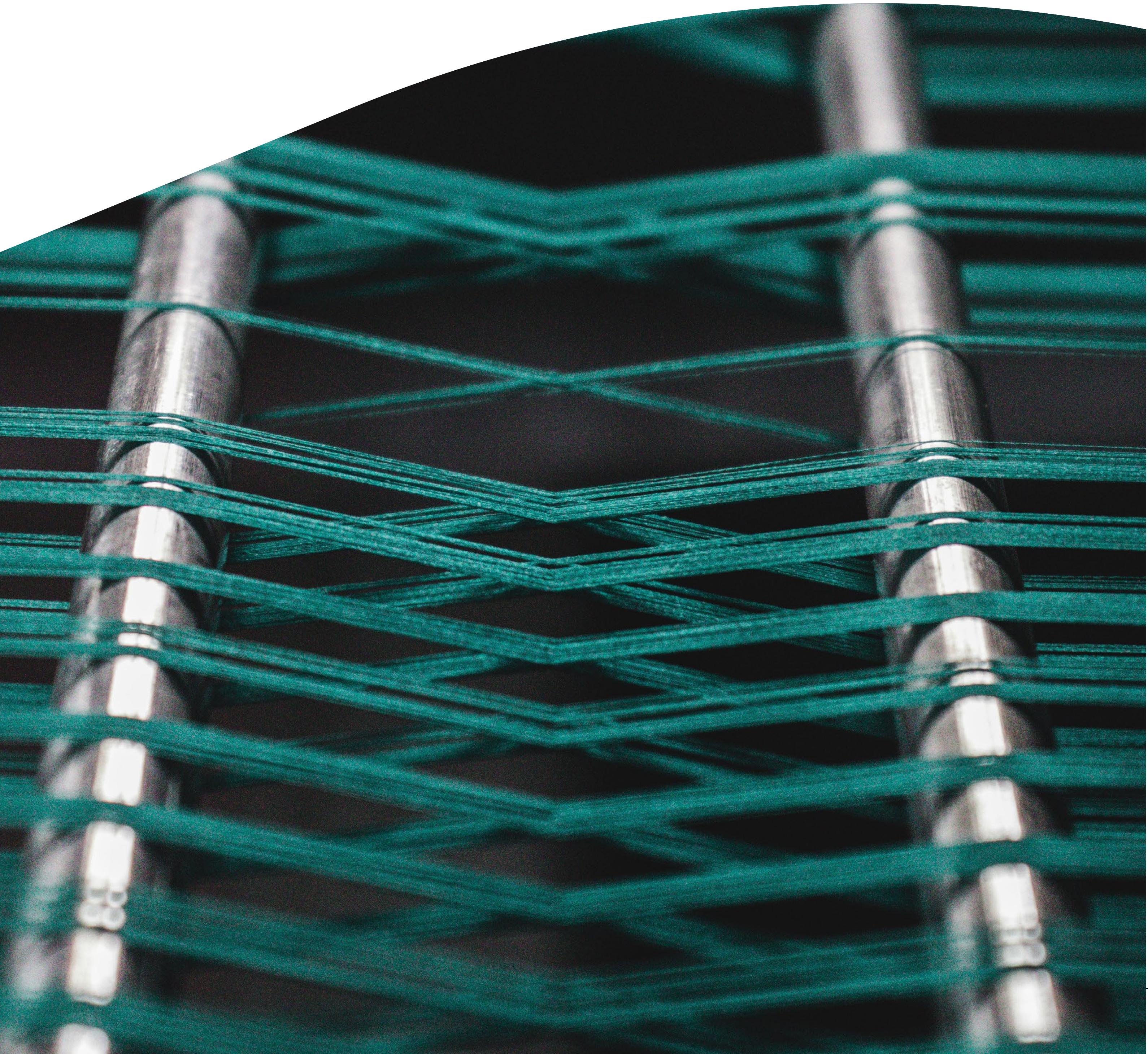


Table 10.

Life cycle assessment and carbon footprint data resources on silk covered in this study, and corresponding life cycle stages in the source study.

Study author, Year	Title	Geographic Scope	Insect and Plant	Type of Study	Life Cycle Stages					
					Leaf Production	Sericulture	Reeling	Processing	Use	End of Life
Ecotextile News, year unknown	The Life Cycle of Luxury – Italian Silk Shows Its Green Credentials	Italy	Silkworm (mulberry)	Report						
Scuola Superiore Saint'Anna, 2020	Product Environmental Footprint report	China	Silkworm (mulberry)	Report						
Astudillo et al., 2014	Life cycle assessment of Indian silk	India: Karnataka, Andhra Pradesh, Tamil Nadu	Silkworm (mulberry)	Peer-reviewed						
Bhalla et al., 2020	Life Cycle Assessment of Traditional Handloom Silk as Against Power-loom Silks: A Comparison of Socio-economic and Environmental Impacts	India	Silkworm (mulberry)	Peer-reviewed						
Fishwick, 2012	A Carbon Footprint for UK Clothing and Opportunities for Savings	UK	Not Specified	Report						
Ecoinvent v3.7	mulberry production | mulberry leaves cocoon production, silkworm rearing | cocoons reeled raw silk hank production | reeled raw silk hank	India Rest of World Global	Silkworm (mulberry)	Database						
Barcelos et al., 2020	Opportunities for Improving the Environmental Profile of Silk Cocoon Production under Brazilian Conditions	Brazil	Silkworm (mulberry)	Peer-reviewed						

4. Findings for virgin animal fibre

4.1 Data gaps

This section develops findings relating to global warming potential of virgin sheep wool, alpaca fibres, cashmere and mohair. It describes data gaps, analyses sources of emissions and identifies hotspots, highlights the importance of using an accurate method to allocate emissions, and suggests strategies to mitigate emissions from raw animal-based fibres.

4.1.1 Regionally limited availability of studies and resources

Most of the studies on virgin wool production are conducted in Australia and New Zealand (Table 5). The limited number of studies available for other regions mainly use secondary data, characterization, and normalization methods that are not specific to the regions assessed.[87] For example, the use of agricultural machinery and wastewater treatment in Ecoinvent are mainly modelled using European data and can be different to utilized region-specific farming practices.[88] Further research is required on the environmental impacts of virgin animal-based fibre production in other key-producing regions, including India, Mongolia, China, South Africa, South America, Europe and North America. This would provide a better understanding of the impact of animal-based fibre production and the effect of production system and regional, temporal and environmental variations on emissions.[89]

4.1.2 Limited data availability with respect to animals and breeds

Most of the studies covering virgin animal-based fibres investigated for this report were based on sheep wool. The only two sources in which cashmere production was evaluated used secondary data on sheep wool as a proxy[90 91] Only two studies derived from the same life cycle inventory look at alpaca fibre production (two different system boundaries based on one life cycle inventory/one data collection process)[92] The authors of this report found no life cycle assessment or carbon footprint studies on mohair and cashmere, and only one life cycle inventory on alpaca fibres.

Table 11 summarizes the life cycle assessments or carbon footprint studies collected and analysed for this report, by type of fibre.

Table 11.

Mapping of data availability by animal fibre type.

Animal-based fibre type	Collected and analysed studies	
	Number of collected studies analysing greenhouse gas emissions from this type of animal fibre	Comment
Wool from sheep	17	• 5 studies model cradle-to-gate sheep greasy wool from farm data • 3 studies model cradle-to-gate sheep greasy wool from experimental, simulated or statistical data • 7 studies use sheep greasy wool data from a previously published study • 2 studies do not calculate cradle-to-gate sheep greasy wool life cycle assessment or carbon footprint.
Alpaca fibre	2	• 1 cradle-to-gate • 1 cradle-to-grave using the other cradle-to-gate study to model the raw wool production stage
Hair from cashmere goats	0	no life cycle assessment or carbon footprint
Mohair from Angora goats	0	no life cycle assessment or carbon footprint

The mapping emphasizes the need for LCA and carbon footprint studies for alpaca fibres (only one cradle-to-gate calculation), cashmere and mohair (no LCA or carbon footprint studies). Looking at the type of studies published globally, even cradle-to-gate sheep greasy wool LCA and carbon footprint studies based on farm data are scarce (only five studies calculate the cradle-to-gate global warming potential of greasy wool directly from farm data).

4.1.3 Limited data quality related to production systems

Table 8 summarizes the description of the virgin wool, fibre and hair production systems and modelling data, and Table 11 maps data availability by fibre type. The tables show that only five studies out of 19 use data collected directly from farms. The other studies use data from other reports, software simulation, statistics, experiments, or databases. This reveals the lack of studies using data retrieved directly from production systems.

No studies calculated the environmental impact from nomadic production systems. All the represented production systems are farms.

Across fibre-producing species, smallholder farms are also under-represented.

4.1.4 Greenhouse gas emissions and removals associated with land use and land use change

Changing forest to pasture for sheep, goats and alpacas can result in large emissions of carbon dioxide through clearing of biomass and reduction of soil organic carbon over time. The Intergovernmental Panel on Climate Change (IPCC) guidelines[93] require that emissions and removals (e.g., when carbon is removed from the atmosphere by trees) from land use and land-use change be accounted for. Because most pastureland for sheep, goats and alpacas was created prior to the period prescribed in the guidelines,[94] usually no direct land-use-change emissions are included in greenhouse gas inventory calculations. Thus, direct land use change does not represent a significant data gap for virgin animal fibres produced on land with established pasture. However, there is a significant gap of scientific data on the impact of different grazing patterns – i.e., land use – for sheep, goats, and alpacas.[95]

Greenhouse gas emissions from land use represent emissions and removals occurring through the human use or management of land. The IPCC categorizes five carbon pools that can either emit or remove GHG gases from the atmosphere:

- Above-ground biomass
- Below-ground biomass
- Dead wood,
- Litter, and
- Soil organic carbon.

Carbon pools in the land vegetation can increase or decrease through the grazing of animals, and restoration or deterioration activities.

The authors of this report analysed 19 studies on virgin animal fibres (17 sheep wool, two alpaca fibres) and two literature reviews. Among the studies calculating climate change impact results, only two clearly[96] integrate GHG emissions from land use: Wiedemann, et al. (2016)[97] and Peri, et al. (2020).[98] Both studies relied on previous studies to assess the evolution of on-farm biomass and pasture soil organic carbon. Wiedemann, et al., reports on the emissions and removals from sheep wool farms in three regions in Australia, separate from the rest of the GHG inventory. Peri, et al., (2020)[99] presents aggregated results for wool production in the Santa Cruz region in Argentina and does not detail the impact of land use on the results. Thus, the assessment of land use emissions and removals in sheep farming for wool production are assessed only in three Australian regions for merino sheep rearing.

This constitutes an important data gap within the climate change indicator assessment. More studies should assess the net variations of the five carbon pools' size, in particular the impact of specific agricultural and grazing practices on the biomass and soil carbon pools. Following the ISO 14067[100] recommendations, the reporting of the land use emissions and removals should be included in the carbon footprint.

In terms of methodology, each carbon pool is assessed separately, and the IPCC has calculations for biomass carbon pools (above-ground and below-ground), dead organic matter (dead wood and litter) and soil organic carbon.[101,102] Across the carbon pools, the IPCC has described two calculation methods: the Gain-Loss method (based on the assessment of the gains and losses over the time period studied for a sample size of land scaled to the concerned area) and the Stock-Difference method (based on the assessment of the difference between the carbon pools in their entirety at the beginning and the end of the time period concerned). These assessments can be challenging because they require that carbon fluxes to be gathered for each carbon pool (Gain-Loss method) or about their beginning and end states (Stock-Difference method). To assess land use emissions, farms would have to collect data consistent with the chosen method for the above-ground biomass, below-ground biomass, dead wood, litter, and soil organic carbon. The choice of method and data collection for each carbon pool can be a hurdle to the assessment of land-use emissions.

With growing awareness of the impact of livestock,[103] especially ruminants, on the global GHG inventory, interest is growing into what can be done to increase carbon pools (e.g., increasing soil organic carbon content, increasing perennial above-ground biomass) through different farming practices. In this context, there is a large gap in scientific data on the impact of different grazing patterns for sheep, goats, and alpacas on above- and below-ground biomass and pasture soil organic carbon.

4.1.5 Scouring and top making

The scouring and top making processes impact the environment in two ways: (1) through use of resources and creation of emissions , and (2) through the yield of scoured fibres and tops produced.

Most studies either stop calculations at the farm gate or aggregate results across life cycle stages. Due to these limitations, it was not possible to compare different techniques of scouring and top making or assess how the processes differ depending on the type of fibre (sheep, alpacas, cashmere, and mohair). No hotspots or recommendations could be extracted from the literature review.

A global effort should be made to assess the climate impact of scouring and top making to better understand this important step in fiber production, including the different yields of clean fibre from raw fibre per animal fibre type.

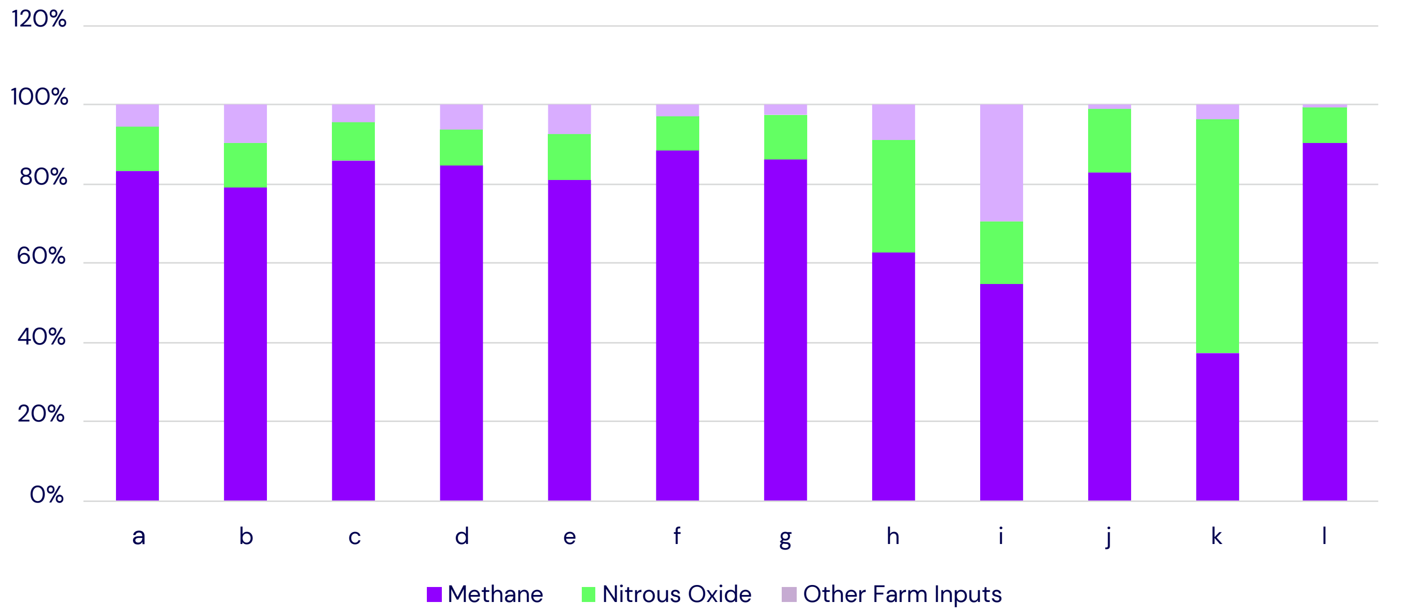
4.2 Contribution analysis in the collected data

Of the 19 studies reviewed, five provide a contribution analysis of greasy wool at the farm gate, separating methane emissions, nitrous oxide emissions and other emissions at the farm.

Some of the five studies performed a life cycle assessment for multiple scenarios. Figure 2 below summarizes the 12 contribution analysis calculations presented in the five studies.

Figure 2.

Contribution analysis of greasy wool at the farm gate from five studies.



a. New South Wales regional average, from Wiedemann, et al., (2016)[104]
b. West Australia regional average, from Wiedemann, et al., (2016)[105]
c. South Australia regional average, from Wiedemann, et al., (2016)[106]
d. New South Wales case study, from Wiedemann, et al., (2016)[107]
e. West Australia case study, from Wiedemann, et al., (2016)[108]
a. South Australia case study, from Wiedemann, et al., (2016)[109]
g. Analysis from Brock, et al., (2013)[110]
h. Analysis from Peri, et al., (2020)[111]
i. Analysis from Ecoinvent[112]
j. Sub-clover plot, from Biswas, et al., (2010)[113]
k. Wheat plot, from Biswas, et al., (2010)[114]
l. Mixed pasture plot from Biswas, et al., (2010)[115]

In nine of the 12 analyses, methane emitted from the animals represented more than 80 per cent of the greasy wool climate change impact.

Two studies (Brock, et al., 2013, and Biswas, et al., 2010) differentiate methane emitted from enteric fermentation and methane emitted from manure management. These two studies (covering four calculations) show that the methane emitted from livestock product systems is almost entirely from enteric fermentation. Methane emitted as a result of manure management (manure deposited on pasture, and manure managed in a shed or barn) is minimal compared to enteric methane (Table 12).

Table 12.

Share of methane emissions from enteric fermentation and methane from manure management in greasy wool production at farm gate, from cited literature.

Case study	Methane from enteric fermentation %	Methane from manure management %	Total methane emitted for greasy wool (cradle-to-gate) %
Brock et al, 2013 Greenhouse gas emission profile for 1 kg of wool produced in the Yass Region, New South Wales	99.98	0.02	100
Biswas et al., 2010 Sub-clover plot	99.99	0.01	100
Biswas et al., 2010 Wheat plot	99.95	0.05	100
Biswas et al., 2010 Mixed-pasture plot	99.98	0.02	100

In analyses *h, i and k* of Figure 2, methane emissions represent 63%, 55% and 37% , nitrous oxide emissions 29%, 16% and 59%, and other farm inputs 9%, 29% and 4%, respectively, of total climate change impact of greasy wool at the farm gate. Case study i from Ecoinvent v3.8 US dataset for greasy wool shows the largest contribution from farm inputs, 29%, including 24% from soybean meal and corn grain. This was the only contribution analysis where sheep feed had a significant impact (24% of the total climate change impact) and was from a husbandry system that is 20% intensive and 80% extensive (pasture grazing). Case study k by Biswas, et al., (2010) looked at a system where wheat and wool were produced through cultivation of the same plot, and found nitrous oxide emissions to have the highest impact (59%). The study included, without detailing the calculation, nitrous oxide emissions from the transformation of the plot from pastureland to cropland.

4.2.1 Importance of methane emissions from enteric fermentation

Overall, the review of the greasy wool contribution analyses showed that most emissions come from enteric fermentation (more than 80 per cent) and nitrous oxide. Farm-related emissions, including machinery, energy, fertilizers, purchased feed, pesticides, veterinary services and upstream transportation, represent a small part of the greasy wool total climate change impact.

Methane emitted through enteric fermentation is belched from the animals' digestive tract. The methane is a co-product of the digestion of carbohydrates in the rumen by microorganisms. The amount of methane released depends on the animal (e.g., cattle, buffalo, sheep, goat, deer, camelid), its age and weight, as well as the quality and quantity of feed.[116] Across the entire agricultural sector, enteric methane emissions are calculated through equations, not measured on farms.[117] This explains the high level of uncertainty for the carbon footprint of animal fibres:[118] the largest source of emission cannot be measured and is estimated mathematically.

The conventional CO2-equivalent metric used to measure the impact to climate (typically 100-year Global Warming Potential, GWP-100), simplifies time-dependent differences among different GHGs by weighing the potency of different gases against CO2 (e.g., methane = 28 GWP based on IPCC 5th Annual Report) based on the atmospheric lifetime of the substance. An alternative metric, GWP* (GWP Star)[119] preserves the link between emissions and warming or cooling of the atmosphere using a dynamic equivalence (change in methane ≈ one-off CO2).[120] GWP* places a greater emphasis on changes in rates of emission, rather than assessing the amortized heat over a defined time period. Groups advocating for the use of animal fibres, such as Australian Wool Innovation,[121] have proposed use of GWP* for assessing the carbon footprint of animal fibres.

The following sections detail the methodology of calculation used in the literature, and in national inventory report from countries with an important level of virgin animal fibre production.

4.2.2 Methodology of enteric fermentation calculations

The IPCC prescribes methodologies to calculate the methane emitted from enteric fermentation.[122] Three levels of calculations are proposed: Tier 1, Tier 2, and Tier 3, with Tier 3 calculations being the most sophisticated. It is recommended to use the higher levels of calculations (Tier 2 and Tier 3) whenever they are available.

The Tier 1 method multiplies the number of animals by a methane emission factor to calculate emissions per head of animal per year. The IPCC provides default methane emission factors sheep, goats, alpacas, and other animals. For sheep and goats, two values are provided: one for high productivity systems and one for low productivity systems. Tier 1 is a simple calculation; however, it lacks detail in terms of age, weight and diet of the animal.

The Tier 2 method is a more disaggregated methodology where the methane emission factor per head per year is calculated based on the gross energy intake of the animal subgroup and a methane conversion factor of the gross energy intake (as a percentage). The Tier 2 method allows for more granular calculations by considering the type of feed, quantity of feed and age of animal. However, it requires calculating the gross energy intake per animal type, which is difficult to assess accurately for grazing animals, and having a gross energy intake conversion factor for each type of feed.

The Tier 3 method adds country-specific variables, such as seasons, activity of the animal, characteristics of the feed (e.g., quality, concentrations) and other details. The Tier 3 method is only recommended internationally for cattle livestock, as it requires substantial research to elaborate emission factors for specific animals and conditions.

4.2.2.1. Enteric fermentation calculations in the virgin wool literature

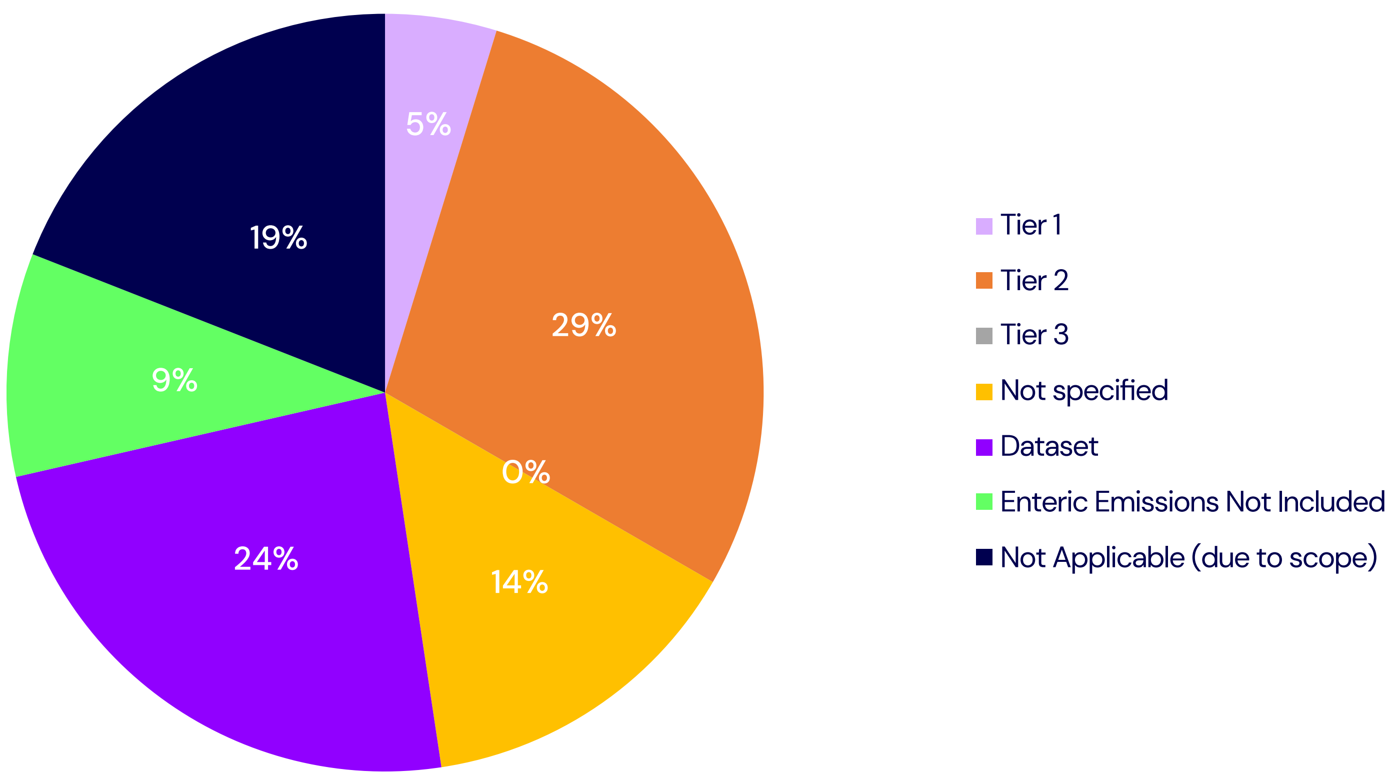
This report reviewed the enteric fermentation calculations performed in animal fibres articles and reports. Table 21 in the Appendix summarizes the findings by document.

The results of the review are summarized in figure 3 below. The review of the enteric fermentation calculations in the collected studies and articles found that:

- 34% of studies (seven studies) performed their own enteric fermentation calculations as part of the carbon footprint measurement. Among these studies, most used a Tier 2 method (29%, equivalent to six studies). One study used the Tier 1 method.
- No studies performed a Tier 3 calculation.
- 14% (three studies) did not specify how enteric fermentation emissions were calculated.
- 24% (five studies) used a pre-existing dataset and did not give additional information on the enteric fermentation calculations in the selected dataset.
- 9% (two studies) excluded enteric fermentation from the carbon footprint measurement.
- 19% (four studies) did not perform their own enteric fermentation assessment due to it being outside their scope of work (literature review, or scope of work excluding the raw material phase).

Figure 3.

Enteric fermentation calculations in the animal fibres articles/reports reviewed.



Despite the importance of enteric fermentation emissions on the greasy wool total carbon footprint, some studies exclude these calculations from the scope of work (e.g., Barber & Pellow, 2006, Brent & Hietkamp, 2003); others do not specify whether enteric emissions are included (e.g., Emanuele, 2017), or are not fully transparent on the calculations performed (e.g., Brock et al., 2013, Peri et al., 2020). A few studies are very transparent with the methodology employed, the default methane emission factor used, or the equation used to calculate the methane emission factor (e.g., Wiedemann, et al., 2015 and 2016, Ecoinvent v3.8, Cardoso, et al., 2013, Biswas, et al., 2010, Duenas, et al., 2010). However, no study described the calculated Tier 2 methane emission factors by subgroup of animal (age, activity, type of diet). Doing so would improve transparency and allow a better understanding enteric fermentation emissions.

Five of the studies reviewed referenced national inventory reports or national agency publications in selecting the equations and Tier method employed. The following section explores the main national inventory reports for sheep, goats, and alpacas.

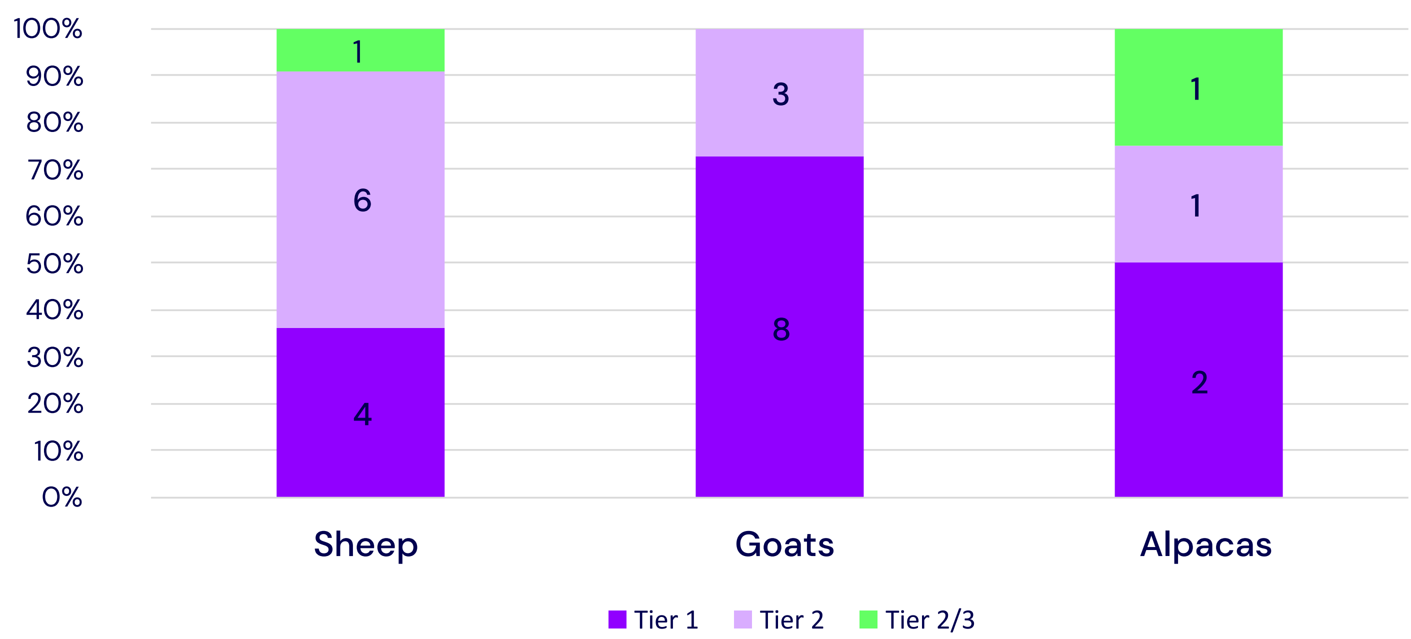
4.2.2.2 National greenhouse gas inventories

The authors looked at the national GHG inventory reports of countries with substantial sheep wool, cashmere, mohair and alpaca fibres production systems for apparel (Argentina, Australia, Bolivia, China, India, Mongolia, Netherlands, New Zealand, Peru, South Africa, Turkey, United Kingdom and the United States of America) and IPCC reports from 2006 and 2019.

Out of the 13 inventory reports studied, 11 included the emission factors used for sheep and goats (Argentina, Australia, China, India, Mongolia, Netherlands, New Zealand, South Africa, Turkey, UK, and USA) and four reported emissions for alpacas (Argentina, Bolivia, New Zealand and Peru). Figure 4 below summarizes the share of methodology used in the eleven national inventory reports, by animal.

Figure 4.

Share of methodology used – Tier 1, Tier 2, and Tier 2/3 – in national inventory reports from 11 countries, by animal.



Out of eleven countries, the majority (six) employed the Tier 2 methodology to estimate the enteric fermentation emissions from sheep. One country (United Kingdom) used a Tier 2/3 methodology (more advanced than Tier 2 by considering differences in diet and age).

Out of eleven countries, the majority (eight) used the Tier 1 methodology to estimate the enteric fermentation from goats. Three countries used the Tier 2 methodology: China, India and South Africa. Overall, more countries could develop Tier 2 and Tier 2/3 calculations for goats.

Out of four countries estimating greenhouse gas emissions from alpacas, Argentina and New Zealand used a Tier 1 methodology, Peru used a Tier 2 (adjusted Tier 1) methodology, and Bolivia used a Tier 2/3 methodology (considered differences by region and age).

Overall, the methane emission factors varied between 4.7 kg and 14.7 kg of methane per head per year for sheep, between 3.4 kg and 9 kg for goats, and between 7 kg and 14 kg for alpacas. Table 22 in the appendix summarizes the emission factor and tier used in each reviewed national inventory report.

The analysis of the methodologies used to calculate the enteric methane emissions provides important learnings:

1. Due to the importance of enteric methane emissions in the fibres' carbon footprint (>80%), studies should pay particular attention to the methodology employed to calculate enteric fermentation emissions and disclose them precisely, including equations and values of the methane emission factors. No studies should exclude enteric methane emissions from animal fibre GHG inventories.
2. As much as possible, Tier 2 or Tier 2/3 should be used for more precise calculations. When Tier 2 or Tier 2/3 methods are used, the calculated emission factors should be transparently shared by type of animal to facilitate benchmarking.[123]
3. National inventory reports can lead the way in use of adjusted Tier 1, Tier 2 or Tier 2/3 methods. Consequently, it is important for more countries to adopt widespread use of Tier 2 and Tier 2/3 methods, especially for goats, including different goat breeds, such as Cashmere and Angora.

Using more detailed methodologies can increase the accuracy of GHG inventory reports and their data quality. In extensive production systems (based on established pasture thus a set, specific feed), using more detailed methodologies would provide more granular data to support herd management.

4.3 Importance of the allocation methodology and the allocation factors

Across sheep production systems, sheep farms producing wool also produce live weight animals. As the farm (or herd in a nomadic setting) produces wool by shearing the animals annually, the herd regenerates itself: old animals are culled, adult animals reproduce and gestate, baby animals are born, and a percentage of female animals grow to replace the herd. Male baby animals, a portion of female baby animals, some youngster and older animals constitute co-products to the virgin animal fibre production. They can be sold to other farms or directly to slaughterhouses. As a result, all resources contributing to the husbandry (e.g., animal feed, water, fertilizers for pasture, agricultural machinery use) and all emissions resulting from the husbandry (e.g., enteric fermentation emissions, manure management emissions) must be allocated between the animal co-products: fibres and live weight.

The allocation of the resources and emissions toward fibres or the live weight has an important influence on the final carbon footprint of the virgin animal fibre. One article by Stephen Wiedemann on sheep wool production in Australia[124] concluded that different allocations between wool and live weight at the farm stage could lead to a factor of three difference in the total GHG emissions for the wool production. The allocation methodology and the assumptions used to calculate the allocation factor have a crucial impact on the wool carbon footprint.

Most production systems that have specialized in high quality wool production do not produce milk as a co-product. However, if a production system produces milk also, the allocation methodology and the calculation of the allocation factors would remain identical – by adding milk as a co-product.

This section of the report is meant to highlight that the carbon footprint of different fibres cannot be compared across studies without an accurate knowledge of the allocation method and allocation factors used. Moreover, a smaller allocation factor toward fibre (so higher for live weight) would decrease the carbon footprint of the fibres, but would keep unchanged the emissions of the entire farm. Modifications of allocation factors result in changes in carbon intensities, not in absolute GHG emissions.

4.3.1 Allocation methodologies

The literature review identified the following allocation methodologies specific to virgin animal fibre:

- Biophysical;
- Economic; and
- Protein mass.

Biophysical allocations are based on the animals' feed requirements. Since animal fibres are entirely made of protein, the biophysical allocation for animal fibres analyses the protein feed requirements necessary for wool and hair production, as opposed to growth, activity, gestation and flock maintenance. To calculate the animal fibre allocation factor, a feed programme specific to the fibre-producing animal is used to retrieve the protein requirements for the different needs of the animals (among growth, gestation, lactation, herd maintenance, activity, fibre production) and to calculate the ratio of proteins specifically needed for the fibre production. For Merino sheep, a common feed standard to consider is the *Australian Feeding Standards Model* from CSIRO 2007.[125]

Economic allocations are based on the revenue generated from the different co-products of the animal system. Emissions and resources are then allocated between the co-products depending on their revenue percentage for the farm.

Protein Mass allocations are based on the mass of protein produced by the different co-products by multiplying their mass by their protein content (e.g., clean wool is made of 100% protein).

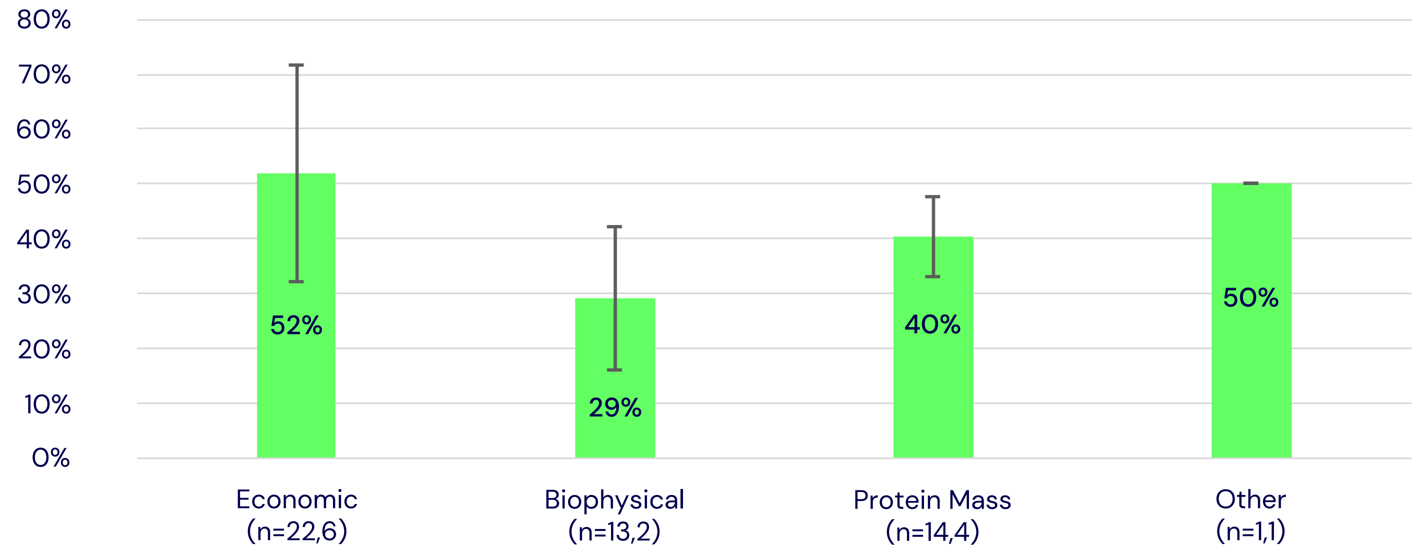
ISO 14044[126] favours allocation methodologies based on physical causality over economic realities. ISO 14044 as well as FAO Livestock Environmental Assessment and Performance (LEAP) Partnership guidelines[127] for small ruminants and the International Wool Trade Organization (IWTO) LCA guidelines recommend the use of biophysical allocation for the fibre production of small ruminants (e.g., sheep, goats). However, these guidelines also recognize that the biophysical allocation calculations are not always feasible since they rely on precise information on feeding requirements by animal, breed and activity (growth, gestation, lactation, herd maintenance, activity, fibre production) that may simply not exist for some animals or breeds. When the protein biophysical allocation calculations are not feasible, i.e. in absence of specific protein feeding requirements, the protein mass allocation is the next recommended methodology by IWTO, following the approach of Wiedemann (2015)[128] since it is a similar method to the protein biophysical allocation and is more easily calculated.

Both methodologies rely on information about the physical properties of the animal. The economic allocation methodology does not reflect a physical constraint, but a reality. The economic allocation illustrates which activity or activities primarily drives the activity of the farm.

The review of literature identified the allocation methodologies and associated allocation factors between greasy wool and live weight. Figure 5 summarizes the average greasy wool allocation factors by methodology across sheep breed and wool producing animals. Fifty allocation factor calculations were identified across 11 studies to separate the resources and emissions between wool and live weight at the husbandry stage. Forty-nine calculations involved the production of sheep wool and only one allocation was for alpaca fibres. No data for the allocation of hair from goats was identified in the review.

Figure 5.

Averages and standard deviations of greasy wool allocation factors by methodology across animal types and breeds.



Note about (n=x, y): x is the number of calculations found in the review, and y the number of studies

The economic allocation was the most-performed method across articles: 22 calculations of economic allocation were performed across six reports. The average economic allocation factor for wool was 52 per cent with a standard deviation of 20 per cent. Biophysical and protein mass allocations were performed 13 and 14 times over two and four reports, respectively. On average, the biophysical allocation factor was 29 per cent and the protein mass allocation factor was 40 per cent.

It is interesting to note that the biophysical method, recommended by the LEAP guidelines and IWTO, led to the smallest allocation factor across animal breed (29%), followed by the protein mass (40%) and economic allocation factor (52%).

Larger standard deviations were seen for the economic method (20%) and the biophysical method (13%), and the smallest for the protein mass method (7%). The standard deviation analysis confirms that the economic allocation method is the least stable: fluctuations in prices of goods (wool, live weight, meat) directly impact the allocation factor calculations.

However, it is to be noted that the biophysical allocation factor calculations are primarily derived from one study from Wiedemann,[129] which accounts for 12 calculations out of the 13 in the entire review. The 12 calculations represent three ways of calculating biophysical allocation in four case studies. In the collected studies, only two authors calculated biophysical allocations factors. The variability observed across the biophysical allocation factors come from the three different ways of calculating the allocation factor, based on the attribution of the protein needs for the maintenance of the flock, the maintenance of the lambs and the gestation, attributed to the wool or the meat co-product (the fibre production protein needs are always attributed to the wool co-product and the growth protein needs are always attributed to the meat co-product).[130] While the biophysical allocation is preferred by international standards, there is an inherent subjectivity in the calculation of the biophysical allocation factor that comes from the decision to attribute the maintenance protein needs and the gestation protein needs to the meat co-product exclusively, to partition them between the wool and the meat co-product or to simply exclude them from the calculation. As a result, the FAO guidelines state that the use of the biophysical allocation is still in a development stage.[131]

Out of the six studies that performed the economic allocation, three detailed their calculations. Wiedemann et al., 2015 used average values for wool and liveweight at the farm gate over a period of two years. Brock et al., 2013 used market values for clean wool, sheep meat at a dressing percentage of 44 per cent, and head for surplus of ewes for the week ending on March 4, 2011. Lastly, Biswas et al., 2010 used market values for sheep meat, wool and wheat retrieved from Livestock Australia 2007, The Australian Wheat Board 2009, and the Department of Primary Industries, Victoria 2008. There are no guidelines overarching the specific calculations of economic allocation: specific values at a point in time, average values over longer periods of time, values at farm gate or market values, etc. These impact the allocation factors and the final product carbon footprint without any difference in the production system. At the farm level, the economic allocation of resources and emissions can reflect a reality: the activity driving the business in terms of revenue. It can provide insights to the owner about the hotspots and most important actions to undertake. However, at the macro level (the level of the industry), the instability of the economic allocation methodology can prevent stakeholders from analysis of the best practices and changes over time.

In the review, one study allocated 50 per cent of the resources and emissions to the wool and 50 per cent to the live weight without describing the method applied.

4.3.2 Allocation methodologies by breed

The 50 allocations identified in the review allocated resources and emissions for different sheep breeds and wool-producing animals: Merino, Meat Merino, Romney, Lleyn and Cheviot, and Corriedale, as well as Alpaca and non-identified sheep breeds. The reported allocation factors for wool across methodologies by breed and animal are presented in Figure 6.

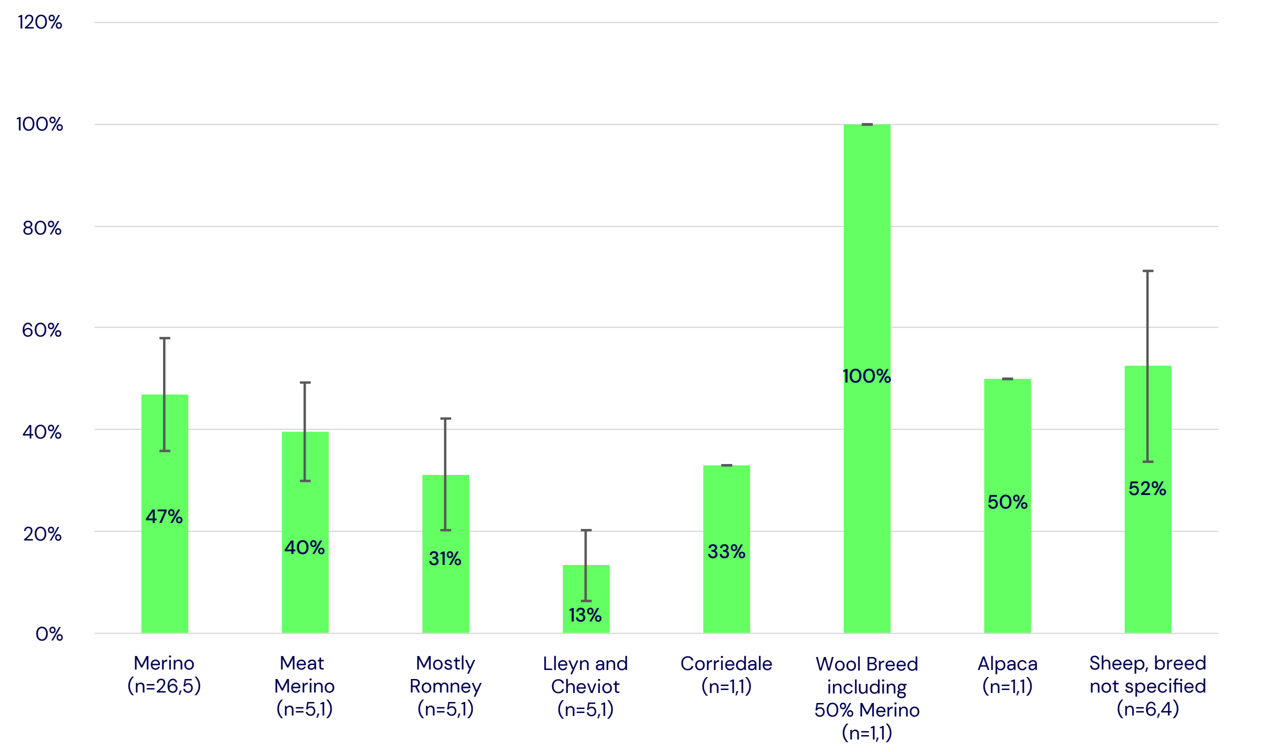
The average allocation factor for Merino (47%) was the highest, followed by Meat Merino (40%), Corriedale (33%), Romney (31%), and Lleyn and Cheviot (13%). The article allocating 100% of the resources and emissions impact to the wool (no allocation toward liveweight) analysed wool produced in South Africa from a variety of sheep breed developed solely for wool production -including 50% Merino sheep. The allocation factor (100%) was assessed by the authors without performing any calculations. This assumption reflects that wool production is the only economic driver for sheep husbandry.

Figure 7 aggregates the allocation factors by methodology (economic, biophysical and protein mass) and animal type (either all sheep breed or only Merino).

Averages of allocation factors for Merino are 2 per cent higher than averages of allocation factors across all animals. Since Merino is a breed with an emphasis on wool production over meat production, the results are consistent with this trend. Interestingly, when focusing on the Merino breed, the standard deviations are smaller for every case (economic, biophysical and protein mass) suggesting that for a specific breed, allocation factors by methodology show less variability.

Figure 6.

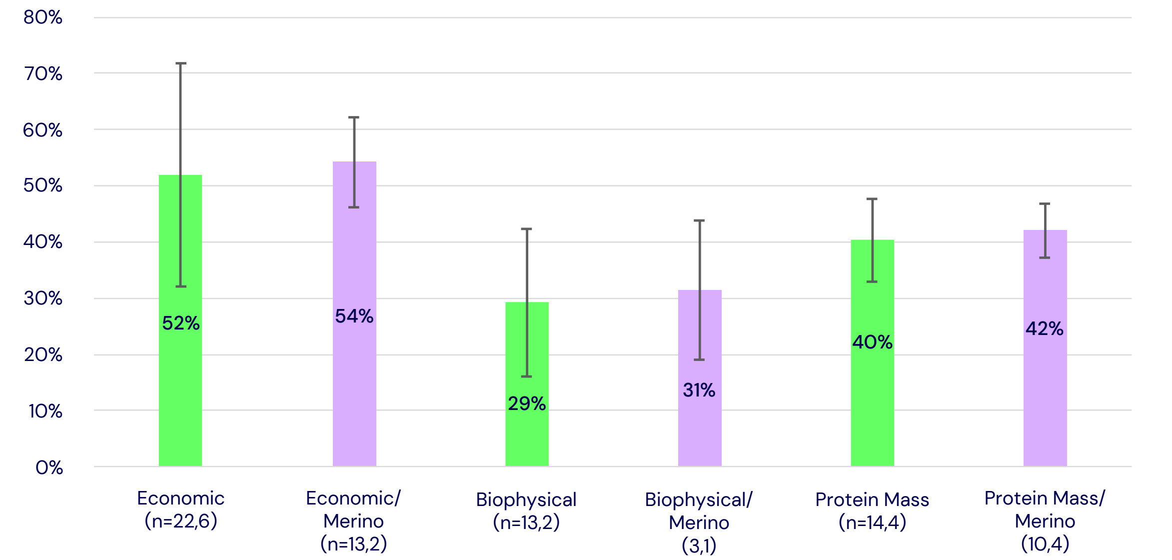
Averages and standard deviations of greasy wool allocation factors by breed across methodologies



Note about (n=x,y): x is the number of calculations encountered in the review, and y the number of studies.

Figure 7.

Averages and standard deviations of greasy wool allocation factors by methodology and animal type (either all sheep breed or Merino only).



Note about (n=x,y): x is the number of calculations encountered in the review, and y the number of studies

Conclusions about the impact of the allocation on the virgin animal-based fibres carbon footprint
This section discusses the importance of allocation method and highlights that carbon footprint of animal fibre can vary solely based on the allocation methodology and allocation calculations without signifying anything about the actual GHG emissions stemming from the animal production system. Thus, benchmarking the carbon footprint across studies among animal-based fibres and with other types of textiles is challenging.

Three allocation methods are commonly used for fibres of small ruminants: protein biophysical, protein mass and economic. While the protein biophysical method is the approach most recommended by FAO and IWTO for its physical causality and stability, it is not always feasible (the calculations depend on the existence and access to protein feeding requirements that are species and breed specific). When use of the protein biophysical method is not feasible, the protein mass method is recommended as a proxy for the biophysical method. The economic allocation method was the most used method across the collected studies, even if it does not rely on physical causality. It is the most accessible method, but the most volatile. Depending on the practitioner's choices (prices at farm gate, market values, averages, one-time values, etc.) and market price fluctuations, economic allocation factors vary.

All methods require transparency into the assumptions used in the calculations: (1) for the biophysical method, the assumptions include the feeding requirements and the aggregation rules (which requirement is attributed to fibres and which is attributed to liveweight), (2) for the protein mass method, the assumptions include the production weight of fibres and liveweight and their protein content, and (3) for the economic allocation, the assumptions include the production weight of fibres and liveweight, the economic values of each product, and the use of price average or time-specific values.

Research into protein feeding requirements for wool-oriented sheep breeds, goat breeds (including Cashmere and Angora) and alpacas would facilitate use of the biophysical allocation method.

4.3.3 System expansion in the literature review

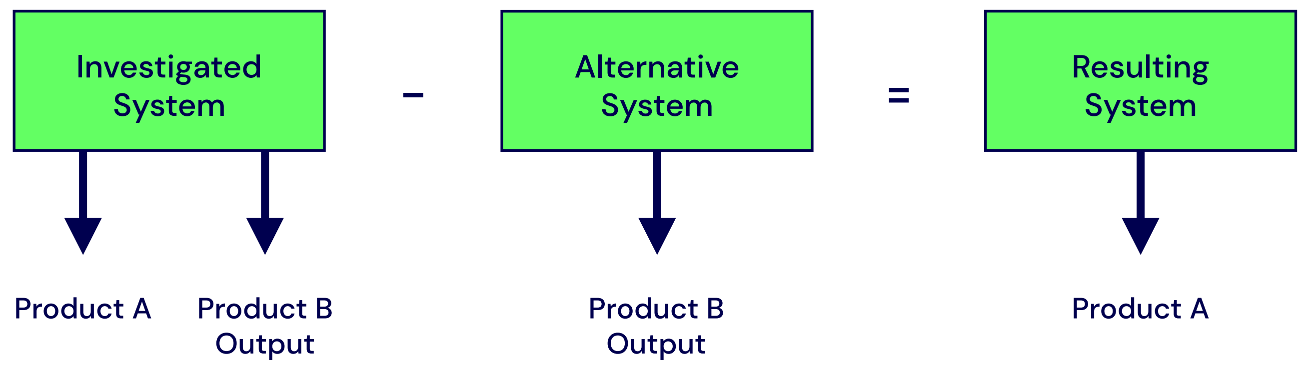
Among the virgin wool reports and studies, two performed some system expansion calculations for greasy wool: Wiedemann, et al., 2015[132] and Wiedemann, et al., 2016.[133] The system expansion methodology is preferred in ISO 14044 to avoid allocating resources and emissions – in this case between wool and liveweight.

System expansion methodology and product carbon footprint
System expansion is a methodology defined in ISO 14044, used to avoid the use of the allocation methodology (explained in detail in sections 4.3.1 and 4.3.2) by expanding the boundaries of the production system. Under system expansion, the expanded system boundaries include additional functions relating to the co-products. For instance, expanding the system boundaries of sheep greasy wool production would mean including liveweight production within the system boundaries, and consequently calculating impact for the combined outputs of wool and liveweight.

The FAO small ruminants LCA guidelines[134] state it is sometimes acceptable to expand the view of a production system and calculate the combined impact of fibres and liveweight, without calculating an impact for each product. For product-specific carbon footprints (e.g., fibre carbon footprint), the system expansion method cannot be used.

Another way to apply the system expansion method is to assess the avoided burden associated with a co-product. For example, the production of fibres (Product A) implies the production of liveweight (Product B); thus, one could consider that the environmental impact of the liveweight production, were it done separately, has been avoided. This method of calculation relies on the identification of substitution products for the co-product (liveweight), on the assessment of their environmental impact (based on literature), and the subtraction of this assessed impact from the impact of the combined production system.

Figure 8.
Expanding System Boundaries – Reference from ISO 14041:1998[135]



This method of calculation is suited to studies, which aim at assessing the consequences of changes in production. Such "consequential LCAs" provide insight about the consequences of increases or decreases in animal fibre production, since a change in the production of fibres has an impact on the liveweight production.

Both the FAO guidelines[136] and the GHG Protocol Standard for Life Cycle Accounting and Reporting[137] prohibit use of the system expansion method by means of substitution for product-specific carbon footprints, since it is not suited for attributional LCAs, benchmarking, hotspot analysis and emission reduction monitoring over time.

System expansion in the collected studies

- Among the virgin wool reports and studies, two articles performed system expansion by means of substitution within other types of calculations for the greasy wool's life cycle assessment: Wiedemann, et al., 2015[138] and Wiedemann, et al., 2016.[139] The two articles develop a thorough approach to select the substitution product to substitute for the sheep liveweight. The alternative product must be (1) a suitable substitution on the market (meat), and (2) a suitable replacement in the production system (e.g., possibility of rearing the alternative animal with the resources of the original sheep production system).

While the first criterion simply requires selecting an animal that produces suitable meat, the second criterion requires that that animal can be raised on the land of the sheep production system. Since the land is mostly non-cultivable and/or non-arable, only certain beef and sheep can be selected as substitution product for the sheep liveweight.

Table 13 below summarizes the substitution products used for the Merino sheep liveweight in Wiedemann, et al., 2015[140] and Wiedemann, et al., 2016.[141]

Table 13.

Substitution products used in the system expansion methodology in two articles assessing raw wool's environmental impact.

Article	Sheep farming model	Substitution products for liveweight
Wiedemann et al., 2015	• Merino/Meat Merino • Fine-medium wool (21 microns) • South Australia	• Sheep liveweight from crossbreed Border Leicester ewes and Poll Dorset rams • Beef
	• Merino • Super fine wool (17 microns) • New South Wales Australia	• Sheep liveweight based on Dorper breed • Beef
Wiedemann et al., 2016	• Merino • Super fine wool (17 microns) • New South Wales, Australia (case study farms, and regional averages)	• - Sheep liveweight from crossbreed Border Leicester ewes and Poll Dorset rams • Beef
	• Merino • Fine wool (20 microns) • West Australia, Australia (case study farms, and regional averages)	• Sheep liveweight from crossbreed Border Leicester ewes and Poll Dorset rams • Beef
	• Merino • Medium wool (21-22 microns) • South Australia, Australia (case study farms, and regional averages)	• Sheep liveweight of based on Dorper breed • Beef

In each case presented in Table 13, the environmental impacts from the equivalent production of the substitution product (found in literature) were subtracted from the total sheep production system under study to obtain the environmental impact of the greasy wool production.

The greasy wool carbon footprint under system expansion was reduced by 70 per cent[142] or divided by a factor of two or three compared to the raw wool carbon footprint under the allocation method. In some instances, using system expansion, the greasy wool footprint could even appear carbon negative.[143]

Conclusions about system expansion findings for animal-based fibres

There are two ways to apply system expansion to a product system: (1) by expanding the system boundaries to include the additional functions covered by the co-products, and (2) by assessing the avoided burden by means of substitution related to the co-products production. These cannot be applied when assessing the carbon footprint of animal-based fibres.

Wiedemann et al., 2015 and Wiedemann et al., 2016 performed system expansion calculations on greasy wool by means of substitution. While the results cannot be used as greasy wool carbon footprint (method not supported by international standards), the results can be interpreted from a consequential LCA perspective. The greasy wool system expansion results provide insights related to a change in the greasy wool production. Since the greasy wool implies a production of liveweight, the greasy wool avoids a portion of the environmental impact. Considering these additional environmental benefits (avoidance of environmental burden from other liveweight systems), the greasy wool's impact can be reduced significantly: by 70 per cent, by a factor two or three, or even appear carbon-negative.[144,145]

While the product carbon footprints developed using the allocation method can be used for analysis, hotspot identification and GHG inventory monitoring, they cannot be used to evaluate impact associated with fibre substitution at a global scale.

4.4 Strategies to reduce the carbon footprint

The dive into contribution analysis of virgin wool in section 4.2 and the influence of the allocation method in section 4.3 help to understand key levers for reducing the carbon footprint of virgin wool. Since the main source of GHG emissions is livestock on a per head basis through methane from enteric fermentation and nitrous oxide from manure, increasing the productivity per animal mathematically reduces the impact per unit of production. Another strategy is to reduce the methane emissions from enteric fermentation directly via innovative solutions, such as feed supplements. Lastly, another path to reduce GHG emissions on a per unit of wool basis, is to implement changes in grazing and vegetation management to induce an increase in the pasture soil carbon or farm biomass.[146]

4.4.1 Increasing the productivity per animal

In this report's review of literature, at least two articles[147] explicitly identified an increase in productivity per animal as a key lever to reduce the climate change impact from wool. Increasing productivity per animal can be achieved through various approaches, including:

- More adapted and consistent shearing practices;
- Raising the average production of fibre per animal; and
- Increasing the quantity of average liveweight produced per head as co-product.

The paragraphs below explore each of these options.

4.4.1.1 Shearing practices

Sheep, alpacas and Cashmere goats are usually sheared once a year after the cold months of winter. The shearing can include young adult and mature adult animals. Increasing the amount of raw wool/hair per head decreases the carbon footprint when all other parameters are unchanged, including in nomadic (e.g., cashmere goats in Mongolia) and traditional production systems (e.g., alpacas in Peru).[148]

An LCA[149] of alpaca in Peru showed great variability in the climate change impact per kilogram of fibres between four productive regions (more than 230% variation). Most of the variability was explained by the difference in percentages of alpacas sheared, which varied from 84 per cent of animals sheared annually in one region, to as low as 34 per cent in another. Increasing the percentage of animals sheared each year is very important to reduce the carbon footprint of the wool. Since emissions from enteric fermentation and manure decomposition are included in the calculation for all animals belonging to the herd, including those that are not sheared,[150] the carbon footprint per unit of raw wool increases when the percentage of sheared animals decreases. The source report goes one step further in its analysis and details two important factors impacting the decision of farmers to shear their animals: climate and price. These are both seasonal factors, so collecting data over many years might better reflect the carbon footprint of alpaca raw wool, and might also provide additional insight for wool buyers. Establishing sustainable relationships with fibres producers and understanding their constraints in shearing animals might unlock solutions to maintain a high ratio of sheared animals every year, for instance by entering long term contracts with stable raw wool prices.

While no LCA or carbon footprint reports could be accessed to analyse raw cashmere, some descriptive reports were analysed. A few of them reported the specificities of cashmere: extremely fine undercoat protected by longer and coarser hair. One study about cashmere goats reared in Kyrgyzstan[151] provided key information about cashmere hair shearing. While cashmere goats can be both sheared and combed, the combing is a preferred method because it yields more fine undercoat fibres than shearing. While shearing extracts both the undercoat and the outercoat together and cuts the hair about one centimeter away from the skin (thus cutting some of the valuable length of the fine fibres), combing retrieves only the undercoat at its full length, before the animal starts its natural shedding. As a result, more and longer cashmere fibres can be harvested per year per animal by combing the animals directly. For cashmere goats, combing the undercoat can be an important option to increase the amount of hair collected per animal per year, and decrease the carbon footprint of the hair.[152]

While the shearing of alpacas and cashmere goats can be optimized once a year, the shearing of Angora goats can be optimized twice a year. Angora goat hair can be sheared once in the spring and once in the fall.

Most sheep wool production systems producing fine wool for the apparel industry already optimize their shearing practices, and carbon footprint improvements from shearing would not be expected. However, maintaining the quality (and quantity) of the shearing is important to maintain the carbon footprint.

4.4.1.2 Increasing fibre productivity per animal

Besides improving shearing practices, another aspect of increasing the average quantity of wool or hair retrieved per animal per year across the herd is to keep improving the herd to increase and maintain a high average of fibre produced per animal.

Depending on the production system, the amount of fibre per animal per year can be raised by a variety of practices, including:[153]

- Culling older animals whose fibre production declines substantially;
- Increasing the longevity of ewes producing a high volume of fibre annually;
- Optimizing the number of lambs in self-replacing flocks by selling off excess animals; and
- Improving the genetics of the herd with cross breeds or improved intentional selection based on observed traits directed toward high fibre production and reproductive characteristics.

4.4.1.3 Increasing co-products per animal

Increasing the productivity per animal not only means increasing the average yield of fibres per head, but also increasing the average liveweight production per head. Raising the production of liveweight reduces the fibre carbon footprint by impacting the allocation of the resources and emissions between the co-products.

Depending on the production system, increasing the liveweight and meat co-products can mean:[154]

- Engaging more (or even starting to engage) in the sale of culled animals and meat – especially for wool and hair production systems that do not sell any animals;
- Increasing the survival rate of lambs at birth;
- Optimizing the number of lambs in self-replacing flocks by selling off excess animals;
- Culling animals with declining or low fibre yield to only keep high-fibre-producing mature adult animals: and
- Exploring new cross breeds that could increase the body mass of the animals.

For Cashmere goats, another co-product to consider could be the outercoat of the goat's hair. There is a small niche market for this long coarse hair to make non-apparel products (e.g., brushes, cloth for suit interlinings, binder in building plaster).[155]

It is important to underline that this subsection does not advocate lowering the carbon footprint of animal fibre by lowering the allocation factor towards fibre (see below).

Conclusion on the productivity per animal

Section 4.4.1 does not advocate for lowering fibres' carbon footprint by reducing the fibre's allocation factor, but emphasizes that it is possible to reduce the animal fibres' carbon footprint through increased productivity in two ways, through:

1. Reduction in the absolute GHG emissions at the production system level by removing all unnecessary emissions while ensuring a steady level of production; and
2. Reduction of the fibres' carbon footprint intensity by increasing the fibres and co-products production while maintaining a steady level of GHG emissions.

This section discusses the benefit from increasing production efficiency and reducing unnecessary emissions without impacting GHG emissions in other parts of the production system.

4.4.2 Research on enteric fermentation emissions reduction

Methane emissions from enteric fermentation are a major part of the carbon footprint of animal-based fibres. It is known that enteric methane emissions vary depending on the digestibility of the animal feed, so that increasing the quality of feed (e.g., high quality forage) decrease the emissions from enteric fermentation.[156] However, more research is underway to mitigate these emissions at the source, for example through use of feed supplements, vaccines, genetics, and bacteria.

While vaccines have not shown significant reduction potential, and herd improvement (by selecting animals naturally emitting less methane) would take generations of animals to make a difference, some feed supplements are showing potential. Some research with one of the leading components, asparagopsis taxiformis (red macro algae), suggests that a low concentration (0.5% or less) of the compound in the diet could reduce enteric methane emissions by up to 90 per cent without negative impact on feed intake or product quality. Other feed supplements, such as 3-NOP, desmanthus, Leucaena and grape marc (left after grape pressing), show a potential for enteric methane mitigation of 10–40 per cent.[157]

These innovations have the potential to change the carbon footprint of ruminant-based products, including wool and hair. Supporting and funding the research on these topics is crucial for carbon footprint reduction. They should be largely explored and analysed – especially in projects occurring in natural settings (pastureland grazing).

4.4.3 Soil organic carbon and vegetation removals

Soil organic carbon and vegetation removals can occur through specific grazing practices and farm vegetation growth (e.g., trees and shrubs used for restoration).[158] This carbon flux is accounted for in the land-use category of the GHG inventory.[159] When articles and studies exclude calculations of emissions and removals from land use, an assumption is made that there is no change over time in the carbon pools described in section 4.1.4, including:

- no change in soil organic content of the pasture due to grazing; and
- no change in the biomass on the farm.

As discussed in section 4.1.4, Wiedemann, et al., (2016)[160] was the only study, accessible for this report, that includes land-use calculations and reports them separately. The article differentiates cropland soil carbon, pasture soil carbon, and vegetation for six scenarios of greasy wool: three from regional averages in New South Wales, Western Australia and South Australia, and three case study farms from the same regions.

For the six specific scenarios studied and modelled in Wiedemann, et al., (2016):

- Cropland soil carbon is either stable or emits carbon dioxide;
- Pasture soil carbon is either stable or captures greenhouse gas depending on assumptions regarding soil carbon sequestration under pasture;
- Vegetation is either stable or capture greenhouse gas depending on regrowth of planted trees and shrubs.

Overall, in the scenarios explored in this study, land-use emissions and removals combined are either negligible or represent a reduction in the total greasy wool carbon footprint.

The Wiedemann study offers an example of how to include land-use emissions and removals into calculations of wool climate impact and illustrates an opportunity to reduce the wool carbon footprint by increasing the carbon stored in pasture soil organic carbon and pasture biomass.

Peri, et al., (2020), integrated land-use emissions and removals into their study of the wool climate impact in the Patagonia region of Argentina, without detailing the calculations. However, the study's conclusions are clear: pasture management through grazing management can determine whether a pasture is a net sink (removes GHG from the atmosphere) or source (emits GHG). Depending on the health of the grassland, overgrazed or not, and the stocking rates, high or low, the carbon content of the Patagonia pasture could vary from 50 to 130 tonnes of carbon per hectare.

Lastly, in his 2020 article,[161] Wiedemann refers to Doran-Browne,[162] whose article demonstrated the carbon neutrality of an Australian wool grazing farm. By planting trees and managing grazing, the studied farm was able to sequester 11-times the amount of GHG emissions produced by the livestock and farm activity over 32 years.

These three articles show the great potential that exists to reduce wool's carbon footprint by considering the roles played by land-use emissions and removals. More research needs to be conducted on soil types, grazing management, grassland health and vegetation restoration to evaluate the carbon removal potential that exists under various conditions.[163]

5. Findings for Recycled Wool

5.1 Contribution analysis across articles and studies

The LCA and climate impact results reviewed by the authors could not be evaluated side-by-side, as most studies and articles investigated recycled wool blended with various amounts of synthetic fibre (e.g., recycled wool 62% with nylon 28%, recycled wool 70% with polyamide 25% and other fibres 5%, recycled wool 75% with polyester 20% and other fibres 5%). However, contribution analysis of different impact contributors within each product system can provide useful information on (1) impact hotspots and (2) effective approaches to mitigate the overall climate impact associated with recycled wool processes. Table 14, below, shows the relative impact of various parts of the recycled wool production process, in CO2-e.

Table 14.

Relative percentage of contribution to the final CO2-e for Recycled Wool production

Sorting (%)	Shredding/ Fibre Production (%) *	Yarn Production (%)	Fabric Production (%)	Use (%)	End of life (%)	Total	Unit	Notes	Source
65.6%			34.4%	OOS	OOS	100%	kg CO2/ m2	62% recycled wool, 38% nylon	Manteco
3.8%	4.5%	91.7%	OOS	OOS	OOS	100%	kg CO2/ kg yarn	100% recycled cashmere	Next Technology
0.6%	0.5%	98.9%	OOS	OOS	OOS	100%	kg CO2/ kg yarn	60% recycled cashmere, 40% virgin wool	Next Technology
22.5%		77.5%	OOS	OOS	OOS	100%	kg CO2/ kg yarn	70% recycled wool, 25% polyamide	Next Technology
28.3%		71.7%	OOS	OOS	OOS	100%	kg CO2/ kg yarn	70% recycled wool, 25% polyester	Next Technology
25.7%	74.3%	OOS	OOS	OOS	OOS	100%	kg CO2/ kg fibre	100% recycled wool (only post-consumer content)	Ergo Srl

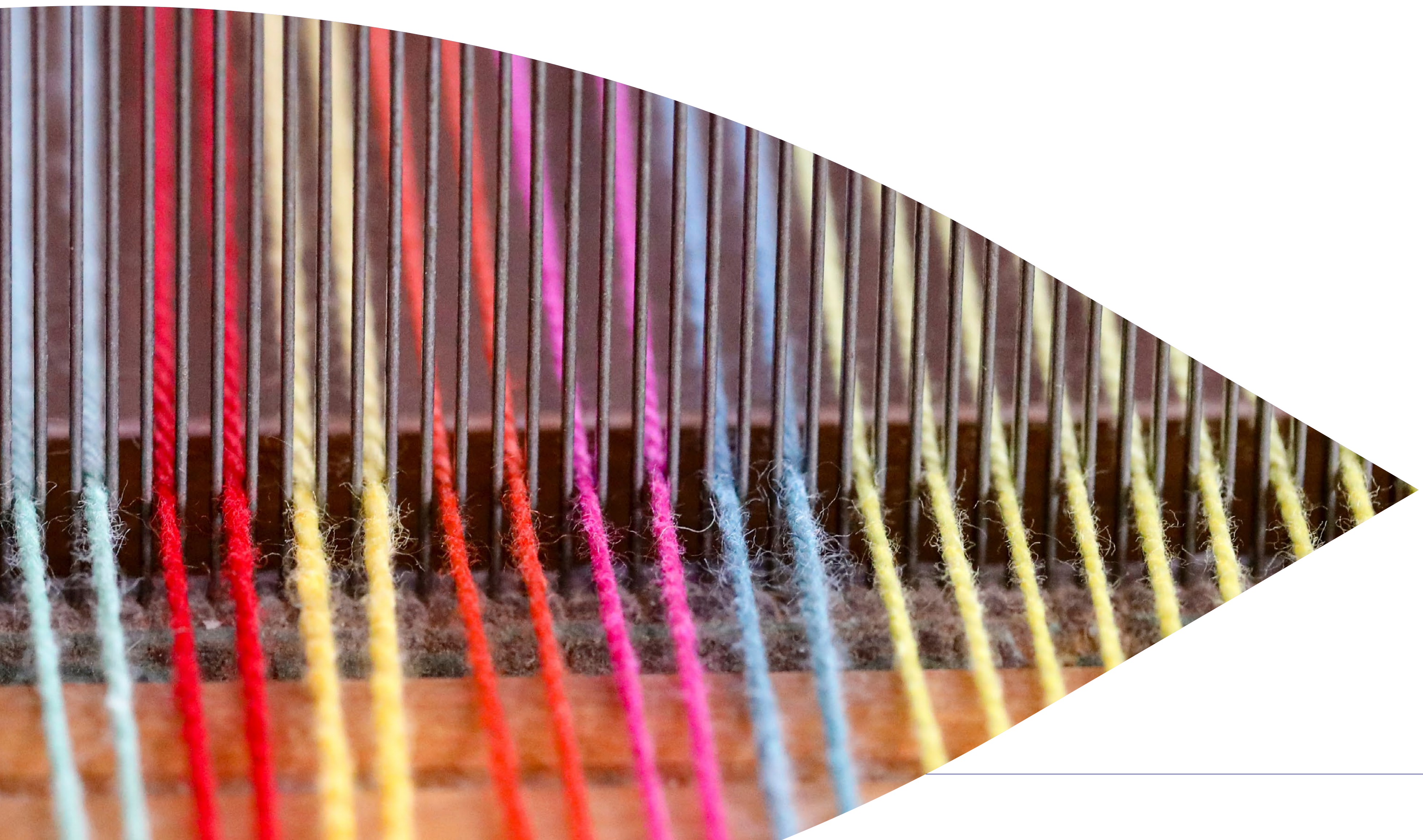
The main conclusions of contribution analyses of recycled wool production are as follows:

- The impacts relating to raw material sourcing for (i.e. fibre sorting, shredding/ fibre production, transport, spinning and winding) are the most important among the overall impact from fabric production, considering a wide range of yarns with different recycled wool and other material content (Manteco S.p.A., 2019). Break down and evaluation of unit processes for the stages up to yarn production are required to highlight the impact hotspots.
- Among the unit processes up to yarn production, the climate impacts of sorting and shredding are comparable. The relative climate impact of processes up to the recycled wool fibre production stage (e.g., sorting and shredding) depends on (1) raw material sourcing (e.g., pre-consumer, post-consumer), (2) transportation demands (e.g., country of origin and means of transportation), and (3) energy and material demands for shredding based on the method used.

It is important to note that recycled wool is not a substitute for virgin wool. There are limitations to its use due to fibre characteristics, blending requirement and other factors.

Recycled wool is normally blended with other fibres with a maximum recycled wool content of around 70 per cent.[164,165]

Most of the available LCA and carbon footprint studies and articles on recycled wool (Table 14) focus on in-facility processes (e.g., yarn production, fabric production) rather than raw material sourcing. Sorting and shredding, initial stages of raw material acquisition and preparation, are usually combined or looked at together with the yarn production stage. This limits the assessment of factors that contribute to the environmental impact of raw material sourcing and alternative strategies to reduce that impact.



5.2 Data gaps for recycled wool

5.2.1 Limited data and region-specific resources

There are few LCA and carbon footprint studies and articles on recycled wool. Most are also not publicly available and were provided by the task team for the review.

Most of the literature on recycled wool focused on Italy (district of Prato), which accounts for about 30 per cent of global production of recycled wool. The lack of literature on other producing regions significantly hampers evaluation of regional and processing variabilities in recycled wool carbon emissions and environmental impacts. India (city of Panipat in Haryana) and China are the other major production centres for recycled wool.[166] Future research should seek to evaluate the GHG emissions associated with the wool recycling processes in those regions.

5.2.2 Fragmentation of the production chain and variability of the collection

Stages in the supply chain of recycled wool fibres production may be outsourced to different companies for collection, sorting and shredding. There is a high potential variability in the specifications from company to company and from year to year (e.g., materials used, pre-consumer or post-consumer, sources of energy, on-site emissions). Consider the difference, for example, between transporting post-consumer materials from India to Prato in Italy and the same enterprise using pre-consumer fabric scraps sourced in Prato. The variability in GHG emissions from production of a similar product (e.g., 1m2 fabric) highlights the need to expand the body of research to evaluate the impact of different choices within the supply chain.

The sourcing and origin of raw materials could alter the impacts associated with recycled wool due to:

1) Differences in the required consequent production processes (further discussed in section 5.2.3); and

2) Differences in transportation requirements (distance and mode) from origin to processing facility.

Choiceof where the initial raw materials come from and where they are processed (sorting, shredding, etc.) will affect distance and mode transport. In the Next Technology studies, sea transport (from America) is assumed to the nearest port (8600 km), and then road transfer to the facility (600-700 km).[167] The Manteco report[168] assumes 10,000 km of sea transport and 300 km of land transport to bring raw material to the sorting facility (representing 20 per cent of the total raw materials used in the facility process). In the Ergo Srl report,[169] raw materials originate from different countries (India 60%, Pakistan 10%, Europe except Italy 10%, and Italy 10%). Means of transport used are road transport (963 km) from Europe and Italy and ship transport (5970 km) from India and Pakistan (adapted from Ecoinvent 3.6).

Variations in transportation requirements could have a significant effect on the GHG emissions associated with recycled wool sourcing. Further focused research is required to evaluate scenarios where the production facilities are in other countries (outside the district of Prato, Italy), and the raw materials are sourced from other countries. The results of such research could help optimize the supply chain of recycled wool and reduce climate impacts.

5.2.3 Raw material source type (i.e., pre-consumer and post-consumer)

Raw material for recycled wool can be sourced from pre-consumer and post-consumer recycled material. Because it can be difficult to produce specific colour shades or meet yarn/fabric quality criteria using 100 per cent recycled wool, most yarn and/or fabrics made from recycled wool will contain some percentage of virgin wool or other virgin fibres, such as cotton, polyester and nylon.[170] For example, the main part of recycled wool portion in Bi Bye TD fabric[171] is sourced from a mix of pre-consumer and post-consumer wool (about 50% post-consumer wool, 12% pre-consumer wool, 38% nylon). Fibre blend is not specified in the Next Technology reports.[172] The Ergo Srl's report only considers post-consumer recycled materials (100% post-consumer wool) as the raw material.[173]

In life cycle assessments, various allocation approaches have been described for partitioning the impacts between product life cycles. This analysis follows the recycled content allocation approach (also known as the 100-0 cut off method), whereby system inputs with recycled content do not receive any burden from the previous life cycle other than reprocessing of the waste material. Therefore, no environmental impact is allocated to the pre-consumer and post-consumer waste that is used as recycled wool material. However, the sourcing of recycled wool content, from post-consumer or pre-consumer recycled sources, can affect the carbon footprint of the resulting products due to the changes in production processes, including (1) potentially eliminating mechanical shredding in the case for pre-consumer recycled materials,[174] (2) reducing sorting requirements for pre-consumer recycled materials (as there are no labels, buttons, or zippers to remove), and (3) potentially reducing or removing the need for dyeing. Future research effort should focus on the influence of raw material sourcing on the GHG emissions associated with recycled wool production systems. In addition, looking at the potential other benefits associated with recycled wool feedstock choice (i.e., pre-consumer and post-consumer sources) beyond GHG reduction could be useful.

5.2.4 Shredding stage

After sorting, recycled material is shredded, which requires input of (1) energy (typically electricity), (2) water, and (3) chemicals.[175] The amount and type of input at this stage depends on the provenance of the raw material (e.g., pre-consumer or post-consumer) and downstream fabric production processes (e.g., applied wet processes after the spinning stage).

None of the reviewed studies and articles provided a detailed look at the quantified GHG impacts associated with these key factors in the shredding stage. Future research should expand knowledge on the contribution of each inventory parameter to the total impact of the shredding stage and how input may vary among different processors.

5.3 Mitigation Strategies for recycled wool

Analysis of the literature on recycled wool highlights the lack of disaggregated data upon which to determine the key GHG hotspots in the production of recycled wool fibres. Life cycle assessment and carbon footprint studies tend to aggregate the sorting, transportation and shredding phases, combining their environmental impact into a single phase.

With the reports listed in Table 9, no hotspots can be identified in the production stage of recycled wool fibres. Despite the lack of regional, detailed and disaggregated studies on recycled material sourcing, the following recommendations can be made:

- Reduce GHG emissions associated with raw materials sourcing by minimizing the distance between sorting and subsequent facility processes (e.g., shredding as next stage); and
- Reduce GHG emissions from shredding by powering facilities with renewable energy (e.g., electricity from a grid with a higher share of renewables).

6. Findings for Silk

6.1 Data Gaps

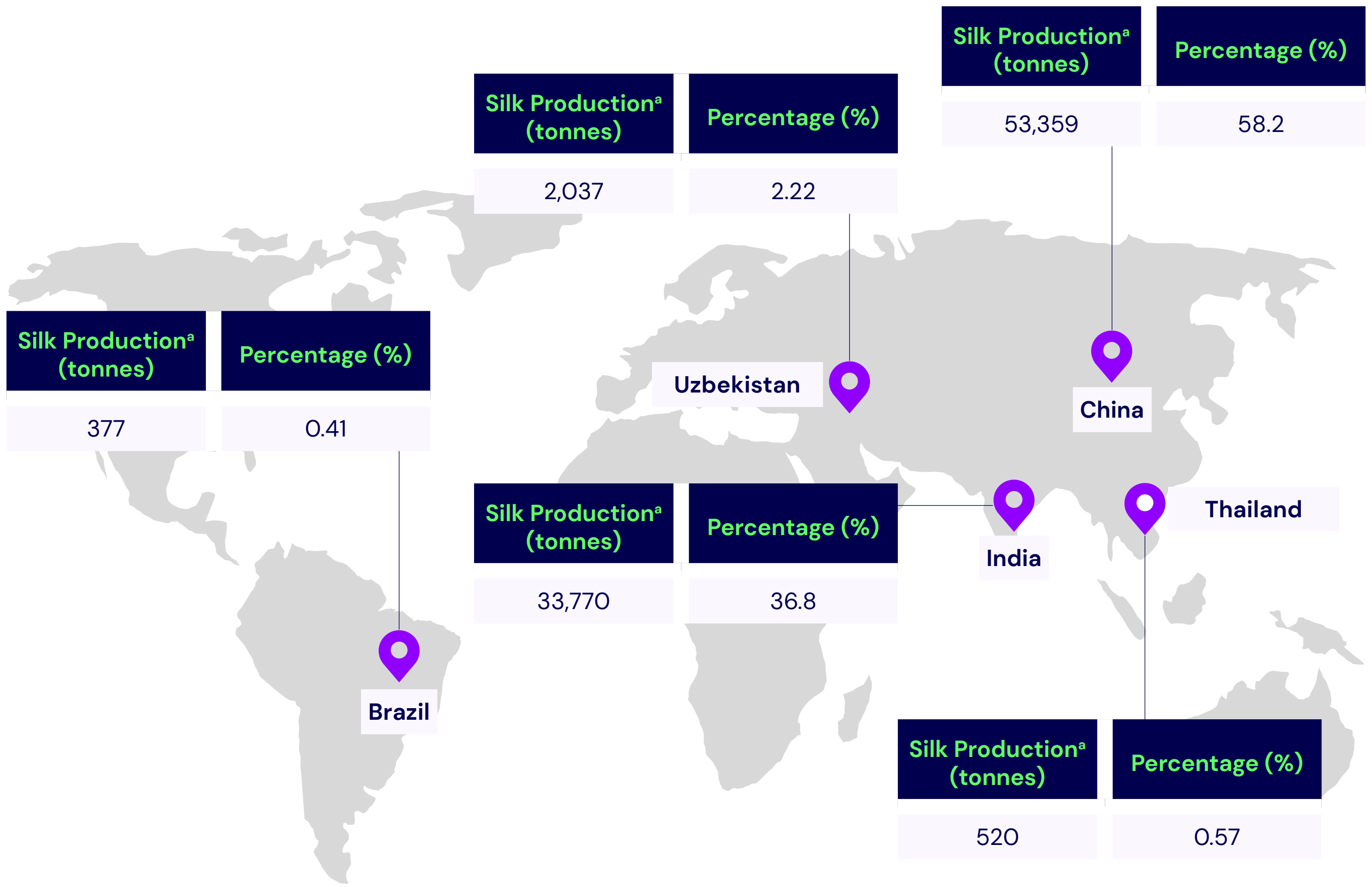
6.1.1 Lack of regional variability in available data

Silk is produced in some 60 countries;[176] however, few LCA and carbon footprint studies are available and these are based on production systems in the major producing countries (e.g., India, Brazil and China). Bhalla, et al.,[177] and Astudillo, et al.,[178] performed LCAs of silk production in India.

Ecoinvent datasets (e.g., cocoon production, silkworm rearing, reeled raw silk hank production) represent production supply chains in India. The silk fabric production pathways evaluated in an LCA by EcoTextileNews represent cultivation in China. Barcelos, et al.,[179] analysed the environmental impacts of cocoon production (with packaging) in Brazil.

Table 15.

Top five silk producing countries based on 2020 data from the International Sericultural Commission, in tonnes and per cent.



[a] Based on 2020 data, International sericultural comwmission, https://inserco.org/en/statistics

6.1.2 Lack of data on using other silk types

More than 90 per cent of commercial silk is produced using the domesticated silkworm "Bombyx mory". The insect's diet is restricted to the leaves of white mulberries, Morus alba, and Morus indica.[180] All studies and articles reviewed for this report evaluated the impact of such mulberry silk production. However, other types of silk, produced by various silkworms (e.g., Tussar, Eri, and Muga) that feed on various types of leaves is produced globally.[181] Production of different silk types can have different fertilization (for production of leaves to feed the silkworms) and production needs. Consequently, this can lead to varying efficiencies in terms of leaves-to-cocoon conversion among different silk-type production supply chains. It is important to mention that other factors, such as climate, soil condition and input demand (e.g., herbicides, insecticides, fungicides), can also influence a farmer's choice of type of silk production.[182 183]

Further evaluation of differences in efficiency between silk types, and their ultimate effect on the products and co-products (see section 6.3.2), is needed to determine the impact of silk type selection on GHG emissions. This is especially important because production of leaves for feed is as an environmental impact hotspot for silk production in some studies (see section 6.2 on contribution analysis).

6.1..3 Effect of silk production on land-use change

The studies and articles reviewed did not account for the effect of raw silk production on land use and land-use change. For example, Astudillo et al. 2014[184] assumed that the biomass required for the harvest is sustainably sourced and no direct land-use change was observed over the prior decade (2001-2011[185]) due to silk production. Further research is required to assess the impact of silk production (including upstream processes) on land-use change and the consequent effect on total carbon emissions associated with silk production.

6.2 Contribution analysis across articles and reports

An analysis of available LCA and carbon footprint studies was carried out to determine the relative contributions of the various stages of silk production to total CO2-e. The in-scope life-cycle stages (provision of raw materials) were categorized as plant production, sericulture (silkworm rearing), degumming and reeling, and wet processing and weaving. Results are summarized in Table 16.

Table 16.

Relative percentage of contribution to the final CO2-e for silk production.

Plant Production	Sericulture	Degumming & Reeling	Wet Processing & Weaving	Processing	Use	End of life	Total	Units	Notes	Source
36%	N/S	N/S	30%	30%	26%	OOS	100%	kgCO2/kg woven silk	Power loom Silk Weaving	Bhalla et al., 2020
51%	N/S	N/S	0%	12%	37%	OOS	100%	kgCO2/kg woven silk	Handloom Silk Weaving	Bhalla et al., 2020
56%	26%	18%	OOS	OOS	OOS	OOS	100%	kgCO2/kg raw silk	Impacts based on using recommended practices. Plant production is quantified as: field emissions + irrigation + urea production, and sericulture as field operations + composting + other.	Astudillo et al., 2014
54%	46%	OOS	OOS	OOS	OOS	OOS	100%	kgCO2/kg cocoon	Final products include packaging.	Barcelos et al., 2020
100%				OOS	OOS	OOS	100%	kg CO2/kg printed silk fabric	Average of three different dyeing paths	Ecotextile-News

N/S: Not specified; OOS: Out of Scope (in the investigated study).

Plant Production	Sericulture	Degumming & Reeling	Wet Processing & Weaving	Processing	Use	End of life	Total	Units	Notes	Source
24%			56%	20%	OOS	OOS	100%	kg CO_2/m2 printed silk fabric	Only electricity demands are included for the stages of mulberry cultivation, sericulture and weaving	T.R.A.C.C.I.A. LCA
83%	17%	OOS	OOS	OOS	OOS	OOS	100%	kg CO_2/kg cocoon	This dataset represents the production of 65 kg of cocoons from 100 disease-free layings.	Ecoinvent 3.7.1

- In Bhalla, et al. (2020),[186] in which sericulture and reeling impacts were not quantified, the mulberry cultivation stage had the highest CO_2-eq emissions based on both handloom and power loom production methods, mainly the result of fertilizer and herbicide.
- Astudillo, et al.[187] incorporated the impacts associated with cocoon production and showed that most environmental impact, including GHG emissions, stem from fertilizer application.
- In Barcelos, et al.,[188] impacts from mulberry production and cocoon production (sericulture) were quantified.
  - Mulberry production showed slightly greater climate impact than did cocoon production;
  - The highest contributors to GHG emissions in plant production were identified as: (a) use of organic fertilizer (poultry manure), (b) transport of organic fertilizer, (c) upstream impacts from production of single superphosphate used in the farm, and (d) upstream impacts from production of lime used in the farm;
  - The GHG hotspots in cocoon production were identified as (a) transport of mulberry leaves to feed silkworms, (b) production of the Kraft paper (used as covering during silkworm feeding and reeling to maintain a stable temperature), and (c) upstream emissions from the production of electricity used on the farm.
- Based on the Ecoinvent dataset for "cocoon production, silkworm rearing" (v 3.7) and IPCC 2021 (assessment report 6, GWP-100):
  - Production of the mulberry leaves (23 kg leaves per kg cocoons) results in higher GHG emissions than does sericulture;
  - The highest contributors to GHG emissions from plant production were identified as: (a) direct farm emissions (emissions from fertilizers and lime application, and crop residue decomposition), (b) waste wood (decomposition of generated wood waste), and (c) upstream emissions from the production of fertilizer used;
  - The highest contributors to GHG emissions from cocoon production (excluding plant production) were identified as: (a) hall building, (b) biowaste treatment and disposal (organic waste produced during rearing process), and (c) production of electricity used on the farm.

6.3 Potential strategies to reduce the carbon footprint

A summary of key GHG emission mitigation strategies for silk production based on the studies and articles reviewed is presented in Table 17. Further explanation is provided in the following sub-sections.

Table 17.

Key proposed strategies to reduce/limit greenhouse gas emissions in silk production.

Strategy	Target Life Cycle Stage	Impact on the Targeted Life Cycle Stage CO_2-eq	Impact on overall Life Cycle's CO_2-eq	Incorporated Life Cycle Stages within System Boundary	Source
Applying government-recommended fertilization practices to provide adequate nutrition requirements for mulberry plant production	Plant production	reduction	reduction	• Mulberry cultivation • Egg production • Silkworm rearing* • Transport of inputs • Silk rearing	Astudillo et al., 2014
Use of stems as firewood as opposed to compost	Plant production	reduction	reduction	• Mulberry cultivation • Egg production • Silkworm rearing* • Transport of inputs • Silk rearing	Astudillo et al., 2014
Replacement of raffia package with jute package to pack the cocoon for sale	Sericulture	increase	increase	• Plant production • Cocoon production	Barcelos et al., 2020
Replacement of raffia package with cotton package to pack the cocoon for sale	Sericulture	increase	increase	• Plant production • Cocoon production	Barcelos et al., 2020

Strategy	Target Life Cycle Stage	Impact on the Targeted Life Cycle Stage CO2-eq	Impact on overall Life Cycle's CO2-eq	Incorporated Life Cycle Stages within System Boundary	Source
Replacement of Incandescent light bulbs with LED light bulbs in the barn	Sericulture	reduction	reduction	• Plant production • Cocoon production	Barcelos et al., 2020
The substitution of Kraft paper (for covering silkworms during feeding/ reeling) with newsprint, nonwoven fabric, or lightweight breathable fabric	Sericulture	reduction	reduction	• Plant production • Cocoon production	Barcelos et al., 2020
Replacing diesel with biogas tractor, micro tractor, or horse cart	Sericulture	reduction	reduction	• Plant production • Cocoon production	Barcelos et al., 2020
Organic agriculture (to reduce fertilizer and herbicide impacts)	Plant production	reduction	reduction	• Plant production • Cocoon production	Barcelos et al., 2020
Optimizing the use of leaves waste (during cutting), and the remains of the rearing beds (mulberry stems, dry leaves, silkworm litter)	Plant production & Cocoon production	reduction	reduction	• Plant production • Cocoon production	Barcelos et al., 2020

*** Egg production and silkworm rearing are included as sericulture in this analysis.**

6.3.1 Farming practices

Astudillo, et al., (2014)[189] evaluated the environmental impacts of 1 kg raw silk production in India, using recommended practices (government guidelines) and current practices (based on survey of monobivoltine[190] cocoon production in Dharmapuri district). In current practice, farmers tend to not provide optimized nutrition requirements. Consequently, leaf yield is lower compared to production using recommended practices (78% mulberry capacity of utilization to 95% mulberry capacity of utilization; capacity of utilization refers to the percentage of mulberry used for rearing.).

The significant divergence of farm practices from recommended practices has led to higher observed impacts per unit kg of raw silk produced. Adequate manure management and changes in fertilization practices could significantly reduce GHG emissions by increasing leaf yield in the plant production stage .

6.3.2 Increase the productivity (products and co-products)

Co-products of mulberry production include leaves unsuitable for silkworms, mulberry stems and rearing waste (compostable), which are commonly used as fodder, fuel and fertilizer.[191]

Co-products generated in reeling are unreelable waste silk, pupae and sericin.[192] The pupae and sericin have insignificant market value.

Astudillo, et al., (2014)[193] provides results based on both economic allocation and system expansion, and compared these against the "no allocation" approach (all burdens attributed to raw silk). Under both allocation approaches, environmental impact was reduced by accounting for use of co-products (i.e., mulberry stems as compost and firewood). The study found that final quantified GHG emissions can change from about 5% to 28% compared to the "no-allocation" scenario, depending on the allocation approach (economic allocation or system expansion) and assuming co-product utilization.

Based on the sensitivity analysis performed in Astudillo, at al.,[194] the most sensitive factors for GHG emissions (based on 10 per cent change in production parameters) were: (a) reeling efficiency, (b) required feed, (c) cocoon yield, and (d) mulberry yield. Given the relatively low value of co-products, changes in the efficiency of cocoon conversion into raw silk have a large observed effect. Therefore, future efforts could prioritize efficiency improvements of processes within the raw silk supply chain from cocoon production to raw silk (i.e., mulberry leaves to cocoon and cocoon to raw silk conversion).

6.3.3 Fertilization management

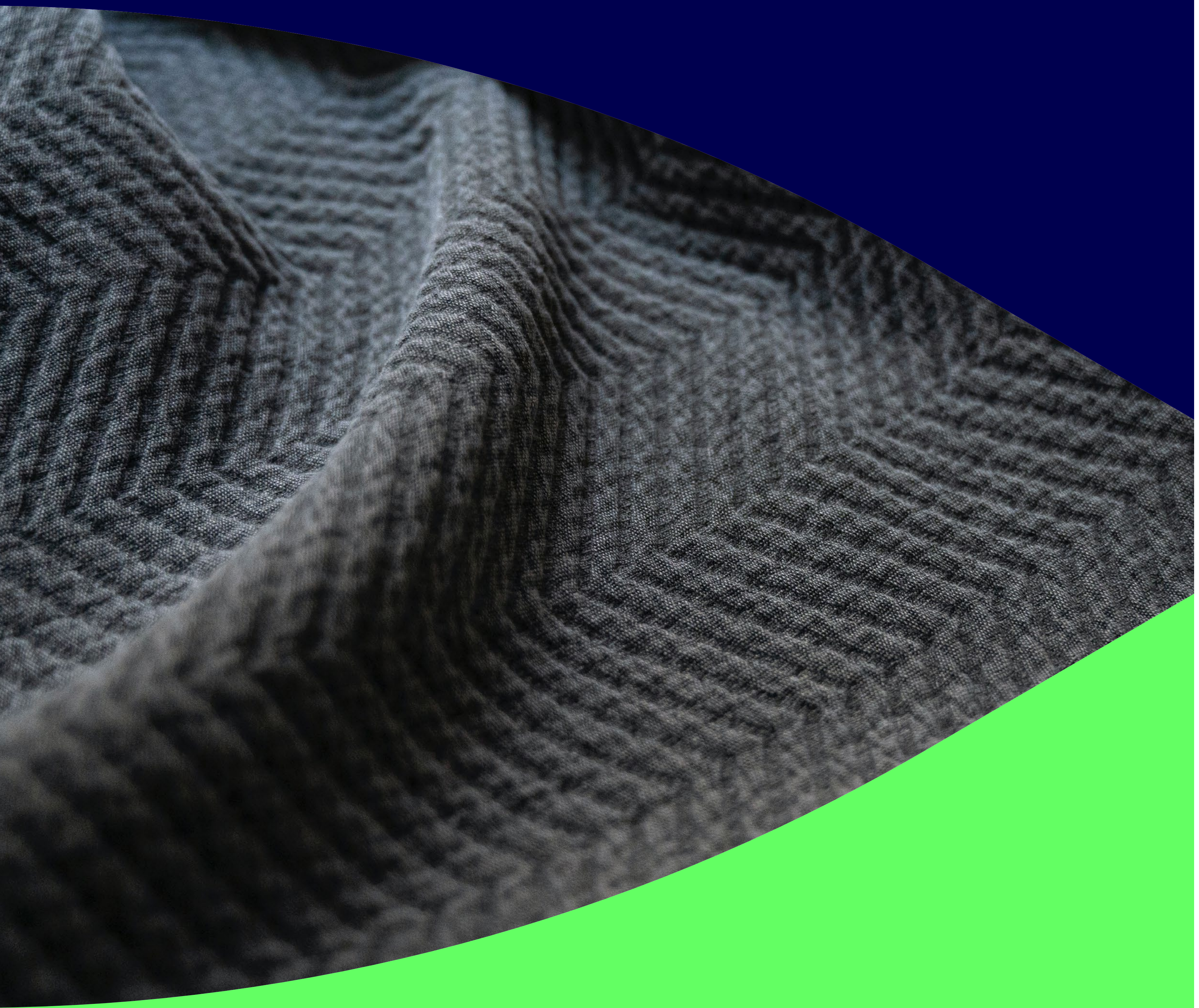
Based on Astudillo, et al.,[195] most GHG emissions from silk production are related to high levels of fertilizer and manure use. Fertilizer use also showed a significant contribution to plant-production stage impacts in Barcelos, et al., (2020).[196] Strategies to improve fertilizer use on the farm include: fertilizer application based on soil testing (especially N demand), more effective use of bio-degradable waste on farm (e.g., using vermicomposting, a decomposition process using various species of worms, to create a compost material) or anaerobic digestion (breakdown of organic materials in the absence of oxygen by bacteria to produce biogas), adequate manure management, and the use of techniques that reduce the need for synthetic fertilizers.

6.3.4 Other potential mitigation strategies

Other potential mitigation strategies suggested in the literature to reduce GHG emissions from raw silk production include:

- Use of solar dryers for silkworm cocoon: solar dryers can reduce the electricity requirements 10-fold compared to using electric dryers;
- Use of more efficient cocoon boilers to reduce energy demand.

7. Conclusions



Summary

A summary of key conclusions for virgin animal-based fibres, recycled wool, and silk is presented below:

- Methane emitted from animals (enteric fermentation and manure) accounts for most of the climate change impact from virgin animal-based fibre production (>80% in investigated studies). IPCC equations and methane emission factors for enteric fermentation are key parameters in the assessment of GHG emissions for animal fibres production.
- The choice of allocation approach greatly affects the greenhouse gas impact from virgin animal fibre production. For example, different approaches to the allocation between greasy wool and liveweight sheep can change the wool carbon footprint by a factor of three.
- Results for silk demonstrated that the yield of leaves usable as silkworm feed and the rate of conversion of leaves to cocoons are the determinant factors in calculating the carbon footprint of raw silk production. Yields vary depending on farming practices, climatic conditions, fertilizer use, etc.
- The climate impact of materials sourcing processes for recycled wool depends on: (1) raw material sourcing (e.g., pre-consumer, post-consumer), (2) transportation demands (e.g., country of origin and the means of transportation), and (3) energy and material demand for shredding/fibre production based on the in-facility method used. The initial stages of raw material acquisition and preparation, sorting and shredding, are usually integrated or placed in the yarn production stage for GHG calculations. This limits the assessment of factors that contribute to the GHG emissions of recycled wool sourcing and finding strategies to reduce them.

Furthermore, major methodological issues or gaps were identified in the investigated studies and articles. These issues need to be addressed in future efforts to provide a better understanding of the climate change impacts from animal-based fibres. These efforts should include:

- Use of a consistent, transparent and standard allocation approach (e.g., using IWTO LCA guidelines) to quantify allocation of GHG emissions between the co-products of animal-based fibre production (e.g., wool, liveweight);
- Development of robust criteria to incorporate GHG emissions and removals associated with land use and land-use change in calculating the climate impact of animal-based fibre and silk production systems;
- Expansion of LCA and carbon footprint studies to include: (1) more animal species and breeds, (2) different regions with varying characteristics with respect to farming practices, climate and soil conditions, (3) different production systems, (4) models based on direct data from production systems, and (5) studies including land-use emissions and removals through the assessment of carbon pools.

Table 18.

Referencing of finding topics in studies and articles about the climate impact of virgin wool and hair fibre production—Findings from the studies and articles referenced in this report.

Study author, year	Title	Goal of study	Finding topics
Wiedemann et al., 2015	Application of life cycle assessment to sheep production systems: investigating co-production of wool and meat using case studies from major global producers	Investigating alternative approaches for handling co-production of wool and live weight from dual-purpose sheep systems	• Importance of choice of methods for allocations • Importance of explicit explanation of allocation methods • Protein mass allocation method as simplified method for biophysical allocation
Wiedemann et al., 2016	Resource use and greenhouse gas emissions from three wool production regions in Australia	Producing a benchmark of GHG emissions for three types of Australian Merino wool	• Wool productivity per breeding ewe for emissions reduction • Importance of land use and land-use change inclusion in carbon footprint measurement.
Wiedemann et al., 2020	Environmental impacts associated with the production, use, and end-of-life of a woolen garment	Identifying impacts associated with using a woolen sweater, including all stages of the value chain	• Importance of methane mitigation strategies and research and development • Possibility of carbon neutrality for grazing systems
Barber & Pellow, 2006	LCA: New Zealand Merino wool total energy use	Developing a detailed inventory of energy use for New Zealand Merino wool	OOS
Brent & Hietkamp, 2003	Comparative evaluation of life cycle impact assessment methods with a South African case study	Evaluating and comparing the applicability of European LCIA procedures within the South African context	OOS
Brock et al., 2013	Greenhouse gas emissions profile for 1 kg of wool produced in the Yass Region, New South Wales: A Life Cycle Assessment approach	Determining the emissions profile and carbon footprint of 19-micron wool produced in the Yass region in New South Wales (Australia). Addressing methodological issues and results variability	• Contribution analysis • Variability from use of different allocation methods • Optimization of pasture production and wool yield • Enteric methane reduction with livestock management: average stock numbers reduction while maintaining production • Culling vs joining flock, improved reproductive genetics, increasing ewe longevity
Van de Vreede & Sevenster, 2010	Lifecycle environmental impact assessment of textiles, For priority streams in Dutch lifecycle-based waste policy	Assessing the environmental impact of Dutch textiles throughput covering the entire life cycle. Identifying potential environmental improvements	OOS
Laitala et al., 2018	Does Use Matter? Comparison of Environmental Impacts of Clothing Based on Fiber Type	Assessing the environmental impact of Dutch textiles throughput covering the entire life cycle. Identifying potential environmental improvements	OOS
Ecoinvent (database)	sheep production, for wool | sheep fleece in the grease	Not Applicable	Not Applicable
Cardoso, 2013	Life cycle assessment of two textile products wool and cotton	Assessing the environmental burdens associated with different life cycle stages of dyed yarns (cotton and wool)	OOS
Peri et al., 2020	Carbon Footprint of Lamb and Wool Production at Farm Gate and the Regional Scale in Southern Patagonia	determining the carbon footprints (CF) of sheep meat and wool on a range of farms	• Contribution analysis • Land use inclusion • Grassland and grazing practices management • Productivity increase • Genetics/breeding, herd management, lamb survival, feed efficiency, grass digestibility, rumen modifiers decreasing methane production (biochar-based supplements)
Nolimal & Klimas, 2018	Life Cycle Assessment of Four Different Sweaters	Providing consumers with information they may use to alter their habits	OOS
Fishwick, 2012	A Carbon Footprint for UK Clothing and Opportunities for Savings	Providing an overview of the carbon impacts of UK clothing life cycle, identifying contributions, and quantifying opportunities for reduction	OOS
Emanuele, 2017	Application of Life Cycle Assessment to a Wool Sweater: A Case Study	Evaluating the application of the LCA methodology in order to obtain a tool to support the company's environmental policy	OOS

Study author, year	Title	Goal of study	Finding topics
Wiedemann et al., 2021	Reducing environmental impacts from garments through best practice garment use and care, using the example of a Merino wool sweater	Examining the potential for consumers to reduce the environmental impacts of a wool garment worn in Western Europe	OOS
The Schneider Group	Environmental Benchmark Summary Report – 2019 and 2020	Tracking environmental performance annually, Benchmarking carbon footprint	OOS
Biswas et al., 2010	Global warming contributions from wheat, sheep meat and wool production	Comparing the life cycle global warming performance of wheat, sheep meat and wool	• Contribution analysis • Enteric fermentation reduction through forage quality, feed efficiency, research with vaccines, acetogen bacteria, feed additives, and selective breeding
Pelcan, PUCP Dueñas et al., 2021 (a)	Analysis, Measurement, Interpretation of the environmental footprint of the alpaca value chain under life cycle analysis (a)	Analysing and calculating the environmental impact of the alpaca fibre life cycle. Contributing to the sustainability and competitiveness of the business sector	• Contribution analysis • Shearing practices: percentage of sheared alpacas
Pelcan, PUCP Dueñas et al., 2021 (b)	Analysis, Measurement, Interpretation of the environmental footprint of the alpaca value chain under life cycle analysis (a)	Identifying and analysing the environmental impact at each life cycle stage of the alpaca fibre sweater	• Shearing practices: percentage of sheared alpacas • Increase fleece yield per animal and per herd
Devaux, 2019	Wool Production – Systematic review of Life Cycle Assessment studies	Understanding key environmental impact of wool and limitations to wool LCA: methodological choices and key elements to consider	• Sensitivity to allocation methods • Contribution analysis • Low inclusion of land use across studies (data gap)
Henri, 2012	Understanding the environmental impacts of wool: A review of Life Cycle Assessment studies	Evaluating available wool LCAs, Assessing the validity of current comparative analyses, and identifying potential future improvements, Providing information to support better communication about wool relative to alternative products	• Lack of consistency across studies for allocation method, and land use inclusion • Lack of quality primary data to develop quality studies

Table note: Findings driven from the analysis of multiple studies are not referenced in this table.

Table 19.

Referencing of findings topics in studies and articles about the climate impact of recycled wool fibre production

Study author, year	Title	Goal of study	Finding topics
Made Green in Italy, 2021	Screening study for carded wool or fine hair fabrics	To support the development of Product Category Rules for tissues in carded wool or fine hairs within the scheme of Made Green in Italy	• Contribution analysis
Next Technology, year unknown	Environmental footprint study for the production of 1 kg yarn made by Recycled Cashmere vs Virgin material	To determine the environmental impact related to the production of 1 kg of yarn from recycled Cashmere compared to virgin raw material	• Contribution analysis
Next Technology, year unknown	Environmental footprint study Yarn wool-polyamide	To evaluate the environmental impact of 1 kg of yarn wool/polyamide mixed (composition 70% WO, 25% PA, 5% other fibres)	• Contribution analysis
Next Technology, year unknown	Environmental footprint study Yarn wool-polyester	To evaluate the environmental impact of 1 kg of yarn wool/polyester mixed (composition WO 75% PL 20% other fibres 5%)	• Contribution analysis
Ergo Srl, unknown	Recycled Wool environmental footprint	To perform a life cycle assessment of recycled wool (wool fibre produced from raw material from post-production or post-consumer)	• Contribution analysis

Table note: Findings driven from the analysis of multiple studies are not referenced in this table.

Table 20.

Referencing of findings topics in studies and articles about the climate impact of silk fibre production

Study author, year	Title	Goal of study	Finding topics
Ecotextile News, year unknown	The Life Cycle of Luxury – Italian Silk Shows Its Green Credentials	To assess the environmental credentials of mulberry silk used in Italian silk yarns and fabrics	OOS
Scuola Superiore Saint'Anna, 2020	Product Environmental Footprint report	To analyse the environmental footprint from cradle to gate of the two products (namely printed silk fabric and yarn-dyed polyester fabric)	• Contribution analysis
Astudillo et al., 2014	Life cycle assessment of Indian silk	To analyse Indian production under recommended and observed practices and identify potential improvements	• Contribution analysis • Fertilization programme • Use of mulberry tree co-product
Bhalla et al., 2020	Life Cycle Assessment of Traditional Handloom Silk as Against Power-loom Silks: A Comparison of Socio-economic and Environmental Impacts	To quantitatively analyse the production process of silk fabric and infer the most energy-consuming and emitting stages; and to propose solutions to make the whole production process environment- and resource-friendly	• Contribution analysis
Fishwick, 2012	A Carbon Footprint for UK Clothing and Opportunities for Savings	To provide an overview of the carbon impacts of UK clothing life cycle, identifying contributions and quantifying opportunities for reduction	OOS
Ecoinvent v3.7	mulberry production | mulberry leaves cocoon production, silkworm rearing | cocoons reeled raw silk hank production | reeled raw silk hank	To provide a dataset	Not applicable
Barcelos et al., 2020	Opportunities for Improving the Environmental Profile of Silk Cocoon Production under Brazilian Conditions	To identify opportunities to improve the environmental profile of mulberry and silk cocoon production under Brazilian conditions	• Contribution analysis • Packaging material for cocoons • Energy use reduction and fuel replacement at the sericulture stage Fertilizers and pesticides optimization at the tree production stage • Co-products and wastes management

Table note: Findings driven from the analysis of multiple studies are not referenced in this table.

Call for action

For farmers, buyers and supply chain stakeholders

Animal fibre production systems are multi-purpose production systems, with multiple co-products. It is shown that the allocation of impacts between fibre and the other co-products of the production system can significantly influence the carbon footprint value, highlighting the importance of co-products utilization. Effective marketing and use of farm co-products (e.g., liveweight) are essential for farmers and other supply chain stakeholders to prevent waste and reduce GHG impact per unit of product and co-product.

Improvement in the average yield of alpaca, Cashmere goat and Angora goat fibre per animal within the herd can reduce climate impact per unit of animal fibre.

For all land-based production systems, strategies to increase carbon pools have a direct impact on the carbon footprint of fibres through the reporting of land use emissions. Such strategies could include rotational grazing or biomass restoration.

Buyers and supply chain stakeholders can explore direct relationships and long-term contracts with raw fibres producers to help implement some of the changes recommended above. Buyers and supply chain stakeholders can consider investing in carbon footprint measurement and analysis.

For study commissioners and practitioners

The choice of enteric methane emission factors can significantly affect the carbon footprint measurement of virgin animal fibre production. For transparency, studies and articles should disclose the methane conversion emission factors they use, on a per head per year basis by type of livestock (under one year, youngster, adult female, adult male). To address the most important contributor to virgin animal-based fibre production climate impact, more research is needed on two aspects of enteric fermentation emissions: (1) on development of Tier 2 and Tier 3 emission factors – specifically for alpacas, Cashmere goats, and Angora goats, and (2) on enteric fermentation reductions.

To the extent of authors' knowledge, there is no LCA or carbon footprint study that applies data specific to cashmere and mohair. In addition, there is only one study (split into two reports based on the covered life cycle stages) that evaluates the environmental impacts of alpaca fibre production. Further research is essential to quantify the climate impact of animal fibre and silk production, covering more breeds and more regions of production.

Further research to evaluate the climate impact of recycled wool, with a focus on the initial stages of raw material sourcing, is essential to gain a better understanding on factors influencing the climate impact of materials sourcing.

Appendix

Table 21.

Review of the inclusion of enteric fermentation emissions within the cradle-to-gate life cycle assessment of raw wool, fibers and hair methodology and parameters

Study author and/or report company, year	Title	Inclusion of enteric fermentation calculations (Y/N)	Methodology of calculation	Parameters
Wiedemann et al., 2015	Application of life cycle assessment to sheep production systems: investigating co-production of wool and meat using case studies from major global producers	Y	Tier 2 • for UK and NZ: NZ GHG Inventory 1990-2006 • for Australia: Australia National Inventory Report 2010	• for UK and NZ: 0.0209 kg CH4/ kg DMI* • for Australia: 0.0204 kg CH4/ kg DMI (from the equation: kg DMI x 0.0188 + 0.00158)
Wiedemann et al., 2016	Resource use and greenhouse gas emissions from three wool production regions in Australia	Y	Tier 2 from National Inventory Report	kg DMI x 0.0188 + 0.00158
Wiedemann et al., 2020	Environmental impacts associated with the production, use, and end-of-life of a woolen garment	Uses Wiedemann et al, 2016 data	-	-
Barber & Pellow, 2006	LCA: New Zealand Merino wool total energy use	N	-	
Brent & Hietkamp, 2003	Comparative Evaluation of Life Cycle Impact Assessment Methods with a South African Case Study	N	-	-
Brock et al., 2013	Greenhouse gas emissions profile for 1 kg of wool produced in the Yass Region, New South Wales: A Life Cycle Assessment approach	Y	National Inventory Report equations NIR and IPCC compatible (Tier 2)	Inaccessible – calculations performed in software; parameters not shared

Study author and/or report company, year	Title	Inclusion of enteric fermentation calculations (Y/N)	Methodology of calculation	Parameters
Van de Vreede & Sevenster, 2010	Lifecycle environmental impact assessment of textiles, For priority streams in Dutch lifecycle-based waste policy, CE	Uses Ecoinvent data	-	-
Laitala et al., 2018	Lifecycle environmental impact assessment of textiles, For priority streams in Dutch lifecycle-based waste policy, CE	NA – Greasy wool not included in the scope of the study	-	-
Ecoinvent	Ecoinvent Database: sheep production, for wool | sheep fleece in the grease	Y	According to EPA 2006 - Inventory of US Greenhouse Gas Emissions and Sinks 1990-2004 (Tier 1)	7.96 kg CH4/ head/year
Cardoso, 2013	Life cycle assessment of two textile products wool and cotton	Y	IPCC 2006 (Tier 2)	8 kg CH4/stock unit/year
Peri et al., 2020	Carbon Footprint of Lamb and Wool Production at Farm Gate and the Regional Scale in Southern Patagonia	Y	IPCC 2006 (Tier not specified)	Only specifies parameter for lamb: 0.13 kg CH4 per head per year
Nolimal & Klimas, 2018	Life Cycle Assessment of Four Different Sweaters	Uses Ecoinvent data	-	-
Fishwick, 2012	A Carbon Footprint for UK Clothing and Opportunities for Savings	Uses Biswas et al, 2010 data	-	-
Emanuele, 2017	Application of Life Cycle Assessment to a Wool Sweater: A Case Study	Not specified	-	-
The Schneider Group	Environmental Benchmark Summary Report – 2019 and 2020	Not specified	-	-
Wiedemann et al., 2021	Reducing environmental impacts from garments through best practice garment use and care, using the example of a Merino wool sweater	Uses Wiedemann et al., 2016 data	-	-
Biswas et al., 2010	Global warming contributions from wheat, sheep meat and wool production	Y	Department of Climate Change 2006. Australian Government (Tier 2)	10.95 kg CH4 per head per year
Devaux, 2009	Wool Production, Systematic review of Life Cycle Assessment studies	NA – literature review	-	-
Henri, 2012	Understanding the environmental impacts of wool: a review of life cycle assessment studies	NA – literature review	-	-
Turley et al., 2009	The role and business case for existing and emerging fibers in sustainable clothing	NA – literature review	-	-
Pelcan, PUCP Dueñas et al., 2021 (a)	Analysis, measurement, interpretation of the environmental footprint of the alpaca value chain under life cycle analysis (a)	Y	IPCC, Quispe Chacón, 2017	17.7 g CH4 per alpaca per day (equivalent to 6.46 kg CH4 per head per year)
Pelcan, PUCP Dueñas et al., 2021 (b)	Analysis, measurement, interpretation of the environmental footprint of the alpaca value chain under life cycle analysis (b)	Uses Pelcan, PUCP, Dueñas et al., 2021 (a)		

***DMI: Dry Matter Intake**

Note: Parameters can be expressed either per head per unit of time, or per kg of DMI. Since the diets of animals vary depending on their breed, environment, age, productivity, physiological activity, etc., parameters expressed per kg of DMI cannot be expressed per head per unit of time.

Table 22.

Enteric fermentation emission factors in national greenhouse gas inventory reports for sheep, goats and alpacas.

Country and report year	Emission factor Tier	Enteric fermentation emission factor in kg CH4 per animal per year (unless specified otherwise)		
		Sheep	Goats	Alpacas
International 2006	Tier 1, IPCC 2006	• Developed countries: 8 • Developing countries: 5	5	8
International 2019	International 2019	Systems: • High Productivity: 9 • Low Productivity: 5	• High productivity systems: 9 • Low productivity systems: 5	8
Argentina, 2019	Tier 1, IPCC 2006	5	5	8
Australia, 2019	Sheep: Tier 2, IPCC 2006 Goats: Tier 1, IPCC 2006	6.8	5	NA
Bolivia, 1990-2000	Tier 2/3 by subregion and animal age	NA	NA	7-14.01
China, 2018	Tier 2, revised IPCC 1996	Calculated but not communicated	Calculated but not communicated	NA
India, 2021	Tier 2, based on type of feed and age of animal	10.84-13.5 g CH4 per kg DMI	10.5-12.5 g CH4 per kg DMI	NA
Mongolia, 2017	Tier 1, IPCC 2006	5	5	NA
Netherlands, 2021	Tier 1, IPCC 2006	8	5	NA
New Zealand, 1990-2019	Sheep: Tier 2, based on Swainson et al 2016 Goats and Alpacas: Tier 1	12.7	9	8
Peru, 2014	Estimated value based on Tier 1, adjusted with equation from IPCC 2000	NA	NA	8.5
South Africa, 2000-2015	Tier 2, equation 10.20, IPCC 2006, emission factors from Du Toit, et al., 2013	Commercial wool: • Merino: 8.07-14.7 • Karakul*: 5.02-10.5	Angora: 3.39-6.01	NA
Turkey, 1990-2019	Tier 1, IPCC 2006, adjusted for Merino sheep	Domestic: 5 Merino: 6.5	5	NA
United Kingdom, 1990-2019	Sheep: Tier 2/3 based on diet and animal age Goats: Tier 1	~4.69 kg CH4 per animal per year	5	NA
United States of America, 1990-2017	Tier 1, IPCC 2006	8	5	NA

*Karakul is another wool-producing sheep breed.

Note: Parameters can be expressed either per head per unit of time, or per kg of DMI. Since the diet of animals vary depending on their breed, environment, age, productivity, physiological activity, etc parameters expressed per kg of DMI cannot be expressed per head per unit of time

Endnotes

1 Enteric fermentation is the digestion process that takes place in the rumen of ruminants [FAO, LEAP definition]. Enteric fermentation is a microbial process that occurs in the digestive systems of animals. In particular, ruminant animals (cattle, buffalo, sheep, goats, and camels) have a large "fore-stomach" or rumen, within which microbial fermentation breaks down food into soluble products that can be utilized by the animal [US EPA, Greenhouse Gas Biogenic Sources]

2 About the Fashion Industry Charter for Climate Action [link]

3 https://www2.globalfashionagenda.com/commitment/#

4 Wu, Jennifer Xiaopei, and Li Li. "Sustainability initiatives in the fashion industry." In Fashion industry-An itinerary between feelings and technology. IntechOpen, 2019.

5 https://wrap.org.uk/taking-action/textiles/initiatives/scap-2020

6 Apparel and Footwear sector, Science-based targets guidance, Science based targets and World Resource Institute, 2019 **https://sciencebasedtargets.org/sectors/apparel-and-footwear**

7 https://sciencebasedtargets.org/companies-taking-action#table

8 Roadmap to net zero: delivering science-based targets in the apparel sector, World resources institute, 2021

9 https://unfccc.int/documents/273670

10 Here, global fiber production includes all types of fiber, not just production dedicated to the apparel, textiles, and footwear sectors.

11 https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

12 https://textileexchange.org/wp-content/uploads/2021/04/Textile-Exchange_Preferred-Fiber-Material-Market-Report_2020.pdf

13 https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

14 https://textileexchange.org/wp-content/uploads/2022/10/Textile-Exchange_PFMR_2022.pdf

15 Ibid

16 Ibid

17 https://iwto.org/wp-content/uploads/2022/04/IWTO-Market-Information-Sample-Edition-17.pdf

18 https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

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20 https://iwto.org/wool-supply-chain/history-of-wool/

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25 https://textileexchange.org/wp-content/uploads/2021/08/Textile-Exchange_Preferred-Fiber-and-Materials-Market-Report_2021.pdf

26 Historical greenhouse gas emissions, Climate Watch [link]

27 Synthesis Report on United Nations System-wide Initiatives related to Fashion, UN Alliance for Sustainable Fashion, 2021

28 United Nations, Facts and Figures, tab Fashion [link]

29 Fashion on climate – How the fashion industry can urgently act to reduce its greenhouse gas emissions, McKinsey & Company and Global Fashion Agenda, 2020

30 Roadmap to Net Zero: Delivering Science-Based Targets in the Apparel Sector, The World Resources Institute, 2021

31 Fashion on climate – How the fashion industry can urgently act to reduce its greenhouse gas emissions, McKinsey & Company and Global Fashion Agenda, 2020

32 Agriculture, Forestry and Other Land Use Emissions by Sources and Removals by Sinks, 1990-2011 Analysis, FAO, March 2014

33 Climate Watch declare 44.89 billion tons of CO_2e emissions in 2011, Historical greenhouse gas emissions, Climate Watch [link]

34 Tackling climate change through livestock - A global assessment of emissions and mitigation opportunities, FAO 2013.

35 Based on an economic allocation in the reference study.

36 Breakdown from Tackling climate change through livestock, FAO 2013, section 4.3 and table 7.

37 Data from 2011 published in FAO report assessing sheep and goat greenhouse gas emissions globally, in report published in 2013

38 Life Cycle Assessment of two textile products: Wool and Cotton, A. Cardoso; 2013

39 Wiedemann, Stephen G., Leo Biggs, Quan V. Nguyen, Simon J. Clarke, Kirsi Laitala, and Ingun G. Klepp. "Reducing environmental impacts from garments through best practice garment use and care, using the example of a Merino wool sweater." The International Journal of Life Cycle Assessment 26, no. 6 (2021): 1188-1197.

40 Bhalla, Kriti, Tarun Kumar, Jananee Rangaswamy, Ranjana Siva, and Vishal Mishra. "Life cycle assessment of traditional handloom silk as against power-loom silks: a comparison of socio-economic and environmental impacts." In Green Buildings and Sustainable Engineering, pp. 283-294. Springer, Singapore, 2020.

41 Wool Notes, IWTO

42 Greenhouse Gas Emissions and Fossil Energy Use from small ruminant supply chains, FAO, 2016, Appendix Table A4.1

43 Farmer's weekly, Join the Merino sheep & Wool Experts Society, 2017 [link]

44 Expert from the animal-based fiber task group: "In apparel wool from

Australia and New Zealand shearing every 6 to 8 months to get the exact staple lengths that deliver the best premiums is becoming more common. Where shearing is typically annual, shearing in August -right at the end of the winter, is common in Argentina, shearing in May/ June -early summer, common in the UK"

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