DIRT



THE CLIMATE AND AGRICULTURAL IMPACT OF TEXTILE PRODUCTION

With Gratitude

Authors; Clara Cecil, Megan Siyi Liu, Sam Fankhauser of Smith School of Enterprise and the Environment, University of Oxford.

Authors; Arizona Muse and Heleen Petzer of DIRT Charity.

Editorial & Production Lead; Lea Lorena Mahlke of DIRT Charity.

Academic Review Leads; Lucy Erickson and Dr Anupama Sen, Smith School of Enterprise and the Environment, University of Oxford.

The authors are grateful to reviewers at the Smith School of Enterprise and the Environment, University of Oxford, for their comments.

Media Relations and Communications; Eco Age

Powered by LOV. Foundation

DIRT

Creative Credits

Anton Corbijn
Fee-Gloria Grönemeyer
Natalie Karpushenko
Hasse Nielsen
Nouvelle
LOV. Foundation
Hen House
Director Josu Ortega
ALWA Production
ADDA Advanced Dance Institue Barcelona
Alisa Gulkanyan
Ezra Patchett
Artefact

A movement cannot live on *urgency* alone. It needs *beauty* to make the world it is moving towards *imaginable*.

DIRT

Contents

A Letter from Arizona Muse, Founder of DIRT Charity 01

Executive Summary 07

Author's Note 19

Introduction 22

Part 1: The Impact of Fashion-Related Agriculture 28

1. Environmental Impact by Fibre Type 32

1.1 Cotton 33

Box 1: Spotlight on Dyeing 48

1.2 Leather 53

Box 2: Mushroom Leather: A Sustainable Alternative? 68

1.3 Wood-Based Fibres (MMCFs) 72

1.4 Wool 82

1.5 Bast Fibres (Linen, Hemp) 95

1.6 Silk 106

1.7 Cashmere 115

2. Comparative Environmental Impact Assessment 127

Part 2: Biodynamic Agriculture: Scientific Assessment and Comparative Analysis 129

1. Methods of Sustainable Agriculture 131

1.1 Overview of Sustainable Agriculture 132

1.2 Organic Agriculture 135

1.3 Regenerative Agriculture 138

1.4 Biodynamic Agriculture 141

1.5 Other Sustainable Agriculture Methods 143

Contents

2. Scientific Evidence on Biodynamic Agriculture 145

2.1 Land Use & Soil Health 150

2.2 Chemical Intensity 159

2.3 Water Consumption 161

2.4 Greenhouse Gas Emissions 163

2.5 Waste and Compostability 166

Box 2.1: Case Study SEKEM Initiative Egyptian Cotton Production 168

3. Towards a Comprehensive Evidence Base 177

3.1 Methodological Considerations: The Systemic Nature of Agricultural Research 178

3.2 Research Gaps and Limitations 181

4. Conclusions & Future Directions 184

Conclusion 188

References 191

Appendices 193

Endnotes 195

With The Earth In Mind

A letter from Arizona Muse,
Founder of DIRT Charity

A Letter

From Arizona Muse

Founder of DIRT Charity

My instinct has always been to turn the torch toward the things most people walk past; the underdog, the overlooked, the foundational work that makes the shiny things possible. That is what this report is.

What you hold, or read, is the result of an unlikely and, I think, quietly historic collaboration: DIRT Charity, which I founded six years ago from a conviction that the fashion industry's roots needed tending, and the Smith School of Enterprise and the Environment at the University of Oxford, one of the most rigorous climate research institutions in the world. Together, we have pulled on a thread, literally, and followed it back through the supply chain to the soil itself.

The questions at the heart of this report are deceptively simple: How much of our land is growing wool? How many chemicals are being applied to cotton? And crucially, what would it look like to do this differently? To move, deliberately and systematically, toward regenerative agriculture, toward biodynamics, toward farming that gives back more than it takes? My path to Oxford began, as many important things do, through conversation and community. I first heard Mette Morsing, Head of the Smith School, speak at COP27 in Egypt, and I watched a room lean in. Her thinking was precise and her conviction contagious. Later, I sat beside her and Samuel Frankenhauser at an intimate fundraising dinner at the home of Howard and Veronika Covington, dear friends, long-time supporters, and now, with Howard as Chair, stewards of the university itself. In that room, across a dinner table, the seeds of this collaboration were quietly planted. What has grown from them is something I believe we will look back on as a turning point: a serious, evidenced, science-grounded conversation about the intersection of fashion, farming, and the future. It is a trio we have not historically seen much of. It is a trio that I believe is now essential.

At DIRT, the work has always been in the foundations. We are currently supporting the global development and adoption of the Demeter Textile Standards, the first move by Demeter, a hundred-year-old agricultural certification body with uncompromising standards, into fabric, into fibre, into dye.
This is not a trend. It is a reckoning.
And so I will end where I began: with the nuts and bolts. With the unglamorous, load-bearing, quietly revolutionary work that happens not on runways but in fields. Not in press releases but in soil samples and certification frameworks and supply chain audits. The future we need; regenerative, honest, alive, is not somewhere ahead of us. It is already being built, thread by thread.
Come with us. Read this report. Change how you dress. Support DIRT. Seek out Demeter-certified biodynamic. And trust, as I do, that the foundation is already there. We just have to choose to build on it.

Arizona Muse
Founder of DIRT Charity

DIRT

Turning Fashion Into a Climate Solution

dirt.charity

POWERED BY

lov.

LOV. Foundation is a non-profit organisation dedicated to fostering peace and collective transformation by connecting humanity through arts and culture. Guided by the belief that the arts have the power to shift societal beliefs and inspire unity, LOV. initiates public art projects, convenes summits promoting dialogue and mutual understanding, and produces art films that speak to the importance of nature preservation. Central to this work is the support of crafts and natural fibres, recognised as a primal source of both mental and physical human well-being. Working predominantly with women, LOV. advances a distinctly feminine approach to leadership, one that places empathy, collaboration, and inclusion at the heart of soft power.

Executive Summary

Textiles make up a significant and often underestimated aspect of global agriculture.

This report examines the environmental impacts of fashion-related agriculture across major natural textile fibres and explores the potential of sustainable farming systems to reduce environmental degradation within the fashion industry. This study is predominantly a literature review, synthesising academic research and industry reports to assess the environmental impacts of fashion-related agriculture.

Executive Summary

Our calculations find approximately 30% of all agricultural land worldwide is influenced by the fashion industry.

While textiles are not solely responsible for the entirety of this land use, it provides a broad quantification of the opportunity for positive change.

The review suggests that the current industry focus on the fraction of land-use that can be directly and solely attributed to textiles risks underestimating the power of the fashion industry, particularly given its global reach, consumer base and economic value.

Cotton accounts for the biggest share (44%) of natural textiles produced in 2023, followed by leather (28%), wood-based fibres (14%), wool (2%), linen (1%), silk (<1%), with livestock for leather and wool as major sources of environmental pressure.

Of the fibres produced, including those from recycled feedstock, approximately 50 percent are used for apparel, 25 percent for home textiles, and the rest on other uses (e.g., industrial products, technical products, medical products, footwear).

Natural textiles produced in 2023

44% Cotton

28% Leather

14% Wood-based fibres

Wool 2% • Linen 1% • Silk <1%

OF ALL FIBRES PRODUCED*

50% Apparel

25% Home Textiles

25% Other Uses

*Including recycled feedstock. Other uses include industrial, technical, medical and footwear applications.

Environmental Pressures

The environmental impact of textile agriculture and processing is particularly significant due to impacts on land use, chemical applications, water consumption, greenhouse gas emissions, and biodiversity and soil health.

01

Land Use

This report considers that if land is used to produce a given textile, the onward supply chain (and ultimately the fashion industry) can influence that production. Livestock production for leather and wool dominates textile-related land use, occupying 876 million hectares and 528 million hectares, respectively, in 2023 (Appendix 4), compared to cotton's 35 million hectares. Together, agricultural land used to produce leather, wool, cotton, linen/hemp, and silk accounts for approximately 30 percent of all agricultural land (Appendix 1). Thus, the fashion and textiles industry can have a significant and currently underestimated impact on global agriculture practices and land usage.

02

Chemical Applications

Textile agriculture is a major consumer of pesticides and fertilisers. Cotton production demonstrates the highest chemical intensity among natural fibres, consuming 4 percent of global pesticides and 10.5 percent of global insecticides, despite occupying less than 0.7 percent of global agricultural land. Conventional cotton farming applies an average of 4.26 kilograms (kg) of pesticides per hectare annually, contributing to soil degradation, pollinator decline, and groundwater contamination in key production regions.

Executive Summary

03 Water Usage

The fashion industry is a significant water user, cited by UNEP as the world's second-highest consumer of water behind agriculture. Water usage varies dramatically across fibre types, with cotton and leather using 256 and 146.9 billion cubic meters per year, respectively – enough water to fill 1.2 trillion bathtubs. Bast fibres (hemp and flax) have comparatively low water usage, ranging from 72.3 - 221.0 cubic meters per tonne of fibre. While not all water that is used is consumed (i.e. permanently removed from the local water cycle), water that is returned to the system after use is often of lower quality due to temperature changes, contamination, or altered composition. Regional analysis indicates that 60 percent of cotton production occurs in water-stressed basins, exacerbating local freshwater scarcity and competing with food production for irrigation resources.

04 Greenhouse Gas Emissions

Apparel production is responsible for 10 percent of global carbon emissions, generating approximately 4 billion tonnes of CO_2 annually (UNEP, 2020). Livestock-derived textiles have the greatest carbon emissions intensity, with leather and wool generating 22 and 54 tonnes CO_2 equivalent (CO_2e) per tonne of textile, respectively. By contrast, bast fibres have comparatively low emissions, emitting less than 2 tonnes CO_2e per tonne of yarn. Cotton production – including agriculture, processing, dyeing, and finishing – is responsible for 228.83 million tonnes of CO_2e per year, roughly equivalent to the emissions from driving 50 million cars for a year (using the standard EPA reference figure of 4.6 tonnes CO2e per car per year).

Executive Summary

05

Biodiversity and Soil Health

Intensive cotton monocultures reduce local biodiversity by an average of 35 percent compared to mixed farming systems, while heavy pesticide usage eliminates beneficial insects and soil microorganisms essential for ecosystem function. Livestock grazing for wool, cashmere, and leather production contributes to soil erosion rates of 10-40 tonnes per hectare annually in degraded rangelands, with overgrazing affecting 73 percent of global grassland ecosystems. Wood harvesting for MMCFs like viscose results in the loss of up to 300 million trees annually, contributing to fire and water risk. Conversely, crop rotation systems incorporating linen and hemp demonstrate improved soil organic matter retention and support 40 percent higher insect diversity than conventional textile monocultures.

06

Data Quality

Environmental data quality – determined by reliability, time representativeness, verifiability, and geographical representativeness – varies significantly by textile. In some cases, data cannot be reliably extrapolated to a global level and must remain at the product or regional unit level. This occurs when data exhibits low geographic representativeness, meaning there is high variability between different geographic regions that makes generalisation inappropriate. Such variability may result from differences in climate, soil conditions, farming practices, economic contexts, or regulatory frameworks that significantly influence agricultural outcomes – highlighting the importance of localised studies in addition to industry environmental impact reports. Plant cellulose-based semi-synthetics such as viscose and Lyocell warrant particular attention, as their environmental credentials span an unusually wide range – from strong (e.g., responsibly produced Lyocell) to poor (e.g., standard viscose) – depending on feedstock and processing method, creating meaningful right-plant-right-place opportunities to optimise yields and minimise impacts.

Sustainable agriculture methods and techniques can reduce the environmental impacts of textile agriculture.

Sustainable agriculture is defined as farming that meets present needs without compromising future generations, but its implementation is complex and context-dependent. It aims to reduce the environmental harms of conventional farming, such as pollution, soil degradation, and biodiversity loss while producing crops for harvest.

Well-known methods of sustainable agriculture include organic, regenerative, biodynamic, and permaculture. They are structured frameworks that bundle together techniques, such as crop rotation, biological pest control, and often have a related certification to guide adoption and ensure consumer trust.

Methods and Techniques

ORGANIC AGRICULTURE

Organic agriculture is the most established and regulated sustainable farming method, promoting ecosystem health and prohibiting synthetic inputs. It is practised globally and supported by well-defined standards, such as those from IFOAM and the EU. It generally outperforms conventional agriculture on biodiversity and pollution metrics, and may involve lower yields and higher land use, requiring careful consideration to determine the net environmental and land use benefit.

REGENERATIVE AGRICULTURE

Regenerative agriculture emphasises land restoration and ecosystem health but lacks a standardised definition or certification. While promising in its ecological outcomes (e.g. carbon sequestration, soil improvement), its adoption is hampered by definitional ambiguity, lack of data, and risk of greenwashing. Glyphosate use in some definitions has also sparked debate.

BIODYNAMIC AGRICULTURE

Biodynamic agriculture is a holistic and ecological approach that conceptualises the farm as a living organism, integrating crops, animals, and soil into a self-sustaining system. Certification of biodynamic farms is governed by the Demeter Standards, which has reached farms in over 60 countries.

OTHER SUSTAINABLE METHODS

Other sustainable methods, such as agroecology and carbon farming, offer alternative or complementary approaches. Most remain uncertified or loosely defined.

Executive Summary

The scientific evidence – while tentative and incomplete – suggests biodynamic agriculture offers significant environmental benefits compared to conventional agriculture. This literature review was not focused on comparing biodynamic to other sustainable farming methods such as organic, and this is a valuable area for further study.

SOIL HEALTH AND CARBON EMISSIONS

Biodynamic systems consistently demonstrate higher soil organic matter and carbon content than conventional systems across long-term trials (Carpenter-Boggs et al., 2000; Krause, 2022). Enhanced microbial diversity and improved soil structure contribute to increased carbon sequestration rates. No synthetic fertiliser inputs and decreased mechanisation contribute to lower carbon emissions than conventional agriculture.

WATER EFFICIENCY AND QUALITY

Comparative studies – while preliminary – demonstrate enhanced water use efficiency in biodynamic systems while maintaining crop yields, attributed to improved soil water retention and reduced runoff. Water consumption data across a broader variety of crops and geographies is a critical gap for further research.

BIODIVERSITY ENHANCEMENT

Organic and biodynamic farming are associated with higher species richness than conventional agriculture across multiple taxa, including beneficial insects, soil fauna, and farmland birds (Bengtsson et al., 2005; Meissner et al., 2019). Furthermore, the use of heirloom seeds supports genetic diversity and promotes resilience against pests and diseases.

TEXTILE FIBER QUALITY

Emerging research indicates that biodynamic cultivation methods may enhance natural fiber properties, with cotton and flax showing improved tensile strength and reduced chemical residue levels, potentially reducing the need for intensive processing treatments.

Executive Summary

EGYPTIAN COTTON CASE STUDY

A five-year comparative trial in the Nile Delta demonstrated that biodynamic cotton production achieved higher fiber quality scores while reducing prior pesticide applications to less than 10 percent of original amounts and increasing yield by 30 percent. Soil salinity levels decreased by 18 percent over the study period, addressing a critical challenge in Egyptian agriculture. (See Box 2.1)

What We Know, What Still Needs Time

However, the evidence base on the environmental benefits of biodynamic practices remains patchy.

SYSTEMIC RESEARCH APPROACHES

Studying the impact of all possible combinations of agricultural practices would require examining more than 100,000 possible combinations, not even considering variations in different climatic conditions. The systemic approach of studying farming systems as integrated wholes, rather than a collection of individual practices, provides the most relevant framework for understanding these complex agricultural systems.

SPECIFIC EFFECTS OF BIODYNAMIC PREPARATIONS

Despite the observed benefits of biodynamic systems, there remains no consensual demonstration of the potential positive effects of biodynamic farming-specific preparations on soil ecological quality, as specific and relevant studies on the subject are lacking.

FUTURE RESEARCH PRIORITIES SHOULD INCLUDE

01 Standardised methodologies for comparing biodynamic, organic, and conventional systems;

02 Systems-based approaches that evaluate whole-farm sustainability rather than single metrics;

03 Longitudinal studies spanning at least 10-15 years to capture transition effects and long-term outcomes;

04 Multi-regional trials across diverse climatic and soil conditions;

05 Socio-economic viability assessments that incorporate social and environmental externalities and certification costs.

Executive Summary

The fashion industry has a pivotal role to play in reducing environmental degradation while actively supporting agricultural practices that can restore ecosystems and enhance climate resilience.

While this study focuses on the environmental impacts of textile-related agriculture and opportunities for developing agricultural systems that support soil health, biodiversity, and carbon sequestration, it is critical for the fashion industry to look beyond sustainable cultivation of virgin materials and towards opportunities to support humane working conditions, reduce unnecessary production, and prevent waste at all stages of the value chain.

Author's Note

On methodology, data sources, and limitations

This study was conducted from January to June 2025, and is predominantly a literature review, synthesising academic research and industry reports to assess the environmental impacts of textile-related agriculture. This independent review was carried out by researchers at the Oxford Smith School, in partnership with DIRT Charity and with partial funding from DIRT.

Data regarding the environmental impact of the fashion industry is often limited, inconsistent, and fragmented. The report presents several data gaps and opportunities for further research. Where possible, the authors have prioritized primary source information. However, in cases where data exhibited high variability, the report notes the limitations and attempts to reconcile using assumptions.

In addition to the literature review, the report includes new primary estimations on global land use for textile fibres, based on data available at the time of research from the Food and Agriculture Organization of the United Nations (FAO) FAOSTAT 2023 database. This is summarised in Appendix 1. Key assumptions for this calculation can be found in the additional appendix for each fiber, and are based on what is available in existing research, which are often limited.

The authors have taken reasonable efforts to ensure accuracy and provide appropriate citations. During the research process, the authors identified several industry reports and commonly cited statistics that were circular in nature, perpetuating statistics within the industry without a clear source of truth.

Author's Note

The authors have taken best efforts to cite primary source information where available. In some cases, sources are cited from the 1990s and 2000s; in those cases, it was the most recent available literature identified at the drafting of the report and should be considered with appropriate context. The literature review covers references available to June 2025, with minor updates made in August 2026.

Given the identified research gaps, this document should be interpreted as a preliminary framework for further academic and industry inquiry rather than a final definitive analysis.
The aim of this work was not to calculate the exact portion of agricultural land for which textiles are directly responsible, but to contribute to ongoing debate and climate action by quantifying the proportion of agricultural land that could be influenced by the fashion industry, and to highlight potential solutions.

The views expressed in this paper represent those of the authors and do not necessarily represent those of the Oxford Smith School or any other institution or funder. The paper is intended to promote discussion and to provide public access to results emerging from our literature review. It has been reviewed by at least one internal referee prior to publication.

The Oxford Smith School was established with a benefaction by the Smith family in 2008 to tackle major environmental challenges by bringing public and private enterprise together with the University of Oxford's world-leading teaching and research.

Our vision is to transform economies and governance so that people and nature can thrive together. Research at the Smith School shapes business practices, government policy and strategies to achieve net-zero emissions and sustainable development. We offer innovative evidence based solutions to the environmental challenges facing humanity over the coming decades.

We apply expertise in teaching, economics, finance, business and law to tackle environmental and social challenges in six areas: water, climate, energy, nature, food and the regenerative economy. The Oxford Smith School has several significant external research partnerships and Business Fellows, bringing experts from industry, consulting firms, and related enterprises who seek to address major environmental challenges to the University of Oxford.

We offer a variety of open enrolment and custom Executive Education programmes that cater to participants from all over the world. We also provide independent research and advice on environmental strategy, corporate governance, public policy and long-term innovation.

For more information on The Oxford Smith School please visit: www.smithschool.ox.ac.uk

Introduction

Where Our Clothes Begin

Fashion's Agricultural Footprint

As global fibre production surges to meet rising consumer demands, the environmental footprint of textile agriculture has become a growing concern. Synthetic fibres[1] have dominated production volumes since 2000, and made up 60 percent of the produced fibre in 2023 (Statistica, 2024; FAO, 2024).

Nevertheless, natural fibres such as cotton, leather, and wood-based fibres continue to play an important role in the textile industry's raw material mix, and will be the focus of this report on textile agriculture. These natural fibres, largely derived from agricultural systems, carry significant environmental implications through land use, water consumption, chemical inputs, and greenhouse gas emissions.

This report presents an environmental assessment of textiles-related agriculture, examining the impacts of different natural textiles types.

Based on the total land-use of five major fibres (cotton, leather, silk, wool, and linen/hemp),

the fashion industry influences approximately 30%[2] of all agricultural land worldwide.

Livestock for leather and wool represent a major source of environmental pressure (FAO, 2023; Ritchie & Roser, 2023). Textile agriculture is also a major consumer of pesticides, fertilisers, and freshwater resources, and generates substantial greenhouse gas emissions.

Social Dimensions

While the primary focus of this report is on the environmental impacts of textile-related agriculture, it is important to acknowledge the deep and far-reaching social dimensions of the textile industry. The textile industry employs over 90 million people globally, often in regions with limited labour protections. Seventy-five percent of garment workers are based in Asia, and the majority are women (International Labour Organization, 2023).

Textile agriculture and production generate vital income in many developing countries, but are also associated with widespread challenges, ranging from low wages and long hours to exposure to hazardous chemicals and gender inequality. Furthermore, the chemical intensity of conventional textile agriculture poses significant health risks for workers, and water-intensive fibre production can strain local freshwater access in already water-stressed areas.

Over
90 Million
people globally are employed by the textile industry

75% of garment workers are based in Asia

The majority are women.

Although these social impacts are critical and interlinked with environmental outcomes, they fall beyond the scope of this report and warrant a separate, dedicated investigation.

Introduction

Similarly, while waste generation and over-consumption represent critical aspects of the fashion industry's environmental impact, these dimensions will not be investigated in this report.

In the United States alone, clothing waste occupies more than 5% of landfill capacity, and more than 85 percent of clothing consumed is sent to landfill as solid waste each year (Hobson, 2013; Wicker, 2016).

The focus of this report remains specifically on the direct environmental impacts arising from the production and processing of natural fibres within agricultural systems. Issues such as textile waste management, garment disposal, consumer behaviour patterns, and the environmental consequences of fast fashion cycles, though significant, require separate analysis that extends beyond the agricultural production and processing phases examined here.

5%

OF LANDFILL CAPACITY

is occupied by clothing waste in the US alone.

85%

OF CLOTHING CONSUMED

is sent to landfill as solid waste each year.

01

PART ONE

The Impact of Fashion-Related Agriculture

The first part of this report explores the specific environmental impacts of current production practices associated with major natural fibres, including cotton, leather, wood-based fibres, wool, linen, and silk. Drawing from global datasets, lifecycle assessments, and emerging research, the findings highlight both the environmental cost and opportunities for improvement within textile agriculture.

02

PART TWO

Scientific Evidence on Biodynamic Agriculture

The second part of this report evaluates various sustainable agriculture methods by drawing on systematic literature reviews and long-term field studies. The section also presents a scientific assessment of biodynamic agriculture, assessing its credibility, limitations, and potential role within the future of textile agriculture.

Part 1

The Impact of Fashion-Related Agriculture

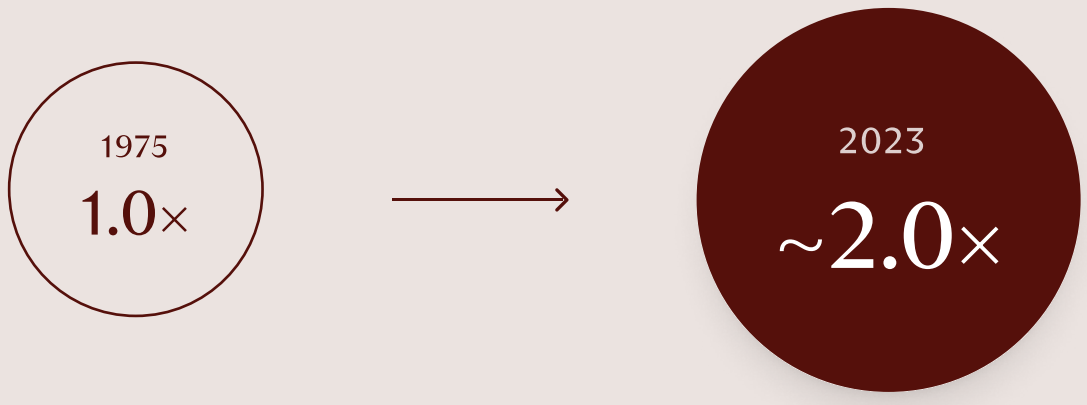
Part 1

The Impact of Fashion-Related Agriculture: An Environmental Assessment

This section of the report assesses the environmental impact of fashion-related agriculture and processing[3] for seven textiles across five key dimensions: land use, chemical inputs, water consumption, greenhouse gas emissions, and biodiversity and soil health.

Natural Fibre Production and Environmental Significance

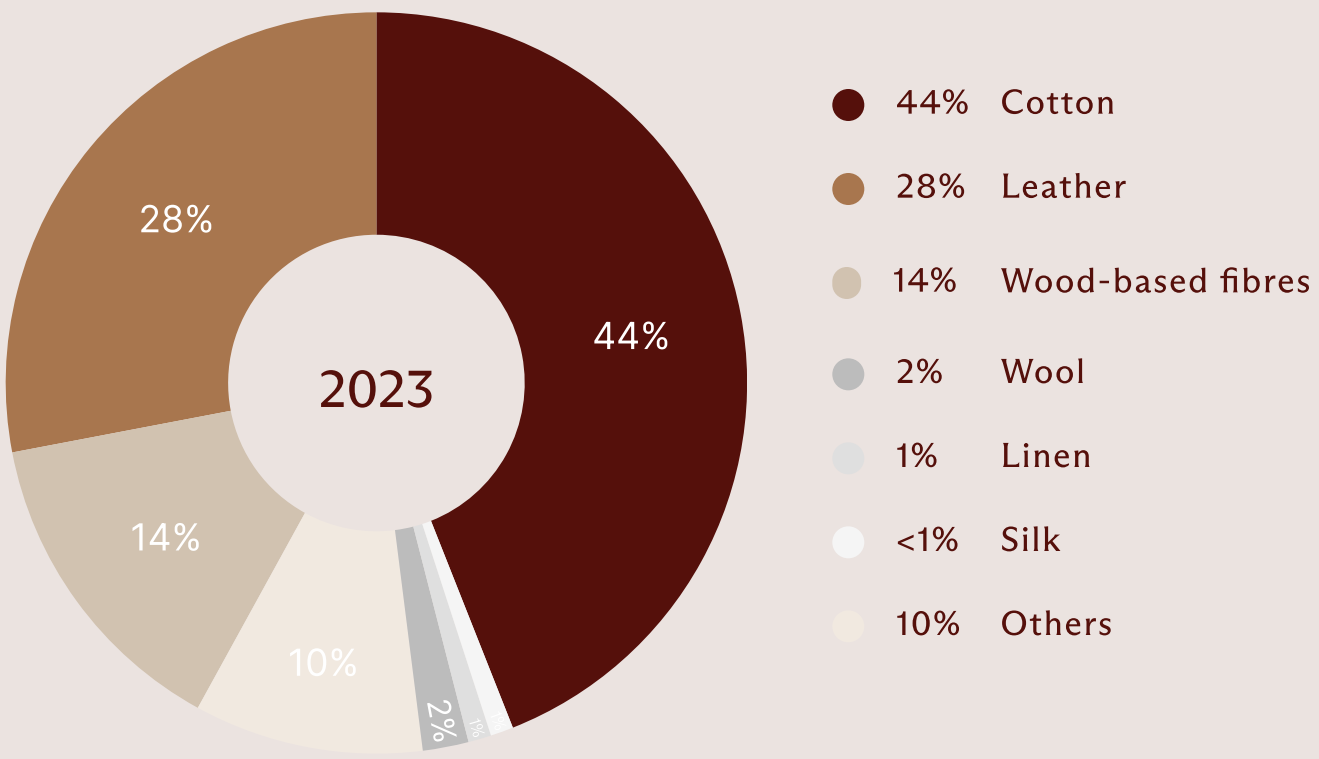
Global fibre production per person has almost doubled since 1975.



GLOBAL FIBRE PRODUCTION PER PERSON (RELATIVE INDEX)

SOURCE: TEXTILE EXCHANGE, 2023 MATERIALS MARKET REPORT

SHARE OF NATURAL FIBRES PRODUCED IN 2023



Cotton accounts for the biggest share of natural fibres produced in 2023.

STATISTICA, 2024; FAO, 2024

Agricultural practices supporting the textile industry represent a significant global environmental concern, with implications that span ecosystems and resource systems worldwide. The findings highlight substantial resource demands, particularly in conventional cotton cultivation, livestock production for leather, and animal fibres.

Part 1

Fibre Use and Material Demand

1.

End uses of fibres produced, including recycled feedstock



Of the fibres produced, including recycled feedstock, approximately 50 percent goes towards apparel, 25 percent towards home textiles, and the rest on other uses (e.g., industrial products, technical products, medical products, footwear).

2.

A defining material reality

Polyester accounts for just over half of all fibres produced.

TEXTILE EXCHANGE, 2023

3.

EU household material demand in 2020

175

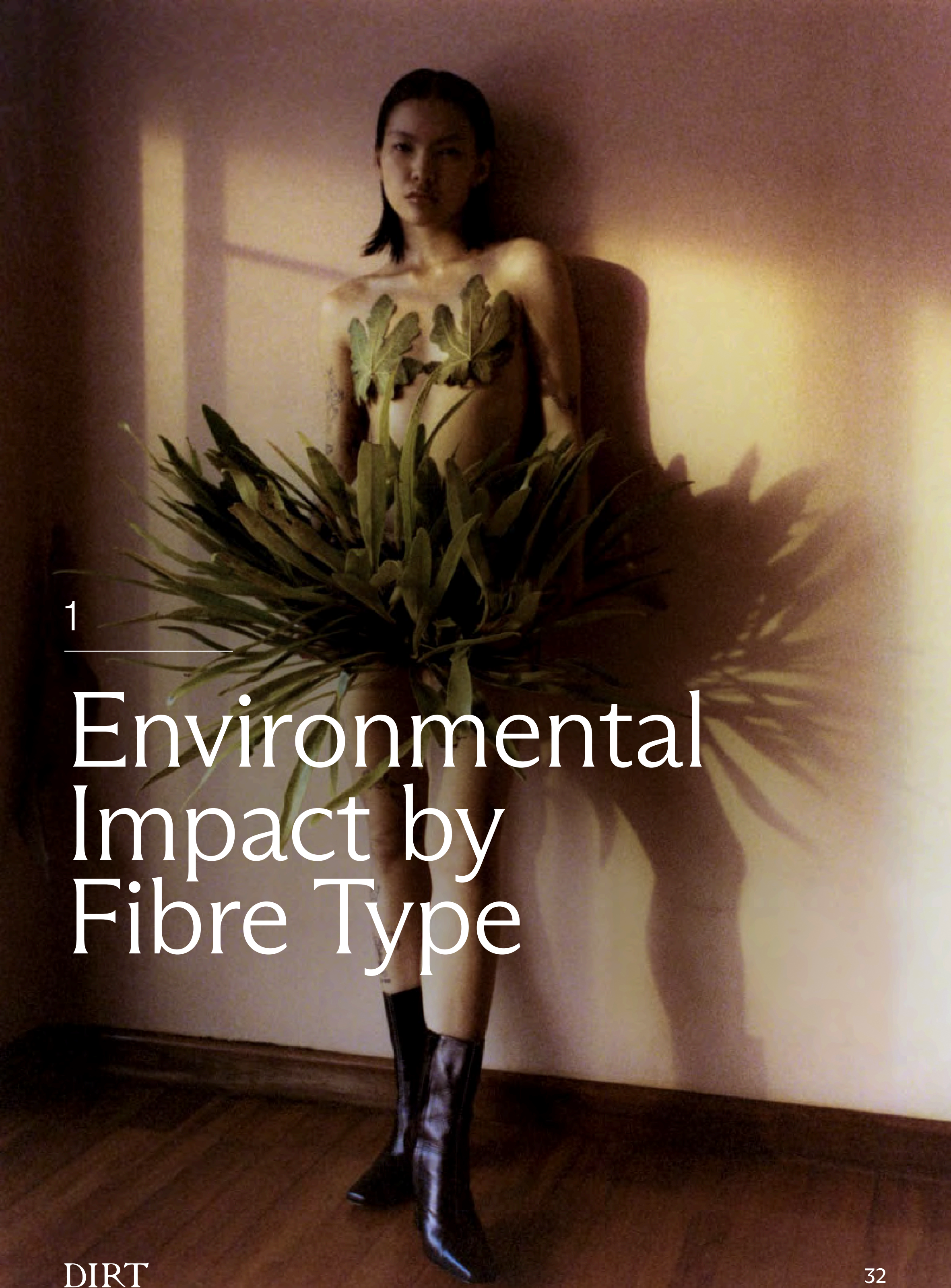
MILLION TONNES

391

KILOGRAMS PER PERSON

To produce all clothing, footwear, and household textiles purchased by EU households in 2020, around 175 million tonnes — or roughly 391 kilograms per person — of primary raw materials, including non-farmed sources, were used.

Sources: Circle Economy, 2024; Textile Exchange, 2023; European Environment Agency, 2022.



1

Environmental Impact by Fibre Type

1.1

Cotton

1.1 Cotton

Cotton stands as one of the most economically significant and widely cultivated textile fibres in the global fashion industry.

$40 Billion
Market Value of Cotton

350 Million
Livelihoods Worldwide

With a market value of approximately US$40 billion and a projected growth rate of 2.7 percent until 2030, cotton cultivation provides livelihoods for over 350 million people worldwide across farming, processing, and manufacturing sectors (Adeleke, 2024; Radhakrishnan, 2017). The crop is cultivated for both the food and textiles industry, which is used towards clothing, home textiles, and industrial textiles (Tobler-Rohr, 2011).

1.1 Cotton

Land Use

Cultivated across 97 countries on approximately 35 million hectares, cotton farming accounts for about 0.7 percent of global agricultural land (FAO, 2023; Ritchiem & Roser, 2024). The cotton plant yields approximately 40 percent lint (used for textiles) and 55 percent seed (used for oil and animal feed), with the remainder as waste material (Tobler-Rohr, 2011). Research indicates that average global yields have increased by nearly 100 percent over the past three decades, likely with contributions from technological advancements in production methods, such as precision agriculture techniques and remote sensing technologies (ICAC, 2014; Adeleke, 2024).

97
Countries

35
Million Hectares

0.7%
Of Global Agricultural Land

40%
Lint
(used for textiles)

55%
Seed
(used for oil and animal feed)

100%
Increase in average global yields in the past three decades

Chemical Applications

Cotton's pesticide[4] usage is substantial. According to ICAC data, cotton accounts for 4.0 percent of global pesticide use (116,083 tonnes) despite occupying only 2.3 percent of arable land, indicating higher-than-average chemical intensity (ICAC, 2024a). Cotton ranks as the third greatest user of pesticides in the USA and fourth globally (ICAC, 2024a). Notably, this data is based on sales volumes, rather than usage, which can conceal regional nuances and actual consumption patterns. According to another study by UNEP, for example, cotton accounts for more than 200,000 tonnes of global pesticide usage, demonstrating significant variation in estimation across studies (UNEP, 2020).

4.0%	116,083	2.3%	>200,000
Global Pesticide Use	Tonnes	Arable Land	Tonnes UNEP Estimate

Cotton and Chemicals

Disproportionate Use, Disproportionate Impact

UNITED STATES

In the United States alone, approximately 22,000 tonnes of pesticides were applied to 5.1 million hectares of cotton in 2017, averaging about 4.26 kilograms/hectare (USDA, 2018). The USDA reports that conventional cotton in the USA used $4.2 billion worth of pesticides in 2017, representing 6.35 percent by value of all plant protection chemicals sold that year (USDA, 2018).

22,000	5.1m	4.26	$4.2bn	6.35%
tonnes of pesticides applied to cotton in 2017	hectares of cotton treated in 2017	kilograms/hectares of average pesticides applied	worth of pesticides used in 2017	of all plant protection chemicals sold by value in 2017

INDIA

In India — an emerging global leader in cotton production — cotton accounted for about 5 percent of the gross cropped area in 2013 but consumed between 36 - 50 percent of the total pesticides in the country, indicating the disproportionately high usage of pesticides on cotton (Devi, 2010; FICCI, 2013; Bhardwaj and Sharma, 2013).

5%	36-50%
Of the gross cropped area accounted for by cotton in 2013	Of the total pesticides consumed in the country

Chemical Applications

Particularly pronounced is cotton's share of insecticide usage, which stands at 10.5 percent of global insecticide application (ICAC, 2024a). Cotton farming utilises approximately 8,671 tonnes of highly hazardous insecticides (HHIs) annually, accounting for 12.69 percent of total insecticide use (ICAC, 2024b).

Highly hazardous insecticides pose significant risks to human health, including causing acute and chronic illnesses such as cancer, birth defects, reproductive harm, hormonal disruption, and damage to genetic material. Furthermore, these hazardous chemicals contaminate soil, water, and the air, as well as contributing to biodiversity loss and the development of pest resistance.

Cotton accounts for 3.1 percent of global herbicide usage, placing it behind crops such as soybeans (20.9%), maize (20.0%), wheat (7.3%), rice (5.3%), and sugar cane (4.2%) (ICAC 2024a). However, cotton's share of highly hazardous herbicides (HHHs) is disproportionately high at 6.99 percent, with an average annual usage of 2,144 tonnes (ICAC 2024b). Brazil and the USA lead in herbicide application rates at 0.35 kg/ha and 0.33 kg/ha, respectively (ICAC 2024a).

10.5%

OF GLOBAL INSECTICIDE USE

is used in cotton

8,671

TONNES OF HIGHLY HAZARDOUS INSECTICIDES

used annually in cotton production

6.99%

OF GLOBAL, HIGHLY HAZARDOUS HERBICIDE USE

is applied to cotton

Chemical Applications

The effectiveness of pesticides has decreased over time due to resistance development, leading to a damaging cycle of increased application rates. USDA data shows that the absolute usage of glyphosate – a controversial broad-spectrum herbicide used to kill a wide range of plants – in conventional cotton doubled between 2011 and 2019, with the area of pesticide-treated cotton increasing by 38.2 percent during this period (USDA 2020).

2x

GLYPHOSATE USE

in conventional cotton doubled between 2011 and 2019

38.2%

INCREASE IN PESTICIDE-TREATED COTTON

between 2011 and 2019

Chemical Applications

Fertiliser use in cotton production is also substantial, with an estimated 9 million tonnes of nitrogen, phosphorous, and potassium fertilisers applied annually (FAO, 2023). While fertilisers can boost plant growth, overreliance on synthetic fertilisers can negatively impact soil health and fertility. Over-fertilization disrupts the natural balance of nutrients, reducing soil organic matter and harming beneficial soil microbes.

After cultivation, agricultural chemicals persist in the fibres, and additional chemicals are incorporated in each stage of cotton processing. Pesticides have been shown to persist in the cotton ginning stage, during which cotton fibres are separated from seeds and other unwanted materials (Egbuta 2019). While spinning and weaving primarily involve mechanical actions, sizing agents and yarn lubricants are applied to strengthen the fibres, which have been shown to result in harm to textile workers (IARC, 1990).

9

MILLION TONNES OF NPK FERTILISERS

applied annually in cotton production

CHEMICALS PERSIST IN COTTON FIBRES

after cultivation and into the ginning stage

EVERY STAGE ADDS CHEMICAL INPUTS

from cultivation to processing, spinning and weaving

Chemical Applications

Furthermore, the scouring and bleaching processes use chemicals such as caustic soda, detergents, and wetting agents to manipulate the natural properties of the fibre in preparation for dyeing and garment development (IARC, 1990).

While some industry reports imply that cotton's chemical use is overstated, other sources suggest that the environmental impacts of cotton are understated (ICAC, 2024a; Antithesis, 2021; Roberts-Islam, 2021). Fashion – and in particular cotton – has a problem with "silenced data," wherein data is privately owned or housed behind a paywall and prohibitively expensive, limiting the ability to transparently review the industry's aggregate impact (Roberts-Islam, 2021).

CAUSTIC SODA DETERGENTS + WETTING AGENTS

are used in scouring and bleaching

SILENCED DATA LIMITS TRANSPARENCY

around fashion's true environmental impact

PRIVATELY OWNED OR PAYWALLED DATA

makes cotton's aggregate impact difficult to review

Water Usage

Water consumption[5] for cotton varies significantly by region and cultivation method. Global estimates suggest that cotton requires between 10-20 cubic meters of water per kilogram of fibre produced, from cradle to gate (Cotton Incorporated, 2012). This translates to annual global water consumption of approximately 256 billion cubic meters for cotton textile and apparel products, with approximately 42 percent coming from irrigation (blue water), 39 percent from rainfall (green water), and 19 percent representing water needed to dilute pollutants (grey water) (Sustainable Business Group, 2015; Hoekstra et al., 2012).

10-20

CUBIC METRES OF WATER

per kilogram of cotton fibre produced

256bn

CUBIC METRES OF WATER

consumed annually by cotton textile and apparel products

42%

FROM IRRIGATION

of cotton's global water consumption

Water Usage

While cotton is frequently referred to as a “thirsty” crop, the Transformers Foundation (2021) cautions that “labelling cotton ’thirsty’ in isolation from its growing context is therefore misleading. Cotton grown in water-stressed regions can contribute to water management challenges, but local climate, poor irrigation systems, poverty, and failure of governance are also contributing factors.” Indeed, regional variations in water consumption during cultivation are substantial: cotton farmers in the southeastern United States use approximately 0.234 cubic meters of irrigated water per kilogram of cotton, while those in western states use up to 3.272 cubic meters (Transformers Foundation, 2021). Approximately half of global cotton production is entirely rain-fed, while the remainder requires irrigation (Transformers Foundation, 2021).

0.234
–3.272

CUBIC METRES OF IRRIGATED WATER

per kilogram of cotton, depending on region

50%

OF GLOBAL COTTON IS RAIN-FED

requiring no irrigation

Green House Gas Emissions

Cotton production and processing generate significant greenhouse gas emissions, estimated at more than 220 million tonnes of CO_2 equivalent (CO_2e) globally (Carbon Trust, 2011). Life Cycle Assessment studies indicate that producing one tonne of conventional cotton fibre results in approximately 1.8 tonnes of CO_2e (Carbon Trust, 2011) These emissions occur throughout cultivation and processing, with fertiliser production and application representing major contributors (Muthu, 2016).

Fertiliser production represents the largest contributor to greenhouse gas emissions in cotton cultivation, accounting for approximately 47 percent of total emissions (Antithesis, 2021). The application of nitrogen fertilisers additionally contributes about 12 percent of total cotton cultivation emissions through the release of nitrous oxide (N_2O), a greenhouse gas with 300 times the global warming potential of CO_2 (Menegat et al., 2022).

220m+

TONNES OF CO_2e

generated globally by cotton production and processing

1.8

TONNES OF CO_2e

per tonne of conventional cotton fibre produced

47%

OF CULTIVATION EMISSIONS

come from fertiliser production

300x

MORE WARMING POTENTIAL

nitrous oxide compared with CO_2

Green House Gas Emissions

The treatment of biogenic carbon in cotton life cycle assessments represents a significant methodological consideration that affects reported emissions profiles. While cotton plants sequester atmospheric CO_2 during growth—with studies crediting approximately 1,540 kg CO_2 equivalent per 1,000 kg of cotton fiber—this biogenic carbon is typically excluded from agricultural phase emissions reporting since it will be re-released during the product's end-of-life phase (Cotton Incorporated, 2012). Current life cycle assessment (LCA) methodologies generally treat this as carbon neutral over the full product lifecycle, accounting for uptake as a negative emission during cultivation and then modeling an equivalent positive emission during disposal.

Green House Gas Emissions

However, this approach may underestimate cotton's climate benefits in the near term, particularly when considering soil carbon sequestration potential (estimated at 0.59 kg CO_2e reduction per kg seed cotton through conservation tillage practices) and natural methane oxidation in cotton soils (Cotton Incorporated, 2021). The exclusion of these biogenic carbon dynamics from standard emissions accounting means that reported cotton production emissions focus primarily on process-related sources like fertilizer production and field emissions, potentially overlooking significant carbon storage benefits that could improve cotton's overall climate profile if more comprehensively incorporated into sustainability assessments.

1.1 Cotton

Biodiversity and Soil Health

The intensive use of agricultural chemicals in conventional cotton production negatively impacts soil health and biodiversity. Many insecticides, nematicides, fungicides, herbicides, desiccants, and defoliants used in conventional cotton have been associated with environmental and health problems in humans and animals (Maumbe & Swinton, 2003; Blackburn, 2009; Settle et al., 2014; Agbohessi et al., 2015).
These chemicals seep into soil, wash into waterways, and leach into groundwater, harming biodiversity, ecosystems, and human health.

The development of pesticide resistance has become a significant concern (Wossink & Denaux, 2006; Benbrook, 2012). For example, insect resistance has been identified in two of the three Bt toxin families (Cry1A and Cry2A) used in genetically modified cotton, reducing the effectiveness of this approach to pest management (Reisig, 2018).

Box 1

Spotlight on Dyeing

Box 1: Spotlight on Dyeing

While this report is focusing on the agricultural and processing phases of textile production, the bleaching and dyeing process represents one of fashion's most water-intensive and polluting phases...

Textile Dyeing

Water Consumption and Pollution

Water Consumption: 0.1-0.15 cubic meters of water are typically needed to process 1 kilogram of textile material

Global Scale: Approximately 28 billion kilograms of textiles are dyed annually, consuming over 5 billion cubic meters of water

Chemical Intensity: Around 6 kilograms of processing chemicals are required per 100 kilograms of textiles to dissolve dyes in water (Allwood, 2006; Raybin, 2009)

0.1 to 0.15 m3

WATER PER KG
of textile processed

28bn kg

TEXTILES
dyed annually

5+bn m3

WATER
consumed globally

The Environmental Toll of Dyeing

20%

OF GLOBAL INDUSTRIAL WATER POLLUTION

linked to textile dyeing and finishing

The environmental toll of dyeing extends far beyond water usage:

Textile dyeing and finishing have been cited as accounting for approximately 20 percent of all global industrial water pollution (Ercin & Matthews, 2017).

Wastewater from dyeing operations often contains salts, alkalis, toxic compounds, and non-biodegradable substances (Khattab et al., 2020).

When irresponsibly discharged, these contaminants:

Clog soil pores, reducing soil health and agricultural productivity

Contaminate freshwater streams, killing aquatic life

Contribute to high alkaline soil, damaging crop potential or fertility of wild land

Contribute to downstream ecosystem degradation (Khattab et al., 2020)

Textile Dyeing Methods

METHOD SPLIT INTO COTTON TEXTILES

Share of cotton textiles produced, National Cotton Council, n.d.



60%

PIECE DYEING

Most common method, where finished fabric is dyed in one batch.

25%

YARN DYEING

Yarn is dyed before weaving, used for patterns like plaids.

15%

OTHER

Including specialised techniques for various woven and knit textiles

Different dyeing methods have varying impacts:

The effects of dyes live beyond the end of the garment's useful life, as the toxins present in the textile from the dye may be the sole reason that a natural fibre textile may not be compostable (Wan 2024).

The market price of vibrant fashion colours does not reflect the cost to waterways, ecosystems, and communities downstream from textile processing facilities.

1.2

Leather

Leather

The global leather industry represents a significant economic force with complex sustainability considerations. The traditional leather market, excluding non-animal leather, was valued at US$95.4 billion in 2023, with an expected Compound Annual Growth Rate (CAGR) of 6 percent until 2030 (GlobalData, 2024). While growth has slowed compared to previous decades, fashion and automotive applications continue to drive demand, even as concerns about ethical sourcing and environmental impacts have become more prominent (GlobalData, 2024).

$95.4bn

IN 2023

6%

EXPECTED GROWTH RATE UNTIL 2030

1.2 Leather

There is wide debate in the industry about whether leather is classified as a by-product or a co-product; however, these terms are often used interchangeably and differ slightly in definition depending on jurisdictional classifications (e.g., in the United States, hides are classified as a byproduct) (Henchion & McCarthy, 2019). The difference also lies in how impact is allocated between leather and other uses of the animal, such as food. Recent research suggests that there has been systematic underreporting of leather's carbon footprint including in numbers widely used by industry (Roncevich, 2026)., and that there is a need to incorporate economic fractional allocation into calculations, rather than assuming that hides are a zero-value byproduct of dairy and/or meat production (Roncevich, 2026).

A notable market trend has been the rise of leather alternatives, such as synthetic leather, plant-based leather, and recycled materials (GlobalData, 2024). The alternative leather market, including apparel, footwear, and accessories, was estimated to total over 41 billion U.S. dollars in 2022 and has been growing by approximately 6 percent year over year (Statistica, 2024).

Despite this competition, genuine leather maintains premium positioning in luxury goods, automotive interiors, and high-performance applications.

$41bn

IN 2022

6%

GROWTH YEAR OVER YEAR

Land Use

Leather production represents the largest land-use category among textile materials. Using FAO data, our calculations find that production of leather from cattle, buffaloes, goats, and sheep happens across 195 countries on approximately 876 million hectares used for animal grazing (for sources, assumptions & calculations, see Appendix 1).It is important to note that other animals are used for leather, such as crocodiles and snakes, and not included in this analysis due to insufficient data.

Leather is not directly or solely responsible for the entirety of this land-use footprint. That responsibility is shared by the meat industry, for example. However, we use the total number in our calculations to account for the broad influence of leather textiles (and therefore the fashion industry) in shaping global livestock demand, treatment, and land-management.

195

COUNTRIES

876m

HECTARES

Land Use

Only land used for ranching, raising and managing animals is accounted for (excluding land use for animal feed production). Cattle ranching is a major driver of deforestation in certain regions, particularly in South America (Nepstad et al., 2008). Pasture for livestock represents the largest human land use globally, occupying 26 percent of the Earth's ice-free land surface (Food Climate Research Network, 2017).

We also assume that the fashion industry has influence over the majority of leather textile use cases. In 2024, over 2.9 billion square meters of genuine leather were processed globally (Market Reports World, 2026). This was used primarily for footwear, handbags, and apparel (1.2 billion square meters). Leather was also used for furniture (510 million square meters) and automobile interiors (412 million square meters), which may also reflect fashion-related choices. Other applications, including leather-bound stationery, watch straps, and accessories consumed a further 280 million square meters of leather (Market Reports World, 2026).

26%

OF EARTH'S ICE-FREE LAND SURFACE

2.9bn

SQUARE METERS

of genuine leather were processed globally

Chemical Applications

The chemical profile of leather spans both animal agriculture and the intensive processing required to transform raw hides into finished leather. Parasiticides – commonly administered for parasite, insect, and tick control – have been shown to cause endocrine disruption in cows (Miclean, 2024). Herbicides like glyphosate and fertilisers like nitrogen and phosphate are widely used in pasture management; these chemicals have been shown to disrupt the rumen microbiome of cows while also having negative effects on metabolism and reproductive capabilities (Heymann, 2021; Brede, 2022).

Chemical Applications

The transformation of raw hides into finished leather involves multiple chemical-intensive stages. Preservation and beamhouse operations use chemicals like sodium chloride and ammonium sulfate for curing hides, hair removal, liming, and bating (softening) (Sivaram, 2019). Tanning chemicals have a particularly damaging environmental impact. Chromium sulfate – an effective agent used in chrome tanning, the most common tanning method – has the potential to convert into hexavalent chromium (CrVI), a known carcinogenic substance, if not properly managed (Zhang, 2018; Shi et al, 2021). Other heavy metals used in leather processing – including antimony, barium, cobalt, copper, lead, mercury, and selenium – along with organic compounds such as azo dyes and formaldehyde, present additional environmental concerns if they enter water systems (Sivaram, 2019; Tasca, 2019).

Water Usage

Water usage represents one of the most significant environmental impacts associated with leather production, occurring primarily during the processing of hides rather than in livestock rearing. The leather production process uses approximately 24.8-33.5 cubic meters of water per tonne of hide processed (Chowdhury, 2015; de Aquim, 2019; Kumar, 2021).

Total life-cycle water usage for fashion-related leather cultivation and processing is estimated to be nearly 150 billion cubic meters per year (Brugnoli 2025). Water is used extensively throughout the preparation, tanning, and finishing/crusting stages.

The beamhouse operations, in which raw hides are prepared for tanning, are particularly water-intensive, including soaking, liming and de-liming (Brugnoli, 2025). Notably, many modern beamhouse operations incorporate water recovery systems that reduce actual water consumption relative to total use.

24.8 *to* **33.5 m3**

CUBIC METERS

of water per tonne of hide processed

150 Billion m3

OF WATER

used annually across the life cycle of fashion-related leather cultivation and processing.

Water Usage

Beyond quantity, the quality of water discharged from leather processing raises significant environmental concerns. Processing chemicals, including chromium and other heavy metals, can contaminate water systems if inadequately treated (Shi et al., 2021).

Organic materials removed from hides contribute to high biochemical oxygen demand in effluent, while salts used in preservation can increase total dissolved solids in wastewater (Brugnoli, 2025).

These pollutants have the potential to disrupt aquatic ecosystems and contribute to water scarcity by rendering water resources unusable without extensive treatment (Brugnoli, 2025). The severity of these impacts varies considerably based on local regulations, treatment technologies, and facility practices.

Greenhouse Gas Emissions

As a by or co-product of animal agriculture, leather inherits a portion of the GHG emissions associated with cattle rearing[6]. The total lifecycle emissions of leather cultivation and processing are estimated at 286 million tonnes CO_2e per year (Brugnoli, 2025).

Enteric fermentation produces methane – a potent greenhouse gas – as cattle digest feed, while manure management releases both methane and nitrous oxide (Zhao, 2017).

Feed production contributes to carbon dioxide from energy use and land use change, with transportation and other operational activities adding further emissions (Brugnoli, 2025). This is a notable contrast with relatively resource-efficient textile production, as the production of animal hides requires significant inputs, primarily in the form of animal feed, to produce the hides themselves.

286

MILLION TONNES CO_2E

estimated annual lifecycle emissions from leather cultivation and processing.

Greenhouse Gas Emissions

Deforestation is another significant emissions impact of cattle ranching. In 2023, 7.5 million hectares of pasture covered recently cleared land in the Brazilian Amazon, up from 5.3 million hectares in 2020 – an increase of over 36% in four years. Deforestation for cattle ranching has increasingly concentrated in the Amazon specifically, rising to 62% of Brazil's national deforestation share in 2023, up from 40% in 2017 (Pereira & Bernasconi, 2025).

The transformation of hide into leather contributes additional GHG emissions through energy-intensive processes, including:

- Heating water for various wet process stages
- Drying operations throughout the production process
- Powering mechanical equipment for processing and finishing
- Manufacturing and transporting the chemicals used in processing (Brugnoli, 2025)

7.5

MILLION HECTARES

of pasture covered recently cleared land in the Brazilian Amazon in 2023, up 36%+ since 2020.

62%

OF BRAZIL'S DEFORESTATION WAS CONCENTRATED IN THE AMAZON IN 2023, UP FROM 40% IN 2017.

Greenhouse Gas Emissions

Life cycle assessment studies indicate that leather production has the potential to cause global warming impacts ranging from 8.5 to 151.9 kg CO_2e per square meter of land (Chen et al., 2014; Nararro, 2020; Kiliç, 2023).

This wide range reflects significant variations in production technologies and efficiencies, energy sources used in processing, allocation methodologies for the livestock phase, and system boundaries and impact assessment methods (Chen et al., 2014; Nararro, 2020; Kiliç, 2023).

8.5–151.9

KG CO_2E/M^2

the estimated global warming impact of leather production, with wide variation depending on production methods, energy sources and assessment methodology.

Biodiversity and Soil Health

Biodiversity and Soil Health – As a by- or co-product of cattle rearing, leather inherits a portion of the biodiversity and soil impacts associated with livestock production:

- Habitat Conversion: Cattle ranching can drive conversion of natural ecosystems to pasture, particularly in regions like the Amazon where it remains a leading cause of deforestation.
- Grazing Impacts: Poorly managed grazing can lead to soil compaction, erosion, and reduced plant diversity.
- Feed Production: Growing feed crops for cattle can contribute to biodiversity loss through monoculture farming and agrochemical use, in addition to land use and greenhouse gas emissions from feed crops (Food Climate Research Network, 2017).

Biodiversity and Soil Health

The severity of these impacts varies dramatically based on production systems and regional contexts. While well-managed grazing – currently challenging to quantify and subject to poor data availability – can potentially support biodiversity and soil health, poorly managed systems drive degradation.

The chemical-intensive nature of leather processing presents additional risks to biodiversity and soil health:

- Solid Waste Generation: Leather production generates substantial solid waste, approximately 400-700 kg per tonne of raw leather processed.
- Chemical Contamination: Heavy metals and organic compounds used in tanning and finishing can contaminate soil if improperly managed.
- Wastewater Effects: Untreated or inadequately treated effluent can impact soil health in surrounding areas (Sathish et al., 2019; Sultana et al., 2023).

Biodiversity and Soil Health

The solid waste produced during leather processing takes various forms, including dirt, trimmed leather, keratin waste, fleshing waste, chrome shaving waste, and polishing waste (Kanagaraj, 2006; Sathish et al., 2019). These materials may contain processing chemicals that present potential risks if they are not properly disposed of.

DIRT

Box 2

Mushroom Leather: A Sustainable Alternative?

Mushroom Leather

A SUSTAINABLE ALTERNATIVE?

Mushroom leather, also known as mycelium-based leather, represents a promising biotechnology innovation that could transform the leather industry's environmental footprint (Bahua et al., 2024). This material is created from mycelium — the vegetative, root-like network of fungi — which is cultivated on organic substrates like sawdust and agricultural waste (Wang et al., 2020). Two prominent examples demonstrate the technology's potential: Indonesia's Mylea™, produced from Ganoderma lucidum mushrooms, and MycoWorks' Reishi™, created using their proprietary Fine Mycelium™ technology (Bahau et al., 2024; Williams et al., 2022).

These materials can achieve similar performance characteristics to traditional animal leather, including flexibility, durability, and hand feel, while containing minimal plastic content (less than 1% in Reishi™) and maintaining complete biodegradability (Williams et al., 2022). However, the environmental impact varies significantly across production methods, and mycellium notably requires growing new material rather than making use of an existing waste product.

MycoWorks uses a "passive growth process" requiring no input gases, while other companies employ "active growth processes" that pump large amounts of CO_2 into growth chambers, potentially making the environmental footprint of some mycelium leathers more harmful than traditional leather (Williams et al., 2022).

Box 2: Mushroom Leather

The environmental advantages of mushroom leather over conventional bovine leather can be substantial, but outcomes depend heavily on production context and design choices.

Research shows that Reishi™ produces as little as 2.76 kg CO_2e per square meter compared to approximately 33 kg CO_2e for bovine leather—representing a potential 92 percent reduction in carbon footprint for a benchmark product (Williams et al., 2022). However, Mylea™ production generates 57.15 kg CO_2e per square meter, primarily due to Indonesia's coal-heavy electricity grid rather than inherent process limitations (Bahau et al. 2024). Material selection also dramatically affects impact: virgin cotton, recycled polyester, and mycelium-only options have carbon footprints of 11.29, 1.11, and minimal kg CO_2e per kilogram respectively, meaning fabric choice can more than double the total environmental impact (Williams et al. 2022). Beyond carbon emissions, true mycelium leather avoids the water pollution, chemical toxicity, and land use impacts associated with livestock farming and hide tanning processes (Williams et al., 2022).

92%

LOWER

MycoWorks' Reishi produces 2.76 kg CO_2e/m^2, compared with ~33 kg for bovine leather, while another alternative reaches 57.15 kg CO_2e/m^2 when produced on a coal-heavy grid.

Box 2: Mushroom Leather

A critical challenge facing the industry is distinguishing genuine sustainable alternatives from "greenwashing." Many products marketed as sustainable leather alternatives are actually plastic-based materials containing significant polyurethane layers that prevent biodegradation and contribute to microplastic pollution (Williams et al., 2022). This makes consumer and industry education essential for driving adoption of truly sustainable options. Additionally, energy consumption emerges as the primary technical obstacle, with electricity usage accounting for 46-81 percent of carbon footprints in current production processes (Bahau et al., 2024; Williams et al., 2022).

Scale represents another significant hurdle: current production volumes measure in thousands of square meters annually, while the global leather industry produces billions of square meters.

The opportunities for mushroom leather adoption are compelling, particularly given the technology's rapid improvement trajectory. Pilot-scale operations have already achieved 57 percent carbon footprint reductions through process optimization, and transitioning to renewable energy sources could reduce impacts by 80 percent or more (Williams et al., 2022). The technology's early development stage suggests much greater optimization potential exists, unlike mature industries where efficiency gains are incremental.

Production also generates valuable byproducts like substrate "bricks" used as soil amendments, which can offset environmental impacts through economic allocation (Williams et al., 2022).

As manufacturing processes mature and economies of scale develop, mushroom leather could capture substantial market share, particularly in luxury goods and environmentally conscious consumer segments where sustainability credentials and natural biodegradability command premium pricing over plastic alternatives.

1.3

Wood-Based Fibres (MMCFs)



Wood-Based Fibres (MMCFs)

Wood-based fibres, known also as man-made cellulosic fibres (MMCFs), are made by dissolving wood pulp into a viscous solution and regenerating it into fibre. Examples of tree-based fibre include traditional rayon and viscose, and newer iterations including lyocell, tencel, modal, and various proprietary cellulose-based innovations. This category of fibres made up about 6 percent of global fibre production in 2023 (UNCCD, 2024).

These fibres have emerged as significant contenders in the sustainable textiles marketplace, with the global man-made cellulosic fibre (MMCF) market valued at approximately US$35 billion in 2024 and projected to reach US$66.6 billion by 2030, reflecting a CAGR of 7 percent (Imarc Group, 2024). This growth is partly attributed to increasing scrutiny of synthetic petroleum-derived fibres and concerns over microplastic pollution.

6%

OF GLOBAL FIBRE PRODUCTION

$35bn

MARKET VALUE

$66.6bn

OF GLOBAL FIBRE PRODUCTION BY 2030

CAGR OF

7%

2024-2030

Land Use

While MMCFs offer certain advantages, such as lower land and water requirements, their production involves intensive chemical processing that creates substantial environmental challenges. Production systems can either be integrated (where pulp and fibre are produced at the same facility) or separate. Integrated production allows for energy recovery and material optimization, while separate production typically relies more heavily on fossil fuels and lacks the same efficiency advantages (Shen, 2010).

Land use for wood-based fibres includes agriculture and forest land used for biomass production. The rate of land use differs dramatically by the source of the input wood, as they have different biomass yields (e.g., European wood has lower biomass yield compared to warmer regions). This is further exacerbated by the use of different pulp mix by factory.

According to a life-cycle assessment report on MMCFs, cultivation of a viscose fibre for one company uses 0.7 hectares of forest land per year per tonne in Austria, but only uses
0.33 hectares in Asia (Shen & Patel, 2010).

Forest land used per year, per tonne of viscose fibre

AUSTRIA

0.7

HECTARES

per year per tonne

ASIA

0.33

HECTARES

per year, per tonne

Chemical Applications

The production of MMCFs involves significant chemical inputs across multiple stages of the value chain, from plantation management to fibre processing. Tree plantations that supply wood for MMCF production utilise various agrochemicals, though application rates and practices vary significantly by region, species, and management intensity, making the global chemical application rate for MMCFs challenging to quantify (Shen, 2010).

In wood production, pesticides and insecticides are used to protect against forest pests and insects. Herbicides like glyphosate are primarily used for site preparation, and fertilisers such as NPK blends are applied at planting, resulting in significant negative environmental impacts from commercial forestry (Shen, 2010). On the other hand, bamboo – which is sometimes used as a cellulose source for MMCFs – is considered more environmentally sustainable as it generally does not require irrigation, pesticides, or herbicides for cultivation and can regenerate growth after harvest (Ireogbu, 2021). Still, there is substantial variation in bamboo production practices, and large-scale bamboo plantations use chemicals to enhance growth and control pests (Xu, 2020).

1.3 Wood-Based Fibres

The conversion of wood to dissolving pulp and subsequently to fibre involves intensive chemical processes. Pulp production uses chemicals for cooking and bleaching, while fibre production requires various modifiers and stabilisers (SCS Global, 2017). The viscose production in particular raises significant environmental and health concerns due to the use of carbon disulfide, which is highly toxic and can cause severe health problems with prolonged exposure (Lawson, 2022).

Alternative processes such as lyocell and tencel use different chemical systems. For example, the production of lyocell – a type of rayon fabric made from cellulose – employs N-Methylmorpholine N-oxide (NMMO) as the primary solvent in a system that is reported to recover more than 99 percent of the solvent, creating a more closed-loop system with reduced chemical emissions (Lawson, 2022).

Lyocell uses N-Methylmorpholine N-Oxide (NMMO) as the primary solvent and is reported to recover more than 99% of the solvent.

Water Usage

Water use in MMCF production occurs at multiple stages of the value chain, with varying intensities and impacts. Water requirements for wood production vary by species and location, ranging from 262 to 740 cubic meters per tonne fibre (Shen, 2010; SCS Global, 2017). For example, European beech forests used for MMCFs are typically not irrigated and rely on natural rainfall (Shen, 2010). Eucalyptus plantations in the southern hemisphere are generally not irrigated (Shen, 2010). This relatively low direct water consumption in the raw material phase stands in contrast to fibres like cotton, which often require intensive irrigation.

The pulp and fibre production processes are water-intensive, particularly for cooling purposes (Shen, 2010). Cooling water accounts for approximately 90-95 percent of total water consumption in cellulose fibre production. Meanwhile, process water (softened, deionized, decarbonized, or tap water) comprises the remaining 5-10 percent (Shen, 2010).

Water consumption varies significantly between different production systems and technologies. For example, viscose production typically requires more water than lyocell production due to differences in process technology, while integrated production systems often have lower water footprints due to water recycling and process optimization (Lawson, 2022).
The majority of water consumption in the MMCF production results from the embedded water requirements associated with the production of chemical inputs such as sodium hydroxide and sulfuric acid, as well as energy generation (SCS Global, 2017). At the same time, direct net freshwater consumption at pulp and MMCF mills accounts for almost 20 percent of the total water footprint (SCS Global, 2017).

262
to 740

CUBIC METERS
per tonne fibre

90-95%

OF TOTAL WATER CONSUMPTION

in cellulose fibre production is cooling water

5-10%

OF TOTAL WATER CONSUMPTION

is process water

ALMOST
20%

OF THE TOTAL WATER FOOTPRINT

is direct net freshwater consumption at pulp and MMCF mills

Greenhouse Gas Emissions

The emissions profile of MMCFs presents a complex picture that includes both fossil carbon emissions and biogenic carbon considerations. Emissions vary significantly depending on the production system and energy sources, ranging from 0.20 to 8.30 tonnes CO_2e per tonne of fibre produced, leading to limited generalisability across the industry (SCS Global, 2017).

Separate production systems, particularly in facilities relying on coal and oil for energy (such as some Asian viscose production), show significantly higher emissions (Shen, 2010).

In these systems, pulp production, process heat, and power from fossil fuels typically account for 75 percent of total fossil carbon emissions, with chemical production (particularly caustic soda) also contributing significantly (Shen, 2010).

0.20 *to* **8.30**

TONNES CO_2e
per tonne of fibre

75%

OF TOTAL FOSSIL CARBON EMISSIONS

1.3 Wood-Based Fibres

On the other hand, integrated production systems (such as Lenzing's viscose facilities in Austria) demonstrate substantially lower carbon emissions due to the use of biogenic energy sources from production by-products and natural gas rather than coal (Shen, 2010). In these systems, the most significant emissions come from the production of caustic soda, accounting for more than half of total fossil fuel emissions (Shen, 2010). It is equally important to consider the biogenic elements of MMCFs. Each kilogram of MMCF contains approximately 0.44 kg of carbon, corresponding to 1.6 tonnes of CO_2e per tonne of MMCF temporarily stored in the product (SCS Global, 2017). Harvesting trees for MMCF production results in "foregone growth" – the carbon sequestration that would have occurred if the trees had continued growing (SCS Global, 2017). This represents a significant impact category in comprehensive life cycle assessments.

During logging, the decay and/or combustion of aboveground logging residues ("slash") and carbon stored in tree roots result in immediate CO_2 emissions (SCS Global, 2017). Typically, slash left on site amounts to approximately 25 percent of the harvest volume, with below ground roots containing a similar carbon mass (SCS Global, 2017). These biogenic considerations introduce complexity when evaluating the complete life cycle of MMCFs.

Each Kilogram of MMCF contains approx

0.44

KG OF CARBON

1.6

TONNES OF CO_2e
per tonne of MMCF

SLASH LEFT ON SITE AMOUNTS TO APPROX

25%

OF THE HARVEST VOLUME

Biodiversity and Soil Health

The impact of MMCF production on biodiversity and soil health primarily occurs at the raw material sourcing stage, with significant variations based on forestry practices and certification status. The scale of wood harvesting for MMCFs is substantial, with estimates suggesting that more than 150 million trees are logged annually for MMCF production (Granskog, 2020). Some sources place this figure even higher, at approximately 300 million trees per year (Canopy, n.d.). While the majority of MMCFs come from certified, sustainably managed plantations, concerns remain about source practices, including:

- Up to 30 percent of MMCFs may come from endangered and primary forests (Granskog, 2020)
- Even when sustainably certified, tree plantations may be detrimental to local biodiversity, e.g., due to the choice of non-native species and routine agricultural chemical application (Granskog, 2020; Seddon et al., 2021)
- The establishment of large plantations can displace native species (Xu, 2020)
- Unsustainable logging practices can lead to forest degradation and deforestation, particularly in regions with weak governance (Granskog, 2020)

MORE THAN
150
MILLION TREES
are logged annually for MMCF production

APPROXIMATELY
300
MILLION TREES
per year

UP TO
30%
OF MMCFs
may come from endangered and primary forests

Biodiversity and Soil Health

The effects on soil health vary significantly based on forestry management practices, and sustainable forest management can maintain or enhance soil quality and prevent erosion. Unsustainable practices, including illegal logging, increase the risk of soil erosion, fertility loss, and increased flooding due to the removal of trees that anchor the soil (PEFC International, 2023).

Monoculture plantations reduce soil biodiversity compared to natural forests, though this varies by the management approach (Granskog, 2020). Water and soil pollution from chemicals used in plantation forests and during pulp processing can drive habitat loss and endanger species, unless the production process is fully closed-loop (Lawson, 2022).

The contrast between integrated facilities with optimized energy recovery and closed-loop chemical systems compared to facilities relying on coal power and open chemical processes reinforces the need for transparency in MMCF sourcing and production methods (Lawson, 2022).

1.4

Wool

Wool

Wool is a biodegradable and renewable resource that is mostly produced in Australia, China, and New Zealand (CFDA, n.d.). It makes up about 1 percent of global fibre production in 2023, when excluding leather (Textile Exchange, 2024).

Wool production can have significant negative impacts on the environment and animal welfare. The wool value chain is notably complex, extending from on-farm production of 'greasy' wool through multiple processing stages to garment production, retail, and consumer use (Wiedemann, 2020).

While wool production occurs in numerous countries, processing is primarily concentrated in China and India, with a smaller proportion in Europe (Johnson, 2003).

Land Use

Wool is produced across 73 countries with 528 million hectares of land requirements (FAO, 2023). Wool production represents a historically and culturally significant agricultural sector, particularly for countries like Australia and New Zealand. Historically, wool production was also prevalent in European countries, but has seen steady decline in part due to the introduction of and changing preference for synthetic fibres in recent decades.

In 2018-2019, New Zealand produced approximately 139 million kilograms of greasy wool from 27.5 million sheep (with approximately 4.5% being Merino), while Australia generated 300 million kilograms from 72.5 million sheep (approximately 85% Merino or allied breed derived) (Ranford, 2022).

These two countries, along with South Africa and parts of South America, dominate the fine apparel wool market, particularly for Merino wool (Wiedemann, 2020).

ACROSS

73

COUNTRIES

WITH

528

MILLION HECTARES

of land requirements

Chemical Applications

The application of agrochemicals in wool production has undergone significant transformation over recent decades. Historical analysis indicates a substantial shift away from older anti-parasite technologies, particularly harmful organochlorine compounds that were common prior to 1985 (Ranford, 2022; Shaw, 1994). Modern wool production primarily relies on chemicals for internal and external parasite control and spray-on applications for insect growth regulation.

Recent data from Australia and New Zealand demonstrates that close to 100 percent of greasy wool harvested from these countries now complies with the European Union Eco-label limits for ectoparasiticide residues. Both Australian and New Zealand greasy wool have met the EU regulation maximum of 2 parts per million over four recent harvesting seasons (2015/16 - 2018/19) (Ranford, 2022).

Chemical Applications

Wool production requires extensive pasture management, involving the application of several herbicide compounds including glyphosate, 2,4D, and dicamba (Long, 2016).

Fungicide use in wool production occurs in two distinct contexts: on living sheep for footbath solutions and treating fungal skin conditions, and in wool processing and storage.

Sheep pastures typically receive various fertiliser applications, including nitrogen, phosphate, and potassium.

Water Usage

Water consumption in wool production occurs at multiple stages of the value chain, with impacts varying significantly by region and production system. On-farm water consumption is primarily associated with sheep drinking water and irrigation for pasture production.

Based on a Chinese case study, the weighted average water usage in sheep rearing across free range, mixed, and industrial methods is 6,030 cubic meters of water per tonne of fibre (Jiao, 2022). Studies in California – a significant wool producer – have identified that water consumption is predominantly from feed production, particularly irrigated pasture and hay (Dougherty, 2019).

WEIGHTED AVERAGE WATER USAGE IN SHEEP REARING

6,030

CUBIC METERS

of water per tonne of fibre

The high protein content of wool has been shown to correlate with increased water footprints when normalised by protein content, especially when compared to more water-efficient animals like goats (Jiao et al 2023). Water stress impacts vary by region (Dougherty, 2019).

Water Usage

In major wool-producing regions such as New South Wales and Western Australia, water consumption is relatively high as a proportion of total supply chain impacts. However, the water stress index (WSI) values in these regions (0.214 in New South Wales and 0.012 in Western Australia) are lower than the global average, which moderates the overall impact (Wiedemann, 2020).

Wool scouring (washing) represents a particularly water-intensive process in the wool value chain, although the volume of water used in processing is significantly lower per tonne of fibre than in sheep rearing. (Wang, 2015). Raw wool contains a high percentage by weight of natural contaminants that must be removed through scouring, which consumes large quantities of fresh water and produces concentrated effluent with high oxygen demand (Wang, 2015).

Wool scouring is a particularly water-intensive process. It consumes large quantities of fresh water and produces concentrated effluent with high oxygen demand.

Wool Scouring

Case studies of wool scouring processes have found that:

- The average original grey water footprint (water required to dilute pollutants) of wool scouring was approximately 51,878 cubic meters/day, approximately 291 times the blue water footprint (direct water consumption).
- Chemical oxygen demand (CODCr) was identified as the most critical pollutant associated with the largest pollutant-specific original grey water footprint.
- Ammonia nitrogen (NH_3-N) was the most critical pollutant associated with the largest pollutant-specific residuary grey water footprint (Wang, 2015).

51,878

CUBIC METERS/DAY

The average original grey water footprint (water required to dilute pollutants of wool scouring)

291

TIMES

Approximately 291 times the blue water footprint (direct water consumption)

0.626

AVERAGE WSI

The average water stress index (WSI) in processing regions

Water stress impacts from processing are influenced by both moderate water consumption volumes and the relatively high water stress index values in processing regions (average WSI of 0.626) (Wiedemann, 2020). While a reasonably high proportion of water is released back to rivers after processing, changes in water quality were not accounted for in some studies, potentially underestimating impacts (Wiedemann, 2020).

Greenhouse Gas Emissions

Greenhouse gas emissions in wool production present a distinctive profile compared to other natural and synthetic fibres, primarily due to enteric methane emissions from sheep. Based on assumptions from an Australian study, global emissions from wool production are over 68 million tonnes CO_2e per year, while emissions from wool processing are over 36 million tonnes CO_2e per year (Wiedemann, 2020).

68m

TONNES
CO_2e PER YEAR

Global emissions from wool production

36m

TONNES
CO_2e PER YEAR

Emissions from wool processing

Greenhouse Gas Emissions

Life cycle assessment studies of wool garments have found that greenhouse gas emissions are distributed across the value chain with distinct patterns:

- Emissions are highest from the wool production phase, with lower emissions from processing, retail, and garment care.
- The contribution by gas type shows 53.7 percent from methane (primarily from wool production), 40 percent from carbon dioxide (associated with fossil fuel), and 5.7 percent from nitrous oxide (associated with manure, fertiliser volatilization, and fossil fuel use).
- Enteric methane emissions – a potent but short-lived greenhouse gas – from sheep digestion account from approximately 48 percent of total value chain GHG emissions impacts (Wiedemann, 2020).

CONTRIBUTION BY GAS TYPE

53.7%
METHANE
(primarily from wool production)

40%
CARBON DIOXIDE
(associated with fossil fuel)

5.7%
NITROUS OXIDE
(associated with manure, fertiliser volatilization, and fossil fuel use)

Greenhouse Gas Emissions

Research suggests that sheep production can sequester carbon in soil and vegetation under appropriate management practices.

Studies from Australian case studies indicate this could potentially reduce emissions by approximately 4 percent for each successive wool production year over a 100-year period (Wiedemann, 2020).

Some Australian grazing farms have demonstrated potential to achieve carbon neutrality over periods exceeding 30 years under optimal management, while also supporting biodiversity and water management (Doran-Browne, 2016).

4%

POTENTIAL EMISSIONS REDUCTION

for each successive wool production year

30+

YEARS

Potential path to carbon neutrality under optimal management

Biodiversity and Soil Health

Livestock grazing for wool, cashmere, and leather production can contribute to soil erosion rates of 10-40 tonnes per hectare annually in degraded rangelands, with overgrazing affecting 73 percent of global grassland ecosystems (Slayi et al, 2024). The impact of wool production on biodiversity and soil health varies significantly based on management practices.

Poorly managed wool production can lead to several environmental concerns, including:

- Overgrazing resulting in land degradation
- Deforestation and habitat loss to create additional pasture for grazing animals
- Water and soil pollution from parasiticide used on sheep and chemicals used in wool processing
- Loss of biodiversity and exclusion of wild grazing species that compete with livestock for forage and space (Sustainable Fibre Alliance, n.d.; Bolotnikova, 2023)

Biodiversity and Soil Health

Management practices vary greatly based on pasture quality, climate and rainfall, grazing systems (e.g., rotational), soil fertility, water availability, and animal health. As a result, limited evidence is available to demonstrate the proportion of livestock that are poorly or properly managed.

Recent research indicates that properly managed livestock grazing can provide environmental benefits, including support for biodiversity, carbon sequestration, soil erosion prevention, and improved water infiltration and reduced runoff (Sustainable Fibre Alliance, n.d.; Bolotnikova, 2023).

Furthermore, studies have shown that free-ranging conditions and high-quality feed positively influence the quality of wool (Khan et al., 2010), providing a further incentive to transition to sustainable management.

1.5

Bast Fibres (Linen, Hemp)

Bast Fibres

Bast fibres represent a more environmentally sustainable alternative to conventional cotton. Hemp in particular is gaining recognition as a sustainable alternative due to smaller requirements for pesticides, fertilisers, and irrigation. For example, chemical use is a standard part of cotton cultivation, whereas this is not the case for hemp.

The crop can simultaneously improve soil health and biodiversity, though production is yet to be widely scalable due to technological limitations (Cherrett et al., 2005). Hemp accounted for approximately 0.2 million tonnes or 0.2 percent of global fibre production in 2023, while flax remains similarly niche despite its historical significance (Textile Exchange, 2024).

Global hemp production is expanding following recent regulatory changes in many countries (Textile Exchange, 2023b). While positioned as environmentally advantageous textile fibres, their environmental impact varies significantly based on cultivation practices and processing methods, and the energy intensity of fibre processing remains a key environmental challenge.

0.2
MILLION TONNES
Hemp production in 2023

0.2%
OF GLOBAL FIBRE PRODUCTION
in 2023

Land Use

Bast fibres are cultivated across 111 countries on approximately 5.8 million hectares, which is 0.1 percent of global agricultural land (FAO, 2023; Our World in Data, 2024). While hemp cultivation can be about 3 times more land efficient than cotton, its share of global fibre production is still minimal (Cherrett et al., 2005).

This category encompasses multiple source crops including flax (for linen), hemp, jute, kenaf, and linseed (Lyu, 2021), all with differing characteristics and rates of textiles usage.

Hemp, for example, is one of the fastest growing plants, with almost all parts of it being used (Kaur & Kander, 2023). These crops typically support diverse applications beyond textiles, including food, feed, construction materials, and paper products (Britannica, 2023).

111

COUNTRIES

5.8

MILLION HECTARES

0.1%

OF GLOBAL AGRICULTURAL LAND

3x

MORE LAND EFFICIENT THAN COTTON

Chemical Applications

Despite their reputation as low-input crops, conventional hemp and flax do utilise various agrochemicals, though typically at lower rates than crops like cotton. Both hemp and flax demonstrate natural resistance to many pests, reducing but not eliminating the need for pesticides and insecticides (Ellen Macarthur Foundation, 2017). Weed management practices vary between conventional and organic production, with glyphosate and bentazone being used for weed control in conventional systems (Mercer, 1990). Hemp's vigorous growth allows it to naturally outcompete many weeds, reducing herbicide requirements compared to flax and other fibre crops (Textile Exchange, 2023a).

Nutrient requirements for both crops are moderate compared to many other agricultural crops. Boron is a common fertiliser, as boron deficiency is relatively common in flax (The Fertiliser Institute, 2024). Research indicates that hemp demonstrates particular efficiency in nutrient uptake and can thrive with minimal fertiliser inputs when grown in suitable soil (CFDA. (n.d.,b)).

Chemical Applications

The transformation of raw plant material to usable fibre involves several chemical processes, particularly during retting, the controlled rotting that separates fibres (Van der Werf, 2008). Chemicals used for processing include hydrogen peroxide and sodium hypochlorite.

Alternative retting methods, including dew retting (using natural dew and soil microbes) and bio-retting, can reduce chemical inputs but may have other environmental trade-offs in terms of energy use and land occupation (Van der Werf, 2008).

Water Usage

Hemp and flax demonstrate favorable water profiles compared to many other textile fibres, particularly cotton. Both crops generally require minimal irrigation in suitable climates. Water use during production and processing ranges from 72.3 to 221.0 cubic meters per tonne of yarn, with substantial variation by processing method (Van der Werf, 2008).

In Europe, flax is primarily grown in areas with sufficient rainfall to make irrigation largely unnecessary (Textile Exchange, 2023a). Hemp is naturally drought-tolerant once established, though it does require adequate moisture during germination and early growth (Textile Exchange, 2023a).

Both crops require substantially less water than cotton during the cultivation phase. The ability of these crops to thrive with limited irrigation in appropriate climates represents a significant environmental advantage, particularly in regions facing water scarcity.

72.3
to
221.0

CUBIC METERS
per tonne of yarn

Water use during production and processing

Water Usage

Water requirements during processing vary by retting method:

01

WATER RETTING

Water retting is a water-intensive process, in which stalks are submerged in water and bacteria in the water decompose the stalk in order to separate the fibres. While faster than dew retting, often taking 1-2 weeks, it can be more environmentally impactful due to the need for water treatment and potential pollution (Van der Werf, 2008).

02

WARM WATER RETTING

Similar to water retting, this method uses warm water to speed up the decomposition process. Warm water retting requires substantial volumes, resulting in a substantial environmental impact, but can utilise thermal water sources or waste heat from industrial processes (Van der Werf, 2008).

03

DEW RETTING

In dew retting, stalks are left outdoors and exposed to dew, sun, and fungi which decompose the stalk. The process takes longer, often 6 weeks, and the reliance on natural dew limits geographic suitability to moist climates, reducing reliance on irrigation (Van der Werf, 2008).

Life cycle analyses indicate that hemp processing typically requires more water than flax processing. However, the environmental impact of this water use depends significantly on wastewater treatment practices (Van der Werf, 2008). Modern facilities with appropriate treatment systems can dramatically reduce the eutrophication potential of retting effluent (Van der Werf, 2008).

Greenhouse Gas Emissions

The carbon profile of hemp and flax is influenced by their biological characteristics and processing requirements. Both crops demonstrate favorable carbon sequestration characteristics during the growth stage. Flax is considered a carbon sink crop, absorbing more CO_2 from the atmosphere than it releases during growth (Ellen MacArthur Foundation, 2017). Hemp is remarkably efficient at carbon sequestration, with estimates suggesting it can capture up to 15 tonnes of carbon per hectare during its growing cycle (Helmore, 2024). The rapid growth cycle of both crops allows for efficient carbon capture within a single growing season.

The environmental footprint of processing represents a significant proportion of overall lifecycle emissions.

Energy use during fibre processing is the most critical issue for both crops' carbon footprints, and drying fibre after retting is particularly energy intensive (Van der Werf, 2008). The choice of energy source for processing significantly impacts overall greenhouse gas emissions – renewable energy sources can substantially reduce the climate impact.

Greenhouse Gas Emissions

Life cycle analyses indicate that different production methods present varying climate impacts. Traditional warm water retting of hemp produces comparable climate impacts to flax production, with greenhouse gas emissions per ton of fibre of 1.35 tonnes CO_2e for hemp water retting and 1.36 tonnes CO_2e for flax dew retting (Van der Werf, 2008).

Bio-retting of hemp typically demonstrates higher climate change impacts (1.81 tonnes CO_2e per tonne of fibre) than conventional methods due to increased energy requirements in fibre processing (Van der Werf, 2008).

Using renewable or waste energy sources for heating the retting water and drying fibres offers significant potential for reducing climate impacts (Van der Werf, 2008).

Biodiversity and Soil Health

Hemp and flax offer several beneficial properties for soil health and biodiversity when incorporated into appropriate agricultural systems. Both crops can contribute positively to soil structure and health. Hemp's deep taproot system helps break up compacted soil, improving soil structure and water penetration (Vujić, 2023). Both crops can be incorporated into rotation systems that enhance overall soil fertility.

Hemp has demonstrated potential for soil remediation, with research indicating its capacity to remove certain contaminants from soil (Textile Exchange, 2023a). The relatively low chemical input requirements reduce soil contamination compared to more chemical-intensive crops.

When grown in rotation systems, hemp and flax contribute to crop diversity, supporting more varied insect and microbial communities (Textile Exchange, 2023a). Both crops flower, providing forage for pollinators during their blooming period. The lower pesticide requirements, particularly for hemp, reduce negative impacts on beneficial insects and soil microorganisms.

Biodiversity and Soil Health

Both crops can be grown on marginal land unsuitable for food production, reducing competition with food systems (Textile Exchange, 2023a). Hemp in particular has been noted for its ability to suppress weeds naturally through rapid canopy development, which outcompetes other plants for sunlight and root space rather than killing them – leaving them often-native species dormant but intact in the soil seed bank. This natural competitive suppression offers significant biodiversity advantages over herbicide application, as herbicides persist in soil systems and chemically eliminate plant species entirely, disrupting the complex web of soil microorganisms, beneficial insects, and wildlife that depend on plant diversity (Pérez-Lucas, 2020). By allowing suppressed plants to remain viable in the ecosystem rather than destroying them chemically, hemp and flax cultivation support greater biodiversity within agricultural landscapes and maintains the potential for native plant communities to re-establish in subsequent growing seasons (Pérez-Lucas, 2020).

1.6

Silk

Silk

Silk is a natural protein fibre produced by silkworms. Though prized for its texture and luxury appeal, silk has a relatively high environmental impact. The silk market is approximately US$11.8 billion in 2024 and projected to grow by a CAGR of 9.25 percent until 2033 (Market Data Forecast, 2023).

The Asia-Pacific region remains dominant in silk production and consumption, with China and India accounting for over 90 percent of global output (International Sericultural Commission, n.d.).

$11.8bn
SILK MARKET
in 2024

9.25%
CAGR
until 2033

>90%
OF GLOBAL OUTPUT
from China and India

Land Use

Despite its relatively small market share, silk production carries significant land-use implications.

It is produced across 26 countries on approximately 2.2 million hectares (Appendix 8).

The majority of land use is attributable to mulberry trees, which are the primary food source for silkworms (CFDA, n.d.c).

PRODUCED ACROSS

26

COUNTRIES

2.2

MILLION HECTARES

of land is used for silk production

Chemical Applications

Mulberry cultivation relies heavily on herbicides to control weeds that compete with the mulberry trees for nutrients, with typical application rates averaging around 4.75 kg of active ingredients per hectare (Khare et al., 2023).

When scaled to production, this translates to approximately 68 grams of herbicide active ingredient used per kilogram of raw silk produced (Khare et al., 2023).

Mulberry trees grown in monoculture environments are susceptible to fungal diseases, prompting the use of fungicides to control diseases (Kumar, 2023). Research shows that these chemicals do not just stay on the trees – they have been detected in soil, water, and air samples, disrupting ecosystem balance (Kumar, 2023). Studies have found that fungicides like pyraclostrobin not only harm the environment but directly impact silk quality (Nicodemo et al., 2018).

4.75kg

OF ACTIVE INGREDIENTS

per hectare

68

GRAMS OF HERBICIDE ACTIVE INGREDIENT

used per kg of raw silk produced

Chemical Applications

When silkworms consume contaminated mulberry leaves, the chemicals interfere with their metabolic processes, affecting mortality rates and reducing cocoon weight (Nicodemo et al., 2018).

Insecticides used in mulberry cultivation present a particular irony – while protecting the mulberry trees from pests, they pose significant risks to the very silkworms meant to consume the leaves (Ashrith et al., 2024). Application rates for insecticides and pesticides vary by region, with Indian guidelines recommending 2-3 kg/ha/year under integrated pest management, while Chinese intensive systems may use up to 5-6 kg/ha/year (Liu et al., 2022).

The residual effects of these insecticides on silkworms include reduced feeding, slower growth, and increased mortality – all translating to lower-quality silk and reduced yields, creating a self-defeating cycle.
(Ashrith et al., 2024; Liu et al., 2022).

Water Usage

Silk's water footprint is substantial throughout its lifecycle, particularly in production phases. Studies show that producing one tonne of raw silk requires between 850-1,000 tonnes of water in basic processing alone (Fashion United, 2021).

More comprehensive water footprint analyses estimated a total water footprint of 1,710.99 cubic meters per tonne of silk, broken down as:

- Blue water (irrigation): 539.23 cubic meters/tonne
- Green water (rainfall): 784.85 cubic meters/tonne
- Grey water (pollution dilution): 386.91 cubic meters/tonne (Wibuloutai et al., 2020)

For India's silk industry alone, this translates to approximately 1,792.2 to 3,584.4 cubic meters of water per tonne annually – much of which is returned to the environment untreated after reeling and dyeing processes, carrying chemical contaminants (Mahadevappa, 2000).

850 *to* 1,000

TONNES OF WATER

required per tonne of raw silk in basic processing

1,710.99 m3

TOTAL WATER FOOTPRINT

per tonne of silk

Much of this water is returned to the environment untreated with chemical contaminants.

Greenhouse Gas Emissions

The carbon footprint of silk varies significantly depending on production methods and study boundaries. The most comprehensive life cycle assessments place silk's carbon footprint at approximately 80.9 tons CO_2e per tonne of silk – from fibre production through the garment life cycle (Liu et al., 2022). Other studies focusing on specific production phases have found:

- Raw silk production: 80.26 tonnes CO_2e per tonne of raw silk (Astudillo, 2015)
- Fabric production: 0.182-0.191 tonnes CO_2e per tonne (Liu et al., 2022)

These carbon emissions stem primarily from energy-intensive processes like reeling, weaving, and especially dyeing and finishing. When compared to other natural fibres like cotton, silk typically shows a higher per-unit carbon footprint due to its complex, multi-stage production process (Liu, 2022).

LCA results are predominantly focused on China, and inconsistent results are produced across studies due to different research objectives and inconsistent accounting boundaries.

80.9

TONNES CO_2e

per tonne of silk from fibre production through the garment life cycle

80.26

TONNES CO_2e

per tonne of raw silk

0.182 *to* **0.191**

TONNES CO_2e

per tonne of fabric

Biodiversity and Soil Health

Unlike cotton, silk production does not necessarily require clearing natural habitats. In fact, well-managed mulberry plantations can provide environmental benefits, sequestering carbon, preventing soil erosion, and improving water infiltration (Liu, 2022). However, concerns arise when natural forests are converted to mulberry plantations, particularly in regions with expanding silk production (CISL, 2021). This conversion can disrupt ecosystems and fragment landscapes, leading to biodiversity loss (Attri et al., 2024). Deforestation can result in reduced genetic diversity in silkworms, further increasing vulnerability to pests and diseases (Wani et al., 2018).

There is a significant data gap in the proportion of global mulberry plantations that are managed sustainably, compared to other sectors where certification data is more readily available; given that about two percent of global agricultural land is certified organic, it can be reasonably assumed that sustainable practices currently represent a small minority of mulberry plantations (iFOAM 2025).

Well-managed mulberry plantations can sequester carbon, prevent soil erosion, and improve water infiltration.

2%

OF GLOBAL AGRICULTURAL LAND

is certified organic

Biodiversity and Soil Health

Beyond environmental impacts, conventional silk production raises ethical questions. Most commercial silk involves killing silkworms before they emerge from their cocoons, with approximately 6,600 silkworms sacrificed for each kilogram of silk (CFDA, n.d.c).

Alternatives like peace silk or wild silk allow moths to emerge naturally before cocoon harvesting, though these options typically yield lower-quality silk with shorter fibres (CFDA, n.d.c). For those committed to vegan or animal-friendly fashion, these ethical considerations add another dimension to silk's sustainability profile.

6,600

SILKWORMS

sacrificed per kg of silk in conventional production

1.7

Cashmere

Cashmere

The production of cashmere is concentrated in high-altitude regions, with Mongolia serving as the world's second-largest producer after China.

The scale of cashmere production in Mongolia is substantial, with 24.6 million goats currently inhabiting Mongolia, outnumbering the human population by more than 8 to 1 (Ooluun, 2024).

Cashmere constitutes nearly 5 percent of Mongolia's GDP, serving as the primary income source for many nomadic herder communities (SWITCH Asia, 2020). Market analysts project the global cashmere industry will grow by more than 6 percent annually until 2030, reaching a value of $4.23 billion (Chan, 2023).

24.6
MILLION GOATS
in Mongolia

8 to 1
GOATS TO
HUMANS

NEARLY
5%
OF MONGOLIA'S GDP

$4.23bn
PROJECTED MARKET
VALUE BY 2030

6%+
ANNUAL
GROWTH
UNTIL 2030

Land Use

There is limited research and data on land use for cashmere-related agriculture or production, and the fibre is generally categorised as a specialised wool variety with distinct production characteristics (CFDA, n.d.,a). However, raising cashmere goats can have severe environmental consequences, particularly when overgrazed.

These goats consume over 10 percent of their body weight daily, forage aggressively across a wide range of plants, and often uproot vegetation entirely, damaging topsoil and preventing regrowth.

In regions like China and Mongolia, this has contributed to widespread desertification, worsening dust storms and threatening already fragile ecosystems. (CFDA, n.d.,a).

10%+

OF BODY WEIGHT CONSUMED DAILY

Overgrazing damages topsoil and prevents regrowth.

Contributes to desertification in China and Mongolia. Worsens dust storms and threatens ecosystems.

Chemical Applications

Like leather and wool, cashmere production involves a different chemical profile than crop-based fibres, focusing on animal health management and pasture management rather than crop protection. The primary chemicals used directly on cashmere goats are parasiticides for controlling internal and external parasites. These treatments – commonly used in conventional veterinary practices to support animal health – must be carefully managed, as some parasiticides like certain fungicides have been documented to be toxic to goats when improperly administered (Grossman, 2015; Tahir, 2009).

In more managed production systems, various chemicals may be used to maintain pasture quality, including herbicides like glyphosate and fertilisers like nitrogen and phosphate. However, it is important to note that chemical usage varies dramatically among production systems. For example, traditional nomadic herding practices in Mongolia and other major producing regions typically employ minimal chemical inputs.

Parasiticides are the primary direct chemicals used on goats.

Traditional nomadic herding typically employs minimal chemical inputs.

Chemical Applications

More intensive farming operations may utilise higher levels of both parasiticides and pasture management chemicals (Dabadi, 2023). Remote, high-altitude production regions often have naturally limited chemical usage due to economic constraints and access limitations.

Once harvested, cashmere undergoes processing that involves several chemical inputs, including sodium carbonate in scouring, non-ionic detergents in washing processes, and hydrogen peroxide for fibre bleaching (Li, 2014). The dyeing and finishing processes for cashmere fabrics can introduce additional chemical concerns. Life cycle assessment studies have identified several pollutants of concern, including total phosphorus, chlorine dioxide, hexavalent chromium, and sulfide.

Processing uses sodium carbonate, detergents, and hydrogen peroxide.

Pollutants of concern include total phosphorus, chlorine dioxide, hexavalent chromium, and sulfide.

Water Usage

Cashmere production in traditional pastoral systems has relatively low direct water requirements compared to irrigated crop fibres. Goats typically rely on natural water sources in grazing areas, and pastoral systems rarely employ irrigation. Water use in goat rearing is estimated at 5,056 cubic meters per tonne of fibre (Jiao et al, 2023).

The indirect impact on water systems can be substantial. Overgrazing reduces vegetation cover, which can increase runoff and reduce water infiltration (Trankman, 2018). Soil compaction from intensive grazing can alter local hydrology. Degraded pasture land may have diminished capacity to retain water, potentially contributing to increased drought and flooding vulnerability (Simões, 2021).

5,056

CUBIC METERS

per tonne of fibre

Low direct water use in pastoral systems

Indirect risk through overgrazing and runoff

Water Usage

The water footprint of cashmere becomes more significant during processing. Life cycle assessment studies indicate that water usage varies significantly between knitted and woven cashmere fabrics. **Woven cashmere fabrics generally demonstrate higher water footprints than knitted cashmere fabrics.** The "combed sliver dyed woven cashmere fabric" production method shows the largest blue water footprint, grey water footprint, and water scarcity footprint among studied cashmere fabric types (Chen, 2021).

Water Usage

Beyond water consumption, cashmere processing raises water quality concerns. Primary pollutants contributing to grey water footprints include total phosphorus, chlorine dioxide, hexavalent chromium, and sulfide.

The main contributors to water eutrophication footprints are total nitrogen (39-48%), ammonia nitrogen (23-28%), chemical oxygen demand (12-24%), and total phosphorus (12-14%) (Chen, 2021). Water ecotoxicity is primarily driven by aniline, hexavalent chromium, and absorbable organic halogens discharged during dyeing and finishing processes (Chen, 2021). These water quality impacts are largely associated with industrial processing rather than the herding practices themselves, highlighting the importance of improved treatment technologies in cashmere production facilities.

KEY CONTRIBUTORS TO WATER EUTROPHICATION

Share of water eutrophication footprints (Chen, 2021)

TOTAL NITROGEN

39-48%

AMMONIA NITROGEN

23-28%

CHEMICAL OXYGEN DEMAND

12-24%

TOTAL PHOSPHORUS

12-14%

Greenhouse Gas Emissions

As ruminants, cashmere goats produce methane through enteric fermentation. Each goat produces 5-7 kg of methane – a potent greenhouse gas with 28 times the global warming potential of carbon dioxide of a 100-year timeframe – annually through digestive processes (Chen, 2021). The large goat population in Mongolia (24.6 million) represents a significant source of methane emissions (Simões, 2021).

Manure management also contributes to emissions through the release of both methane and nitrous oxide. However, in traditional pastoral systems, manure is typically deposited directly on pastures rather than concentrated in management facilities, which can reduce these emissions compared to intensive systems (Gonzalez-Torres, 2024). Goats emit less methane per unit of body weight than cows and can be raised on land unsuitable for cows, reducing their overall carbon footprint; however, when measured per unit of output, goats can have higher emissions than cows, especially in intensive farming systems.

5-7kg

METHANE PRODUCED

per goat annually

28x

GLOBAL WARMING POTENTIAL

of methane relative to carbon dioxide over 200 years

24.6m

GOATS

in Mongolia

Greenhouse Gas Emissions

The land degradation associated with cashmere production has significant implications for carbon storage. While healthy grasslands serve as important carbon sinks, the degradation of pastureland reduces the carbon sequestration of these ecosystems. Severe overgrazing that leads to desertification can result in the net release of previously stored soil carbon (Muthu, 2016). The extent of these impacts depends on both stocking density and management practices. Research indicates that stocking rates (approximately 70 head per hectare) can improve soil properties, while excessive stocking (140 head per hectare) can lead to soil degradation (Abdul Rahman, 2019).

The processing of cashmere textiles generates additional greenhouse gas emissions. Life cycle assessment studies indicate that knitted cashmere fabrics generally have a greater carbon footprint than woven cashmere fabrics (Chen, 2021). Energy use in processing, particularly for heating water and drying fibres, represents a significant contribution to the carbon footprint. As with other materials, the choice of energy sources for processing facilities substantially influences the overall emissions profile.

70

HEAD /HECTARE

can improve soil properties

140

HEAD /HECTARE

can lead to soil degradation

Knitted cashmere
> Woven Cashmere

GREATER CARBON FOOTPRINT

Key drivers:

Heating water and drying fibres

Energy use in processing

Choice of energy source

Biodiversity and Soil Health

Intensive cashmere production can pose threats to biodiversity. For example, goats may compete with wild grazing species for space and forage. The selective grazing behavior of goats can alter plant community composition, potentially reducing plant diversity.

Habitat degradation from overgrazing can impact a wide range of species beyond competing herbivores (Cherny-Scanlon, 2016). However, well-managed cashmere production can maintain biodiversity. For example, research indicates that controlled goat corralling – in which livestock are moved from one pasture to another – can increase broadleaf, grass, and sedge species compared to ungrazed areas (Abdul Rahman, 2019). Traditional pastoral systems often coexisted with natural ecosystems for centuries before recent intensification (Abdul Rahman, 2019).

Goats have demonstrated an ability to survive in harsh climate conditions, including adaptability to both cold and warm climates, ability to thrive in drought conditions due to lower water requirements, and feed conversion efficiency (Pragna, 2018).

Controlled goat corralling can increase broadleaf, grass, and sedge species compared to un-grazed areas.

GOAT ADAPTABILITY

01 *Cold and warm climate adaptability*

02 *Lower water requirements*

03 *Feed conversion efficiency*

Biodiversity and Soil Health

The impact of cashmere goats on soil health depends significantly on management practices. At appropriate stocking densities, goat manure can improve soil chemical properties, including pH, organic carbon, total nitrogen, available phosphorus, and exchangeable potassium (Abdul Rahman, 2019). Soil biological properties, including microbial biomass carbon, microbial biomass nitrogen, and earthworm activity, can increase with moderate goat densities. However, excessive stocking rates increase soil bulk density and reduce porosity, negatively affecting soil physical properties. Actual and optimal stocking rates vary greatly based on soil, ranges, climate, rainfall, and other factors (White et al 1977).

Research on goat manure applications indicates potential benefits for agriculture. For example, the addition of goat manure combined with supplementary organic materials (such as nopal components) has demonstrated positive effects on plant germination, development, and production in experimental settings (Gonzalez-Torres, 2024).

STOCKING DENSITY MATTERS

The choice of stocking rate plays a critical role in determining soil health outcomes.

2

Comparative Environmental Impact Assessment

2. Comparative Environmental Impact Assessment

Summary of Environmental Impacts by Fibre Type

Textile	Land Use, 2023 (Ha)	Chemical Intensity	Water Consumption	GHG Emissions
Cotton	34.7 million	Very High	Very High	Moderate
Data Quality	High	High	Medium	Medium
Leather	876 million	Moderate	High	Very High
Date Quality	High	High	High	High
Tree/Wood-based Fibres	Limited Data	Moderate	Moderate	Low-Moderate
Data Quality	Low	Medium	Medium	Medium
Wool	528 million	Low-Moderate	High	High
Data Quality	High	High	High	Medium
Line/Hemp	5.8 million	Low	Low	Low
Data Quality	High	Medium	Medium	Medium
Silk	2.2 million	Moderate	Moderate	Low
Data Quality	High	High	High	High
Cashmere	Limited data	Low-Moderate	Moderate	Moderate
Data Quality	Low	Medium	High	High

Source: Land Use: FAO 2023. See Appendix 1 for an explanation of the scoring methodology. See Appendix 2-8 for detailed data regarding environmental impacts and sources.

Note: Impact assessments reflect conventional production practices based on available LCA data. Actual environmental impacts vary significantly depending on specific cultivation methods, geographic location, and scale of production. Materials produced under certified organic, biodynamic, or other sustainable farming systems typically demonstrate substantially reduced environmental impacts across multiple categories, particularly in areas such as greenhouse gas emissions, water pollution, and biodiversity conservation.

Legend - Impact Intensity: Assessed by authors based on available data (see appendix)

Very High Impact	High Impact	Moderate Impact	Low-Moderate Impact	Low Impact

Legend - Data Quality: Assessed by authors based on reliability, time representativeness, verifiability, and geographical representativeness (see Appendix)

High	Medum	Low

Part 2

Biodynamic Agriculture: Scientific Assessment and Comparative Analysis

Biodynamic Agriculture

This section of the report examines the scientific evidence on biodynamic agriculture as an alternative method for growing fashion-related crops and managing land, with particular focus on its environmental impacts compared to conventional, regenerative, and organic farming practices. Based on systematic literature reviews and long-term comparative studies, this report assesses the effectiveness, knowledge gaps, and comparative advantages of biodynamic approaches.



1

Methods of Sustainable Agriculture

1.1

Overview of Sustainable Agriculture

Overview of Sustainable Agriculture

Sustainable agriculture, based on the definition of sustainable development, is generally defined as “farming that meets society's present food and textile needs, without compromising the ability for current or future generations to meet their needs” (UC SAREP, 2023). While this definition captures the broad goal of sustainable agriculture, implementation is more ambiguous and wider ecosystems are not included. The concept resists simplification and instead calls for practitioners to “embrace the complexity of sustainable agriculture with its varied and seemingly contradictory aspects” (Velten et al., 2015). Fundamentally, sustainable farming aims to address the environmental degradation associated with conventional agriculture, such as habitat loss, soil erosion and acidification, and pollution from synthetic fertilisers and pesticides (Tait & Morris, 2008). Numerous techniques, methods, and certification systems fall under the umbrella of sustainable agriculture, often overlapping in both practice and philosophy (Velten et al., 2015). Techniques refer to specific practices like crop rotation, biological pest control, or organic fertilisation. Methods, or farming systems, typically combine several of these practices into a cohesive framework, such as organic or regenerative agriculture.
Some of these systems are eligible for third-party certification, which can help standardise practices and support market recognition. While organic agriculture is widely regulated, regenerative agriculture currently has limited formal certification systems, primarily concentrated in the United States.

Table 1. Comparative Overview of Farming Methods

Farming methods overview

Non-exhaustive Illustrative (depends on specific certifications and standards) Environmental Impact Negative Mixed Positive

FARMING TECHNIQUE	CONVENTIONAL	ORGANIC	REGENERATIVE	BIODYNAMIC
Synthetic fertilizers	Common	Prohibited	Prohibited	Prohibited
Pesticides / herbicides	Common	Limited	Prohibited	Prohibited
GMOs	Common	Prohibited	Prohibited	Prohibited
Soil health plan	Not required	Encouraged	Required	Required
Composting / organic matter	Not required	Encouraged	Required	Required
Crop rotation	Not required	Required	Required	Required
Monocultures	Common	Limited	Limited	Prohibited
Cover crops / ground cover	Not required	Encouraged	Required	Required
Livestock integration	Not required	Encouraged	Encouraged	Required
Animal welfare	Not required	Required	Required	Required
Antibiotics & hormones	Common	Mostly Prohibited	Mostly Prohibited	Prohibited
Biodiversity & habitat care	Not required	Required	Required	Required
Farm as a closed loop system	Not required	Not Required	Encouraged	Encouraged

Certifications

- USDA National Organic Program
- Soil Association Certified Ltd
- Ecocert
- Regenerative Organic Certified
- Certified Regenerative byAGW
- Regenefied
- Demeter Certification

Note: Illustrative and non-exhaustive; techniques depend on specific certification. Much of the academic research on agriculture focuses on food crops, but findings are generally applicable to fibre cultivation.

Different sustainable agriculture methods often share core principles and practices. Techniques such as crop rotation and biological pest control are widely regarded as fundamental to sustainable outcomes. Some scholars argue that the most resilient approach is a diverse landscape of farming systems tailored to local ecological, social, and economic contexts (Tait & Morris, 2008). While not all techniques fit neatly within one method, formalised systems provide practical frameworks to guide farmers and facilitate transitions away from conventional practices. Moreover, standardised methods and certifications can increase adoption and improve economic viability through consumer trust and premium pricing.

1.2

Organic Agriculture

1.2 Organic Agriculture

Organic agriculture is one of the most established forms of sustainable farming. It is guided by international frameworks such as the Codex Alimentarius Guidelines and the Basic Standards of the International Federation of Organic Agriculture Movements (IFOAM), and is rooted in the principles of health, ecology, fairness, and care (Tuomisto et al., 2012). In practice, organic farming promotes a holistic production system that enhances soil health and bans the use of synthetic fertilisers and pesticides (UK Government, 2022).

These systems may be adapted to local environmental and social conditions, leading to some variation in standards between jurisdictions (FAO, n.d.). For example, the European Union maintains its own certification standards for organic products (European Commission, n.d.), which have occasionally sparked debate about consistency and rigour across regions.

As of 2023, the global area under organic production, which includes both food and fibre, reached approximately 98.9 million hectares, more than doubling over the past decade (Statistica, 2025).

Organic farming operations now exist in 188 countries. In the UK for example, the organic farmland area grew from 489,000 hectares in 2020 to 507,000 hectares in 2021, representing 2.9 percent of the total farmed area (UK Government, 2022). This includes both fully converted land and areas undergoing conversion.

Several meta-analyses have compared the environmental and economic outcomes of organic and conventional farming systems.

1.2 Organic Agriculture

A European review concluded that organic farming generally delivers better environmental outcomes per unit of land area, particularly in terms of biodiversity and reduced pollution, though often at the cost of lower yields and higher land use per unit of product (Tuomisto et al, 2012). Organic farms tend to host greater species abundance and richness (Hole et al., 2005) and have lower risks of biodiversity loss and ecotoxicity (Hashemi et al., 2024).

Organic agriculture faces several significant limitations that constrain its widespread adoption and effectiveness.

Key challenges have included a lack of information, economic viability, and contentious rules regarding weeds and pest control. A systematic review found that despite ambitious policy targets worldwide to boost organic agriculture, structural barriers continue to limit organic farming's expansion and effectiveness (Möhring et al., 2024).

1.3

Regenerative Agriculture

Regenerative Agriculture

Regenerative agriculture is an emerging method of sustainable farming focused on restoring soil health and biodiversity (UC SAREP, 2023). Its core aim is to regenerate degraded land while delivering environmental, social, and economic benefits (Khangura et al., 2023). Unlike organic farming, regenerative agriculture lacks a legal definition or universally accepted framework (Newton et al., 2020). Definitions typically centre on specific techniques, such as cover cropping, composting, and livestock integration, and outcomes like improved soil structure and carbon sequestration.

The absence of standardised definitions or third-party certifications presents both flexibility and challenges. As a result, the prevalence and impact of regenerative agriculture remain difficult to measure. Nonetheless, several studies highlight the potential benefits of regenerative practices. A literature review suggests that practices like minimal tillage, crop residue retention, and cover cropping can improve soil carbon, yields, and resilience, particularly when used together and tailored to specific climatic and ecological conditions (Khangura et al., 2023). These practices should be used in combination to regenerate the health of the land. However, given the variability in practices and outcomes, caution should be taken when generalising findings across farms or regions.

1.3 Regenerative Agricutlure

Regenerative agriculture, while promising, faces considerable implementation challenges that limit its practical application. Key limitations include the diverse definitions, lack of consensus on indicators and models, lack of baseline data, limited digital integration, and insufficient locally relevant information and evidence (Khangura et al., 2023). This has also contributed to concerns around potential greenwashing due to the lack of consensus on its definition (Schreefel et al., 2020). An example of a controversial topic is that certain standards and definitions of regenerative agriculture allow for the use of the herbicide glyphosate, which is prohibited in organic agriculture (Soil Association, n.d.).

1.4

Biodynamic Agriculture

1.4 Biodynamic Agriculture

The farm as a *living organism.*

Biodynamic farming is a holistic and ecological approach to agriculture that conceptualises the farm as a living organism, integrating crops, animals, and soil into a self-sustaining system (Biodynamic Association, n.d). In contrast to conventional and some organic systems, biodynamic farming emphasises the farm's individuality and resilience, seeking to generate fertility and vitality from within the farm ecosystem itself.

Developed from the work of Rudolf Steiner in the 1920s, biodynamic agriculture shares many principles with both organic and regenerative agriculture (Santoni et al., 2022). Biodynamic agriculture is unique for its inclusion of biodynamic preparations, or unique and fermented natural remedies used to enhance soil health and vitalise plant health; for example, preparations like horsetail tea may be used to prevent fungal infections (Biodynamic Association, n.d.).

Certification of biodynamic farms is governed by the Demeter Standards, mostly used for food and wine production. Standards for fish are available as well, and standards for textiles are being developed in collaboration with DIRT Charity. Farms certified by Demeter have increased, reaching more than 5,900 farms in 2019, across 63 countries (Santoni et al., 2022). The current scientific evidence on biodynamic agriculture will be explored in a later section of this report (See 2. Scientific Evidence On Biodynamic Agriculture).

1.5

Other Sustainable Agriculture Methods

1.5 Other Sustainable Agriculture Methods

Beyond organic and regenerative systems, many other methods contribute to sustainable agriculture. The World Economic Forum highlights innovations such as soil conservation techniques, vertical farming, and vegan agriculture (WEF, 2021). The European Commission additionally recognises agroecology, precision farming, carbon farming, high nature value (HNV) farming, and animal husbandry plans as viable approaches (European Commission, n.d.).

- Soil Conservation
- Vertical Farming
- Vegan Agriculture
- Agroecology
- Precision Farming
- Carbon Farming
- HNV Farming
- Animal Husbandry

While these methods differ in scope and definition, many share goals such as reducing environmental harm, promoting animal welfare, or enhancing ecosystem services. However, few have widely accepted standards or associated certification schemes.



2

Scientific Evidence on Biodynamic Agriculture

Scientific Evidence on Biodynamic Agriculture

Biodynamic agriculture presents comprehensive principles and practices for farming in harmony with nature. Scaling the adoption of biodynamic agriculture requires a robust scientific evidence base; however, the scientific basis for biodynamic agriculture – particularly for fashion-related cultivation – presents a mixed picture regarding data availability and quality.

2 Scientific Evidence

Overall data availability and quality are limited, although several robust long-term studies – particularly the DOK trial in Switzerland (running since 1978) and similar comparative experiments – provide substantial evidence for the soil health, biodiversity, and carbon sequestration benefits of biodynamic agriculture (Krause et al., 2022). Notably, studies are largely limited to Europe, potentially hindering the generalizability of this evidence.

Fashion-specific evidence remains limited, with low data availability and quality. The majority of research has focused on food crops and general agricultural systems, with cotton being the primary fashion-related crop studied in detail, largely through case studies like the SEKEM initiative in Egypt (see Box 2.1).

Water consumption data represents a particular weakness across all crop types, with limited quantitative information available even for well-studied agricultural systems. This gap is especially pronounced for fashion-related applications where water efficiency is increasingly critical for supply chain sustainability.

2 Scientific Evidence

Much of the evidence supporting biodynamic agriculture's benefits for fashion applications is case study-based rather than derived from controlled comparative trials. While these case studies provide valuable real-world insights and demonstrate practical feasibility, they lack the experimental rigour needed for definitive scientific conclusions.

Further research specifically targeting fashion-related crops through controlled, long-term comparative studies is needed to strengthen the evidence base for biodynamic fibre cultivation and support informed decision-making in sustainable fashion supply chains. This section reviews the existing literature on the environmental impacts of biodynamic agriculture, with a focus on comparisons to organic and conventional agriculture.

The Data

Table 2. Biodynamic Agriculture Data Quality Assessment by Environmental Impact Category: Overall and Fashion-Related

Environmental Impact Category	Biodynamic Data Quality: Overall	Biodynamic Data Quality: Fashion-Related
Land Use & Soil Health	Medium-High	Low
Chemical Intensity	Medium-High	Low
Water Consumption	Low	Low
GHG Emissions	Medium	Low

Note. Assessed by authors based on reliability, time representativeness, verifiability, and geographical representativeness (see Appendix).

2.1

Land Use & Soil Health

2.1 Land Use & Soil Health

Biodynamic agriculture demonstrates superior soil health outcomes compared to both organic and conventional systems across multiple long-term studies.

2.1 Land Use & Soil Health

Systematic analysis reveals that 70 percent of biological indicators measured in biodynamic farming are higher than in conventional farming, while 52 percent of microbial indicators are higher than in organic farming (Christel et al., 2021). The DOK trial in Switzerland, running since 1978, provides some of the most robust evidence. After 42 years, biodynamic systems with higher manure input (BIODYN 1.4)[7] increased soil organic carbon (SOC) content, while conventional systems showed stable or declining SOC levels (Krause et al., 2022). In the same study, pure mineral fertilisation and organic fertilisation at 0.7 livestock unit (LU) per hectare led to a decline in SOC content (Krause et al., 2022). While raising SOC levels in organic systems is possible, it is a much slower process, demonstrated to take up to two decades, compared to biodynamic systems, which demonstrate significant improvements in as little as two years (Krause et al., 2022). This trial consistently shows biodynamic management supporting improved biological soil quality closely linked to positive SOC dynamics.

70%

OF BIOLOGICAL INDICATORS

higher than in conventional farming

52%

OF MICROBIAL INDICATORS

higher than in organic farming

Land Use Considerations

Biodynamic standards require 10 percent of farm area to be dedicated to encouraging biodiversity, inherently requiring greater land use than conventional agriculture (Demeter International 2025). There is mixed data regarding the impact of sustainable practices on crop yields.

Agricultural yields in biodynamic and organic systems have been demonstrated to be 20 to 34 percent less than conventional farming systems in some studies (De Ponti et al., 2012; Seufert et al., 2012). In other studies, resource-conserving agricultural practices, including reduced pesticide use, have been demonstrated to increase yields by as much as 42 percent in developing countries (Pretty et al., 2006).

10%

OF FARM AREA

dedicated to encouraging biodiversity

42%

INCREASE IN YIELDS

in resource-conserving agricultural practices

2.1 Land Use & Soil Health

Practices that promote biodiversity and soil health, like cover cropping and crop rotation, may reduce overall yield per unit compared to monoculture-focused systems (De Ponti et al., 2012; Seufert et al., 2012). However, this perspective must be contextualised within a holistic understanding of agricultural sustainability. Reduced yields per hectare are not inherently negative when considered alongside the broader environmental benefits and the need for sustainable consumption patterns.

Slower, more regenerative land use that builds soil health and biodiversity contributes to maintaining and restoring natural ecosystems rather than degrading them. This approach supports long-term agricultural viability and reduces pressure on remaining natural habitats by creating farming systems that work with rather than against ecological processes. While yield measurements typically directly compare two plots of land growing the same crop, biodynamic systems focus on growing multiple types of crops in the same space, often including perennial crops that persist for multiple seasons, thus contributing to a diversified system that may indeed have a higher overall yield.

Microbial Community Enhancement

A systematic literature review of the impact of farming systems on soil ecological quality found that biodynamic farming enhances microorganism abundance compared to organic farming, with an increase in 71 percent of the abundance measurements studied (Christel et al., 2021). Microorganism activity is also more stimulated, with 54 percent of measurements showing positive effects (Christel et al., 2021). Microbial biomass increased by 11 percent relative to organic farming, while microbial respiration – the final step of decomposition which supports carbon and nutrient flows in the soil food web – was 54 percent higher in biodynamic systems, attributed to soil acidity regulation by biodynamic preparations (Reeve et al., 2010). By contrast, conventional farming consistently presents the most unfavourable outcomes for soil ecological quality, even after practices became more sustainable in the 2000s (Bengtsson, 2005; Lori, 2017). It is important to note that soil type and sampling time effects also influence the impact of the farming systems on microbial communities (Ilieva-Makulec et al., 2017; Santos et al., 2012).

71%

INCREASE

in microorganism abundance measurements

54%

POSITIVE EFFECTS

for stimulated microorganism activity

11%

INCREASE

in microbial biomass relative to organic farming

54%

HIGHER MICROBIAL RESPIRATION

in biodynamic systems

Enzymatic Activity and Efficiency

Dehydrogenase enzyme activity – crucial in metabolic processes and energy production – increased by 29 percent in biodynamic farming compared to organic farming, with biodynamic systems showing 52 percent better energy efficiency of microorganisms through decreased metabolic quotient (Fliessbach et al. 2007). Principal component analysis of microbial phospholipid fatty acids demonstrated distinct differentiation in microbial communities between biodynamic-treated and control composts, suggesting biodynamic preparations positively influence microbial diversity (Carpenter-Boggs 2000a). This aligns with findings from the DOK experiment showing higher biological activity and better carbon utilisation by microbial biomass in biodynamic systems (Fliessbach et al., 2007). However, not all studies show consistent results. Aher et al. (2018) found that organic agriculture registered 27-102 percent higher enzymatic activities than biodynamic agriculture in central India, suggesting regional variations or methodological differences may influence outcomes.

29%

INCREASED DEHYDROGENASE ENZYME ACTIVITY

in biodynamic farming

52%

BETTER ENERGY EFFICIENCY OF MICROORGANISMS

through metabolic quotient

Soil Fauna Benefits

Earthworm populations, crucial for soil aeration and nutrient cycling, show significant responsiveness to biodynamic practices, with abundance 49 percent higher in biodynamic than organic farming (Meissner et al., 2019). The DOK trial reports biodynamic fields hosting approximately twice the number of spiders and beneficial insects compared to conventional fields.

However, it is important to note that 86 percent of soil fauna results show similar effects between biodynamic and organic farming, and no difference between biodynamic and organic systems is observed in 52 percent of measurements on organisms as a whole (Fliessbach et al., 2007).

49%

HIGHER

earthworm abundance

APPROXIMATELY

twice

THE NUMBER OF SPIDERS AND BENEFICIAL INSECTS

86%

OF SOIL FAUNA RESULTS

showing similar effects between biodynamic and organic farming

Soil Resilience

Further studies on cereal growth in Washington and Wisconsin, USA, demonstrate the linkages among biodynamic preparations, greater root growth and health, stress resistance and soil organic matter increases (Goldstein et al., 2019). Multiple applications of preparations are more likely to result in statistically significant increases in yield (Goldstein et al., 2019).

The superior performance of biodynamic systems stems from specific practices including organic fertilisation, crop protection free of synthetic pesticides, diversified crop rotations, and simplified tillage. Organic amendments stimulate heterotrophic microorganisms – organisms like yeast, moulds, and bacteria – which depend on organic carbon as food (Chen et al., 2016c; Saison et al., 2006; Wada and Toyota, 2006).

An important distinction is that tillage is generally more intensive in organic farming than in biodynamic farming, which may explain one of biodynamic farming's advantages for soil ecological quality (Robertson et al., 2014).

2.2

Chemical Intensity

2.2 Chemical Intensity

Biodynamic agriculture's elimination of synthetic pesticides, herbicides, and fertilisers provides clear environmental advantages over conventional systems and shares this principle with organic farming. The absence of pesticides is favourable to soil ecological quality because pesticides can be toxic to soil organisms (Pelosi et al., 2013; Bünemann et al., 2018) or alter abiotic conditions and habitats (Wardle et al., 2001). Conventional farming's continued reliance on mineral fertilisation and synthetic crop protection practices significantly impacts soil ecological quality, with practices including intense tillage, frequent absence of soil cover, and monocropping remaining deleterious to soil biodiversity (Marschner et al., 2004; Bünemann et al., 2006; Pelosi et al., 2013; Le Guillou et al., 2019).

The comparative literature ranks biodynamic farming as having the highest soil ecological quality among farming systems, followed by organic farming (with 69 percent of biological parameters higher than conventional farming), attributing biodynamic's superiority to the combination of chemical-free practices with additional regenerative approaches including diversified crop rotations and simplified tillage practices (Christel et al., 2021). These practices contribute to the higher biodiversity consistently observed in biodynamic systems. Bavec and Bavec's review of the impact of organic farming on biodiversity demonstrates a significantly positive impact of low-chemical or chemical-free cultivation on biodiversity in more than 80 percent of observations (2015). In organic and biodynamic farming plots, for example, the number of earthworms was an average of two times higher compared to integrated, conventional, and control plots (Bavec & Bavec, 2015). The presence of pollinators was significantly higher on organic and biodynamic plots than on conventional plots, further demonstrating the positive contributions of low-chemical cultivation to biodiversity (Bavec and Bavec 2015).

2.3

Water Consumption

Water Consumption

Research on water conservation in biodynamic agriculture shows promising results, though fewer studies focus specifically on this aspect compared to soil health.

One comparative study found that biodynamic systems increased water use efficiency per crop yield by 1.96 percent compared to organic and 10.67 percent compared to conventional systems for maize and 3.62 percent compared to organic and 10.68 percent for conventional systems for faba beans (Sabahy et al., 2024).

The improved soil structure and increased organic matter content associated with biodynamic practices enhance soil water retention and infiltration. These improvements reduce runoff and erosion, suggesting more efficient water use compared to conventional systems (Carpenter-Boggs, 2000b). However, the literature acknowledges that specific quantitative data on water consumption related to biodynamic practices are limited, highlighting a research gap.

2.4

Greenhouse Gas Emissions

Greenhouse Gas Emissions

Biodynamic agriculture shows considerable potential for reducing greenhouse gas emissions compared to conventional and organic systems. The DOK trial demonstrates that biodynamic farming systems emit 63 percent fewer greenhouse gases than conventional systems, and when accounting for humus changes, show a 74 percent reduction in CO_2e (Fliessbach et al, 2007). This reduction is linked to enhanced carbon sequestration in the soil and lower nitrous oxide emissions due to reduced nitrogen fertilisation.

63%

FEWER GREENHOUSE GASES

74%

REDUCTION IN CO_2e

2.4 Greenhouse Gas Emissions

Energy efficiency studies by Alfoldi et al. (1994) found that biological systems (including biodynamic agriculture) used between 16-38 percent less energy to produce one tonne of crop compared to conventional systems. While direct energy consumption was similar between systems, indirect energy use—especially for nitrogen fertiliser production—was much lower in biodynamic systems.

16-38%

LESS ENERGY

Biological systems used between 16–38 percent less energy to produce one tonne of crop compared to conventional systems.

100-500

kg C/ha/year

Aubert (2009) reported carbon sequestration in biodynamic farming varies between approximately 100–500 kg C/ha/year in most cases.

42

YEARS

The DOK trial showed that after 42 years, the biodynamic system exhibited a mean annual increase in SOC content.

35.8

$mg\ kg^{-1}\ yr^{-1}$,

Mean annual increase in SOC content of 35.8 $mg\ kg^{-1}\ yr^{-1}$, indicating enhanced soil health and carbon sequestration potential (Krause et al 2022).

Aubert (2009) reported carbon sequestration in biodynamic farming varies between approximately 100-500 kg C/ha/year in most cases. The DOK trial showed that after 42 years, the biodynamic system exhibited a mean annual increase in SOC content of 35.8 $mg\ kg^{-1}\ yr^{-1}$, indicating enhanced soil health and carbon sequestration potential (Krause et al 2022).

2.5

Waste and Compostability

Waste and Compostability

Biodynamic agriculture emphasises closed nutrient cycles and waste reduction within the farm system. Composting is a central practice, with biodynamic preparations intended to enhance compost quality. Studies found that biodynamic-treated composts showed 10 percent lower CO_2 respiration rate and higher dehydrogenase enzyme activity to CO_2 production ratios, suggesting more efficient microbial processes (Carpenter-Boggs, 2000a). Final samples of biodynamic-treated compost contained 65 percent more nitrate than control piles, indicating enhanced nutrient content and improved nutrient availability (Carpenter-Boggs, 2000a).

This approach to waste management supports what Muhie (2021) describes as a "circular economy" model in biodynamic agriculture, where "production and consumption strategies involve recycling of wastes and by-products to regenerate farm products," thereby reducing material use and redesigning systems to be less resource-intensive.

Box 2.1

Case Study

SEKEM Initiative Egyptian Cotton Production

Box 2.1: Case Study

SEKEM Initiative

EGYPTIAN COTTON PRODUCTION

BACKGROUND AND CONTEXT

The SEKEM (Ancient Egyptian: 'vitality from the sun') initiative in Egypt provides one of the most compelling real-world examples of biodynamic agriculture applied to fashion-related crop production. Founded in the Egyptian desert in 1977, SEKEM has transformed degraded land into productive agricultural systems using biodynamic principles, with cotton as a primary crop for textile production (Huebner, 2022a). This case study offers valuable insights into the practical application and outcomes of biodynamic methods in cotton cultivation.

Key Findings

Pesticide Reduction and Yield Improvements

The transformation of Egyptian cotton agriculture through biodynamic methods demonstrates remarkable environmental and productivity benefits. After the construction of the Aswan High Dam stopped fertile Nile mud flooding, Egyptian farmers increasingly relied on agrochemicals (Egyptian Biodynamic Association, 2025). By the early implementation period, cotton cultivation required 1,800 tonnes of pesticides across 400,000 hectares, while yields remained stable at approximately 900 kg per acre (Luske & van der Kamp, 2009).

Following the adoption of biodynamic insect control methods, now promoted by Egyptian authorities, pesticide use was reduced to less than 10 percent of previous amounts across nearly the same cultivation area (Egyptian Biodynamic Association, 2025). Simultaneously, these methods achieved a nearly 30 percent yield increase to 1,220 kg per acre (Egyptian Biodynamic Association, 2025). This demonstrates that biodynamic approaches can simultaneously reduce chemical inputs while improving profitability.

1,800
TONNES OF PESTICIDES

400k
HECTARES

900
KG PER ACRE
YIELDS REMAINED STABLE

LESS THAN
10%
PESTICIDE USE REDUCED TO LESS THAN 10%

30%
YIELD INCREASE TO
1,220
KG PER ACRE

Box 2.1: Case Study

FIBRE QUALITY IMPROVEMENTS

Beyond yield improvements, biodynamic cotton showed superior quality characteristics compared to conventional production. The biodynamic cotton exhibited less contamination with leaf fragments, better fibre elasticity, and improved overall fibre quality parameters (Innovation in Textiles, 2025). These quality improvements are particularly relevant for fashion applications, as they directly impact textile performance and processing efficiency.

ENVIRONMENTAL AND ECONOMIC ASSESSMENT

SEKEM's comprehensive monitoring system, documented in annual sustainability reports since 2007, provides insights into broader environmental impacts (Seada et al., 2020). A comparative study of five crops found that while direct input costs were slightly higher for organic methods, the long-term costs considering environmental impacts (pollution of soil, water, air) were substantially lower (Seada et al., 2020). When accounting for environmental and health damage costs, sustainable agriculture demonstrated better long-term cost-effectiveness and higher profitability for society as a whole (Abouleish & Arlt, 2025).

BETTER FIBRE ELASTICITY
superior quality for a fashion application

SINCE
2007
COMPREHENSIVE MONITORING
for broader impact insights

HIGHER PROFITABILITY FOR SOCIETY AS A WHOLE.

BETTER LONG-TERM COST-EFFECTIVENESS.

Box 2.1: Case Study

SOIL HEALTH AND CARBON SEQUESTRATION

Recent developments on SEKEM-associated farms demonstrate continued soil improvements (Innovation in Textiles, 2025). Ramadan Kamel Farm in Behira and Salsol Farm in Dommiat reported enhanced soil organic matter, increased microbial activity, and improved overall soil fertility (Innovation in Textiles, 2025). Quantifiable outcomes include the generation of 380.83 carbon credits and the production of 390 tonnes of verified compost, indicating substantial carbon sequestration potential in desert reclamation contexts (Ventile, 2025). Furthermore, investments in soil health were linked with reduced soil salinity and increased water availability, addressing a critical challenge in Egyptian agriculture (Huebner, 2022b).

380.83

CARBON CREDITS

generated on SEKEM-associated farms

390

TONNES

of compost produced and verified

Box 2.1: Case Study

Research Validation

Academic research supports SEKEM's practical outcomes. El-Haddad (2008) found that the complete biodynamic package, following proper timing and preparation applications, produced "very significant increases in all measured parameters" for cotton, sesame, and wheat crops. Optimisation studies showed that increasing applications of one of the biodynamic preparations, quartz (BD501), from three to five times increased cotton yield production by almost 10 percent (El-Haddad, 2008).

Broader research in Indian cotton systems by Forster et al. (2013) and Lori et al. (2024b) confirms that biodynamic farming systems improve soil quality and shape microbial communities across cotton-based crop rotations. After twelve years, biodynamic systems showed improved soil quality and fostered beneficial microbial taxa associated with organic compost degradation and phosphorus mineralisation, while conventional systems promoted genetic potential for ammonium oxidation that increases nitrogen loss risks (Lori et al., 2024b).

Biodynamic systems showed improved soil quality and fostered beneficial microbial taxa associated with organic compost degradation and phosphorus mineralisation, while conventional systems promoted genetic potential for ammonium oxidation that increases nitrogen loss risks

Box 2.1: Case Study

Lessons Learned

01 **Scalability and Knowledge Transfer**

SEKEM's success in transforming nearly 80 percent of Egyptian cotton cultivation areas to reduced-pesticide methods demonstrates the scalability potential of biodynamic approaches (Egyptian Biodynamic Association, 2025). The worldwide recognition of these results led SEKEM to organise the first international IFOAM conference on sustainable cotton cultivation in Cairo, indicating the model's broader applicability (Egyptian Biodynamic Association, 2025).

02 **Technical Optimization**

Research findings suggest that biodynamic preparation timing and frequency require careful calibration. While increased applications can improve yields, excessive use may negatively affect product quality, as noted by Bisterbosch (1994) in lettuce studies. This highlights the need for crop-specific optimisation protocols.

03 **Integrated Approach Benefits**

The SEKEM model demonstrates that biodynamic agriculture's benefits extend beyond individual farms to regional agricultural systems. The integration of environmental monitoring, community development, and supply chain partnerships creates synergistic effects that support long-term sustainability.

Box 2.1: Case Study

Opportunities for Future Advancement

Research Priorities: Future research should focus on understanding the mechanisms behind biodynamic preparation effects to optimise application protocols for different cotton varieties and growing conditions. El-Haddad (2008) specifically calls for research into "how the preparations function, to better understand how they produce such great influence on crop productivity."

Scaling and Replication: The SEKEM model provides a framework for scaling biodynamic cotton production in other arid and semi-arid regions. The successful desert reclamation aspects are particularly relevant for expanding cotton production without competing with food crop land use.

Supply Chain Integration: SEKEM's partnership with textile companies like Ventile demonstrates the potential for integrating biodynamic principles throughout fashion supply chains. The provision of dedicated engineers for farmer support and comprehensive monitoring systems offers a model for responsible sourcing initiatives.

Climate Change Mitigation: The documented carbon sequestration outcomes suggest significant potential for biodynamic cotton production to contribute to climate change mitigation goals while meeting the fashion industry's fibre needs. The generation of carbon credits provides additional economic incentives for adoption.

Box 2.1: Case Study

Implications for the Fashion Industry

The SEKEM case study demonstrates that biodynamic agriculture can simultaneously address multiple fashion industry sustainability challenges: reducing chemical inputs, improving fibre quality, sequestering carbon, and supporting rural livelihoods. The economic viability when environmental costs are properly accounted for provides a compelling business case for fashion brands seeking to reduce supply chain environmental impacts.

3

Towards a Comprehensive Evidence Base

3.1

Methodological Considerations: The Systemic Nature of Agricultural Research

Understanding the environmental impacts of different farming approaches requires recognising agriculture as a complex system where multiple practices interact in ways that cannot be predicted by studying individual components in isolation.

As demonstrated by Rillig and Lehman (2019), studying the impact of all possible combinations of agricultural practices would require examining more than 100,000 possible combinations, not even considering variations in different climatic conditions. This complexity underscores why the sole effect of any given practice cannot predict the impact of combined practices on farms due to compensation or synergistic effects.

The development of modern research tools over the past two decades has enabled more robust diagnoses of soil ecological quality, defined as the capacity of soil to host a great quantity and diversity of interacting living organisms involved in its functioning (Cortet et al., 1999; Ferris et al., 2001; Bouchez et al., 2016; Stone et al., 2016). These tools have provided solid knowledge on the impact of individual agricultural practices, but the systemic nature of farming necessitates a more holistic approach.

3.1 Methodological Considerations

Given these methodological challenges, studying complete farming systems (conventional, organic, biodynamic, and soil conservation farming) rather than individual practices appears to be the most relevant way to evaluate the systemic impact of agricultural practices on soil ecological quality and broader environmental outcomes.

This systems approach allows researchers to capture the cumulative and interactive effects of multiple practices as they occur in real-world farming conditions.
This method forms the foundation for the comparative analyses presented throughout this report, where biodynamic agriculture is evaluated not as a collection of isolated practices but as an integrated system whose environmental benefits emerge from the interaction of its component elements.

Due to this systemic nature and limited adoption compared to conventional agricultural practices, there is relatively limited academic literature on the holistic impacts of biodynamic agriculture, offering substantial opportunities for further research.

3.2

Research Gaps and Limitations

3.2 Research Gaps and Limitations

The literature on biodynamic agriculture suggests significant benefits in improving soil quality, enhancing biodiversity, and improving fibre quality. However, several important research gaps remain:

1. Specific Effects of Biodynamic Preparations: Despite the observed benefits of biodynamic systems, there remains no consensual demonstration of the potential positive effects of biodynamic farming-specific preparations (for example, preparations 500-508 and herbal preparations) on soil ecological quality, as specific and relevant studies on the subject are lacking (Chalker-Scott, 2013). Christel et al's systematic review of the literature confirms that certain practices like reduced tillage and organic fertilisation can explain the positive global impact of biodynamic farming, but the efforts of harder-to-investigate practices – especially preparations, farmer technicity, or application timing – still remain to be demonstrated conclusively. Some studies suggest that organic fertilisation influences microbial communities more than biodynamic preparations do, and further research is needed to understand the various applications of biodynamic preparations for soil and plant health (Carpenter-Boggs et al., 2000a; Mäder et al., 2002; Birkhofer et al., 2008).
2. Temporal Dynamics: A more detailed understanding is needed of conversion timelines and long-term impacts across different farming systems.
3. System Integration Studies: Research is needed on systems combining organic farming principles, biodynamic practices, and soil conservation practices to optimise soil ecological benefits.
4. Methodology Standardisation: Different sampling depths and methodologies make cross-study comparisons difficult and reduce the generalizability of conclusions.
5. Water Usage Data: Quantitative data on water consumption in biodynamic agriculture remains limited compared to other environmental indicators.
6. Regional Variability: Most comprehensive studies come from European contexts, with fewer long-term trials in other climatic and soil conditions.
7. Fashion-Specific Crops: Limited research specifically addresses fashion-related crops beyond cotton case studies.

3.2 Research Gaps and Limitations

New research integrating soil quality indicators, greater climatic diversity of studies, studying farming systems as a whole, including consolidating data on biodynamic and organic farming effects, and studying fashion-related agriculture will increase the generalisability of conclusions from preliminary research on biodynamic agriculture. These data points will benefit farmers, agricultural advisers, fashion value chain actors, and policymakers in driving fashion-related agricultural production toward agroecological transition at a large scale and in the long term.

4

Conclusions & Future Directions



Conclusions & Future Directions

The comparative analysis of biodynamic, organic, regenerative, and other sustainable agricultural approaches reveals both significant overlaps and important distinctions.

- Biodynamic agriculture offers a spiritually informed, holistic approach, with distinctive practices that remain open to scientific debate but within systems that demonstrate positive environmental outcomes.
- Organic agriculture provides a standardised, regulated approach that has achieved mainstream market success while maintaining core ecological principles.
- Regenerative agriculture represents an evolution focused specifically on reversing degradation through intensive soil health management and carbon sequestration.
- Other approaches like agroecology, permaculture, and conservation agriculture offer additional frameworks emphasising different aspects of sustainability.

The scientific evidence, while incomplete, suggests biodynamic agriculture offers significant environmental benefits compared to conventional agriculture, with systematic analysis showing 70 percent of biological indicators performing better in biodynamic systems. The comparison with organic agriculture reveals a more nuanced picture: while biodynamic systems show advantages in 52 percent of microbial indicators and demonstrate superior performance in long-term soil quality studies like the DOK trial, 52 percent of overall measurements show no difference between the systems.

4 Conclusions and Future Directions

The SEKEM case study provides real-world evidence that biodynamic methods can be successfully applied to fashion-related crop production, achieving simultaneous improvements in environmental impact, yield, and fibre quality. While yield reductions compared to conventional systems are commonly reported in academic studies, the Egyptian cotton experience demonstrates that properly implemented biodynamic systems can achieve productivity gains while dramatically reducing chemical inputs.

The key differentiator appears to be biodynamic agriculture's emphasis on simplified tillage practices compared to organic farming, and its comprehensive elimination of synthetic inputs compared to conventional agriculture. However, the specific contribution of biodynamic preparations beyond standard organic practices remains insufficiently documented, representing a critical research gap.

Economic analyses suggest comparable or improved profitability for biodynamic systems due to premium pricing, lower input costs, and reduced environmental externalities. The holistic nature of biodynamic farming appears to create synergistic benefits that support overall system sustainability, though more research is needed to fully understand the mechanisms and optimise practices for specific contexts and crops.

Further research should prioritise rigorous investigation of biodynamic preparations, expand regional diversity of study sites, develop standardised methodologies to facilitate cross-study comparisons, and explore scaling opportunities for fashion supply chain integration. The systemic approach of studying farming systems as integrated wholes, rather than as collections of individual practices, provides the most relevant framework for understanding these complex agricultural systems. Furthermore, future research should consider the land use implications of transitioning to biodynamic practices.

4 Conclusions and Future Directions

While this study has focused on the environmental impacts of fashion-related agriculture and opportunities for developing agricultural systems that support soil health, biodiversity, and carbon sequestration, it is critical for the fashion industry to look beyond sustainable cultivation of virgin materials and towards opportunities to support humane working conditions, reduce unnecessary production, and prevent waste at all stages of the value chain.

Rather than viewing biodynamic, organic, regenerative, and other approaches as competing alternatives, they might better be understood as complementary perspectives within a broader movement toward agricultural sustainability. Moving forward, greater cross-pollination among these sustainable agriculture approaches, combined with rigorous research and context-specific adaptation, offers the most promising path toward truly sustainable fashion agricultural systems.

Conclusion

Conclusion

The fashion industry is deeply entangled with global agriculture, influencing approximately 30 percent of all agricultural land worldwide. This industry is exerting significant environmental pressures across multiple dimensions, from land use to water consumption to chemical inputs, greenhouse gas emissions, and biodiversity loss. While much of the discourse around more sustainable consumption of fashion focuses on later stages in the value chain, this research highlights the urgent need to address the agricultural origins of textile production. With such a significant impact on land, textile producers have a big role to play in influencing change, through the agricultural systems they use and support.

To drive meaningful change, fashion brands and industry stakeholders must expand their definition of sustainability to include support for agricultural systems that are ecologically sound and socially just. This includes investing in further research, transparent certifications, and farm-to-fibre partnerships that prioritise ecosystem regeneration. This research provides a comparative analysis of sustainable agricultural systems and their relevance to textile cultivation, with a particular focus on biodynamic agriculture.

Conclusion

While biodynamic methods show promising environmental benefits, more long-term, system-level research is needed to fully understand their potential and scale their adoption across diverse contexts.

With the right support and alignment across the value chain, textile agriculture can shift from being a driver of environmental harm to a powerful lever for regeneration. By transforming how fibres are grown, the fashion industry has the potential to not only reduce its impact but to actively restore ecosystems, support rural livelihoods, and contribute to a more resilient and climate-positive future.

Acknowledgments

The authors are grateful to reviewers at the Smith School of Enterprise and the Environment, University of Oxford, for their comments.

References

References

SOURCEBOOK

Complete bibliography and source list supporting the research, data, methodologies and claims in the report.

VIEW REFERENCES

Appendices

Appendices

EVIDENCE COMPANION

Full data quality scoring, LCA boundaries, fibre-by-fibre environmental impact assessments, chemical application data and methodology notes for the technical appendix.

VIEW APPENDICES

Endnotes

Endnotes

[1]Including polyester, polyamide, and other synthetics

[2]Calculated from the land-use for cotton, linen/hemp, leather, silk, and wool analysed in this report. See Appendix 1.

[3]The scope of the life cycle assessment is cradle-to-gate. See Appendix 2-8 for additional details on the life cycle assessment boundaries for each material.

[4]The term pesticide encompasses herbicides, fungicides, insecticides, and various chemicals used to control pests.

[5]The report refers to “water usage” rather than “water consumption.” Water usage refers to the total amount of water withdrawn or used in a process, regardless of whether it is returned to the system. Water consumption refers specifically to water that is permanently removed from the local water cycle through evaporation, incorporation into products (embedded water), or discharge to different watersheds. LCAs typically focus on water usage rather than consumption due to the impacts on water availability, which is particularly important in water-stressed regions where timing and competing demands matter. Additionally, water returned after use is often lower quality due to temperature changes, contamination, or altered composition. Furthermore, water usage is easier to measure and track than true consumption, which requires complex accounting to determine what is lost versus returned to usable sources. Where possible given data availability, the report distinguishes between blue water (surface/groundwater), green water (rainwater), and grey water (water needed to dilute pollution) to provide a more nuanced understanding of water sources.

[6]The proportion of these emissions allocated to leather varies based on economic allocation methodologies. Using standard Product Environment Footprint Category Rule (PEFCR) allocation factors, leather products typically show significantly higher CO_2e loads than fossil-based alternatives, though this comparison remains subject to ongoing methodological refinement (Brugnoli, 2025; Ecoinvent, 2019)

[7]BIODYN 1.4 referring to stocking densities of 1.4 LU (Livestock Unit) per hectare