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ENVIRONMENTAL IMPACTS OF RECYCLING-BASED CELLULOSE CARBAMATE FIBER

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TIIVISTELMÄ

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Kierrätyspohjaisen selluloosakarbamaattikuidun ympäristövaikutukset

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Globaali tekstiiliteollisuus kuluttaa yli 100 miljoonaa tonnia tekstiilikuituja joka vuosi. Suurin osa näistä kuiduista tuotetaan edelleen neitseellisistä raaka-aineista, ja niiden tuotannon ympäristövaikutukset ovat vakava kestävyysuhka. Suljetun kierron tekstiilikuitukierrätykselle onkin valtava kysyntä. Infinited Fiber Company (IFC) kehittää pilottitehtaallaan selluloosakarbamaattiteknologiaa, käyttäen raaka-aineena kierrätettyä puuvillarikasta tekstiilijätettä ja muuta vaihtoehtoista selluloosapitoista raaka-ainetta. Näistä raaka-aineista regeneroidaan uutta selluloosakarbamaattimuuntokuitua (CCA). Tällä uudella selluloosamuuntokuidulla voidaan korvata puuvillaa, viskoosia ja muita perinteisiä tekstiilikuituja niiden nykyisissä käyttökohteissa. Yhtiön tavoitteena on kehittää ja skaalata selluloosakarbamaattikuidun tuotanto teolliseen mittakaavaan.

Tämän diplomityön tavoitteena on arvioida IFC:n teollisen kuidunvalmistustekniikan ympäristövaikutuksia elinkaariarvioinnin (LCA) avulla. Tutkimus rajataan kehdosta portille, ts. tekstiilijätteen keräyksestä aina paalattuihin CCA-katkokuituihin asti. Tutkittu systeemi sisältää selluloosakarbamaattiprosessin sovellettuna puuvillapitoiselle tekstiilijätteelle, ja kaikki tähän liittyvät tukitoiminnot. Elinkaari-inventaarion tulokset esitetään suoralle ja epäsuoralle energiankulutukselle, sekä suoralle makean veden kulutukselle ja maankäytölle. Elinkaaren aikaisissa ympäristövaikutuksissa keskitytään mahdollisiin ilmastonmuutosvaikutuksiin arvioimalla hiilijalanjälki (GWP, 100a) tutkitulle systeemille. CCA-kuidun teollisesta tuotannosta muodostetaan viisi hypoteettista skenaariota, ja näiden tulokset lasketaan toiminnallista yksikköä kohti. Tässä työssä käytetty toiminnallinen yksikkö on tonni valmiita katkokuituja. Osana tutkimusta tehdään myös lyhyt kirjallisuuskatsaus, jonka tavoitteena on löytää vertailukelpoista tietoa puuvillan ja viskoosin tuotannon ympäristövaikutuksista.

Elinkaariarvioinnissa laskettujen tulosten perusteella CCA-katkokuitujen hiilijalanjälki voi skenaarioista riippuen vaihdella 776 ja 6169 kg CO_2 -eq välillä kuitutonnia kohti. Hiilijalanjälkeen eniten vaikuttavat kemikaalien- ja energiantuotannon päästökertoimet. Inventaariotuloksina kuitutonnia kohti lasketaan yhteensä noin 8,8 MWh suorana energiankulutuksena, 54 m^3 suorana vedenkulutuksena ja 15 m^2 suorana maankäyttönä. Inventaariossa käytetyt kulutusluvut on alustavasti arvioitu mallintamalla IFC:n pilottimittakaavassa demonstroitu prosessi pienen teollisen yksikön mittakaavaan (30 kt / a). Alustavista mallinnuksista johtuen, tuloksissa voi olla vielä mahdollisia epävarmuuksia. Jatkotutkimuksissa tämän diplomityön rajauksia voitaisiin laajentaa kokonaisvaltaisemmin tekstiilien kiertotalouteen, sekä useampiin ympäristöindikaattoreihin. Myös laskennassa käytettyä primaari- ja sekundaaridataa on syytä tarkentaa tulevaisuudessa.

ABSTRACT

Lappeenranta–Lahti University of Technology LUT
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Environmental impacts of recycling-based cellulose carbamate fiber

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Over 100 million tons of textile fibers are consumed by the global textile industry every year. Most of these fibers are currently produced from virgin raw materials, and the environmental impacts of their production are an acute concern to sustainability. Thus, there is a huge demand of closed-loop recycling technologies for textile fibers. Infinited Fiber Company (IFC) runs a pilot factory developing cellulose carbamate (CCA) technology, utilizing cotton rich textile waste and other cellulose containing feedstocks for production of cellulose carbamate fibers. This recycling-based textile fiber has the potential to replace cotton, viscose and many other fibers in their current use. The aim of the company is to scale up the CCA fiber production into industrial capacities.

This Master's thesis aims to assess the environmental performance of IFC's fiber manufacture technology by using the life cycle assessment (LCA) method. The scope is cradle to gate, from textile waste collection to baled staple fibers. The studied system includes the CCA fiber process for cotton rich textile waste, and all the related up- and downstream operations. The inventory results are presented for direct and indirect energy demand, direct freshwater consumption and land use. Environmental impact assessment focuses on potential climate change impacts, calculated as carbon footprint (GWP 100a). Five hypothetical scenarios are formed of the industrial scale CCA fiber production, and their results are calculated per functional unit, which is one ton of staple fibers. In addition, a literature review is conducted to find comparable data on cotton and viscose production.

According to the calculated results, the carbon footprint of CCA fibers can range from 776 up to 6169 kg CO_2 -eq per ton of fibers, depending on the scenario. The total inventory results per ton of fibers are approximately 8,8 MWh for direct energy consumption, 54 m^3 for direct freshwater consumption, and 15 m^2 for direct land use. The carbon footprint results are strongly affected by the emission factors of chemicals and energy production. Inventory results are calculated based on scaled-up simulations from the IFC pilot process, so there still are possible uncertainties in the assessed in- and outputs. Further studies should expand the scope of this Master's thesis into other environmental impact categories, a broader textile ecosystem, and more precise primary and secondary data.

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This great project occupied most of my brain capacity in the year 2020. Due to reasons not so hard to guess, it ended up being a very independent project that was done 95 % remotely from Lahti and Lappeenranta. There is not much more to say as a foreword (…or time remaining to write it!) but a few thank yous must be delivered. First, thanks to Sakari at IFC who taught me so much of interesting technologies during this project and had the nerves to dive into this thesis' topics as well. Also, thanks to my LUT supervisors Jarkko and Ville for the crucial commenting and good spirit. And "MOT sanakirja" that helped in the translations.

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In Lahti, 7 December 2020

Mitja Hokkanen

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LIST OF SYMBOLS

Abbreviations

CCA	Cellulose carbamate
CFP	Carbon footprint
CmiA	Cotton made in Africa
EU	European Union
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
IFC	Infinited Fiber Company
LCA	Life cycle assessment
LCI	Life cycle inventory analysis
LCIA	Life cycle impact assessment
PCR	Product category rules
PET	Polyester
SOC	Soil organic carbon

1 INTRODUCTION

The global textile industry used over 100 million tons of different fiber materials in 2018. The majority of this was polyester and other synthetics, followed by natural fibers like cotton and cellulose fibers like viscose. (Statista, 2019; Suomen tekstiili ja muoti ry, 2020, p. 9) Currently almost all the fibers are made from virgin raw materials and used for very short-lived textile products. Many resources are overconsumed, for example water and fertilizers in cotton cultivation (Bevilacqua et al., 2014, pp. 1–2). In 2015, the production of textiles emitted 1 200 million tons of greenhouse gases in CO_2-equivalents. After usage, most of the textiles end up in landfill or incineration, losing the materials from further utilization. (Ellen MacArthur Foundation, 2017) Most of the current global statistics do not even mention recycled fibers as a feedstock for new textiles.

The growing environmental and social issues are starting to get noticed in the industry, so the aim is now towards more circular and sustainable textile ecosystems (Ellen MacArthur Foundation, 2017). It would be the only way to reduce the use of virgin raw materials, as the consumption of textiles shows no signs of decrease. The public demand is also emerging into legislation: for example, separate collection of textile waste will be mandatory in the European Union by 2025 (European Commission, 2018).

In a smaller scale, many textile waste treatment methods have already been developed. These can be divided into mechanical, chemical, thermal and mixed technologies, which all have very different purposes. Mechanical treatment is rather simple, usually leading to low value applications like insulation. Chemical processing is more demanding, but also the end products are better comparable to the original fibers. Mixed technologies combine elements from various systems, and thermal utilization is not actually considered recycling but energy recovery. (Palm et al., 2014, pp. 131–137) To lower the burden of virgin fiber production, a widely usable closed-loop recycling system is still acutely needed for textiles. More efficient textile reuse is vital as well.

Cellulose is a natural biopolymer, modifiable into numerous applications. Because of the strong hydrogen bonds, it does not dissolve in typical solvents. To further utilize the material, many dissolving methods have been developed for cellulose. Still, the most common way is cellulose xanthate process, familiar from viscose manufacturing. Harmful chemicals are needed in that, so cleaner alternatives are constantly sought after. One of these options is cellulose carbamate technology, where the cellulose is first reacted with urea to make it soluble in water-based diluted alkaline media. Its main advantages are a higher technical tolerance to utilize recycled raw material feedstocks, use of less harmful chemicals, and the applicability to existing wet spinning technology. Carbamate derivatives of cellulose have already been studied for years, revealing a wide range of possible raw materials and end products. (Fu et al., 2015, p. 1; Harlin, 2019, p. 4) Supportive infrastructure (e.g. collection and sorting of textile waste), as well as the demand for recycling based cellulose fibers, are expected to grow in the near future (Heikkilä et al., 2018).

Infinited Fiber Company (IFC) runs a pilot factory to develop their cellulose carbamate (CCA) technology, utilizing cotton rich textile waste and other cellulose containing feedstocks in the production of CCA fibers. The company’s aim is to scale up and commercialize this production into industrial capacities. Synthesis method of the cellulose carbamate polymer, which IFC is now applying, was originally developed by VTT Technical Research Centre of Finland. IFC’s focus has been to develop the industrial applicability of this method, especially for recycled cellulose feedstocks. The resulting cellulose carbamate fiber has features comparable with cotton and viscose, able to replace them, and also other types of textile fibers, in textile manufacturing. (Infinited Fiber Company, 2020a; Siren, 2020)

The goal of this Master’s thesis is to assess the environmental performance of IFC’s fiber production. Every process step is included into an Excel-based model for life cycle assessment (LCA), with five different hypothetical industrial scenarios. The scope is cradle-to-gate; from textile waste collection to baled staple fibers at the factory gate. The inventory targets are energy demand, water consumption, chemical inputs and land use. They are assessed per a functional unit, which is 1000 kg of CCA fibers. The impact assessment primarily focuses on global warming potential (GWP), and the aim is to find the most crucial points for future process development. Depending on the available data, also other impacts can be estimated. Before the LCA, a literature review is done for comparable environmental data on cotton and viscose production.

2 ENVIRONMENTAL PERFORMANCE OF TEXTILE FIBERS

This chapter views the current environmental situation of textile fiber production. The main focus is on cotton and viscose, because they are the most widely used cellulosic fibers: cotton in the natural fiber category, and viscose in the man-made cellulose fibers. IFC's fiber can substitute the use of these fibers in the cellulose fiber category.

In the literature view, information is sought about global warming potential, energy demand, water use and land use; these are rather commonly studied environmental indicators, and will be assessed for IFC's fiber production later in this study. The found studies will also guide the calculation methods and assumptions in the forthcoming LCA, enabling results comparison.

2.1 Overview

In a textile's life cycle, the production of fibers accounts for 8–15 % of the total greenhouse gas emissions and up to 93 % of water use (Niinimäki et al., 2020, p. 5; Quantis, 2018, p. 20). The estimations vary a lot, depending on what is included in them. Choices in fiber production may anyway be the easiest way to reduce a textile's environmental footprint, since it's one of the only steps fully in the manufacturers' control. Shen and Patel (2008, pp. 2–3) also note that the energy use of fabric processing is not very dependent on its feedstock, meaning that most of the differences already occur in the fiber production stage. The use phase (e.g. washing) can have even bigger environmental impacts in a textile's life cycle, but that is harder to affect by the manufacturers.

There are various types of textile fibers in use, and their environmental impacts appear through very different routes. The production of synthetic fibers like polyester, nylon and acrylic are very energy intensive (generally around 100 MJ per kg fiber), whereas natural fibers like cotton have bigger potential impacts due to water used in cultivation (from 2 up to even 24 m^3 per kg fiber). Man-made cellulose fibers (e.g. viscose) fall somewhere in between of these, with possibly the highest risks in hazardous chemicals like carbon disulfide. (Cotton Incorporated, 2012, p. 11; Muthu et al., 2012, p. 3; Sandin et al., 2019, pp. 30–36; Shen and Patel, 2010, p. 8)

Environmental impacts also vary within the fiber types themselves, especially via geographical location: production methods are not globally constant, nor the energy emission rates, water availability or the sensitivity of ecosystems. That is why absolute environmental ranking of fibers is rather irrelevant, and often avoided in the studies. Instead, Sandin et al. (2019) propose that the eventual solution would be optimizing all kinds of fiber production, while keeping the range of materials diverse enough to suit any intended application.

There already are some LCAs focusing on textile fibers only. Their objectives can be defining the global average environmental impacts of a certain fiber type (Cotton Incorporated, 2012; Thylmann et al., 2014), comparing various production scenarios (Schultz and Suresh, 2017), or more exact views on existing processes (Yacout et al., 2016). As there has not been specific LCA guidance for textile fibers, the used assumptions and study boundaries differ a lot between the studies. This may change in the future, since product category rules (PCR) for man-made fibers were published in May 2020 (EPD International, 2020). These rules are not obligatory, except for environmental product declarations (EPD), but may help unifying the calculation practices anyway. More PCRs are needed to cover the whole range of different fiber types.

To make the LCA results more comparable, Sustainable Apparel Coalition (SAC) recently introduced a new Higg MSI methodology for all textile materials, including also the intermediate products like fibers. A web database is being built for results calculated that way, and it can guide the designers' material choices in the future. (Sustainable Apparel Coalition, 2020) While these kinds of weighted single-score comparisons may help understanding the overall environmental picture, they do not remove the uncertainty behind those numbers. That is why the following literature review focuses on individual reports, critically assessing the found data.

Fiber moisture is a less discussed source of uncertainty in textile fiber LCAs. Most of the fibers are dried to a commercial moisture content during their final production phase. For man-made cellulose fibers like viscose, this commercial allowance is 13 %, as defined by a standard. Cotton does not have the same kind of absolute limits. (ASTM, 2016) In fiber production, it can be assumed that all its resource consumption and environmental impacts arise from the fibers only, not the water absorbed by them. Thus, a choice must be made if the final LCA results are presented against dry fibers, or fibers in their commercial moisture content. This choice is not often clarified in the current studies, and also not instructed by any LCA guidelines. Depending on the assumed moisture content of fibers, the final results can thus be affected by 13 % or even more. This may distort results comparison between studies. However, it is safe to assume that the reviewed studies have textile fibers in their commercial moisture content, since LCAs are usually calculated per final product that leaves the study boundary.

2.2 Cotton

Over 26 million tons of cotton was produced in 2018, representing 24 % of global fiber production (Suomen tekstiili ja muoti ry, 2020, p. 9). Cotton is a plant-based product that has most of its environmental impacts via agriculture. While heavy irrigation and the use of pesticides generally make the crops more productive, they also introduce many risks in water-scarce cultivation areas like India and China. Soil salinization, poisonous leaks and inefficient resource use have been noted by textile industry, but the unique features of cotton fiber make its replacement very hard in certain applications. (Bevilacqua et al., 2014; Rex et al., 2019) The environmental burden of cotton is not globally constant; crop location and cultivation habits have led to very different conclusions by researchers.

Global warming potential is the most consistently assessed impact in cotton LCAs; GWP values for 100 years are found from all the studies in this review. Per one ton of cotton, the results range from 620 kg CO_2-eq at the “best farm” in USA (Bevilacqua et al., 2014) to 1808 kg CO_2-eq as the average of China, India and US. These countries produce about two thirds of all cotton, so the latter value is likely closer to conventional cotton’s global average. (Cotton Incorporated, 2012) A big share of the GWP is due to field emissions, especially nitrous oxide that is a powerful greenhouse gas. Also the fossil fuel-related emissions from machinery, irrigation and ginning affect the results. Conventional cotton gets a major burden from fertilizer production, which is mostly avoided in the organic alternative. (Cotton Incorporated, 2012, p. 62; Thylmann et al., 2014, p. 36)

Cotton plant yields two valuable products: lint to fiber production, and seed to oil extraction and animal feed (Thylmann et al., 2014, p. 22). Therefore, the environmental burden is often allocated between them. Fiber is considered as the main product due to its higher price, even though 1,4 units of cottonseed are produced per unit of fiber. By economic allocation, 84–93 % of the total impacts get assigned for the fiber and the rest for the seeds (Cotton Incorporated, 2012, p. 27; PE International, 2014, p. 17). Varying allocation factors widen the range of cotton LCA results: as Thylmann et al. (2014, p. 48) demonstrate, slightly different choices would make the fiber's GWP from 11 % lower to 7 % higher than their baseline result. Without any allocation, the value would get even 19 % higher.

Carbon sequestration is another challenge in GWP comparisons. Most of the reviewed inventories include carbon uptake of the cotton plant, but exclude the changes in soil organic carbon (SOC). This is because SOC changes are hard to quantify or generalize, and they also depend on the time frame considered. (Cotton Incorporated, 2012, pp. 55–56; PE International, 2014, p. 24; Thylmann et al., 2014, pp. 28–29) Cotton fiber is often assumed to have 42 % of carbon, meaning that in 1 kg of fiber there is 1,54 kg CO_2-eq sequestered. This is only a temporary storage, since the carbon is likely released in the end of a textile's life. That is why no credit is given for it in most cases. (Cotton Incorporated, 2012, p. 17; Thylmann et al., 2014, p. 37) Bevilacqua et al. (2014) do not mention carbon sequestration in their study, so the assumptions remain unknow. A bigger estimation of soil carbon storages could explain the remarkably lowest GWP values, together with the fact that only the best-performing farms are presented.

Cotton is a very water intensive crop, but the usage of external irrigation varies a lot between the farms and geographical locations. Conventional cotton production demands approximately 2120 m^3 of blue water (i.e. freshwater that's removed from a natural watershed) per ton of fiber, whereas organic cotton is managed with 182 m^3 (Cotton Incorporated, 2012, p. 17; Thylmann et al., 2014, p. 40). If flood irrigation is used, Bevilacqua et al. (2014) assess that the farms consume millions of liters of water per hectare and can seriously threaten the local water supplies. Cotton made in Africa (CmiA) -labeled small farms rely solely on natural precipitation: only 1 m^3 of blue water is consumed per ton of fiber, all from upstream processes like production of fertilizers and energy. CmiA covers about 22 % of African cotton farmers. (PE International, 2014, pp. 15 & 34) Comparing the results of abovementioned studies, it seems that water consumption does not directly correlate with field productivity; local climate and soil conditions may have even bigger effects in that.

In cotton fiber production, most of the energy is used in irrigation, tractor operations and ginning. Outside the fields and gins, a lot of energy is also needed in fertilizer production. The reported energy demands range from 0,4 to 4,2 MWh per ton of cotton. Some of the variation is explained by different production methods, but also the coverage of LCA calculations may differ. More energy is consumed in the later life cycle phases of cotton textile: for example, the energy demand of fabric manufacturing is almost 10 times higher than the energy needed in cotton fiber production. (Bevilacqua et al., 2014; Cotton Incorporated, 2012, pp. 17–62)

In most of the reviewed cotton LCA studies, land use is only reported as crop areas that are required in cultivation. Since multiple factors can have effects on a field's productivity, these land areas show a wide range between geographical locations: from 0,4 up to 2,3 hectares per ton of fibers (Cotton Incorporated, 2012; PE International, 2014). In addition to the fields, there are minor areas occupied by gins and other infrastructure, which is usually excluded from the calculations. Most of the current cotton LCAs lack information about the environmental effects that are caused by this land use. They are hard to assess in detail, and can differ a lot depending on the surrounding ecosystems' properties (Sandin et al., 2013).

Table 1 presents the found cotton LCA results, converted to somewhat comparable units. With the limitations described above, they show the estimated range of water- and energy consumptions, GWP and land use per ton of fibers. Some differences appear between the studies' methods and terminology, possibly widening the range of these results.

Table 1. Cotton LCA results comparison, per 1000 kg of fibers.

TYPE OF COTTON	Conventional	Organic	CmiA	Not specified	Not specified
Representativeness	Average of USA, China and India	Global average	Africa, CmiA -labeled	USA, "best farm"	India, "best farm"
Source of data	Cotton Incorporated 2012	Thylmann et al. 2014	PE international 2014	Bevilacqua et al. 2014	Bevilacqua et al. 2014
GHG EMISSIONS:					
Category	GWP (100)	GWP (100)	GWP (100)	GWP (100)	GWP (100)
Amount	1808	978	1037	620	890
Unit	kg CO2-eq	kg CO2-eq	kg CO2-eq	kg CO2 -eq	kg CO2-eq
Note	1)			5)	9)
ENERGY DEMAND:					
Category	Primary energy demand	Primary energy demand		Electrical energy	Electrical energy
Amount	15000	5759	Not presented, likely minimal	1537	3283
Unit	MJ	MJ		MJ	MJ
Note				6)	10)
WATER USE:					
Category	Water consumption	Blue water consumption	Blue water consumption	Water consumed in cultivation	Water consumed in cultivation
Amount	2120	182	1	1,5	14742,5
Unit	m3	m3	m3	m3	m3
Note				7)	11)
LAND USE:					
Category	Crop area	Crop area	Crop area	Crop area	Crop area
Amount	India: 16639 to 20367 USA: 6540 to 12579 China: 4103 to 6671	5450	Zambia: 22624 Ivory Coast: 9515	9872	17762
Unit	m2	m2	m2	m2	m2
Note	2)	3)	4)	8)	12)

1) Original study included carbon sequestered in product, worth 1540 kg CO2-eq. This would bring the result down to 268 kg CO2-eq, and uncomparable with the other studies.
2) Converted from the given yields (kg/ha)
3) Converted from the given average yield (1835 kg/ha)
4) Converted from seed cotton yields (kg/ha)
5) Converted from the original functional unit (1 kg of fiber)
6) Converted from the original unit (0,427 kWh per kg cotton)
7) Calculated from water consumption (1500 l/ha) and crop productivity (1013 kg/ha)
8) Converted from farm productivity (1013 kg/ha)
9) Converted from the original functional unit (1 kg of fiber)
10) Converted from the original unit (0,912 kWh per kg cotton)
11) Calculated from water consumption (8 300 000 l/ha) and crop productivity (563 kg/ha)
12) Converted from farm productivity (563 kg/ha)

None of the alternatives are superior in every category, but it can be concluded that Chinese soil quality and American farm practices lead to less consumed resources per unit. Organic cotton and CmiA save a lot of water and chemicals, but occupy bigger land areas. However, organic farming with crop rotation can reduce soil erosion by even 90 %, eventually sustaining the area (Thylmann et al., 2014, p. 31). Local effects on the ecosystems, such as eutrophication and water scarcity, could be remarkable but outside the scope in this review.

2.3 Viscose

The majority of man-made cellulose fibers are viscose, with about 5,47 million tons produced in 2018 (Suomen tekstiili ja muoti ry, 2020, pp. 24–25). Its raw material is dissolving wood pulp, but also dissolving pulp prepared from e.g. cotton linters and recycled cellulose containing feedstock can be used. The production is divided into three separate stages: forestry, pulping and fiber manufacturing. Whereas the fiber process is rather established, location and raw materials bring a lot of variance in viscose's environmental performance. Allocation between the fibers and other wood products can also affect the estimations. Sodium sulfate (Na_2SO_4) is formed as a by-product of the viscose process, which is often compensated in the LCAs by using substitution or allocation. With integrated pulp and fiber production, many external inputs can be avoided by sharing the recovered materials and heat energy between these units. (Schultz and Suresh, 2017; Shen and Patel, 2010)

As viscose needs more industrial processing than cotton, its energy uses are generally higher. Depending on the system and location, 19 to 61 GJ non-renewable energy is consumed per ton of fiber (Shen and Patel, 2010, pp. 9–19). Pulp- and fiber productions each consume about one third of the total non-renewable energy, and the remaining third comes from other processes like sodium hydroxide production. Considering global warming potential, also forest logging can be remarkable due to carbon storage losses. (Schultz and Suresh, 2017, pp. 42–48) In this review, changes in carbon storage are excluded due to uncertainties that were already introduced in chapter 2.2. Most of the found GWP -values for viscose clearly exceed any type of cotton, though it must be noted that (Schultz and Suresh, 2017) use GWP for 20 years, making it incomparable with the other results that are in GWP (100).

A major share of viscose's water consumption is from upstream processes, especially energy generation and the production of sodium hydroxide and sulfuric acid (Schultz and Suresh, 2017, p. 48). These water consumptions are not very uniformly assessed in the existing LCAs. (Shen and Patel, 2010, p. 23) report that 11 – 42 m^3 of process water and 308 – 403 m^3 of cooling water is needed per ton of fibers. The net freshwater consumptions in Schultz and Suresh' (2017, p. 39) viscose scenarios range from 310 to 740 m^3 per ton of fiber, with no mention of cooling waters. Zhu et al. (2020, p. 3) fall in between of these with 117 m^3 of freshwater used. The latter report is not peer-reviewed, so the data should be very critically assessed. This range of results is partially explained by different production scenarios, but likely there is also some discrepancy between the assessment methods. It can anyway be concluded that viscose production is less water-intensive than conventional cotton, since irrigation is avoided.

The land use impacts of viscose come mainly from the forestry. Approximately 8,10 m^3 of biomass is needed for a ton of wood-based fibers (Sandin et al., 2013, p. 5). The needed area and growth time depend on the forest location, tree species and the part of wood that is used.

Asian wood yields are typically higher, so the land uses per unit of viscose are only about half of those in Europe (Shen and Patel, 2010, p. 30). Viscose’s land uses are usually lower than cotton land uses, but potential impacts on biodiversity and other local factors are rarely examined. If infrastructure is excluded, Schultz and Suresh' (2017) recycled pulp scenario has no land use impacts.

The main chemical inputs of viscose fiber preparation are caustic soda (NaOH), carbon disulfide (CS_2), sulfuric acid (H_2SO_4) and zinc sulfate ($ZnSO_4$) (Shen and Patel, 2010, pp. 8–9). Carbon disulfide is a problematic solvent due to its high toxicity, introducing many risks to health and safety if emitted (ILO and WHO, 2017). Nowadays over 70 % of CS_2 can be recycled inside the viscose process, but it is still the main reason for acidifying hydrogen sulfide (H_2S) emissions. The second biggest pollutant for acidification is sulfur dioxide (SO_2) from pulp mills, contributing to many other impact categories as well. (Schultz and Suresh, 2017, p. 78) These kind of chemical impacts can be very hazardous to local ecosystems, but more information would be needed to assess them in detail.

The LCA results of viscose are gathered in Table 2. These are cradle to gate results, including the preparation of dissolving pulp and its further processing to fibers. As earlier explained, some of the variation may result from different assessment methods and related terminology. Moisture of the fibers is only mentioned by Shen and Patel (2010, p. 5), where the value is 11 % for viscose scenarios.

Table 2. Viscose LCA results comparison, per 1000 kg fiber.

TYPE OF VISCOSE	Lenzing viscose	Lenzing viscose	Viscose from recycled pulp	Viscose from Indonesian plantation pulp
Representativeness	Austria	Asia	Germany (fibers), Sweden (pulp)	China (fibers), Indonesia (pulp)
Source of data	Shen & Patel 2010	Shen & Patel 2010	Schultz & Shuresh 2017	Schultz & Shuresh 2017
GHG EMISSIONS:				
Category	GWP (100)	GWP (100)	GWP (20)	GWP (20)
Amount	1200	5300	3100	12000
Unit	kg CO2-eq	kg CO2-eq	kg CO2-eq	kg CO2-eq
Note	1)	5)	9)	10)
ENERGY DEMAND:				
Category	Cumulative energy demand	Cumulative energy demand	Nonrenewable energy resource depletion	Nonrenewable energy resource depletion
Amount	70000	106000	21000	37000
Unit	MJ	MJ	MJ eq	MJ eq
Note	2)	6)		
WATER USE:				
Category	Process water	Process water	Net freshwater consumption	Net freshwater consumption
Amount	42	11	377	310
Unit	m3	m3	m3	m3
Note	3)	7)		
LAND USE:				
Category	Land use	Land use		Terrestrial distrurbance
Amount	6900	3300	n/a (infrastructure excluded)	3040
Unit	m2	m2		m2
Note	4)	8)		11)

1) Carbon sequestered in the product (1,5 kg CO2-eq / kg fiber) would bring the sum negative, but uncomparable with other studies.
2) Of which 51 000 MJ (73 %) is renewable energy, and 19 000 MJ (27 %) non-renewables.
3) Cooling water is separately assessed: 403 m3
4) Converted from the original unit (0,69 ha/a)
5) Carbon sequestered in the product (1,5 kg CO2-eq / kg fiber) not considered due to comparability.
6) Of which 45 000 MJ (42 %) is renewable energy, and 61 000 MJ (58 %) non-renewables.
7) Cooling water is separately assessed: 308 m3
8) Converted from the original unit (0,33 ha/a)
9) Climate cooling impacts (-3,5 t CO2-eq) and carbon sequestered in product (1,6 t CO2-eq) would make the result -2 t CO2-eq, but uncomparable with other studies.
10) Climate cooling impacts (-9,5 t CO2-eq), carbon sequestered in product (1,6 t CO2-eq), and biogenic carbon storage losses (5,4 t CO2-eq) would make the result 6300 t CO2-eq, but uncomparable with other studies.
11) Converted from the original unit (304 eq hectares disturbed*yrs, per 1000 t fiber)

The Asian scenarios' GWP is about four times bigger in both studies, mainly due to the higher share of non-renewable energy sources. On the other hand, water use and forestry seem more effective in Asia, so none of the alternatives stand out in every category. More site-specific data is needed to avoid any critical impacts on sensitive ecosystems.

2.4 Conclusions of the literature review

There are many unsolved environmental challenges in the production of cotton and viscose fibers. One of the problems is lack of coherent information, which makes it impossible to define the least harmful production methods. However, some regional differences can be observed from the reviewed studies. The forestry land use of viscose is lowest in Asia, but further processing would be cleaner in Europe. Cotton could be preferably farmed in Chinese climate conditions, but with more efficient water management. In reality, environmental performance is not the only basis for location choices. Also, the current global volumes are very hard to produce solely in the optimal way. That is why the most sustainable results would be achieved by reducing the consumption of these fibers.

So far, most information is available about textile fibers' climate impacts. This is because greenhouse gas emissions are easy to compare globally, and climate change is a very widely noticed environmental problem. The biggest limitation of the found GWP analyses is the exclusion of soil organic carbon and other natural carbon sinks or -sources. They are hard to assess with the current knowledge, but could be remarkable for all bio-based fibers. Carbon sequestration of the product is more often noted: in 1 kg of fiber, cotton and viscose both have at least 1,5 kg CO_2-eq stored (Cotton Incorporated, 2012, p. 17; Shen and Patel, 2010, p. 32). Proper recycling would keep this carbon bound, lowering the carbon footprint or even making it negative. Currently the stored carbon gets released in the end of a textile's short life.

Whereas the greenhouse gas impacts are global despite the source, all the other pollutants can have very different effects depending on the local circumstances. Poor local data easily makes the LCAs inaccurate, so categories like eutrophication and biodiversity are often excluded or overly simplified in the studies. For cotton, this means that pesticide leaks are not always evident in the results, and regional water scarcity is ignored while plainly assessing the amount of water consumed. The chemicals used in viscose production rarely get a mention for their potential impacts, and even the most effective forestry can risk the habitat of species or decrease natural carbon sinks. Wider environmental research is still needed for a clearer overview of textile fibers.

Land use impact assessment is ambiguous in agriculture and forestry. If a natural area is transformed into a managed forest or cotton field, how are the environmental burdens allocated per ton of fibers? The choice is whether to allocate all the land transformation impacts to the first harvest, or to divide them between the expected operation years. If the occupied area has already been used before, land use impacts due to cultivation or forestry are multiple times smaller: this is because in that case, the impacts only come from land occupation and not from any new transformations of natural area. If biodiversity impacts of land use are considered, it must be chosen what species to focus on: vascular plants, animals, or something else? (Sandin et al., 2013) Another unsolved LCA challenge is how to acknowledge different styles of land use: for example, clear-cutting likely has bigger environmental effects than occasional logging.

Because of all these complexities, it is understandable that most of the reviewed cotton and viscose studies only report land use as a plain measure of occupied areas. The same kind of challenges also limit the assessment of water use impacts: changes in natural run-offs, or the hydrological cycle in general, are very hard to quantify or predict in detail. Comparisons between studies and geographical locations are always distorted by this kind of aspects.

Though some details are still missing, many environmental improvements can already be done with these fibers. The worst-performing cotton fields could be developed or shifted to other products, better suitable to that land. Some of the viscose could be replaced by other man-made cellulose fibers (e.g. lyocell) that demand less harmful chemicals (Shen and Patel, 2010, pp. 8–9). The land use impacts would mostly be avoided with recycled feedstock. However, the most sustainable options are sometimes impossible to define: it depends on which categories are prioritized, and how are they assessed. Commonly agreed LCA rules are still needed for textile fibers, and future studies should include more site-specific data.

3 LIFE CYCLE ASSESSMENT METHOD

LCA is a common tool for finding the environmentally relevant aspects of a product system. It’s done by quantifying all the material and energy flows entering or leaving the system, and assessing their related emissions and other environmental impacts. The studies should include all the life cycle phases from cradle to grave: raw materials extraction, manufacturing, usage and end of life treatment. Sometimes the scope is more limited, e.g. cradle-to-gate studies that only focus on the production phase. The results are calculated against a functional unit, a predefined outcome of the product system. (SFS-EN ISO 14040, 2006; SFS-EN ISO 14044, 2006) LCA can produce useful information about various environmental impacts and their critical sources.

3.1.1 Phases

Life cycle assessment has four major phases: goal and scope definition, inventory analysis, impact assessment and results interpretation. The whole process is iterative, so some subsequent findings may lead to changes in the previous phases. (SFS-EN ISO 14040, 2006) For example, if a new type of impact proves to be remarkable, its estimation may be added to the original goal.

The goal of an LCA defines why is the study made and to whom is it intended for. The scope definition includes the studied product system and its functional unit, impacts to be considered, system boundaries and the desired level of detail, assumptions and calculation methods and so on. It is essential to set the goal and scope properly, since they guide every following step and determine the possible applications of the study. If aiming for comparative assertions, more strict criteria should already be applied to the goal and scope. (SFS-EN ISO 14044, 2006)

In life cycle inventory analysis (LCI), data is collected from all the unit processes inside the system boundary. This usually includes both primary data from the studied sites, and secondary data from LCI databases and literature. All the data sources are reported, and their quality and representativeness are consistently assessed. If the system yields valuable by-products, environmental burdens may have to be allocated between them. Allocation is preferably avoided, for example by system expansion to the by-products. When the relevant in- and outputs of all processes are known, the inventory results are calculated per functional unit. The results already show the aggregated emissions and consumed resources, but not their potential environmental effects yet. If the analysis ends here, it is called an LCI study. (SFS-EN ISO 14044, 2006)

The flows defined in LCI are converted into potential environmental effects in the next phase, life cycle impact assessment (LCIA). There are various impact categories to consider, for example climate change, eutrophication and ecotoxicity. The flows that affect a certain category are multiplied by characterization factors, which are predefined coefficients to convert the flows into standard units. For example, climate change impacts are quantified in CO_2-equivalents, so all the greenhouse gases have their own global warming potential (GWP) -values to assess them with a common unit (SFS-EN ISO 14044, 2006). Impact categories and characterization factors develop all the time: some are already well established, while newer ones may still lack basic information.

Results analysis can be used to examine the reliability of inventory or impact assessment. One of the most common methods is sensitivity analysis, where some data and assumptions are altered to see their effects on the results. More checking is done in the last phase of LCA, interpretation. Most significant issues are now recognized, leading to conclusions of the study and future recommendations. (SFS-EN ISO 14044, 2006) The draft report may undergo a critical review, where another expert verifies that the study is consistently made and its conclusions are justifiable (SFS-EN ISO 14040, 2006). Again, the eventual findings may demand changes to the previous phases.

3.1.2 Guidelines

LCA is most often understood in reference to ISO-standards 14040 and 14044. However, these only describe the general structure and requirements, leaving a lot of space to individual choices. More specific guidance is found in product category rules, but so far they only exist for a few sectors. Extending from the ISO standards, there are many parallel methodologies with their own guidelines, for example greenhouse gas (GHG) protocol and product environmental footprint (PEF). Also, some more specific impact measures are drawn from LCA, most notably carbon- and water footprints with their detailed criteria. The abundant optional methods make life cycle thinking applicable to many cases, but the results are not always comparable.

Despite the possible uncertainties, comparison is often necessary for LCA to guide decisions: a single result is rather useless, if it's not relative to other studies. According to SFS-EN ISO 14040, even the purpose of a functional unit is to enable comparisons. If no product category rules are available, comparable results are best achieved by following the previous studies about similar systems. Very simplified comparisons are also possible by grouping or weighting the category indicator results, but that is not recommended due to value-based distortions (SFS-EN ISO 14044, 2006).

There are currently two fundamental approaches in LCA, attributional and consequential. They share the same modelling principles, but differ in what processes are considered in the system. Attributional LCA is the traditional way, focusing on the potential impacts of a given system. Consequential LCA expands the scope into market mechanisms that are affected by the decisions. The choice between these approaches depends on the type of desired information. The consequential approach still has many challenges to improve, but its future scenarios can be more realistic. (Zamagni et al., 2012) Some other emerging applications include life cycle costing, social LCA and life cycle sustainability analysis (Guinée et al., 2011). In general, the trend is towards more complete and systematic assessment. As the research continues, new LCA habits and guidelines are formed, and the databases get more accurate.

3.1.3 Limitations

LCA does not present any absolute environmental impacts, and its accuracy depends on data quality and modelling choices. While rough estimations are sometimes enough, in many cases the initial goal and scope can not be reached due to lack of data. The missing primary data is often replaced with database values, but also the uncertainty rises along them. When Takano et al. (2014) modelled the same building types' GHG emissions with five different databases, their results spread into a wide range. The source of variation could not always be traced, because the base of some values remained unknown. The order of assessed building types was the same in all versions, reminding again of LCA’s relative nature. (Takano et al., 2014) Transparency of database values should be increased to avoid any confusion and misinterpretations.

There are many scoring systems for final LCA results, with different emphasis on certain impact categories. These systems may present the same product in a very different light, as demonstrated by Stavropoulos et al. (2016): comparing three impact assessment methods (ReCiPe, Eco-indicator ’99 and IMPACT 2002+) in an LCA for cylinder heads, some scores were even negative while the others remained above zero. Also the ISO-standard SFS-EN ISO 14044 reminds that personal values always get involved in ranking and weighting of impact categories, making them only optional non-scientific steps. Even though the original results must be presented as well, there is a risk of overly simplified public conclusions.

Apart from calculation issues, the studied scenarios bring uncertainty to LCA as well: even the best analyses become obsolete if they are based on unrealistic assumptions. For example, lighter machine components can obviously save fuel in vehicles, but the opposite happens if the weight savings are used for bigger fuel capacity and longer cruises instead. If new technologies are studied, better understanding of the industry’s tendencies and human behavior are needed, but still often overlooked in LCA. Multiple scenarios will help assessing the wide range of possible future outcomes. (Gutowski, 2018)

In conclusion, LCA still has many limitations and uncertainties that must be acknowledged when using the tool and its results. A properly made study explains all the assumptions transparently, not claiming anything that can’t be proved. The variety of LCA applications and methods mean that not all results are comparable with each other. False interpretations can lead to higher environmental impacts, though the initial aims are opposite. However, the method only improves if more consistent studies are made and mistakes are learnt from. As there are no globally agreed LCA practices yet, a cautious mindset is always needed.

4 LIFE CYCLE ASSESSMENT OF CELLULOSE CARBAMATE FIBER PRODUCTION

During this chapter, the CCA fiber's life cycle model is built in Excel. Data collection, assumptions and limitations are explained for all the studied scenarios. As some of the data is confidential, reporting is more focused on the calculation process itself. The final LCA results will be further analyzed in chapters 4.2.4, 4.3. and 5. Unless otherwise noted, all information of the IFC process is primary data from documents sent by the company, and from personal communications with the chief technology officer (Siren, 2020).

4.1 Goal and scope

The goal of this study is to assess the environmental performance of IFC's fiber production. The scope is cradle to gate, including the CCA fiber process for cotton rich textile waste, and all the related up- and downstream operations. System boundaries are more precisely defined in Figure 1. The chosen functional unit is 1000 kg of baled CCA staple fibers, comparable with most of the referenced cotton and viscose studies. For methodological choices, ISO-standards 14040 and 14044 are followed. When required, more specific guidance is gained from the PCR of man-made fibers (EPD International, 2020) and the standard for product carbon footprints (SFS-EN ISO 14067, 2018).

The life cycle inventory (LCI) phase is targeted to all the quantifiable material and energy flows, without any cut-off criteria. Final inventory results will be presented for energy demand, water consumption and land use. The aim is to separately report both direct and indirect energy consumptions. In contrast, only direct land use and freshwater consumption are calculated, since the data is only available for direct estimations. Due to limitations in data, the direct inventory is more complete for the energy consumption as well. After the inventory, life cycle impact assessment (LCIA) is applied to climate change impacts, which are calculated as global warming potential (GWP) for 100 years in kg CO_2 -equivalents. The used characterization factors for greenhouse gases are IPCC 2013 values, taken from the CML-IA database (CML, 2016). In the needed secondary data sources, some of the values are calculated by other methods like ReCiPe. This may have minor effects on the final results.

The most important outcome of this study is a modifiable Excel-based LCA calculator, illustrating the environmental relevance of different industrial options. This calculator will not be publicly available, but the main modelling principles are explained in chapter 4.2.2. For the current report, two possible factory solutions are examined in two hypothetical locations. Altogether five scenarios are formed, as described in chapter 4.1.3. From the calculated scenario results, the most environmentally critical process parameters are sought for further development. Sensitivity analysis is made to give a more certain range of possible outcomes, and to find out which LCA data should be specified in the future. The results are also analyzed in relation to the earlier presented cotton and viscose studies.

4.1.1 System boundaries of recycling-based CCA fiber production

In the studied textile waste recycling system, textiles are first collected, sorted and mechanically pretreated to achieve the suitable raw material. Then they are fed into IFC's cellulose carbamate process that consists of four main processes. The produced staple fibers are dried and baled to be sent forward as raw materials for textile yarn manufacturing or non-wovens. (Infinited Fiber Company, 2019) There are many variables affecting the system, for example the location perspective and possibilities of integrating the cellulose carbamate production into supporting facilities. Integration to pulp or viscose factories would enable efficient exchange of materials and energy, as later explained in chapter 4.1.3.

Table 3 clarifies the production route of cotton waste derived CCA fibers, as perceived in this Master's thesis. To protect IFC's intellectual property rights, further process details can not be publicly reported.

Table 3. The main phases of industrial CCA fiber production, when applied to cotton-based textile waste (Infinited Fiber Company, 2020b, 2019; Siren, 2020).

#	OPERATION	DESCRIPTION	OTHER ASPECTS
1	**Collection and transportation #1**	Textile waste is collected and transported to a sorting plant	Management of the collection logistics
2	**Sorting**	Manual and automatic selection of the suitable materials	Cotton rich fraction is separated for use
3	**Transportation #2 (optional)**	Sorted cotton-based textiles to mechanical pretreatment	
4	**Mechanical pretreatments**	Phase 1: Removal of non-textile materials. Phase 2: Final size reduction (by shredding and disintegration). This phase can be integrated in phase 1, or done separately before chemical pretreatment	Phase 2 is most likely done at the production plant before chemical pretreatment. If size reduction is done in a separate facility, a transportation is needed in the middle of the phases
5	**Transportation #3 (Optional)**	Cotton-rich textile to chemical pretreatment plant	
6	**Chemical pretreatment**	Cellulose fibers are separated from impurities, cotton waste pulp is formed	
7	**Carbamation**	Urea is added into a cotton waste pulp, a stable CCA polymer is formed by heating	Packaging of the powder form CCA is needed, if it is transported

8	**Transportation #4 (Optional)**	CCA powder transported to the fiber manufacture plant	In case the processes are not integrated together
9	**Dissolving and filtration**	Dissolving of CCA in alkali solution. Filtering to produce CCA spinning dope, a honey-like high viscosity solution	
10	**Wet spinning and after-treatments**	The dope is extruded into spin bath (regeneration bath), forming a continuous cellulose carbamate fiber filament tow. The filament tow is cut into desired length staple fibers before washing, after-treatment and drying the fibers	Bleaching is possible during the after-treatment
11	**Baling**	Automated packing of the staple fibers into transportable bales	

Within the chosen scope, the studied system includes a wide range of different sub-processes. In addition to the four main processes (marked blue in Figure 1), the assessment deals with e.g. textile waste management, chemicals production, packaging and transportations. This brings a more complete environmental view of the system, but may also increase the results' uncertainty due to variation and gaps in data. Whereas supportive processes like textile sorting likely stay negligible in the final results, more caution is needed for some literature-based estimations of energy production. The most vital or contradictory parameters will be included in a sensitivity analysis.

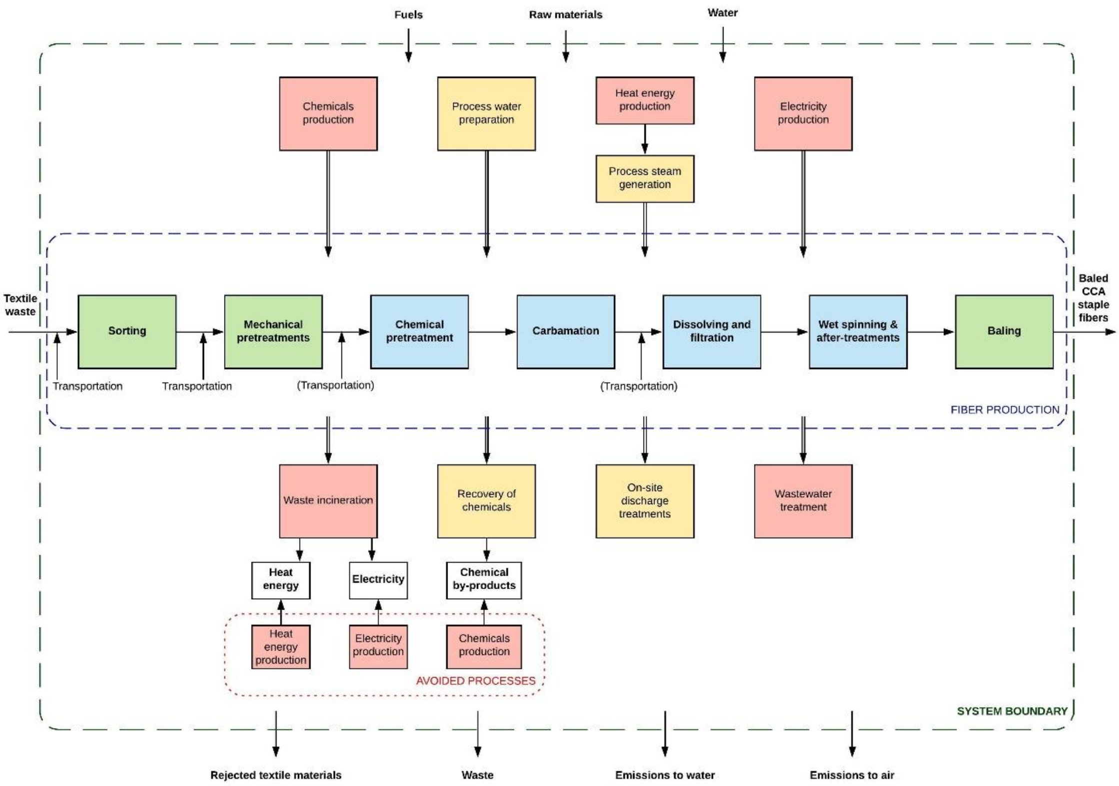

Figure 1. System boundaries of CCA fiber production, for the scope of this study.

4.1.2 Assumptions and limitations

As the studied system is rather complex and not all its details are obvious yet, some assumptions are needed to manage the calculations. All the choices are intended to be in line with the previously mentioned LCA guidelines. For results comparability, also the referenced cotton and viscose studies are considered. As an initial assumption, no environmental burdens or credits are given to the textile waste entering the system. The same was decided by Schultz and Suresh (2017) in their recycled pulp scenario of viscose production. For all the recovered by-products and energy, system expansion is applied to avoid any allocation problems. This is also recommended in ISO 14044. Some assumptions are driven by data availability: for example, transportation of chemicals must be excluded so far. All the used global assumptions (applicable to every scenario) are gathered below in Table 4.

Table 4. Global assumptions and limitations used in the study.

ASSUMPTIONS AND LIMITATIONS	AFFECTED FEATURES OR PROCESSES
GENERAL ASSUMPTIONS	
Cotton rich textile waste as the only initial feedstock	Collection and sorting system, minor process details
No environmental burdens from the textile waste input	Total results
Set-up of infrastructure excluded	All processes, except for the direct land use
Transportation of inputs: not assessed (except for textile waste)	Total results / share of transportations
Final product in the commercial moisture content (13 %)	Total results
Biogenic CO2 emissions excluded, but separately assessed	Total results
MAIN PROCESSES	
Annual production capacity of the CCA fiber plant: 30 000 t / a	Process details
The efficiency of heat energy production is 90 %	Emissions from heating Indirect energy consumption
Heat transfer via process steam	All heating processes
Process water and its preparation: both accounted as direct freshwater consumption	All main processes
Cooling and heating waters: excluded from freshwater consumption (not contaminated in the process)	Freshwater consumption results
Some recovery process details are literary or rough estimations	All main processes
Some minimal chemical flows and electrical devices can not be assessed yet	Total results
SECONDARY DATA	
Values from the average range preferred, when possible	Data with multiple alternatives
Limited data on indirect energy consumption	Total results
BY-PRODUCT CREDITS	
Recovered chemicals substitute their average production, assessed from literature	All main processes
Recovered heat energy substitutes natural gas	All main processes
Recovered electrical energy substitutes electricity from average EU public grid	All main processes

4.1.3 Definition of scenarios

In the scope of this study, the industrial CCA fiber production is evaluated in two principal ways: as a stand-alone factory, or integrated to kraft pulp mill operations. These solutions are likely to have different heat supplies and reject treatments, since the integrated version may utilize some existing infrastructure around it. The environmental performance of both factory types will be assessed by forming a total of five hypothetical scenarios out of them. The supporting system is also modified accordingly, to see the relative importance of location and transportations.

As defined in Table 4, all the studied scenarios are based on CCA fiber factories with an annual fiber production capacity of 30 kilotons. Production capacity can affect the consumed energy, water and chemicals per ton of fibers. The option of kraft pulp mill integration can be viable to these relatively small CCA fiber factories: excess waste heat is available from a much bigger pulp mill, that assumedly has a pulp production capacity of 500 kt / a. Stand-alone solutions are more likely for large scale CCA fiber plants, but the current study is limited to 30 kt / a factories only.

Two hypothetical factory locations are assessed for the CCA fiber production: one in Central Europe, and another one in Asia. In the formed hypothetical scenarios, location mainly affects the emission factors of electricity and distances of transportation. As the scope is cradle to gate, transportation of the final product is not assessed. Freshwater consumption and direct land use are only calculated for the European scenario, so they are excluded from the comparison part.

Table 5 presents the differing parameters between scenarios. The first two can be seen as baseline scenarios. The last three scenarios are modifications of these baseline scenarios: third one is the best case of an integrated factory, and the fourth and fifth are based on stand-alone factories. Eventual fuel choices, reject treatments and other details will also depend on the economic viability, which is not assessed in this study. However, the LCA results can guide those choices by highlighting the most environmentally crucial points to focus on.

Table 5. Major differences between studied scenarios. For more detailed information, see Appendix 1.

	HEATING SYSTEM	ELECTRICITY	BY-PRODUCTS	TRANSPORTATIONS	
SCENARIO NAME	Source of heat energy	Supply	Average rate of recoveries*	Total trans-portations [km]	Vehicles used
Stand-alone, Central Europe	Natural gas	Local public grid mix	Medium	2000	Diesel truck
Integrated, Central Europe	Waste heat from kraft pulp mill	Local public grid mix	High	2000	Diesel truck
Best case: integrated, Central Europe	Waste heat from kraft pulp mill	Renewables 50 % Local public grid mix 50 %	Very high	1000	Diesel truck
CCA in Central Europe, fibers in Asia	Natural gas	Local public grid mix	Medium	20000	Diesel truck Container ship
Stand-alone, Asia	Brown coal (lignite)	Local public grid mix	Medium	2000	Diesel truck

**The actual rates (for every recovery process) are detailed separately in Appendix 1.*

As can be seen in the table, the only site-specific emission factors are related to electricity and fuels. Chemicals' production methods are not compared between the scenarios: while they also may differ between the suppliers in global market, only average literature data is used here due to consistency and missing secondary data. The chemicals' emission factors are anyway included in the sensitivity analysis, and they also affect the credits from by-products.

Some scenario details, apart from Table 5, can also have very minor effects on the system. For example, if a transportation is needed after CCA manufacturing, a packaging process is added before it. This increases the electricity consumption of "supportive processes" in the final results, which is included in the fourth scenario. These kind of additions are negligible to the total results, but included for consistency.

4.2 Life cycle inventory

The highest priority of this study is a careful inventory of the main processes, as well as all the supportive operations around it. The formed mass- and energy balances enable more precise impact assessment, which can also assist in further process optimization. When more specific data becomes available, the inventory results may be applied to new impact categories in the future.

4.2.1 Data collection

The life cycle inventory is based on primary data from IFC, which is mainly collected from various documents delivered by the company. These include scaled-up calculations from the pilot process, device specifications from the industry and overall plans for the whole supply system. Also interviews and pilot plant visits were made during the research. The four main processes are well studied by the company, but secondary data is still needed to complete the inventory and compare different options between scenarios. Secondary data is found from literature (mainly other LCA studies), and several public databases (BioGrace, 2015; EC, 2015; EEA, 2018; JRC, 2019; VTT, 2017). All the used secondary data sources, excluding confidential data, are specified in Appendix 2.

The benefit of not using a paid LCA database or -software is that most of the data can be traced back to their original literature sources. The initial methods and assumptions can be checked, and verified that they comply with this study's principles. Conversely, a limiting factor is the availability of representative data. For indirect energy consumption calculations, the energy consumptions in chemicals production are only found for 64 % of all the input chemicals. Nearly every studied chemical has GWP data available, though the calculation methods in them are not always constant. There is no data available for two chemicals, but their GWP values are successfully calculated from the known raw materials and formation reactions by stoichiometry. As expected, data availability is not an issue for any of the assessed fuels and electricity supplies.

There are a few cases open to choices in the data collection. Some of the studied inputs have contradictory GWP values available, so the ones chosen to modelling are those that stay close to the average range. This assumption is already defined in Table 4, and the average range is checked from a widely used LCA software. It must be noted that due to the software's license agreements, those values are not used in the final LCA calculator itself.

Another choice concerns sub-processes that are assessed from literature: some of the original studies are only LCIs, so their GWP values should be defined independently. The given in- and outputs of these processes are very common energy forms and chemicals, so the missing sub-process GWPs can be calculated using the same emission factors as elsewhere in the study. This makes the sub-process GWPs better representative of the studied scenarios.

As data is gathered from various sources, no all-inclusive criteria can be applied to it. The most recent and representative studies are anyway prioritized. Some presumptions can also be made of the most doubtful parameters. If these, or some other factors, stand out in the final results, they can be modified in the sensitivity analysis. A separate uncertainty analysis is not included in this study.

4.2.2 Construction of the LCA calculator

The life cycle calculations must be flexible for future changes in primary or secondary data. It is also important to enable quick comparison between scenarios, helping to specify the choices with most impact. Thus, the LCA calculator is designed to have five parallel scenarios, and the formulas have a lot of user-defined variables. The main challenge is to construct this kind of calculator in a clear and accurate way. This chapter explains how the LCA calculator is built in Excel, and what kind of limitations are noticed along its building and use.

Secondary database

Before the actual calculations, all the found secondary data is gathered in its own database sheet. This includes the emission factors and energy demands that were introduced in the previous chapter. Also, the data of supportive processes, like sorting, packaging and transportations, is added into the secondary database. As earlier explained, some values are calculated from various sources; all these calculations, as well as possible unit conversions, are presented in the secondary data sheet. This simplifies the tracing of mistakes, if needed. By keeping a separate sheet for all the secondary data, specific values are easy to find for updates and not mistaken for any actual process data.

Global parameters

Even though the calculations are based on five different scenarios, some parameters stay the same in all of them. These are called global parameters, and they are defined in a separate sheet. One of these global parameters is the intermediate mass flow. It means the flows that exit a sub-process and continue into the next one. For example, CCA powder (output of the carbamation process) enters the next process (dissolving and filtration) as a raw material input. This kind of basic mass flows are defined as global parameters, because they are constant between the scenarios and needed in the transportation calculations later. Global parameters can be changed in the LCA calculator, but the user must consider how they affect on the other inventory details.

Scenario details

A separate sheet is formed to define all the scenario-specific information. These include transportation distances, by-product recovery rates, heating system details etc. The fundamental scenario differences were already presented in Table 5, whereas Appendix 1 has all the chosen details for every sub-process. In the final LCA result calculations, energy emission factors and many other data is retrieved from the scenario definitions sheet. Thus, all the differences between scenario results come from these parameters. Again, it must be noted that the current scenarios are only hypothetical, formed to the purposes of this LCA.

Supportive processes and transportations

In this study, supportive processes mean textile waste sorting, mechanical pretreatment, and bale packaging of fibers. In the fourth scenario, where CCA in powder form is transported overseas to fiber production, a bale packaging is also added in the end of CCA manufacturing process. These supportive processes have only energy inputs, and they are assessed with literature data, except for the size reduction part of mechanical pretreatment, which already is evaluated by IFC. No material losses are assumed to occur in the supportive processes or transportations. In the mechanical pretreatment of textile waste, the removed excess parts (buttons, zips etc.) are thus excluded from this study. If pre-consumer textile waste (leftover bits from industry) is used, the excess parts are more likely avoided in the first place.

Nørup et al. (2019) have declared the energy consumptions of a European textile sorting center. A three-year average electricity consumption is 14,7 kWh per ton of incoming textiles, and a minor amount of gas is needed for heating of infra. Whereas the sorting is done manually in the center, there are also automatic packing devices, conveyors etc. that explain these energy needs. As no other studies are found about textile sorting centers, the energies from Nørup et al. (2019) are used in all the scenario calculations. It is not considered if this kind of centers are actually found near every assessed location, or if they use the same sorting methods. Anyway, effective textile sorting should become more common soon, and these energy consumptions are expected to stay minor in the total results. In the future, automatic textile recognition may increase the electricity demands of sorting.

From data in Ismail et al. (2011), the electricity needed for baling of cotton fibers can be calculated. After unit conversions, the average electricity consumption is 35,6 kWh per ton of fibers, and this is now used for both bale packaging calculations. The production of packaging material is excluded since there is no data about it and the plastic bale wrappings can be recycled. If mechanically pretreated textile waste must be transported, it is assumed that no similar bale packaging is needed there.

All the transportation details are taken from the Lipasto database (VTT, 2017). Most of the transports are modelled by a diesel-driven truck, with GHG emissions of 38 g CO_2 -eq / ton*km and fuel energy consumption of 0,58 MJ / ton*km. These are the average values from 2016, for a fully loaded truck with 25 tons capacity. Emission factors in this database only include the direct emissions from vehicles, so the fuel production emissions are added from another source (di Lullo et al., 2016, p. 6): per one MJ of fuel energy, the upstream emissions of diesel are 15,74 g CO_2 -eq. The overseas trip of the fourth scenario is assessed in the same way, using the VTT Lipasto dataset of a container ship (2000 TEU, 65 % load). Only one-way trips are assumed in all the transportations, because the vehicles may carry other products on the way back. More transportation details can be seen in the appendices.

Chemical pretreatment

The chemical pretreatment needs heat energy, electricity and chemicals in the main process stage, as well as in the bleaching and reject treatments. Some of the reject can be purified and returned back into the process, which reduces fresh chemicals consumption. The remaining output effluents include valuable by-products that can be recovered. Best outcome is gained in the integrated scenarios, where the kraft pulp mill’s cooking liquor recovery system is directly utilized. Stand-alone factories use other treatment options instead. After recoveries, the remaining wastewater is led to biological wastewater treatments.

There is some uncertainty in the overall water balance of this sub-process. The by-product recoveries must also be simplified in this LCA: not all the options can be examined in detail yet, so only two of the most likely pathways are chosen here. These are the kraft pulp mill's cooking liquor recovery system in integrated scenarios, and a separate recovery of by-product B in stand-alone scenarios (see Table 8 in chapter 4.2.4). As earlier explained, the recovered by-products and energy are assumed to replace equivalent amount of conventional production elsewhere, and a credit is given from those avoided emissions.

Carbamation

Following the chemical pretreatments, carbamation is a lot simpler process concerning life cycle assessment. Energy, water and chemicals are needed much less, and the outputs only have one by-product. In the scope of this study, the carbamation process is integrated in the chemical pretreatment process at the same mill site. Again, it is possible to recycle leftover chemicals back into the process, and water inside the process. Chemical recycling is already taken into account, but overall water balance is not quantified in detail yet. The current heat energy input is a rather high estimate from the pilot process, and the goal is to reduce it in the industrial scale-ups. The output of carbamation process is a stable cellulose carbamate polymer in the powder form, so it can be transported to another location for the next process stages if needed. In the current calculations, this is only assumed in the fourth scenario. Based on a zero emission process target, wastewaters from the carbamation process are minimized and thus excluded from the current calculations.

Dissolving and filtration

To enable the dissolving of cellulose carbamate, some cooling and heating are needed in the dissolving and filtration. The cooling process releases energy that is utilized in the heating stage, minimizing external heat inputs. Two input chemicals are added in this sub-process, and some of it forms by-products later in the wet spinning phase. Wastewaters of this process are negligible and excluded in the current calculations. A minor solid reject is removed in filtration, and it is assumed to be incinerated in the pulp mill's waste treatments (integrated scenarios) or transported to a waste incineration plant (stand-alone scenarios). Both options produce electricity and heat, but also release some CO_2 emissions. The waste treatment modelling is further explained in chapter 4.2.3.

Wet spinning and after-treatments

This phase is the last one of four main processes, and it has a diverse set of small operations needed to finish the CCA fibers. Two remarkable by-products are formed in the process, and majority of that can be recovered to further commercial utilization. The wastewaters from this process have some chemical emissions that are treated inside the factory. The remaining wastewater is then sent to biological treatments.

Result calculations

When all the necessary data and parameters are defined, final cradle to gate results can be calculated in their own sheet. Life cycle inventory is basically done with cumulative sums of all the in- and output flows, and carbon footprint is then calculated by linking these sums with their related GWP values. Besides plain sums, the total results are divided into categories to see their contributions to the big picture. Also graphs are created to enable quick comparison between scenarios. The final results are illustrated in chapters 4.2.4 and 4.3.

4.2.3 Life cycle modelling choices

When the preliminary LCA calculator is built, there are still a few cases open to discussion. Before final results can be understood, these modelling choices are briefly explained and justified here.

Process water preparation

To avoid unwanted side effects in the four main processes, all the input process water is assumed to be purified by reverse osmosis, deionization or other relevant method. In the industrial scale, this will be done inside the factory. However, there are currently no estimations about the electricity and chemicals needed for this. Purification technologies will also depend on the local freshwater source, since hardness and other properties vary a lot between natural water systems. For these reasons, it is beyond the scope of this study to define the electricity and chemicals needed in the process water preparation. They are thus excluded until more site-specific plans get made. However, the excess water requirement of process water production is included in the freshwater consumption: these values are taken from Shen and Patel (2010, p. 16).

Waste effluent treatments

Moderate amounts of waste are generated in the studied system. These rejects mainly consist of impurities that originate from the textile waste input. Most of the material is organic, and it is assumed to be incinerated into energy and CO_2 emissions. As earlier mentioned, integrated scenarios can utilize the kraft pulp mill's recovery, whereas the stand-alone factories transport the wastes to an external incineration plant. Related energy efficiencies are assessed from Gaudreault et al. (2012) in integrated scenarios, and Reimann (2013) in stand-alone scenarios. The wastes are assumed to have a lower heating value of 17 MJ / kg, which is a rough average from all the organic materials in it.

The energy outputs from waste incineration are rather easily calculated, but its CO_2 emissions demand more attention. The waste composition is not constant, and the carbon content can not be precisely defined. However, it is known that most of this carbon is biogenic because it originates from cotton-based textile waste. As defined in Table 4, biogenic CO_2 emissions are excluded in this LCA. Thus, it is enough to focus on fossil-based carbon. In the CCA fiber process, the major source of fossil carbon is polyesters (PET) in the sorted cotton rich textile waste feedstock. It is assumed that all the PET is removed along the process, ending up to waste incineration or otherwise decomposed in the waste treatments. The input textiles are determined to have a certain PET content, so the consequent non-biogenic CO_2 emissions can be calculated from the carbon content of PET and basic stoichiometry. These emissions likely have a minimal role in the total carbon footprint, but they still are a possible source of uncertainty because the PET content varies in textile waste. It is also possible to separate the PET from effluents instead of incineration. This is excluded from the current study.

Wastewater treatment

The wastewaters from CCA fiber production can be handled by common biological treatments. These are done outside the current system boundaries, and general literature data is sought about them. The used calculation values are found from Meneses et al. (2015), but it can not be verified if this data is representative to all the assessed CCA fiber production scenarios. If some other treatment is needed before the biological wastewater treatment, it will be done inside the CCA fiber production plant. An example of this is the chemicals recovery of wet spinning process. Primary data from IFC is available on these recoveries, but some details are currently based on rough estimations. As the process development continues, the wastewater flows will be further specified.

Direct and indirect energy consumption

To get a more detailed environmental view of the studied system, the energy inputs are divided into direct and indirect consumption. There are no all-inclusive rules about what must be included to each. Table 6 clarifies the choices made in this study.

Table 6. Classification of direct and indirect energy consumptions.

DIRECT	INDIRECT
The four main processes	Chemicals production
Mechanical pretreatments	Energy production (heat losses in power plants)
Transportations (also waste transportation)	Wastewater treatment
Sorting	
Bale packaging	

The direct energy consumptions are more important knowledge to IFC, because they are easier to control by the manufacturer and may also affect their factory designs. Indirect consumption can be seen as supplementary information, aiming to identify the most energy intensive parts in the whole supply chain. Location of the mill-site may also have an impact on both the direct and indirect consumption figures. Because of the previously mentioned gaps in secondary data (see chapter 4.2.1), the indirect results are not as complete yet. In this study, carbon footprint is not separated to direct and indirect GHG emissions, because their climate impacts are the same despite the source.

4.2.4 Inventory results

With the methods described above, life cycle inventory is now completed. Table 7 shows the total inputs of the studied system, per ton of CCA fibers. As the basic consumptions do not change between the current scenarios, it is enough to present the results for the first scenario (Stand-alone, Central Europe). In fact, a couple of inputs actually differ between the scenarios; these are explained after the inventory result tables.

Table 7. Total inputs of the system, per ton of CCA fibers (results from the first scenario).

CHEMICAL INPUTS: [L = low consumption M = medium consumption H = high consumption]	
Chemical A	L
Chemical B	M
Chemical C	M
Chemical D	L
Chemical E	L
Chemical F	L
Chemical G	M
Chemical H	M
Chemical I	M
Chemical J	H
Chemical K	H
Chemical L	L
Chemical M	M
Chemical N	M

ENERGY INPUTS	[MJ]
Fiber production processes	
Heat energy	21657
Electricity	8206
Supportive processes and transportations	
Electricity, heat and transportation fuels	1707
>>> TOTAL (cradle to gate)	
DIRECT energy consumption	31569

WATER INPUTS	[m3]
Total DIRECT water consumption	54

OTHER INPUTS
Cotton rich textile waste

INDIRECT inputs (outside the main system)		
Total result	**Unit**	**Amount**
Indirect energy consumption	MJ	15601

All outputs of the studied system are summed up in Table 8. Since the scenarios have different reject treatments and by-product recoveries, some of the output results differ a lot between the scenarios. That’s why this table presents some of the scenario results separately.

Table 8. Total outputs of the system, per ton of CCA fibers.

OUTPUT CHEMICALS: [X = recovered mass 0 = not utilized as a chemical]	Stand-alone, Central Europe	Integrated, Central Europe	Best case: integrated, Central Europe	CCA in Central Europe, fibers in Asia	Stand-alone, Asia
By-product A	X	X	X	X	X
By-product B	X	0	0	X	X
By-product C	0	X	X	0	0
By-product D	X	X +2 %	X +30 %	X	X
By-product E	X	X	X	X	X
OUTPUT ENERGY [MJ]					
Heat energy output	26	2449	2449	26	26
Electricity output	11	257	257	11	11
WASTEWATER [m3]					
Wastewaters to biological treatment	36	31	31	36	36

OTHER OUTPUTS (same in all the scenarios)	Amount	Unit
Baled CCA textile fibers	1	t
Fossil-based CO2 from PET in wastes	147	kg (CO2e)

The energy outputs show a remarkable difference between stand-alone and integrated scenarios. This is because waste incineration is more often utilized in the latter ones. One of the waste streams has a high water content, so it must be concentrated before incineration is possible; this is done in the integrated scenarios only. Stand-alone factories treat the same stream as wastewater.

Because the driven distances are not the same in all scenarios, there is some variance in the transportation fuel energies. Most of them stay marginal in the total results anyway. The only exception to this is the fourth scenario that includes a long overseas trip. Because of that, the total energy consumption of its “supportive processes and transportations” is as high as 7743 MJ. Apart from transportations, the direct energy inputs do not have notable differences between scenarios. This may obviously change in the real-life industrial systems. For indirect energy consumptions, the only source of variation is currently the biological wastewater treatment; slightly different wastewater volumes end up there in the integrated and stand-alone scenarios. This variation is negligible in the total indirect energy consumption, which is dominated by production of chemicals.

The calculated direct energy consumption of the CCA fiber factory (four main processes) is 8,3 MWh per functional unit (ton of CCA fibers). Other processes (supportive processes and transportations) consume 0,28 to 2,15 MWh per functional unit, and the indirect energy consumption in roughly 4,3 MWh per FU. Figure 2 and Figure 3 illustrate the energy contributions of the first scenario (Stand-alone, Central Europe).

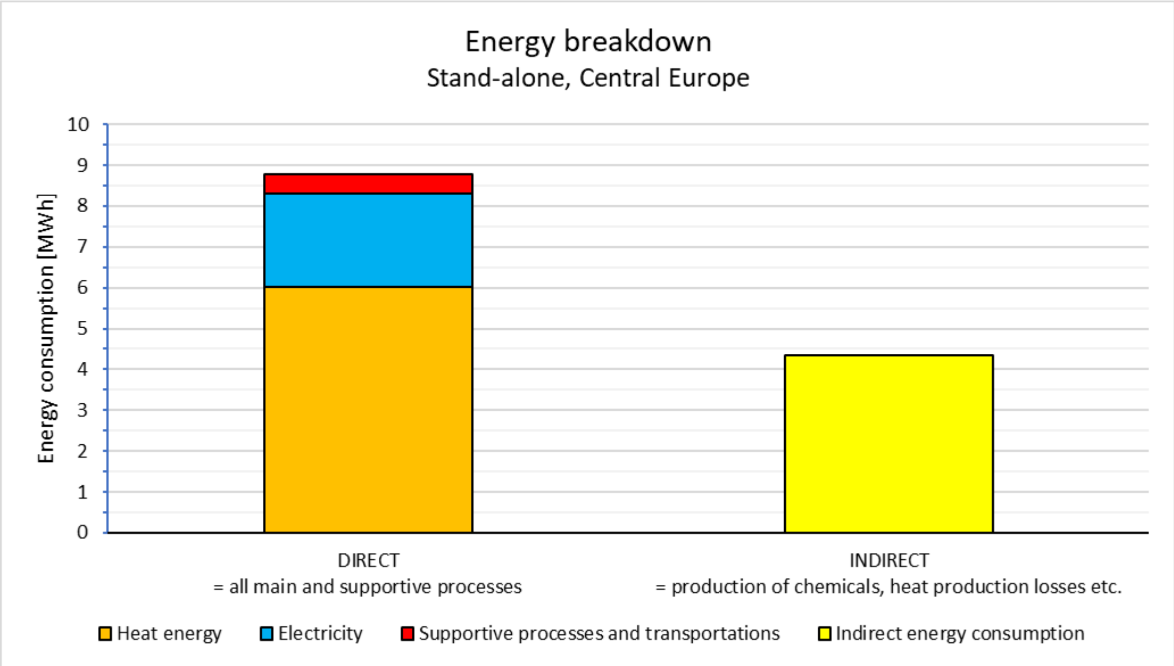

Figure 2. Direct and indirect energy consumptions, per FU (first scenario).

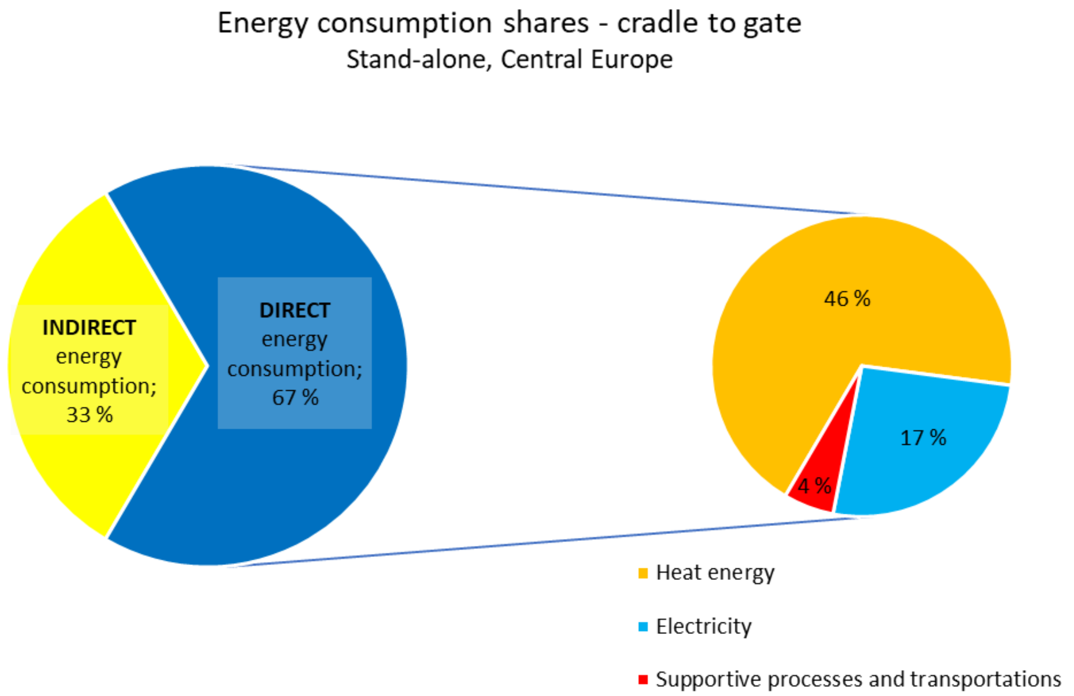

Figure 3. Relative shares of different energy categories (first scenario).

The figures show that heat energy plays the biggest part in the studied system, and that supportive processes and transportations stay marginal in the cradle to gate energy consumption. Indirect energy is about one third of the total, and obviously not consumed in the factory itself. The indirect result could be bigger, if there was more data available about energy consumptions in chemicals production; currently it is missing from five input chemicals. It can now be foreseen that the production method of heat energy will have big impacts in the energy-based GHG emissions of CCA fiber production.

The total direct freshwater consumption of the system is 54 m^3, all originating from the four main processes. As previously noticed, the indirect freshwater water consumption results are incomplete due to data availability. Thus, they are not presented here but are a potential object of future LCAs. The contributions of direct freshwater consumption are illustrated below in Figure 4. Even though the total water usages seem moderate, their local impacts should be considered for every future factory.

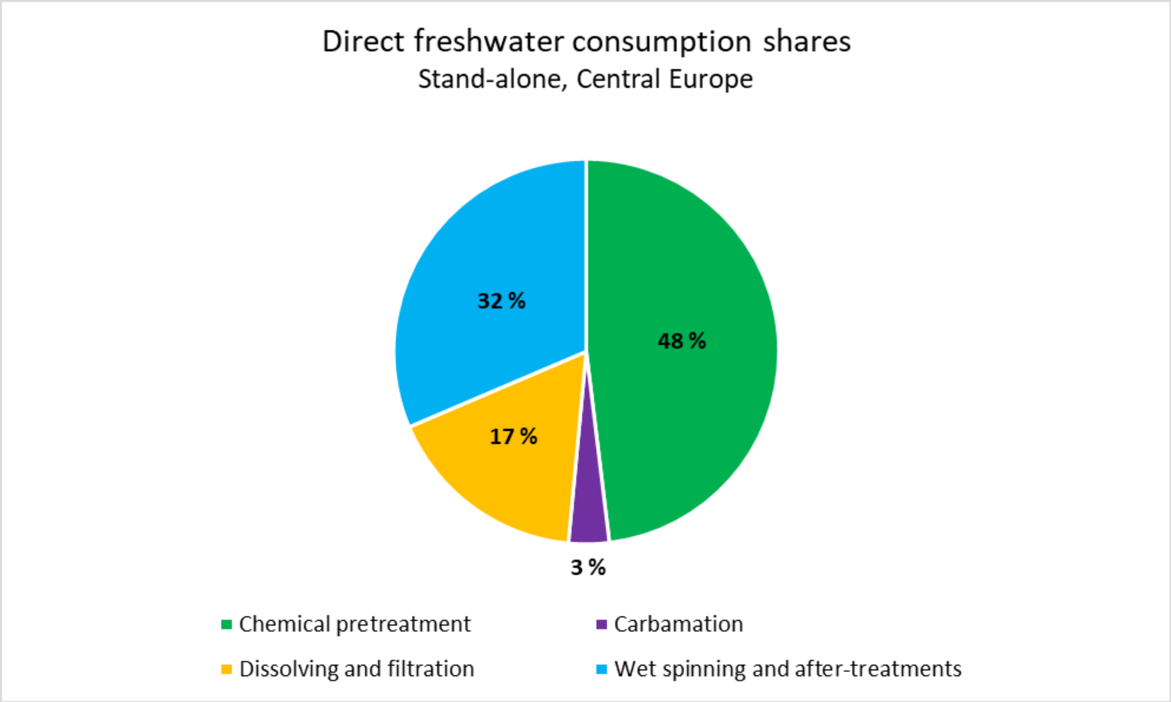

Figure 4. Relative contributions in the direct freshwater consumption (first scenario).

In this study, land use can be only defined for the first scenario. This direct land use is calculated by dividing the factory area with annual fiber production in tons, and the result is 15 m^2 per ton of CCA fibers. It is only a directive value, and its comparability to other land uses can't always be guaranteed: in some studies, like Schultz and Suresh (2017), infrastructure is totally excluded from land use, so their result for recycled viscose fibers is plainly set to zero. If the same assumption was made here, the result would be zero as well. Anyway, the conclusion is that land use is not a big issue for the textile waste feedstock derived CCA fiber production, though its local impacts should of course be noted in every factory under design.

4.3 Life cycle impact assessment

When the inventory is finished, the environmental impacts of CCA fiber production can be assessed by linking the in- and output data with their emission factors. In this thesis, the chosen impact category is carbon footprint (GWP 100). It is not separated to direct and indirect emissions, but the major GHG emission sources can be identified by sub-processes and the operations inside them.

4.3.1 Carbon footprint

To calculate the carbon footprint of all scenarios, the inventory results are simply multiplied with their related emission factors. Table 9 below shows the greenhouse gas emissions and -savings per ton of CCA fibers.

Table 9. Total GHG emissions, by scenario.

CRADLE TO GATE GREENHOUSE GAS EMISSIONS [kg CO2e]	Stand-alone, Central Europe	Integrated, Central Europe	Best case: integrated, Central Europe	CCA in Central Europe, fibers in Asia	Stand-alone, Asia
Supportive processes and transportations	135	135	71	728	190
Energy-based GHG emissions	2231	605	302	3762	5190
GHGs from chemicals production	1332	1332	1332	1332	1332
Other GHG emissions	133	133	133	133	133
>>> Total GHG emissions of system	**3832**	**2204**	**1837**	**5955**	**6845**
Credit from by-products	-676	-930	-1061	-676	-676
>>> Total GWP result of scenario	**3156**	**1274**	**776**	**5279**	**6169**

Figure 5 presents the calculated GWP results by process and contributors. The by-product credits are considered as negative emissions that diminish the environmental burden of the scenario. The results show that for stand-alone factories, heat energy is the most critical source of emissions. Integrated factories are assumed avoid the heat energy emissions, so chemicals production appears the biggest contributor to their carbon footprint. As with the energy consumption results, supportive processes and transportations stay minor in the total GHG emissions. The fourth scenario is an exception to this, since it includes a long overseas transportation.

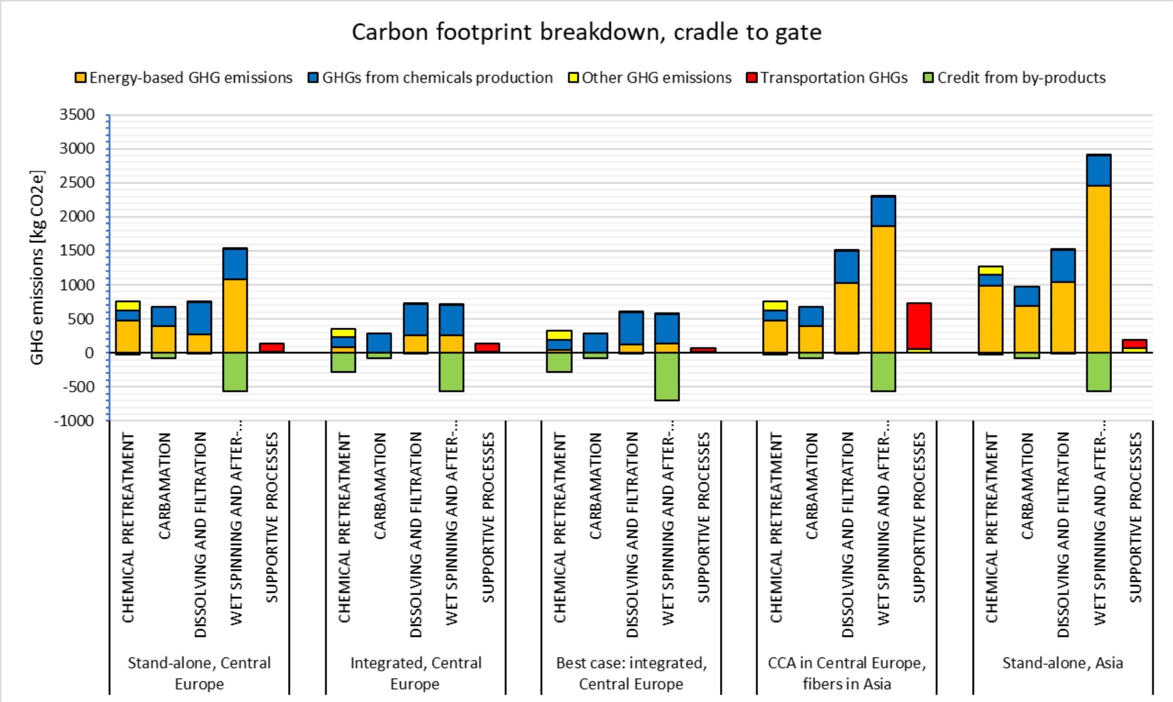

Figure 5. Breakdown of total carbon footprint results, by scenarios and processes.

With the assumptions of this study, the most GHG emission intensive sub-process modules are wet spinning and after-treatments in the stand-alone scenarios, and dissolving and filtration in the integrated scenarios. Some of the sub-processes have only minor differences in their GHG emissions, so the rankings may eventually change in real-life scenarios. If GWP data becomes directly available from the chemical- and energy suppliers, there could also be more variance in the CFPs between the geographical locations.

4.3.2 Biogenic GHG emissions

Biogenic greenhouse gas emissions are a constant debate in LCA studies. Usually they are excluded from the total carbon footprint, whereas the CFP standard (SFS-EN ISO 14067, 2018) advices to report biogenic GHG emissions separately from the fossil-based emissions. If biogenic CO_2 is excluded from calculations, the assumption is that all the biomass-based CO_2 emissions are sequestered back during the regrowth of that biomass. In reality, this assumption can’t always be guaranteed; as described in chapter 2.2, unnoticed changes may happen in the soils’ carbon storage or elsewhere in the ecosystem.

For CCA fiber production, this issue mostly concerns the emissions of waste heat used in the integrated scenarios. It is justifiable that if only bio-based waste fuels are used, and the heat energy would otherwise be lost in the kraft pulp mill, it enters the IFC process with zero emissions. As the kraft pulp mill is expected to be multiple times bigger than the integrated CCA fiber factory, it is also safe to assume that enough waste heat is really available to cover these demands. The origins of this waste heat, and the natural carbon storages that it may affect, are beyond the scope of this study. That is why biogenic CO_2 emissions of the integrated CCA fiber production cannot be quantified here. Also, if there was any primary data available on those emissions, it would not be obvious if they are allocated to the kraft pulp mill, or to the CCA fiber factory that uses only a small fraction of the total formed waste heat. The aforementioned issues are not applicable to the stand-alone scenarios, because this study assumes that fossil fuels are used for their heat energy.

In chapter 4.2.3, the LCA choices of waste treatment were discussed. The wastes' total carbon content could not be precisely defined, but the fossil-based fraction was estimated by determining the PET content in textile waste feedstock. The resulting fossil CO_2 emissions were already calculated, but there are also some biogenic GHGs emitted simultaneously. These waste-based biogenic CO_2 emissions are harder to quantify, because they originate from various substances and may not stay constant in the waste. Thus, following the initial assumption in Table 4, biogenic GHG emissions are excluded in this study. The sources of these emissions are identified above, but their quantification must be left for the future LCA studies.

Beyond biogenic CO_2 emissions, also the carbon sequestration mentioned in chapter 2 could be considered. All plant-based fibers have a major amount of carbon sequestered in them during growth; for cotton, this corresponds to 1540 kg CO_2 -eq per ton of fibers. As earlier explained, this can not be assumed to stay bound long enough in the current linear life cycle of textiles. If incineration and landfills could be avoided by recycling, a substantial CO_2 burden could be saved. It is ambiguous, to which product's carbon footprint this credit of 1540 kg CO_2 -eq would be allocated: to the cotton fiber that stored carbon in the first place, or to the CCA fiber that can sustain this storage by avoiding landfills or incineration for disposed textiles. If this credit was given to the CCA fiber, the integrated scenarios in this study would even have a negative carbon footprint: –266 kg CO_2 -eq for the second scenario, and –764 kg CO_2 -eq for the third one. However, the system boundaries of this study should be broadened to include this kind of factors in it.

4.3.3 Other potential impacts to environment

Besides the greenhouse gas emissions, there are many other potential environmental impacts in industrial fiber production. Even though the calculated freshwater consumption and land use are relatively small, they might be risky in some circumstances. For example, continuous water consumption may amplify the freshwater scarcity of a certain region, and land use can have negative impacts to biodiversity. It is beyond the scope of this LCA to specify factory locations and study their ecosystems' sensitivity in detail. That is also why emissions to water are not assessed in this study.

Compared to cotton and viscose production, the CCA fiber process uses generally less harmful chemicals; no carbon disulfide is needed, nor fertilizers or pesticides for cultivation. In addition, majority of the reaction by-products in process effluents can be recovered. It is clear from the environmental and economical point of view, that efficient recoveries are needed despite the plant location. If the by-products really substitute the equivalent amount of conventional production, all recoveries can be recommended according to the LCA results as well. Real-life choices also depend on the costs of these recovery units. In the integrated factories, there is potential synergy if the used chemicals and process by-products can be shared between the CCA fiber production plant and the kraft pulp mill.

This study focuses on hypothetical industrial scenarios, so more site-specific environmental impacts are not included in it. When eventually setting up the CCA fiber production plants, new impact categories could be added to the current LCA calculations. For example, eutrophication and acidification potentials may be valuable information in further improvements of environmental performance. These are hard to assess yet since local data and LCA databases are not available.

5 RESULTS INTERPRETATION

Along the LCA calculations, observations were made about potential uncertainties, as well as the results' relation to other textile fibers. Some targets of future improvement were also noticed, for better environmental performance and more comprehensive LCAs. The aim of this chapter is to put the calculated LCA results in context, and to specify the biggest uncertainties in them.

5.1 Sensitivity analysis

Some factors appeared open to interpretation in the LCA calculations. Whether the inventory data was deemed uncertain, or the literary sources indicated a high variation in the calculation values. Also, some assumptions had to be made along scenarios, especially about energy production methods and their efficiencies. As the CCA fiber production is still in pilot phase, this study is based on the preliminary modelling. There are some uncertainties when predicting how the consumptions change when the system is scaled up into a continuous industrial process.

To find out which of the used calculation parameters are crucial to the final results, a sensitivity analysis is needed. It is done for the carbon footprint and energy consumptions. A total of five factors will be modified, as explained below:

- **Device usage time per ton of fibers (+ / - 50 %):** Some of the electricity consumptions were assessed from given device powers, by allocating a certain usage time for a ton of fibers. This can bring some uncertainty to energy consumptions per unit, affecting their related GHG emissions as well.
- **Efficiency of heat energy production (+ / - 5 %-units):** In the original scenarios, it was assumed that heat energy is produced from natural gas or other fuels with 90 % efficiency. The actual efficiencies are not known yet, so this assumption is changed to 95 % and 85 % to see how it impacts the final results.
- **Chemicals consumption (+ / - 50 %):** As with the energy measures, there is still some uncertainty in the eventual chemical consumptions per ton of fibers. This is especially true if a more closed-loop system is achieved.

- **Emission factors of energy (higher / lower estimates):** Some chemicals have a wide range of emissions data available. A higher estimate was found for 1/3 of the used chemicals, and they were averagely 71 % higher than the original emission factors. Lower emission factors were available for 2/3 of the chemicals, with an average difference of – 42 %.
- **Emission factors of energy (higher / lower estimates):** The heat and electricity supplies also have some variation in their emissions data. The found higher and lower values are tested here. The lower values basically mean that the fuel upstream emissions are excluded. This is only an experimental assumption that should be avoided in standard LCAs. The higher emission factors are other estimations from literature and databases. In the higher estimate test, some emissions are also included to the waste heat used by integrated scenarios.

The sensitivity analysis results are below in Table 10. The analysis is only done for the first two scenarios, because they are the basic situations of stand-alone and integrated factory types. As the other three scenarios are only modifications of these two, their changes stay relatively the same and bring no new information.

Table 10. Sensitivity analysis results (for the baseline scenarios).

	Chemicals consumption		Device usage time per ton of fibers		Efficiency of heat production		Chemicals emission factors		Energy emission factors	
	+50 %	-50 %	+50 %	-50 %	95 %	85 %	Higher	Lower	Higher	Lower
Stand-alone, Central Europe										
Carbon footprint	10,4 %	-10,4 %	7,3 %	-7,3 %	-2,7 %	3,0 %	27,9 %	1,9 %	20,0 %	-12,8 %
DIRECT energy consumption	-	-	9,9 %	-9,9 %	-	-	-	-	-	-
INDIRECT energy consumption	42,2 %	-42,2 %	-	-	-8,1 %	9,1 %	-	-	-	-
Integrated, Central Europe										
Carbon footprint	23,1 %	-23,1 %	18,0 %	-18,0 %	-	-	62,5 %	6,0 %	26,5 %	-7,2 %
DIRECT energy consumption	-	-	9,9 %	-9,9 %	-	-	-	-	-	-
INDIRECT energy consumption	42,2 %	-42,2 %	-	-	-8,1 %	9,1 %	-	-	-	-

According to these results, the most sensitive LCA calculation parameters are related to chemicals. As the estimated chemicals' GHG emissions and energy consumptions rely on secondary data only, it is indeed uncertain to define their actual values. An interesting notion is that even with the lower chemical emission factors, the total CFPs become slightly higher in both scenarios. This is because the by-product credits are a lot smaller when the lower emission factors are used. However, the sensitivity analysis does not point out any unexpected details, so the original results can be deemed rather reliable.

5.2 Comparisons with cotton and viscose production

In Table 11, the main life cycle results of CCA fiber production are compared with earlier presented cotton and viscose studies. The presented numbers are not directly comparable, but more general observations can be made from them. As already noticed in the literature review, absolute environmental ranking of these fibers is not possible: all the systems can be managed in different ways, and none of the scenarios are superior in every category. It anyway seems that the best case of integrated CCA fiber production is very promising in the GHG emissions and water consumption, and that the stand-alone baseline scenario is in the same range as European viscose production. The direct land use of recycling-based CCA fiber production is the lowest of all the compared scenarios, because cultivation and forestry are avoided.

To enable deeper environmental comparisons between textile fibers, it should be verified that the compared results are calculated by the same LCA methods. This is currently a big limitation, because the reviewed studies have very different goals, assumptions and system boundaries. For example, the viscose CFP results of Schultz and Suresh (2017) are calculated as global warming potentials for 20 years, so it is not comparable to all the other studies (including this thesis) that use GWP (100a). Cotton Incorporated (2012) uses allocation and cut-off criteria, which were both avoided in this study. Also the production systems differ: Shen and Patel (2010) assess existing viscose factories with large production capacities, whereas this study is based on hypothetical scenarios of a much smaller facility. Even more, the fiber moistures mentioned in chapter 2.1 can result in differences of the environmental impacts per functional unit: out of the reviewed studies, the moisture content could only be verified from Shen and Patel (2010), where it is set to 11 % for viscose. The commercial allowance in this study was slightly higher (13 %), but this difference does not change the relative order of any result. Since not all the details can be similarly checked, the following table should be viewed as an approximate comparison only.

Table 11. Results comparison: CCA fibers, cotton and viscose.

FIBER TYPES	GWP 100a [kg CO2-eq]	ENERGY DEMAND [MJ]	WATER USE [m3]	Category	LAND USE [m2]	Category	Source of data
Recycled CCA fibers: stand-alone (Central Europe)	3156	31 569	54	Freshwater consumption	15	Direct land use	This study
Recycled CCA fibers: integrated, best case (Central Europe)	776	30 867	54	Freshwater consumption	15	Direct land use	This study
Cotton: conventional	1808	15 000	2120	Water consumption	4103 to 20367	Crop area	Cotton Incorporated 2012
Cotton: organic	978	5 759	182	Blue water consumption	5450	Crop area	Thylmann et al. 2014
Viscose: Lenzing Austria	1200	70 000	42	Process water	6900	Land use	Shen & Patel 2010
Viscose: Lenzing Asia	5300	106 000	11	Process water	3300	Land use	Shen & Patel 2010

The results of this Master's thesis indicate the same trend as viscose LCAs: carbon footprint of industrial production is closely tied to the energy it uses. Even with the equivalent energy consumptions, the Asian scenarios stand out because of the expected higher shares of fossil energy. Cotton does not represent the same trend, since its cultivation doesn't necessarily demand external energy; for cotton, farming practices and local circumstances have bigger impacts to the production efficiency and GHG emissions.

5.3 Recommendations

Based on the current study results, some advice can now be given about the future environmental improvements in CCA fiber production. The preferred choices are slightly different for integrated and stand-alone factories, so these are reported separately. Being an environmental study, the economic viability of these improvements is not considered.

For stand-alone factories, it seems that the most effective way of reducing carbon footprint is by proper energy supply choices. The current calculations are done by assuming natural gas for heat supply, and public grid for electricity. If any kind of bioenergy or renewables were available, the stand-alone scenarios' GWP results would be very close to the integrated ones. Another way towards lower emissions is trying to reduce the energy consumption, especially heat energy which is by far the biggest energy type in use. Stand-alone factories do not have external waste heat available, but there might be ways of utilizing the existing heat flows inside the factory. This could be done, for example, by using the energy released from cooling processes to heat another phase where higher temperatures are needed. This kind of plans already exist, but optimization is still needed to quantify the full energy-saving potential.

Reducing the integrated scenarios' carbon footprint demands more external factors. If the factories can be managed with bio-based waste heat only, their biggest source of GHG emissions are chemicals production. Thus, choosing less harmfully produced chemicals would best reduce the total impact. It may anyway be hard to find optimal suppliers to all the chemicals within a moderate distance. That is why the chemical emissions could also be cut by reducing their consumption. As with energy, there may be ways of optimizing the chemicals consumption and managing more closed-loop systems for the critical chemicals. In addition, as seen between the second and third scenario, electricity production also has notable impacts in the integrated scenarios. If the integrated kraft pulp mill has more excess waste heat available, some of it could be used to produce electricity for the CCA factory. That would cut the emissions down even more.

The sensitivity analysis results in Table 10 may help understanding the biggest points of uncertainty in the current LCA calculations. To get more accurate results in the future, the inventory details should be eventually updated for every industrial CCA fiber factory. The Excel worksheet made in this study enables these updated calculations rather quickly, unless the used fuels and chemicals differ from the current ones. The secondary data should be updated when possible, because major changes are possible in e.g. emission factors of electricity. Biogenic CO_2 emissions could not be assessed in this study, but they are rather easily calculated when the missing data is available. The emission factors of chemicals could be changed to more supplier-specific ones. Even though the transportations stay minor in the current results, they could be better specified as well. At least, the transportations of chemicals and other process inputs should be added whenever the distances can be estimated.

As explained in chapter 4.3.3, adding new impact categories could bring a more complete environmental view of the CCA fiber production. These demand more data and calculation efforts, but may point out some crucial points outside the current study limits. It must also be noted that environmental research is not limited to LCAs only; some of the more local parameters, like biodiversity and natural water run-offs, may be easier to assess by field studies and other methods.

6 CONCLUSIONS

The goal of this study was to assess the environmental performance of IFC's fiber production. Another target was to find out the most crucial points for future process development. With the assumptions and system boundaries presented in chapter 4, these goals were met and the results were further analyzed. In addition to the LCA calculations, the limitations and uncertainties in them were identified. The outcomes of this study can assist IFC in the further environmental improvements, and also guide the company towards more precise LCAs.

In the assessed hypothetical scenarios, the best case of industrial CCA fiber production has better environmental performance than the European viscose production in Shen and Patel (2010), for almost all the compared categories. Also in the other studied scenarios, less energy and smaller land areas are used in the CCA fiber production system, and the use of some harmful chemicals are avoided. However, more detailed comparisons are not possible between these LCAs, as the scenarios' fiber production capacities and some other details are different in the studies. Also, when the pilot CCA fiber process is scaled up into 30 kt / a industrial production, the chemical-, water- and energy consumptions may still change from the current simulations. Despite these kind of uncertainties, it can be stated that the environmental performance of IFC's fiber production is at an acceptable level when compared to conventional textile fibers like viscose and cotton.

This study focuses on the industrial CCA fiber production, using only textile waste as a feedstock. It does not take into account any other benefits of using recycled raw materials, like the avoided emissions from textile waste incineration or landfills. With broader system boundaries, the prolonged carbon sequestration mentioned in chapters 2 and 4.3.2 could be considered. Technically, the CCA fibers could replace cellulose fibers, but also other textile fibers, in their current use. As the fiber is recyclable, its wide usage can bring a lot of environmental savings by reducing the need of virgin fiber production. The CCA fiber also has a better color intake than cotton and viscose, which can save energy and chemicals in further processing.

If the CCA fiber process is applied to other cellulose containing feedstocks instead of cotton rich textile waste, its environmental footprint may be very different. Hypothetically, even if the process would remain identical with e.g. cardboard feedstock, the supportive system around it would change and bring a lot of variation to the life cycle environmental impacts. Another point of interest would be industrial CCA fiber production where many different cellulose rich feedstocks are used simultaneously. These kind of modifications reveal potentials to new LCA considerations; for example, the use of different waste feedstocks could be compared in the environmental sense. As the CCA fiber process continues to develop, the scope of this study should be expanded into all the multiple possibilities offered by the cellulose carbamate technology.

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Appendix 1. Scenario-specific calculation parameters, by process.

PROCESS DETAILS	UNIT	Stand-alone, Central Europe	Integrated, Central Europe	Best case: integrated, Central Europe	CCA in Central Europe, fibers in Asia	Stand-alone, Asia
Collection and transportation #1						
Collection range of textile waste	*km*	1000	1000	500	1000	1000
Type of transportation		Diesel truck	Diesel truck	Diesel truck	Diesel truck	Diesel truck
Sorting						
Location of sorting center		EU	EU	Location in Central Europe	EU	Location in Asia
Electricity supply		Local public grid mix	Local public grid mix	Local public grid mix	Local public grid mix	Local public grid mix
Source of heat energy		Natural gas	Natural gas	Natural gas	Natural gas	Natural gas
Transportation #2 (optional)						
Distance to mechanical pretreatment	*km*	1000	1000	500	1000	1000
Type of transportation		Diesel truck	Diesel truck	Diesel truck	Diesel truck	Diesel truck
Mechanical pretreatments						
Location of process		Location in Central Europe	Location in Central Europe	Location in Central Europe	Location in Central Europe	Location in Asia
Electricity supply		Local public grid mix	Local public grid mix	50 % local public grid mix, 50 % renewables	Local public grid mix	Local public grid mix
Transportation #3 (optional)						
Distance to chemical pretreatment	*km*	0	0	0	0	0
Type of transportation		-	-	-	-	-
Chemical pretreatment						
Location of process		Location in Central Europe	Location in Central Europe	Location in Central Europe	Location in Central Europe	Location in Asia
Electricity supply		Local public grid mix	Local public grid mix	50 % local public grid mix, 50 % renewables	Local public grid mix	Local public grid mix
Source of heat energy		Natural gas	Waste heat from pulp factory	Waste heat from pulp factory	Natural gas	Brown coal (lignite)
Efficiency of heating system	*%*	90	90	90	90	90
Share of outputs led to the kraft pulp mill's recovery system	*%*	-	100	100	-	-
If the recovery system is not available, this output is led to biological wastewater treatments.						
Recovery rate of by-product B	*%*	70	0	0	70	70
Carbamation						
Location of process		Location in Central Europe	Location in Central Europe	Location in Central Europe	Location in Central Europe	Location in Asia
Electricity supply		Local public grid mix	Local public grid mix	50 % local public grid mix, 50 % renewables	Local public grid mix	Local public grid mix
Source of heat energy		Natural gas	Waste heat from pulp factory	Waste heat from pulp factory	Natural gas	Brown coal (lignite)
Efficiency of heating system	*%*	90	90	90	90	90
Recovery rate of by-product A	*%*	100	100	100	100	100
Transportation #4 (optional)						
Distance to dissolving and filtration	*km*	0	0	0	18000	0
Type of transportation		-	-	-	Container ship	-
If this distance is over zero, bale packaging is automatically included in the calculations.						
Dissolving and filtration						
Location of process		Location in Central Europe	Location in Central Europe	Location in Central Europe	Location in Asia	Location in Asia
Electricity supply		Local public grid mix	Local public grid mix	50 % local public grid mix, 50 % renewables	Local public grid mix	Local public grid mix
Source of heat energy		Natural gas	Waste heat from pulp factory	Waste heat from pulp factory	Natural gas	Brown coal (lignite)
Efficiency of heating system	*%*	90	90	90	90	90
Share of outputs led to the kraft pulp mill's recovery system	*%*	-	100	100	-	-
If the recovery system is not available, this output is transported (200 km, by truck) to a waste incineration plant.						
Wet spinning and after-treatments						
Location of process		Location in Central Europe	Location in Central Europe	Location in Central Europe	Location in Asia	Location in Asia
Electricity supply		Local public grid mix	Local public grid mix	50 % local public grid mix, 50 % renewables	Local public grid mix	Local public grid mix
Source of heat energy		Natural gas	Waste heat from pulp factory	Waste heat from pulp factory	Natural gas	Brown coal (lignite)
Efficiency of heating system	*%*	90	90	90	90	90
Recovery rate of by-product D	*%*	70	70	90	70	70
Recovery rate of by-product E	*%*	100	100	100	100	100

Appendix 2. Secondary data sources for inputs and processes.

IN- OR OUTPUT	LINKED DATA SOURCES	
	GHG emissions	Energy consumption
Chemical A	BioGrace 2015	
Chemical B	Literature	Literature
Chemical C	Literature	Literature
Chemical D	JRC 2019	JRC 2019
Chemical E	Literature	Literature
Chemical F	EC 2015	
Chemical G	JRC 2019	JRC 2019
Chemical H	Literature	
Chemical I	Calculated	
Chemical J	JRC 2019	JRC 2019
Chemical K	BioGrace 2015	BioGrace 2015
Chemical L	JRC 2019	JRC 2019
Chemical M	Literature	Literature
Chemical N	Literature	
By-product A	Literature	
By-product B	Literature	
By-product C	JRC 2019	
By-product D	Literature	
By-product E	Calculated	
Brown coal (lignite) - production and combustion	BioGrace 2015	
Natural gas - production and combustion	BioGrace 2015	
Electricity from grid - location in Asia	Literature	
Electricity from grid - location in Central Europe	EEA 2018	
Electricity from grid - European Union average	EEA 2018	

PROCESS	Data source
Bale packaging of textile fibers	Ismail et al. 2011
Process water preparation: Water consumptions	Shen & Patel 2010
Textile sorting center	Norup et al. 2019
Transportation - Container ship, 2000 TEU, 65 % load	VTT 2017
Transportation - Diesel truck, 25 t, full, highway driving	VTT 2017
Transportation fuels: Diesel production	Di Lullo et al. 2016
Waste incineration - solid waste incineration plant	Reimann 2013
Waste incineration in pulp factory	Gaudreault et al. 2012
Wastewater treatment - default closed loop	Meneses et al. 2015