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Prospective life cycle assessment of an antibacterial T-shirt and supporting business decisions to create value

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ABSTRACT

Global production and consumption of textiles is increasing and as a result putting pressure on the environment. In the EU-25 countries for example, 2–10% of environmental impacts are associated with clothing consumption, with washing during the use phase as one of the most significant contributors. Antibacterial textiles, which prevent undesirable odours, may reduce the number of washing cycles, thus offering an opportunity to reduce environmental impacts. This article assesses to what extent different antibacterial T-shirts offer opportunities. Life cycle assessment (LCA) is used to assist the producer in making business decisions to create value during product development process. To this end, we conducted an LCA for an antibacterial T-shirt made in Europe from bio-based man-made cellulose fibres (modal). The antibacterial property is obtained by silver nanoparticles that are produced with colloidal techniques such as the sol–gel process and in-situ formation. It was found that the T-shirt made of 50% antibacterial fibres with the in-situ process (50AB in-situ) caused 15–20% lower cradle-to-gate CO₂ emissions than commercial antibacterial T-shirts. The cradle-to-grave comparison with non-antibacterial modal T-shirts showed that the 50AB in-situ T-shirt exhibited better environmental performance, resulting in 20–30% lower impacts in key categories such as climate change, freshwater toxicity and eutrophication. LCA demonstrated value creation opportunities such as lower environmental impacts, lower costs and risks. Moreover, the product's environmental performance can be transparently communicated to customers, which helps differentiating with competing products in the market, thus offering the producer a competitive advantage.

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1. Introduction

The global population is steadily growing and may reach around 9.3 billion by 2050 (UN, 2011). Due to economic prosperity and higher per capita income, per capita consumption is also increasing in emerging economies such as Brazil, Russia, India, China, Mexico and South Africa. This growth will spur the consumption of food, clothing, energy and housing. According to the EU EIPRO project (Tukker et al., 2006), clothing accounts for 2–10% of the environmental impacts of consumption in the EU-25 countries. A study by Nijdam et al. (2005) found similar results for The Netherlands. Widespread disparities exist between clothing consumption in developing and developed countries. The per capita consumption of textile fibres in India and China is 4 kg and 6 kg, respectively, in contrast to Europe and the US, which have a per

capita consumption of around 19 kg and 34 kg, respectively (FAO and Bank of Japan, 2000; Terinte et al., 2014). This suggests that the per capita consumption in developing countries may substantially increase as income rises.

To satisfy the basic needs of the billions of people in the developing countries while simultaneously reducing the current and impending impacts on our society, the material and energy efficiency of all sectors including the textile sector need to be further improved, hence calling for continuous innovations. Previous research has demonstrated that there are several stages in the product chain during which these improvements and innovations should take place. First, the environmental impacts of fibre production should be reduced (IMPRO, 2014). For example, compared to other fibres, cotton cultivation is known to cause higher toxicity and eutrophication impacts, and involves greater water consumption (Shen et al., 2010a,b; Cotton Inc, 2012). It was found that lower productivity of cotton cultivation and lack of crop rotation cause higher environmental impacts (Bevilacqua et al., 2014). According to Ismail et al. (2011), ginning contributes to 6–17% of the life cycle GHG emissions of cotton from Australia.

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The importance of land use and biodiversity and water use impacts of cotton and wood based fibres have been highlighted by Sandin et al. (2013). Second, in the fibre to garment stages, the environmental footprint of the manufacturing stages should be further reduced by means of more efficient processes (IMPRO, 2014). Energy consumption of spinning and weaving is inversely proportional to yarn thickness (Van der Velden et al., 2014), thus requiring better process development for products made from thinner yarns such as shirts. Dyeing nowadays still significantly contributes to water pollution and to other, energy-related impacts of textile manufacturing (Ren, 2000). It was found that manufacturing processes and conditions can affect the life time of the product and thus influence the environmental impacts of textiles such as cotton bed sheets (De Saxce et al., 2012). This finding is also relevant for apparel such as T-shirts because similar manufacturing processes, such as combing, carding, dyeing and easy care finishes, are required for both home textiles and apparel. Similarly, Bevilacqua et al. (2014) concluded that the most critical impacts of cotton yarn production are due to spinning and yarn dyeing. Third, the impacts of consumer use and disposal stages should be substantially reduced. The use phase is the largest contributor to the impacts of the whole textile life cycle (Walser et al., 2011; Steinberger et al., 2009; IMPRO, 2014). Moreover, it is possible to conserve virgin materials and reduce the associated impacts of their production through end-of-life recycling of fibres (Woolridge et al., 2006; IMPRO, 2014). Fourth, with regard to the chemicals used for manufacturing and consumer use, it is necessary to develop new textile chemicals like dyes, finishing and laundry chemicals that have lower environmental impacts during their production and use, but also help improve the manufacturing and use phases of textiles by needing fewer resources and further improving process efficiency (Allwood et al., 2008). These improvements not only benefit environment and society but also reduce resource scarcity which poses risks to business operations. In order to ensure that innovation and sustainability go hand in hand, sustainability should be integrated in business decisions during the product innovation and development phases.

It is expected that there will be a sharp increase in environmental impacts during product manufacturing and use (e.g. from washing), due to the potentially huge future consumption of textiles in the emerging economies as well as the extant current consumption patterns of developed countries. Furthermore, the trend of global temperature raise due to climate change might also requires us to change consumption behaviour such as increasing number of washing cycles due to sweat/odour. A growing number of companies may offer products such as antibacterial textiles (also referred to as antimicrobial) as mainstream products, provided consumers are keen to reduce washing cycles as well as lower the associated costs and impacts (Windler et al., 2013). It is prudent to assess the impacts of antibacterial textiles and the associated technology before these become mainstream.

Antibacterial fabrics are presently used for T-shirts, sportswear, socks, underwear, bedding, mattresses and mattress covers in order to prevent undesirable odours, and for hospital gowns and wound dressing to prevent bacterial activity on the skin (Windler et al., 2013). The antibacterial chemicals used that are most prevalent are silver (including metallic Ag and AgCl nanoforms), triclosan, silane quaternary ammonium compounds (Si-QAC) and zinc pyrithione (ZnPT) (Windler et al., 2013). These can be applied to a limited number of fibre material types. The possibility of blending different fibre materials is therefore limited. Nanotechnology has been used to impart the antibacterial property by various synthesis techniques such as solid phase, liquid phase and gas phase syntheses (Şengül et al., 2008). Making use of these innovative finishing

materials and techniques, antibacterial T-shirts are emerging products in the textile sector.

Walser et al. (2011) investigated the production of silver nanoparticles (NP), from gas phase techniques such as Flame Spray Pyrolysis (FSP) and plasma polymerization with silver co-sputtering, their application on polyester garments such as T-shirts, and the environmental impacts of silver nanoparticles throughout the complete lifecycle, including the use phase. The behaviour of different types of antibacterial textiles during washing has also been studied, including NP loss and their characterization (Geranio et al., 2009; Lorenz et al., 2012; Windler et al., 2013). However, liquid phase NP synthesis techniques such as colloidal techniques using water as a solvent, the application of NP on modal fibre, and the resulting environmental impacts of antibacterial clothing have not been reported so far. The SurFunCell project (2012), an EU FP7-funded project, has developed liquid phase synthesis techniques and application technologies for NP on products as a result of collaboration between academia and industry. A yarn producer was a research partner in the SurFunCell project who intends to expand their product portfolio with antibacterial textile yarns.

In the present article, the silver NP produced by precipitation and sol–gel techniques will be coated onto bio-based fibres such as modal fibres, as opposed to the application on the final fabric or garment by other technologies that has been used so far. The coating of NP at the fibre stage makes it possible to blend the modal fibres with other fibres such as cotton and polyester, depending on the type of end product. There are several advantages in improving the finishing process, i.e. coating at the fibre level. First, there is an increase in the flexibility of application or end product configuration to achieve the desired functionality. Second, coating the whole fabric with anti-bacterial compounds can be avoided, which reduces the wasteful use of resources and decreases cost. Another advantage is that antibacterial compounds are coated on fibres, i.e. contained in the yarn matrix, which may lead to lower loss during use and possibly to an increased lifetime of the textile's antibacterial activity. This may also reduce the concentration and quantity of the antibacterial compounds needed per garment, compounds which are usually both resource and energy-intensive. A disadvantage might be the loss of silver during fibre finishing, fabric dyeing or the washing stages of T-shirt production; however, this can be addressed by developing efficient silver-coating processes at the fibre-finishing stage. Therefore, the antibacterial T-shirt is an innovation which may well have the potential to improve the environmental performance of such textiles during their entire product lifecycle.

Life cycle assessment (LCA) is a comprehensive and systemic tool that helps to identify environmental hot-spots and can show improvements throughout product life cycles during product innovation and development. It can therefore help guide decisions in business. A few studies have published inventories and impacts of textile value chains and innovative dyeing, finishing approaches and their influence on the use phase (Steinberger et al., 2009; Walser et al., 2011; Terinte et al., 2014). Most of the studies describe the application of LCA to assess alternative products and processes at a given point in time, as an impact calculating tool, rather than its iterative use in the course of an R&D and product development trajectory to support decision-making (Sandin et al., 2014). To the best of our knowledge, no article has described the contribution of LCA to product innovation of antibacterial T-shirts made by liquid phase synthesis techniques. Thus, the main objective of this article is to understand the environmental impacts of various types of antibacterial T-shirts and to show how LCA can guide business decisions during innovation and new business development to improve the product's environmental performance and, thereby, creating value for business.

2. Methods and materials

2.1. Goal and scope of LCA

The purpose of this LCA is to analyse the impacts of different configurations of antibacterial T-shirts to select an environmentally friendly configuration and make improvements in the product design, especially at the yarn level. In addition, a comparison is made between conventional finishing agents and nanoparticle synthesis techniques. We present an analysis for the whole life cycle of the T-shirt, from cradle to grave. It should be noted that the use phase can significantly vary between different users and different geographical regions due to consumer habits, environmental conditions, types of washing and different parameters of washing. These parameters can significantly influence the cradle-to-grave impacts. The main audience of this LCA is product design and development team of yarn producer. We followed [ISO 14040 \(2006\)](#) and [ISO 14044 \(2006\)](#) standards for conducting this LCA study.

2.1.1. Functional unit and impact categories

The function of a T-shirt is to wear so that it can adorn and protect the human body. Depending on the type of activity, it can be a sports or casual wear. By applying certain chemicals to T-shirt matrix, a T-shirt might be used for more days/times before it is washed because bacterial activity is suppressed (provided it satisfies other aspects such as no stains, no wrinkles). In order to capture this benefit at the functional unit level or reference flow level, we account for the different number of uses before washing the antibacterial and normal T-shirts. Our approach is confirmed by the literature, e.g. by [Walser et al. \(2011\)](#) who chose a similar approach. Thus, we choose as functional unit (FU) one T-shirt being worn for 100 days. For a normal T-shirt this would be assumed as 50 washing cycles, i.e. assuming two uses (days) per wash ([Steinberger et al., 2009](#); [IMPRO, 2014](#)). For an antibacterial T-shirt, the number of washing cycles in its lifetime would depend on the effectiveness of the antibacterial coating and on consumer habits (Section 4.3). We assume a medium size T-shirt which weights 245 g (regardless of the type of antibacterial coating). The geographical scope of the study is Europe. This boundary is chosen because different processes take place in different countries such as fibre production in Austria, textile processes in Italy and Slovenia, use and disposal phases (incineration) may take place in any European country. Please see [Table 1](#) for more details.

The main environmental indicator studied in this paper is carbon footprint, following the IPCC 2007 GWP 100a method ([Hischier et al., 2010](#)). To cover other impact categories, we used the ReCiPe (v1.05, July 2010) midpoint impact assessment method with Hierarchist perspective and European normalization factors ([Goedkoop et al., 2009](#)). To assess the freshwater toxicity impacts of silver NP, we used the characterization factors of dissolved silver fraction calculated by [Walser et al. \(2011\)](#) based on the USES-LCA toxicity model ([Huijbregts et al., 2000](#)). According to [Walser et al. \(2012\)](#), one of the limitations presented by this model was that it did not account for the chemical transformation of the silver downstream of the wastewater treatment plants (WWTP). Also, we did not calculate the impacts of incineration of wastewater sludge with silver. Moreover, it was found that incinerators can avoid air emissions of NPs in waste products, if they are equipped with state-of-the-art flue gas cleaning equipment (wet scrubbers and electrostatic precipitators). Appendix A presents a description of the freshwater toxicity calculation. We used [SimaPro v7.3.0 \(2007\)](#) to model the life cycles.

2.1.2. Business value creation with LCA

In a company, different activities are managed by business functions such as marketing and innovation ([Porter, 1985](#); [Porter and](#)

Table 1

Data sources for the LCA.

Process	Data source	Comments
Modal fibre production	Literature	Produced in Austria, Shen et al. (2010a,b)
Fibre finishing	Supplier	Site-specific, on-site data collection from a supplier in Italy
Sol-gel NP production	Supplier	Site-specific, a company which is part of SurFunCell project consortium, Germany
In-situ formation of NP	University of Maribor and a supplier	Site-specific, a supplier in Italy
Spinning	Producer	Site-specific, on-site data collection from a yarn producer, a company which is part of SurFunCell project consortium, in Slovenia
Knitting	Supplier	Site-specific, on-site data collection from a supplier in Slovenia
Dyeing	Supplier	Site-specific, on-site data collection from a supplier in Slovenia
Confection	Supplier	Site-specific, on-site data collection from a supplier in Slovenia
Energy and chemicals	Ecoinvent v2.2	SimaPro (2007) , Frischknecht et al. (2007)
Waste management	Ecoinvent v2.2	SimaPro (2007) , IMPRO (2014) , Frischknecht et al. (2007)
Use phase	Literature	Walser et al. (2011) , IMPRO (2014)
Detergent formulation	Literature	Subramanian et al. (2011)

[Kramer, 2006](#)). To consider sustainability in business decisions, various business functions should be provided with decision support ([Manda, 2014](#)). This study explicitly describes how LCA can be used to support decisions during product development and innovation as well as how the LCA results can be used in other business functions to create value, such as cost reduction, innovation, product differentiation, and reputation. We used the sustainable value framework developed by [Hart and Milstein \(2003\)](#) for the theory of sustainable value creation.

2.2. Description of product system and its components

[Fig. 1](#) shows the whole life cycle of the T-shirt from cradle to grave with a distinction between background and foreground processes. To impart the antibacterial property to the T-shirt, the staple modal fibres are coated with silver nanoparticles during the fibre finishing stage. This process is conducted in a package dyeing machine which is conventionally used for dyeing of yarns and fibres. The coated fibres go to the spinning mill, where antibacterial yarns can be produced with different blends of antibacterially coated fibres and virgin modal fibres or other fibres depending on the application. Ring spinning technology has been used to spun the yarn. Subsequently, the antibacterial yarn is converted into a fabric by knitting. Next, the fabric goes through a dyeing mill and subsequent heat treatment to improve the dimensional stability of the fabric. The fabric is dyed in a jet dyeing machine with a liquor ratio of 12:1. The dyed fabric goes to the confection or T-shirt manufacturing facility where it is cut and sewed to make the intended garment. The T-shirt is used by consumers and disposed at the end of its useful life. The T-shirt sales and distribution stage is not considered in this study since it will be identical for conventional T-shirts and will have a negligible contribution to the overall impacts ([Steinberger et al., 2009](#)). [Terinte et al. \(2014\)](#) give a detailed description of the different textile processes.

2.2.1. Finishing at fibre level

In the [SurFunCell project \(2012\)](#), two approaches were developed and demonstrated for coating silver nanoparticles at the fibre

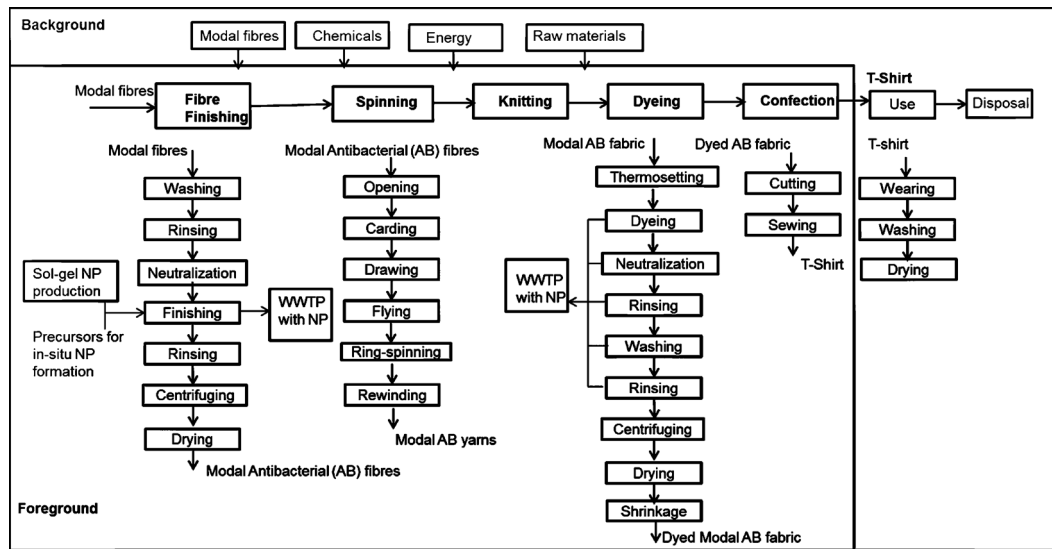


Fig. 1. Life cycle of T-shirt showing foreground and background processes; AB means antibacterial, WWTP means wastewater treatment plant.

level. They are sol-gel coating and in-situ formation of NP directly on the fibre surface. Sol-gel coating makes use of preformed silver nanoparticles (trade name: iSYS Ag) and a silane matrix (trade name: iSYS MTX). The silane matrix has an organic and an inorganic part. The organic part binds to the cellulose of the fibre, while the inorganic part binds to the silver nanoparticles. The coating process needs a subsequent thermal treatment. For reasons of confidentiality, the production of iSYS Ag and iSYS MTX is not explained here but all the steps involved are included in the impact calculation.

Instead of using preformed NP, in-situ coating can be applied by reacting the nanoparticle precursors such as silver nitrate (AgNO_3) with sodium hydroxide on the washed and neutralized fibres in the finishing stage. This process is currently going through patenting procedure and the availability of details are limited. A reduction reaction in the presence of NaOH and AgNO_3 results in the formation of silver NP directly on the fibre surface (Pivec et al., 2013). Then the fibres are rinsed with hot water to remove NaOH. In the case of in-situ coating, heat treatment of fabric (thermosetting and shrinkage) is not required before and/or after the dyeing step. This provides a clear advantage over sol-gel coating, which needs heat treatment before and after dyeing to give dimensional stability to the silane-based matrix serving as NP-containing coating on the fibres.

2.3. Data collection

The research partner, a yarn producer, pilot tested the T-shirts made from sol-gel and in-situ techniques with the involvement of value chain companies for different processes, namely fibre finishing, spinning, knitting, dyeing, confection/garment manufacturing. Knitting and dyeing processes together took place in a supplier company and spinning process took place in the facility of the SurFunCell research partner. As a result of this collaboration, we collected site-specific supplier information for all the processes involved in the process chain of the T-shirt in the year 2012. All processes took place in Europe. The processes represent commonly applied textile processes, except for the finishing step where innovative NP coating is applied at fibre level, with site-specific data from companies in the value chain. Use phase and end-of-life phases were modelled with the help of literature as well as current practices (IMPRO, 2014). NP production process data of the sol-gel technique and in-situ coating were collected from the research partners of the SurFunCell project. For background

process data on energy, materials, chemicals and waste management, we used the Ecoinvent v2.2 (2007) database. We have used electricity of average European grid mix from the Ecoinvent (v2.2.) database for modelling the life cycle. Transportation between different processing steps until the final T-shirt manufacturing is included. Transport between T-shirt manufacturer, retailer, consumer and disposal is not included because they can be same for average T-shirts available in the market and have no significant impact on results (Steinberger et al., 2009).

During the piloting process, we observed a considerable difference in the material efficiency of processes, mainly due to the small batch size throughout the value chain. In order to understand the actual impacts of the production on a commercial scale, we consulted textile experts and found the maximum possible efficiencies of each process. Appendix B shows the efficiencies that were obtained for each configuration at the pilot scale and the maximum possible efficiency of the corresponding process on a commercial scale. For silver coating and losses in sol-gel and in-situ techniques, we assumed the same efficiencies on both the pilot and the commercial scale because they depend on the underlying chemistry of the process irrespective of batch size. Table B2 in Appendix B provides inventory data of all unit processes.

3. Results

This section shows the cradle-to-gate and cradle-to-grave results of T-shirts made from different finishing techniques. A comparison is made with conventional antibacterial coatings at the cradle-to-gate level.

3.1. Cradle-to-gate carbon footprint and environmental impacts

Fig. 2 shows that modal production (without considering the embedded bio-based carbon in the material), finishing and dyeing are the steps in the T-shirt's cradle-to-gate processes that contribute most significantly to CO_2 emissions. In fibre finishing and dyeing, energy for washing and rinsing steps contributes most significantly. The commercial scale in-situ and sol-gel based T-shirts cause lower CO_2 emissions than the pilot scale. This is mainly due to the smaller amount of waste in each process step in terms of fabric material, energy and chemicals used for the required output. The 50AB commercial scale T-shirt (50% antibacterial fibres in T-shirt matrix) causes lower CO_2 emissions than the 100AB commercial

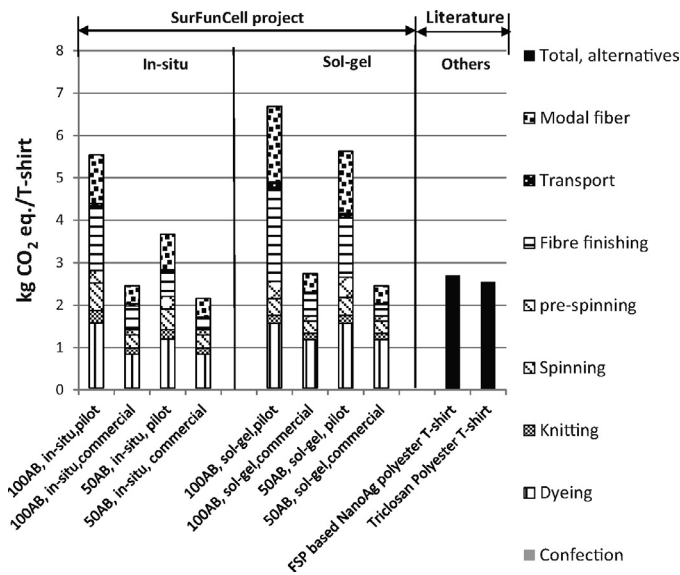


Fig. 2. Cradle-to-gate CO₂ emissions of in-situ and sol-gel T-shirts of different configurations and developmental stages compared to commercially available alternatives from Walser et al. (2011). 50AB means T-shirt matrix with 50% antibacterial (AB) fibres; 100AB means T-shirt matrix with 100% antibacterial fibres.

scale T-shirt (100% antibacterial fibres in T-shirt matrix) because the 50AB T-shirt uses only 50% NP-coated modal fibres and 50% normal modal fibres as opposed to 100% NP-coated modal fibres used in the 100AB T-shirt. The commercial in-situ T-shirt causes lower CO₂ emissions than the commercial sol-gel T-shirt due to the smaller number of heat treatment steps required in the dyeing mill. According to Terinte et al. (2014) the dyeing impacts can be further reduced by lowering the liquor ratio and the number of washing cycles.

The 50AB, in-situ, commercial scale T-shirt results in 15–20% lower CO₂ emissions than other configurations including the Triclosan-treated polyester T-shirt and the NanoAg coated polyester T-shirt prepared by the FSP process, respectively. The latter two are antibacterial T-shirts produced with commercially available alternative technologies (Walser et al., 2011).

Freshwater eutrophication, natural land transformation, fossil depletion and acidification are the most significant impacts of the T-shirt production as shown in Fig. 3. The 50AB, in-situ commercial T-shirt and the 50AB, sol-gel commercial T-shirt cause the lowest environmental impacts compared to all other configurations. Toxicity impacts are shown in discussion, Section-4. Owing to a lack of consensus on freshwater toxicity impacts of nano silver emissions, we have shown toxicity impacts of dissolved silver fraction in Section 4.2. The characterization factor of dissolved silver was calculated by Walser et al. (2011) which is in the same range as nano silver reported by Gottschalk et al. (2010).

3.2. Cradle-to-grave carbon footprint and environmental impacts

Experiments have been conducted to find the durability of the antibacterial property of in-situ and sol-gel knitted and dyed fabrics during the use phase. In-situ fabrics showed satisfactory results for the antibacterial property for the first 20 washing cycles; no tests have been conducted beyond this. It has also been observed that the silver loss substantially declined and levelled off after 10 washing cycles. These findings suggest that the durability might last for more than 20 cycles, but in the absence of experimental data we have conservatively assumed that the antibacterial property will only last for 20 cycles. The 100AB sol-gel fabric displayed antibacterial properties for only the first four washing cycles and

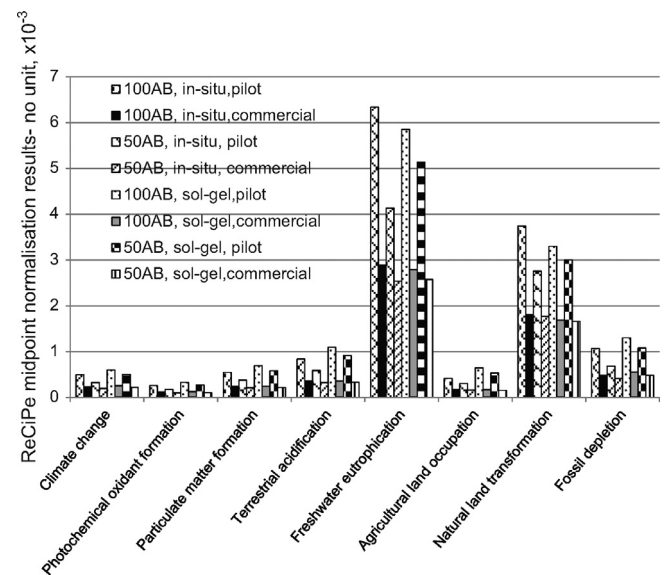


Fig. 3. Cradle-to-gate impact assessment of in-situ and sol-gel T-shirts of different configurations and developmental stages; per T-shirt, using the ReCiPe midpoint method, Hierarchist perspective, normalized for Europe (impact categories with negligible results are not displayed).

the 50AB sol-gel fabric did not display antibacterial properties anymore already after the first washing cycle; therefore this option was not included in the analysis any further. All experiments were conducted for dyed fabric. In order to draw conclusions for T-shirts, we made the reasonable assumption that the durability of antibacterial property at garment level (i.e. the T-shirt) would be similar to the dyed fabric level for all configurations. After the loss of its antibacterial property, the T-shirt can still be used as a normal T-shirt. We also assume that a consumer can wear an antibacterial T-shirt twice as long as a normal T-shirt before each washing (Steinberger et al., 2009). Therefore, if a T-shirt has antibacterial properties for 20 washing cycles and a consumer wears it four times before every wash, then the T-shirt would be washed 30 times in its lifetime of 100 uses ($20 \times 4 + 10 \times 2 = 100$ days of use). A normal T-shirt would have to be washed 50 times in its lifetime of 100 uses. We also assumed that the number of tumble drying cycles is 50% of the washing cycles; this is in the estimated range of 25–70% calculated by IMPRO (2014), considering ownership of tumble dryers in the EU-27 countries. The average load of washing machines and tumble dryers is assumed to be 3 kg (compared to the maximum load of 6 kg), which is also close to the 3.4 kg suggested by IMPRO (2014). However, we conducted a sensitivity analysis for all these assumptions, which is included in Section 4. Table 2 shows the use phase/washing conditions of different configurations of T-shirts. According to IMPRO (2014), landfilling and incineration are the predominant end-of-life disposal options of textiles in the EU-27 countries. Given the NP content in the T-shirt and potential legislation to ban landfilling of textiles in many EU member states (WRAP, 2012), we assumed incineration as the disposal option for the antibacterial T-shirt at the end of its life.

Fig. 4 shows that the 50AB in-situ commercial T-shirt causes around 5% lower CO₂ emissions than the 100AB in-situ commercial T-shirt and 22% lower CO₂ emissions than the conventional modal T-shirt which has no antibacterial properties. The consumer use phase contributes to 50% and 70% of life cycle impacts of the 50AB in-situ commercial T-shirt and the conventional modal T-shirt, respectively. The 100AB sol-gel commercial T-shirt generates more CO₂ emissions than the other configurations and even around 10% more emissions than the conventional modal T-shirt. This is due to the higher CO₂ emissions of the sol-gel antibacterial

Table 2
Use phase conditions applied in the cradle-to-grave calculations.

	Antibacterial T-shirt, 100AB in-situ commercial	Antibacterial T-shirt, 50AB in-situ commercial (reference case)	Antibacterial T-shirt, 100AB sol-gel commercial	Conventional modal T-shirt
Total use in lifetime (days)	100	100	100	100
Total washes in lifetime	30	30	46	50
Tumble dryings in lifetime (half of total washes)	15	15	23	25
Washing load (no. of T-shirts washed per cycle)	12	12	12	12
Washing temperature (°C)	40	40	40	40

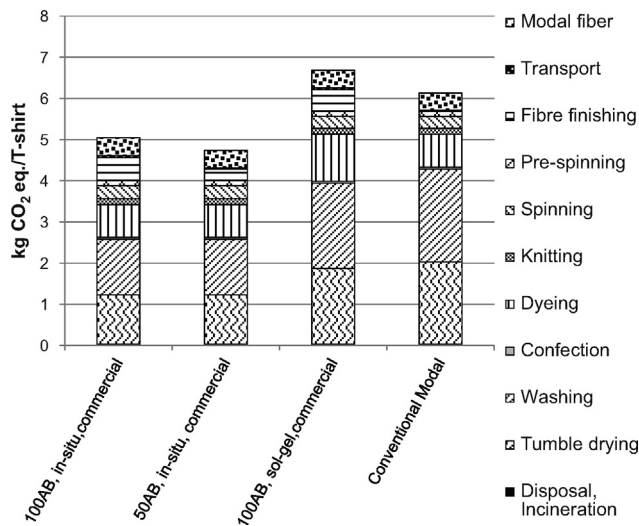


Fig. 4. Cradle-to-grave CO₂ emissions of in-situ and sol-gel T-shirts of different configurations and conventional modal T-shirt.

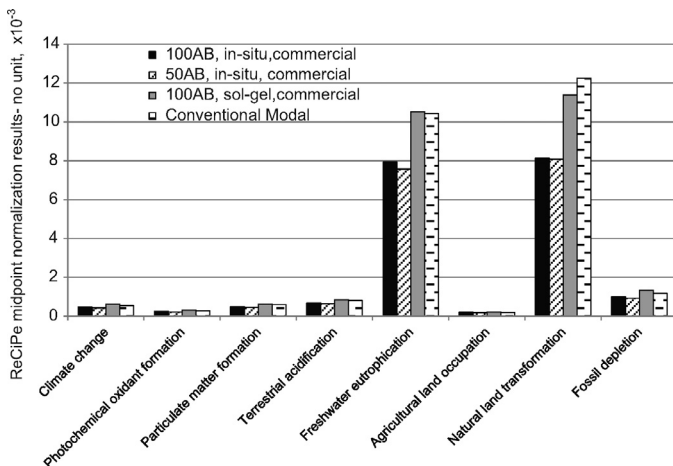


Fig. 5. Cradle-to-grave impact assessment of in-situ and sol-gel T-shirts of different configurations; per T-shirt, using the ReCiPe midpoint method, Hierarchist perspective, normalized for Europe (impact categories with negligible results are not displayed).

finishing process, including heat treatment processes in combination with the low savings from the avoidance of washing cycles during the use phase. There is little knowledge about the consumer behaviour in use phase, thus we conducted a sensitivity analysis in Section 4.3.

Fig. 5 shows that the 50AB in-situ commercial T-shirt causes lower environmental impacts than all other configurations. The 100AB sol-gel commercial T-shirt performs worse in all environmental impacts compared to other configurations, including the

Table 3
Silver loss in gate to gate processing steps, from fibre finishing until fabric dyeing, of antibacterial T-shirts.

	100AB, in-situ	50AB, in-situ	100AB, sol-gel
Input silver (g)	100	50	35.4
Input fibre (kg)	100	50	100
Silver loss			
Fibre finishing (g)	42.3	21.1	23.1
Dyeing (g)	19.7	7.7	1.4
Total loss (g)	62	29	24.5
Efficiency of coating, %	38	42	31
Loss per T-shirt (g)	0.15	0.07	0.06

conventional modal T-shirt. Eutrophication and fossil fuel depletion are the most significant impact categories in the life cycle of the T-shirt. Natural land transformation is another significant impact which arises from the use of vegetable oil, palm kernel oil produced in Malaysia, for the production of detergents. Contribution of Modal fibre production, from wood, to natural land transformation impact is low, around 15%. With fewer washing cycles, the in-situ commercial T-shirts cause lower impacts in this category than other T-shirts. These insights would be valuable for supporting business decisions of innovation team and concentrating efforts to optimize the product to improve environmental performance (Section 4.6).

4. Discussion

4.1. Resource efficiency of antibacterial T-shirts

We have calculated the loss of silver in the gate to gate processing steps, from fibre finishing until fabric dyeing, of the antibacterial T-shirt configurations. Table 3 shows that the efficiency of coating for the 50AB in-situ T-shirt is 42%, which is better than for other configurations. It also shows that there is a significant silver loss in the finishing and dyeing stages. The in-situ finishing process should improve fastness of silver to fibres, which will reduce loss of silver, reduce costs and reduce the environmental impacts of T-shirt production. In the case of the sol-gel process, silver loss is high during the finishing stage and low during the dyeing stage, also in comparison to the in-situ process. There is no recovery of lost silver in this study.

Fig. 6 shows the silver content of each T-shirt after finishing, dyeing and washing. It has been found that the 100AB sol-gel T-shirt has a lower silver content than all other configurations and that the antibacterial property does not last for more than 4 washing cycles. The 50AB in-situ T-shirt has a lower silver content at the final product level than the 100AB in-situ T-shirt and the alternative technology FSP based NanoAg polyester T-shirt. However, the advantage of the in-situ T-shirts is the lower loss of silver during the use phase washing cycles. Silver emissions from consumer use are more difficult to recover than from the T-shirt production because emissions during consumer use are dispersed and difficult to recover as opposed to in the manufacturing stage, during which

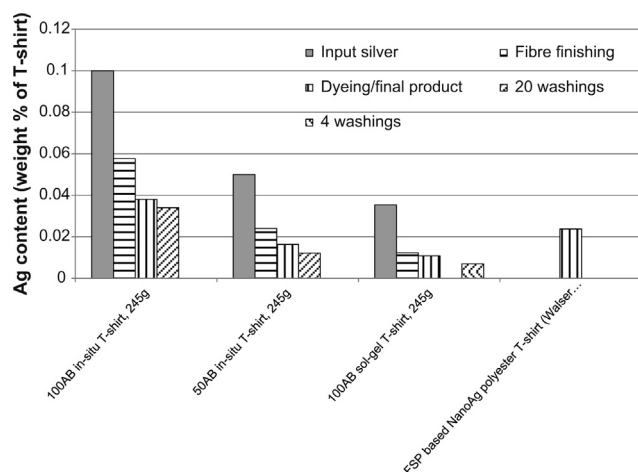


Fig. 6. Comparison of nano silver content in different T-shirt configurations and for different positions in the life cycle stages.

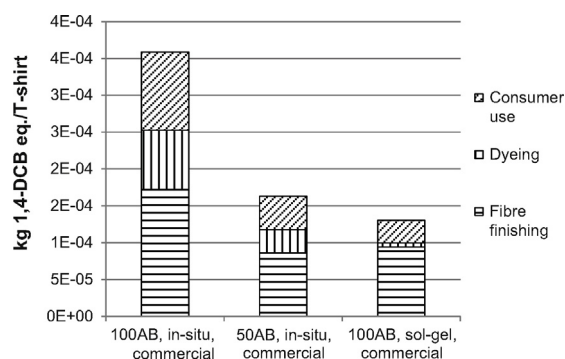


Fig. 7. Freshwater toxicity impact of silver emissions from T-shirt configurations (characterization factor calculated with the USES-LCA method (Walser et al., 2011)).

better wastewater treatment technologies can be employed (Kiser et al., 2009; Westerhoff et al., 2011).

4.2. Freshwater toxicity impact of T-shirts

We assess only the dissolved fraction of silver releases from WWTP, which was considered as bioavailable, using the characterization factors provided by Walser et al. (2011) with the USES-LCA model. Although this model does not directly address nanosilver, it was found (Walser et al., 2011) that the characterization factors calculated by this model for dissolved silver are in the same range as nanosilver reported by Gottschalk et al. (2010). The calculation of the freshwater toxicity impact is described in Appendix A. As shown in Fig. 7, the most significant impact of freshwater toxicity from silver emissions during the life cycle of a T-shirt occurs during the fibre finishing stage. Fig. 8 shows that the freshwater toxicity impact of T-shirt production, washing and tumbling, resulting primarily from their energy use related fossil energy production activities such as lignite mining waste, is most significant in the whole life cycle of a T-shirt; In contrast, the impacts of silver emissions, shown as life cycle silver emissions, are insignificant. The silver emissions impact is lower because the chances for bioavailable silver formation are rather low in natural waters due to the formation of sulphide complexes (Nowack, 2010). The pattern of these results also agree with Walser et al. (2011). For the 50AB in-situ commercial T-shirt, the T-shirt production impact is similar to the impacts of washing and of tumble drying. The freshwater toxicity impacts of modal fibre production are negligible due to lower fossil energy use during this bio-based fibre production.

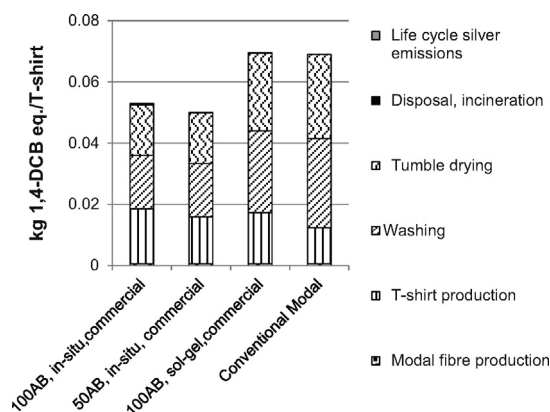


Fig. 8. Cradle-to-grave freshwater toxicity impact of T-shirts calculated with the USES-LCA toxicity impact assessment method as applied in ReCiPe (v1.05, July 2010).

It was found that the formation of dissolved silver is influenced by water chemistry (Jin et al., 2010). According to Lorenz et al. (2012), the release of silver from the textiles does not only depend on the form and amount of silver in the fabric but also on the washing medium used. For example, in some washing powders bleaching agents can rapidly oxidize the nano silver and cause rapid release of dissolved Ag^+ (Geranio et al., 2009). Further research needs to be conducted to understand different aspects of freshwater toxicity, including the behaviour of the in-situ T-shirt under different washing conditions, the type of silver released to wastewater in processes such as fibre finishing, dyeing and washing, and the occurrence of agglomeration and their environmental fate further downstream.

4.3. Sensitivity of results to use phase assumptions

The impacts during the use phase depend on many factors. One of the important parameters is the number of uses between washing cycles, which depends e.g. on the washing behaviour of individuals, the awareness of the T-shirt's antibacterial qualities, the type of weather, the user's occupational activity (if used at work). As reference we assume the antibacterial activity of the in-situ T-shirt to last for 20 washing cycles case (see Section 3.2). Table 4 shows the use phase parameters that are most important for conducting a sensitivity analysis. Life-time or total number of washing cycles is a function of the number of uses between washes and the durability of the antibacterial property. Hence, if one of these parameters is varied, then the other is taken from the reference case to calculate the total number of washing cycles, shown in brackets for each parameter. For example, if the T-shirt is used for three times before it is washed, then the durability is taken from reference as 20 washing cycles, thus making the total number of washing cycles 40 per FU ($20 \times 3 + 20 \times 2 = 100$ days of T-shirt use; 3 uses between washes for the first 20 washing cycles with antibacterial properties and 2 uses between washes after that when the antibacterial properties are lost, and the T-shirt is therefore the same as a conventional T-shirt).

Fig. 9 shows washing load as the most significant parameter influencing climate change impacts, followed by the number of uses between washes, tumble drying frequency, washing temperature and durability of the antibacterial property of the T-shirt. It is important to communicate to consumers that they can significantly reduce the cost and environmental impacts of washing by using their washing machine at the proper washing load and by wearing the antibacterial T-shirt more often between washes, which need not affect hygiene or other consumer criteria. These recommendations are also in line with the improvements suggested by

Table 4
Parameters of sensitivity analysis for the functional unit, 100 days of T-shirt use.

	A	B	C (reference)	D	E
Uses between washes (corresponding life-time or total washing cycles)	2 (50)	3 (40)	4 (30)	5 (20)	
Durability of anti-bacterial property of T-shirt, in washing cycles (corresponding lifetime or total washing cycles)	10 (40)	15 (35)	20 (30)	25 (25)	
Washing load, T-shirts/washing cycle	6	9	12	15	18
Tumble drying frequency in T-shirt lifetime	25	20	15	10	5
Washing temperature (°C)	60		40	30	20

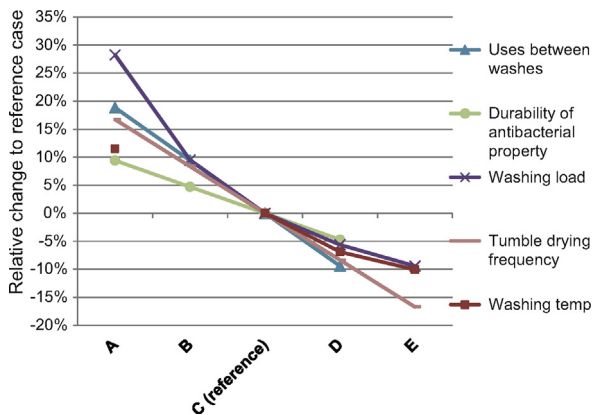


Fig. 9. Sensitivity of important parameters on the 50AB in-situ commercial T-shirt cradle-to-grave CO₂ emissions in kg CO₂-eq./T-shirt compared to the reference case.

IMPRO (2014). If the number of uses between washes is high, this can reduce the number of lifetime or total washing cycles and may also lead to reduced tumble drying cycles. Reducing the number of tumbling cycles or by totally avoiding them, CO₂ emissions can be further reduced.

4.4. Other possible scenarios to fulfil the functional unit

In the current model, we assumed that the antibacterial property of the in-situ T-shirt lasts for 20 washing cycles, after which its use will be continued as a conventional modal T-shirt. Therefore, this T-shirt needs 30 washing cycles to satisfy the functional unit (20 × 4 + 10 × 2 = 100 days of use). In order to fulfil the FU, we can replace the T-shirt after 20 washing cycles (i.e. 80 days of use) with a new T-shirt with antibacterial properties. In this case, we need to account for only one quarter of impacts of the production of the new T-shirt; in other words we need 1.25 T-shirts to meet the FU. Hence, the total number of washing cycles required for 100 days of T-shirt use is 25. We calculated the carbon footprint of this configuration with the original modelling approach and found that there is no change in overall emissions. This is due to the fact that the benefits of avoiding 5 washing cycles (and associated tumble drying cycles) is almost equal to 25% of the impacts of the production of the T-shirt.

However, it is possible that the antibacterial properties of the T-shirt last for 25 washing cycles as opposed to 20 washing cycles, since the silver loss decreases somewhat less quickly and then levels off after 10 washing cycles. This depends on the severity of use and the washing conditions applied by the consumer. If the antibacterial properties last for 25 washing cycles, the cradle-to-grave CO₂ emissions of the 50AB in-situ T-shirt will be around 28%

lower and the other impacts will also be substantially lower than for the conventional modal T-shirt.

We also modelled the possibility of using spun-dyed fibre for antibacterial in-situ finishing, so that conventional fabric dyeing could be avoided (Terinte et al., 2014). This simple process modification can lead to a reduction of around 30% in cradle-to-grave CO₂ emissions (with the actual durability of the antibacterial property assumption of 20 washing cycles) compared to conventional modal T-shirts. However, it should be noted that the technical feasibility of applying in-situ finishing on spun-dyed fibres has not yet been demonstrated.

Note that a commercial scale was assumed with maximum possible efficiencies i.e. as best practice commercial scale. In reality, many textile companies does not operate with best practice levels due to inefficiencies.

4.5. Management of textile waste with silver NP

Textile waste containing silver NP is generated from the fibre-finishing until the garment-manufacturing stages. Presently there is no standard procedure to deal with this type of waste in all the steps involved. Hence these silver-NP-coated pre-consumer or industrial waste fractions are mixed with other conventional textile waste in different process steps. Post-consumer textile waste, i.e. at the T-shirt's end of life, will be mixed with different other textile waste fractions from households. With increasing quantities of antibacterial clothing, it may be necessary to set up a separate collection system at textile production hubs and find secondary uses and recycling options for this type of pre-consumer textile waste.

Fig. 8 shows that the silver NP emissions have only a negligible contribution to aquatic toxicity. The municipal solid waste incinerators are the eventual end-point for the pre-consumer waste containing silver NP, the post-consumer waste with the remainder of silver NP in the T-shirt, and the sludge from wastewater treatment plants (WWTP) containing silver NPs from upstream processes and washing. The melting temperature of silver is 700 °C, which is lower than the temperature of the incinerator (950–1200 °C in various zones of the incinerator). Therefore, it is likely that the silver will oxidize into AgO, and it is possible that secondary silver nano-objects will be formed due to interaction with various other chemicals present in the incinerator (Walser et al., 2012; Roes et al., 2012). However, it was found that incinerators can avoid air emissions of NPs in waste products, if they are equipped with state-of-the-art flue gas cleaning equipment (wet scrubbers and electrostatic precipitators)(Walser et al., 2012). In order to avoid potential impacts from products containing NP, companies need to adopt the following design strategies (Manda and Patel, 2012):

1. Reduce the waste of NP during its formation and application on the product in order to improve resource efficiency.

2. Limit the concentration of NP in the product such that it is just sufficient to satisfy the function i.e. required number of washing cycles.
3. Avoid textile waste at all manufacturing steps as much as possible.
4. Design products with the end of life in mind, such as products that release large particles or agglomerates that are easy to recover and reuse.
5. Devise strategies to safely recover and recycle NPs or nano-objects in similar or different products.

4.6. Supporting business decisions with LCA

The LCA presented here was conducted for a yarn producer who considered to venture into the specialty yarns market with antibacterial yarns. In order to successfully launch the product in the market, the producer needs to carry out several improvements in the design of the product to establish a good balance between functionality, cost, risks and environmental impacts. From the environmental impact perspective, this LCA has been used to guide business decisions in the innovation, business development, procurement and marketing departments of the yarn producer to create value for business.

The innovation and business development department has used the results shown in Figs. 2–5 to understand how the different configurations influence functionality, impacts of the product use phase and the overall impacts of the product. The department selected the in-situ finishing process because it has a better functionality, durability, environmental performance and avoids extra heat treatment steps in the dyeing mill, thus saving costs. Another advantage of the in-situ process is that the yarn producer is not dependent on only a few suppliers, which is the case with the sol-gel-based patented materials. Because the 50AB in-situ T-shirt performs better than other product configurations, the innovation and business development department intends to further optimize the percentage of fibres with silver in the T-shirt matrix. In the future, it may be possible to avoid conventional dyeing by directly using spun-dyed fibres of the intended colour in the fibre finishing stage to impart antibacterial properties. This would substantially reduce the costs, risks and impacts of the antibacterial T-shirt (Section 4.4). Terinte et al. (2014) provide a more elaborate discussion of the environmental performance of spun-dyed fibres.

The supply chain/procurement department obtained insights into the hot spots in the product manufacturing stage to improve the environmental performance of the product that can save costs, reduce risks, and conserve resources. These insights will be very useful for selecting suppliers in the future when the product is part of regular portfolio. It becomes clear from Figs. 2 and 3 that fibre finishing and dyeing are the steps in the product manufacturing phase which have the greatest impact. Fig. 10 shows that the waste produced further downstream (e.g. after dyeing) causes substantially higher environmental impacts of the final product compared to the waste produced in the upstream, such as spinning and knitting. This higher environmental impact is due to the cumulative resource addition in each process step which requires energy and other resources. Additionally, labour and capital costs are also ill-spent. Additionally, all these aspects can increase the cost to the company and consequently to the product costs. Thus, LCA shows the opportunities throughout the value chain to reduce environmental impacts as well as process steps that need to be given more focus than other steps. The procurement department can communicate these results to their supply chain partners to further fine-tune the processes. In some cases, it is possible that the speciality fibre producer can directly convey these insights to brands and retailers who can influence textile value chains. Brands and retailing companies have little data on textile supply chains

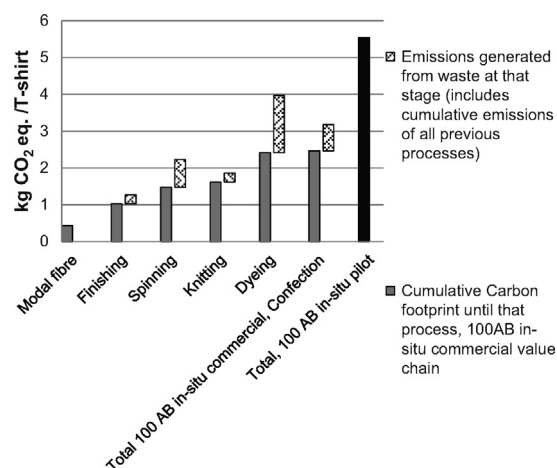


Fig. 10. Waste generation and inefficiency in different process steps and their impact on the final product's CO₂ footprint at pilot and commercial scale.

and processes. Thus, the results and insights of this LCA are useful to the procurement/supply chain and sustainability teams of apparel brands and retailers for engaging their suppliers in improving performance and also selecting their supply chain partners.

The marketing department can use the results, such as the environmental performance, functionality and durability of the in-situ antibacterial T-shirt with respect to other alternative technologies available in the market, from this study to communicate to their end-customers such as brands and retailers. This product differentiation can create a competitive advantage and help increase market share of the new product. Currently many retailers and brands have sustainability targets. This LCA study can help convince prospective customers by showing the ecological advantages of this technology as well as the contribution of this product in reducing the environmental footprint of the product portfolios of brands and retailers and thus in meeting their corporate sustainability targets.

By using life cycle assessment as a decision support tool, various business functions can create business value from insights provided by LCA. First, the LCA-based insights make it easier to find hot spots in the product value chain to focus investment and other resources to further optimize the product. Second, they enable transparent communication of the environmental performance of the product in business to business transactions, thus building the reputation of the product and enabling a differentiation in the market which creates a competitive advantage. Consequently, third, they can lead to a reduction in costs and business risks. LCA can help brands and retailers to measure their end product performance and reach their sustainability targets. LCA studies can also be used to engage members in the value chain by raising awareness and improving the environmental performance of processes that reduce costs.

5. Conclusions

This article contributes to the scientific understanding of the life cycle environmental impacts of antibacterial clothing by the application of liquid phase nanoparticle synthesis techniques to bio-based modal fibres. 50 AB in-situ commercial scale T-shirt (50% antibacterial fibres in the T-shirt matrix) has lower impacts than all other configurations and, especially, lower impacts than 50 AB sol-gel commercial T-shirt due to lower number of heat treatment steps required in dyeing. Fibre finishing, dyeing and consumer use are the most impact causing steps in the life cycle of the antibacterial T-shirt. Consumer use phase, washing and tumbling, has the highest impacts in the antibacterial T-shirt life cycle, however, antibacterial T-shirt has 20% lower climate change impacts than

conventional non-antibacterial T-shirts. A sensitivity analysis of consumer use phase showed that washing load as the most significant parameter, followed by the number of uses between washes, tumble drying frequency, washing temperature and durability of the antibacterial property of the T-shirt.

This LCA contributes to the understanding of industry in terms of key areas for improvement such as dyeing, fibre finishing, share of antibacterial fibres in the T-shirt matrix, silver fastness which can further improve resource efficiency and reduce environmental impacts. To reduce consumer use phase impacts, proper information about antibacterial textiles and washing aspects should be communicated to the consumers.

Furthermore, this article contributes to the application of LCA in corporate sustainability. Throughout this collaborative work with industry and research partners we displayed how business value can be created by using LCA-based insights during the product development process through the involvement of various business functions such as innovation, marketing and procurement. The value creation opportunities found are as follows. First, the LCA-based insights make it easier to find hot spots in the product value chain to focus investment and other resources to further optimize the product; Second, they enhance transparent communication of the environmental performance of the product, thus building the reputation of the product and enabling a differentiation in the market which creates a competitive advantage; Consequently, third, the product level improvements can lead to a reduction in costs and business risks through resource conservation and lower impacts.

Further research needs to be conducted to understand the toxicity impacts of the T-shirt throughout its life cycle by considering the influence of water chemistry on different forms of silver emissions and their environmental fate further downstream. The technical feasibility of using spun-dyed fibres to produce the 50AB in-situ T-shirt should be further explored to totally avoid conventional dyeing and the associated impacts. To improve the application of LCA in business, research should be conducted to understand the support it can provide to different business functions and different ways to connect LCA studies with value creation opportunities.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.resconrec.2015.07.010>

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