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Linear, reuse or recycling? An environmental comparison of different life cycle options for cotton roller towels

Kiia M. Mölsä [a,*], Susanna Horn [a], Helena Dahlbo [a], Marja Rissanen [b]

[a] Finnish Environment Institute, Latokartanonkaari 11, 00790, Helsinki, Finland
[b] Tampere University of Applied Sciences, Kuntokatu 3, 33520, Tampere, Finland

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ABSTRACT

The environmental impacts of current, predominantly linear, life cycles of textiles are widespread and substantial. Although applying circular economy (CE) approaches offers the potential to support the transition to more sustainable textile value chains, there is a lack of empirical evidence supporting the choice of individual CE strategies for different types of textiles. The aim of this paper is to study and compare the environmental impacts of introducing different CE strategies (reuse, recycle) into the life cycle of cotton roller towels in terms of climate change impact and water consumption. According to the results, a linear life cycle of a cotton roller towel causes a climate change impact of 12.4 g CO2e/hand-drying and water consumption of 2.4 l/hand-drying. Combining different CE strategies (reuse and recycling), the roller towel's impacts could be reduced to as low as 8.9 g CO2e and 0.5 l water/hand-drying. The results indicate that the key to reducing the climate change impacts and water consumption of the towel is the increase of use times of the product, but the impacts are more ambiguous for recycling. The benefits of recycling, and even the prioritization between different CE strategies depends on the type of recycling technology and substituted material. For gaining clearer benefits from CE of cotton roller towels or any cotton textiles, there is a further need for technology development and support for selecting the correct strategies and processes.

1. Introduction

The high-volume textile market with its resource intensive value chains creates widespread and substantial environmental impacts (Manshoven et al., 2019). The textile industry is estimated to produce 8–10% of the global CO2-eq. emissions (United Nations Climate Change, 2018) and is also a major consumer of water. It contributes to oceanic primary microplastic pollution, produces vast quantities of textile waste (Niinimäki et al., 2020), and uses significant amounts of hazardous chemicals (Chequer et al., 2013).

Current textile life cycles still operate in a predominantly linear "take-make-dispose" way (Ellen MacArthur Foundation, 2013), in which the raw material is cultivated or extracted, the fiber is spun into yarn, the yarn is woven or knitted into fabric and the product is manufactured. It is then used by the consumer and discarded to either landfill or incineration. Globally, 73% of waste textiles are landfilled or incinerated, while only 12% are recycled – mainly into low-value products. Textile products are also often underutilized and they are discarded before the actual technical lifetime has ended (Niinimäki et al., 2020; EEA, 2021a). Due to the increasing use of textiles, the short life cycles of textile products and the relatively small recycling rate of textile fibers, traditional fibers cannot meet the increased demand for fiber (Muthu and Gardetti, 2020; Ellen MacArthur Foundation, 2017).

Circular economy (CE) is "a regenerative system in which resource input and waste, emission, and energy leakage are minimized by slowing, closing, and narrowing material and energy loops" (Geissdoerfer et al., 2017). Different CE strategies comprise refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover (Potting et al., 2017). By focusing on these strategies, there is potential to support the transition from current linear practices to more sustainable textile value chains (Bhamra et al., 2018), noting that prevention of waste should be accompanied with increasing resource efficiency in production and consumption. This transition requires an understanding of the underlying system, its material flows, circularity challenges and related environmental impacts.

Even though there is a strong push towards CE practices, there is a lack of empirical evidence supporting the choice of CE strategies for different types of textiles. Often, all CE approaches are considered

* Corresponding author.
E-mail address: kiia.molsa@syke.fi (K.M. Mölsä).

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equally beneficial, regardless of what the solutions are in practice. Recycling processes as well as other CE solutions also cause environmental impacts, even though they are generally viewed as a sustainable option without further quantification of their benefits. The environmental benefits vary between the different CE alternatives (Potting et al., 2017), and ultimately the choice of the CE strategy should be based on knowledge of the potential benefits of each option even though such information is seldom available. For example, though textile reuse is viewed as more environmentally friendly than textile recycling (Sandin and Peters, 2018), textiles cannot be reused endlessly, and at a certain point recycling may prove to be the only option. Also, the environmental benefits of recycling originate from the assumption that recycled materials substitute virgin ones. The speculative nature of substitution, i.e., what products or materials are assumed to be substituted, has gained little attention in scientific literature and requires further research (Sandin and Peters, 2018). The complexity of assessing the environmental benefits of CE strategies is further amplified by the variety of environmental impacts arising from the different options and possible tradeoffs between impacts. Currently, climate change impacts are often emphasized over other environmental aspects (Zamani et al., 2014; Levänen et al., 2021).

While different stakeholders, such as policymakers, companies and consumers, seem to be aware of CE and support the transition towards it, the concrete CE measures and their impacts and benefits are difficult to assess on a quantitative basis. Hence, this study explores an analytical scenario approach for assessing individual CE strategies and their prioritization in terms of how much environmental benefits can be achieved by implementing them. The aim of this paper is to study the environmental benefits of introducing different CE strategies into the life cycle of (monomaterial) cotton roller towels by utilizing the life cycle assessment (LCA) method. The research questions are: 1) What are the environmental impacts (climate change impact and water consumption) and benefits of selected CE options applied to a cotton roller towel and how do these options compare with each other? 2) How do the different assumptions used for substitution in the LCA affect the overall environmental impacts of the CE strategies? The selected CE options are reuse and recycle as they are the most viable ones for the roller towel operator participating in the study.

The present study focuses on cotton roller towels used in public spaces, which is topical due to the increasing demand for hand dryers and tissue products – a consequence of the rising hygiene standards and growing public awareness, accelerated by the COVID-19 pandemic (Joseph et al., 2015). Such usage puts an increasingly heavy strain on the environment, as it requires more hygiene materials and chemicals.

2. Literature background

2.1. Environmental impacts of textile materials and hand drying

Taking a closer look at the environmental concerns of various textile materials, several unique problems arise. As a natural cellulose fiber, cotton is a renewable raw material, but its cultivation causes many environmental concerns. In processing cotton, substantial amounts of irrigation water are required (Chapagain et al., 2006) and due to cotton being susceptible to various pests and plant diseases, pesticides and insecticides are used intensively (Indhu Kavi et al., 2018). Cotton can be replaced with man-made fibers, such as synthetic or man-made cellulosic fibers (MMCFs). The raw materials for the synthetic textile fibers are non-renewable crude oil distillation products, which are non-biodegradable and often associated with microplastic debris further along the life cycles (Sillanpää and Sainio, 2017). Viscose technology, the main production method of MMCFs, causes environmental pollution through the use of highly toxic chemicals (Paunonen et al., 2019; Sayyed et al., 2019). Alternatives to viscose produced with conventional technology, either commercially available MMCF fibers or fibers still under development, are NMMO (N-methylmorpholine N-oxide)-based lyocell fiber, ionic liquid -based lyocell fiber (trade name Ioncell), urea-treated cellulose carbamate (CCA), and enzymatically pre-treated Biocelsol, all of which are considered more environmentally friendly (Shen et al., 2010; Paunonen et al., 2019).

The review by Munasinghe et al. (2021) found that the most damaging life cycle stages in various textile chains are the raw material extraction, dyeing and use phases of a textile product. In their study, Levänen et al. (2021) compared selected CE approaches of jeans (cotton) and concluded that increasing the lifespan of a textile product benefits the environment most. The fact that textiles are most often discarded before the end of the technical lifespan (EEA, 2021b), underlines the importance of this conclusion.

Different hand-drying methods have also been studied using LCA, mostly from the climate change impact perspective by comparing electric drying, disposable paper towels and roller towels (e.g., Gregory et al., 2013; Joseph et al., 2015). These studies have indicated electric dryers to have the lowest climate change impact, depending heavily on the used electricity mix. Electric hand dryers were not conclusively the preferred method due to the lack of acceptance by consumers (Carvalho and Abrahao, 2017) and potentially higher risks of virus contamination (Reynolds et al., 2020). A study by WIRTEX and ETSA (2016) compared cotton roller towels with paper towels and concluded that roller towels are, in general, better for the environment. In terms of water-related studies, Eberle and Möller (2006) calculated paper towels to consume less water during their life cycle than cotton roller towels. Due to the lack of studies including the water consumption of other hand-drying methods, conclusions cannot be drawn on the best hand-drying option from the water perspective.

2.2. Solutions for reuse and recycling of textiles

The traditional, linear model of textile production and consumption is based on virgin raw materials, including no significant repairs and discarding the fabric into landfills or by incineration. There are different options for improving the circularity of textile production and consumption, the most predominant being reuse and recycling. Textile reuse refers to prolonging the service life of textile products (Fortuna and Diyamandoglu, 2017), with or without prior modification, such as dyeing or mending. This means that overall consumption of products can be reduced as primary products may be substituted with reused ones. Different forms of reuse include collaborative consumption, product-service systems, commercial sharing systems and access-based consumption (Belk, 2014).

Textile recycling refers to the reprocessing of pre- or post-consumer textile waste for use in new textile or non-textile products (Sandin and Peters, 2018). Hence, even though a product does not have a long life cycle, the material value can still be maintained by investing additional energy, chemicals and labor (Keβler et al., 2021). The textile material recycling routes are typically classified as mechanical, chemical, thermal, or a mix of these. Depending on the route, the quality and strength properties and thus the technical lifetime of the fiber and applications vary. Though mechanical recycling, i.e., the shredding of textile material back into fiber form, is currently the most common way of recycling textile material, this process lowers the fiber quality by shortening the fiber staple length (Ütebay et al., 2019). Also, a considerable amount of virgin fibres is needed to produce a new textile product of mechanically recycled fibres (Keβler et al., 2021). In contrast, chemical recycling can allow the production of MMCFs out of recycled material while maintaining, or even increasing the fiber properties (Haule et al., 2016). Chemical recycling includes pretreatment, the dissolving of cellulosic material and regeneration. Cotton textile waste is an arising alternative to the raw material of MMCFs. Monomaterial products, such as cotton roll towels, are typically easier to recycle than more complex multimaterials (Stahel, 2013), and e.g. zippers, buttons, fibre blends, chemical additives and contaminations cause significant obstacles for recycling.

Sandin and Peters (2018) reviewed 41 studies related to textile reuse and recycling and concluded that there was a strong focus on recycling, instead of reuse. The findings also indicated that both textile recycling and reuse reduce environmental impacts compared to incineration or landfilling, with some restrictions, e.g. if the substituted production through recycling is relatively clean, or if high additional transports are linked with the reuse options.

2.3. *Prioritization of CE strategies*

The EU's Waste Framework Directive (Directive, 2008/98/EC) has set out a waste hierarchy, according to which preventing waste is the preferred option, and incinerating (or landfill) should be the last resort. Potting et al. (2017) have stated that there is a prioritization between the more specific CE strategies: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover (the last of which hardly meets the general understanding of CE, as the material is ultimately disposed of).

Reviewing textile reuse and recycling studies, Sandin and Peters (2018), concluded that both reduce environmental impacts compared to incineration and landfilling, adding that reuse is more beneficial than recycling. Also, Levänen et al. (2021) showed that extending the garments' use time leads to the lowest climate change impacts, determining that clothes and other textiles should be kept in use for as long as possible. Reuse can be achieved with no or only minor modifications to the product, in which case the further environmental impact of reuse may be relatively low (Keβler et al., 2021). The relative environmental impact from reuse of a textile is product dependent as life cycle lengths and use times between different products can vary significantly.

The quantitative impacts or benefits of each CE strategy need to be studied case-by-case. Textiles can only be reused up to a certain point and many of the CE strategies are restrained by entropy and material complexity (Stahel, 2013) as well as the point until which the materials may be recycled due to quality losses (Ghisellini et al., 2016). As opposed to recycling, reuse and repair may also have a local or regional dimension in which the economies of scale determine the most efficient solution (Ghisellini et al., 2016). Fig. 1 depicts the various CE strategies along the textile value chain in line with Sandin and Peters (2018), highlighting in darker colors the more preferred strategies, as discussed by Potting et al. (2017). The various CE practices can also be used in sequence and combination, in which case they can generate cumulative environmental benefits, and thus reduce the environmental impacts of textile products.

When assessing and choosing the environmentally best CE strategy, the key factors are connected to the rate of replacement with which the recycled or reused fibers are assumed to avoid primary production, and the type of production assumed to be replaced. The estimation of substitution impacts is often ambiguous and based on speculations about what the substituted material is. Substitution of environmentally intensive primary materials can be a considerable benefit and thus should not be neglected.

3. Methods and data

In this study, the LCA method is used to compile and evaluate the inputs, outputs and potential environmental impacts of our product system throughout its life cycle (ISO 14040, 2006). The comprehensive scope of LCA is useful to avoid problem-shifting between life cycle phases, regions or environmental problems (Finnveden et al., 2009), and allows actors to compare and optimize the environmental performance of their products (Hellweg and Milà i Canals, 2014). The methodology of LCA can be described by four interrelated phases: 1) goal and scope definition; 2) life cycle inventory (LCI); 3) life cycle impact assessment (LCIA); and 4) interpretation and reporting.

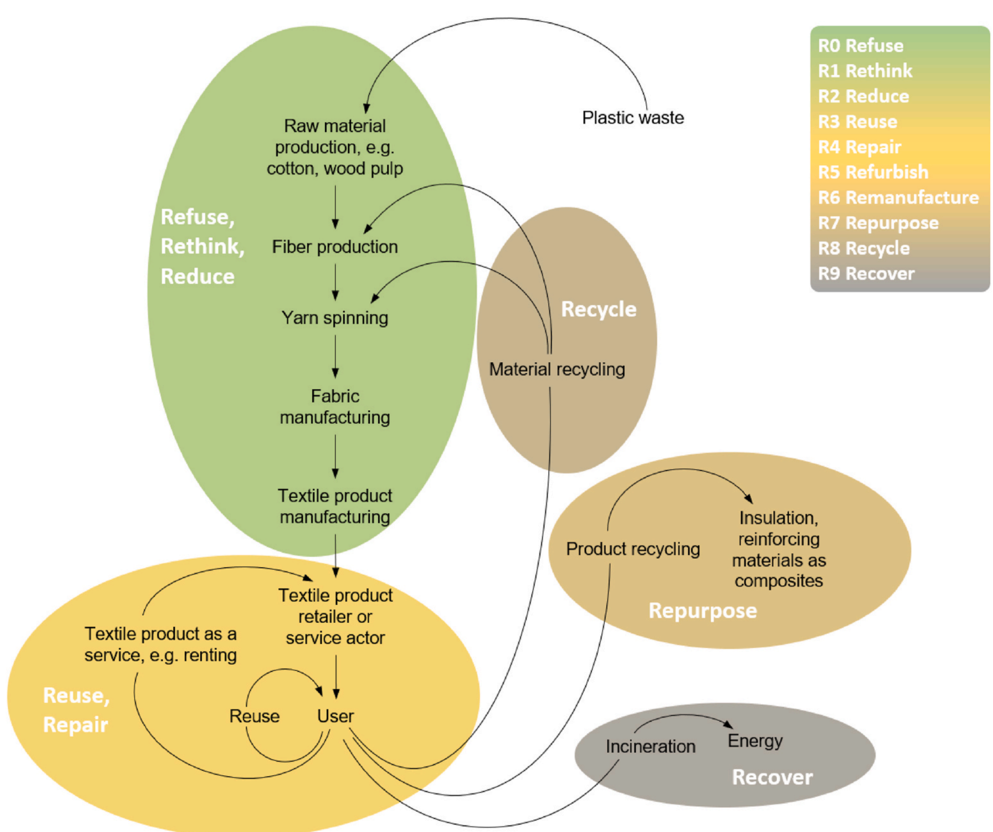


Fig. 1. Textile circular economy strategies. Modified from Sandin and Peters (2018) and Potting et al. (2017).

3.1. Goal and scope

The goal of this LCA study is to assess the selected environmental impacts of a roller towel during its life cycle. The study will 1) assess the climate change impact and water consumption of a roller towel during its full life cycle and compare selected CE strategies with a scenario approach, and 2) assess the impact of various substitution assumptions on the environmental performance of the roller towel. The results may be utilized by decision-makers when choosing between different CE strategies for roller towels and provide information for decision making concerning other fully cotton-based textile products.

The life cycle of a new, white towel roll starts from its manufacture from cotton in southern Asia with conventional methods. The rolls are then shipped to Finland for hand-drying in public restrooms. Modern roller towel dispensers are equipped with sensors that recognize when the towel runs out and needs to be changed. This allows for the use of the towel for its full length before replacing it and sending it to be washed. To secure towel sufficiency in dispensers without sensors, towels are often changed prematurely.

Ideally, a roller towel can be used for 100 wash cycles, each lasting for around 105 pulls (total of 10 500 uses) until the fabric wears out. Often, the towel gets stained already before the 100 washes (typically, and in certain uses, during the first 40–60 washes) and cannot reach its maximum lifetime. At this point, the roller towel is usually discarded and incinerated. The life cycle of these roller towels can be extended by dying them with a darker color (blue) to hide the blemishes. According to the roller towel operator, the dyed towels can be reused to reach the total 100 washes, after which the fabric is incinerated.

The roller towel operator currently uses two life cycle models for the roller towels: the linear model and the extended life cycle by reuse model. After the roller towel can no longer be used for hand-drying, it could be chemically recycled into new MMCF products, which can maintain the value of the fiber (upcycling).

To study the different scenarios available for the roller towel operator, four scenarios were distinguished for the life cycle after the towel no longer fulfills the visual standards (Fig. 2):

1. Scenario 1 (S1): Incinerating the tarnished roller towel.
2. Scenario 2 (S2): Dyeing and reusing the tarnished roller towel, and incinerating it at the end of its lifetime.
3. Scenario 3 (S3): Recycling the tarnished roller towel either as viscose (Scenario 3.1, S3.1) or as CCA (Scenario 3.2, S3.2).
4. Scenario 4 (S4): Dyeing and reusing the tarnished roller towel and recycling it at the end of its lifetime either as viscose (Scenario 4.1, S4.1) or as CCA (Scenario 4.2, S4.2).

The chosen system boundary considers the life cycle of the roller towel from cradle to grave with an extension of raw material substitution for the material recycling option and fuel substitution for the energy recovery option. Fig. 2 presents the processes included in the system boundaries of each scenario. Equipment and infrastructure, including the roller towel dispenser are excluded from the studied system. The functional unit (FU) of the assessment is defined as one hand-drying (i.e., towel pull). Substitution impacts are considered for processes connected to the end-of-life of the product, such as the energy recovery of the discarded roller towel by incineration and material recovery by recycled yarn production. No allocation procedures are used.

For reference, LCA calculations are also conducted for a situation where one towel is used for 100 washing cycles without getting tarnished. It is not treated as a separate scenario as it is not comparable to S1–S4 due to differing base assumptions. The calculation from this situation is conducted for both a towel sent to incineration, as well as a towel recycled after the use phase.

3.2. Life cycle inventory and related assumptions

Primary LCI data is available for the input and output flows of the foreground system of roller towel use, dying and transport processes. All relevant assumptions used for the LCA modelling are presented in Table 1.

The LCI data for each life cycle phase, with respective data sources for flow quantities and emission factors are presented in Tables A.1–A.8 in Appendix A.

3.3. Life cycle impact assessment

The calculations were carried out using a combination of Excel and the Ecoinvent 3.3 database. The Ecoinvent 3.3 database was used in connection with SimaPro where the climate change impact factors were calculated with the ReCiPe 2016 midpoint (H) method (RIVM, 2016). The indicator of water consumption is a simple mass balance. Calculating LCA results at midpoint means quantifying single environmental impacts whereas an endpoint calculation would aggregate those impacts to damage caused to human health, biodiversity and resource scarcity.

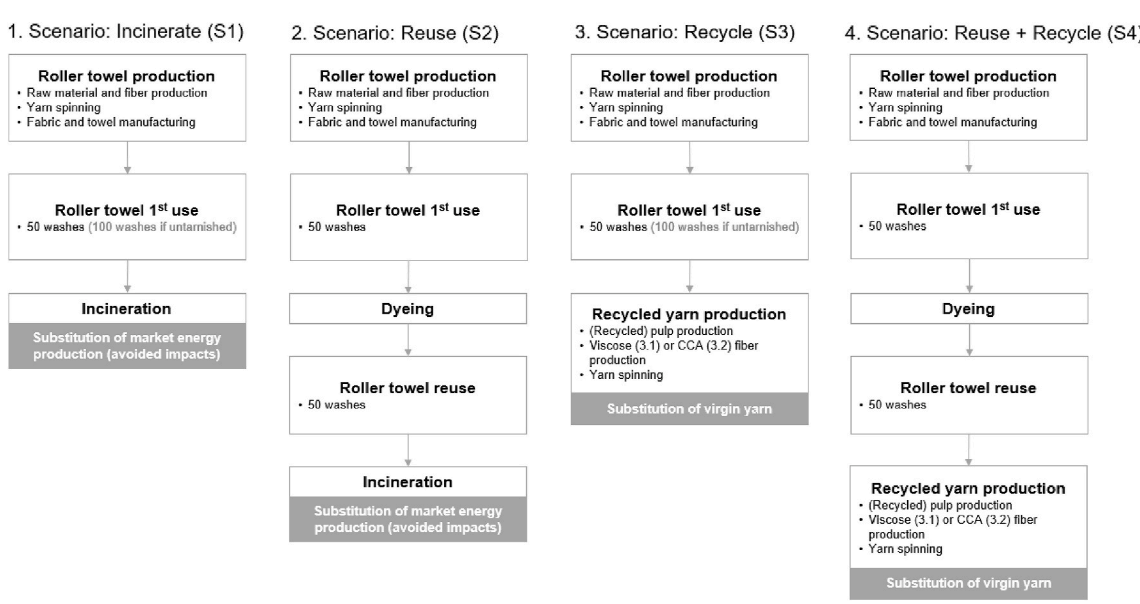


Fig. 2. Four different scenarios to be compared.

Table 1
Assumptions and limitations used in the study.

Assumptions
– Cotton for a roller towel is produced in a conventional, average process. – The lifetime of a cotton roller towel is assumed to be 50 washes (average) or 100 washes (technical maximum). One roller towel serves for an average of 105 pulls between washing cycles. During its life cycle, a towel used for 50 washing cycles offers then 5250 pulls, while a towel used for 100 washing cycles 10 500 pulls. – All life cycle stages from roller towel use onwards are operated in Finland. – Electricity and heat recovered from the towel incineration process substitute Finnish local average production. – The amount of wastewater to treatment from washing the roller towels is assumed to be the same as water consumed in washing. The wastewater is assumed to be of a similar quality to municipal wastewater. – Cotton fabric used for roller towel fixing is not included in the calculation as it is considered waste material. – Due to coherent waste material composed only of cotton, the collection and sorting stage of the recycling process are not required and thus excluded from the emission factor of climate change impact calculation. These steps, however, are not excluded from the water consumption calculation as data is only available for the entire recycling process. Water consumption is also assumed to be minor for the collection and sorting compared to the other processing steps. – The de-dyeing and bleaching steps of the cotton waste recycling process are not excluded from the calculation even if they are not required as their contribution to the results are minor compared to other processing steps. – CCA fiber is produced in a factory that is not integrated with a pulp factory but has chemical recycling. – The yarn spinning process and fiber losses are assumed to be similar for different fibers. – Produced viscose and CCA yarn substitute either viscose, cotton or organic cotton yarns manufactured from virgin materials with a replacement rate of 1:1.

When secondary data was unavailable in Ecoinvent 3.3, also literature sources are used. A sensitivity analysis was carried out for the most impactful parameters (electricity and towel manufacturing) by using different available emission factors to improve the results' robustness in comparative decision contexts (Henriksson et al., 2015).

The assessed environmental impacts were climate change impact and water consumption. Climate change impact quantifies the greenhouse gas (GHG) emissions caused by the life cycle of a product or a process and thus its contribution to global warming. Climate change impact is expressed as a carbon dioxide equivalent (CO_2e). In this study, only the GHGs of non-biogenic origin were accounted for. The impact category of water consumption refers to freshwater used that is not returned to the watershed of origin (ISO 14046, 2014). As an environmental indicator, the use of water consumption has limitations in precision and comprehensiveness and doesn't consider the geographical context (Weckström et al., 2020), but including the water perspective in textile LCA studies is important due to heavy irrigation needs of cotton crops.

The results of the LCIA and their interpretation are detailed in the following sections.

4. Results

When presenting net results for climate change impacts and water consumption, the impacts avoided by substitution are subtracted from emissions generated during the life cycle of the roller towel.

The net climate change impact of the roller towel is 12.35 g CO_2e/hand-drying if the towel is incinerated (S1) and 9.39 g CO_2e/hand-drying if the life cycle is extended by reuse (S2). Depending on the type of recycled yarn produced and virgin yarn substituted, the net climate change impact varies between 11.36 and 13.48 g CO_2e/hand-drying if the towel is recycled (S3) and between 8.89 and 9.96 g CO_2e/hand-drying if it is first reused and then recycled (S4). The detailed climate change impact results for different scenarios are presented in table B1 in appendix B. The gross climate change impact results for S1-4 are visualized in Fig. 3, also showing the numerical net results. The results obtained by using three different virgin yarn types for substitution are all presented to demonstrate the significant impact of the choice. The detailed climate change impact results for different scenarios are presented in Table B1 in Appendix B.

The most important life cycle phases contributing to climate change impact in all studied scenarios are the use and manufacture of the roller towel. The contribution of the use phase, 6.24 g CO2e/hand-drying, is the same for all scenarios, causing 43–66% of the total climate change impact. The climate change impact of the use phase is primarily caused by electricity used for washing the towel.

From towel manufacturing, the climate change impact is 5.57 g CO2e/hand-drying for towels used for 50 washing cycles (S1 and S3) and the impact is halved to 2.79 g CO2e/drying with reuse (S2 and S4) as

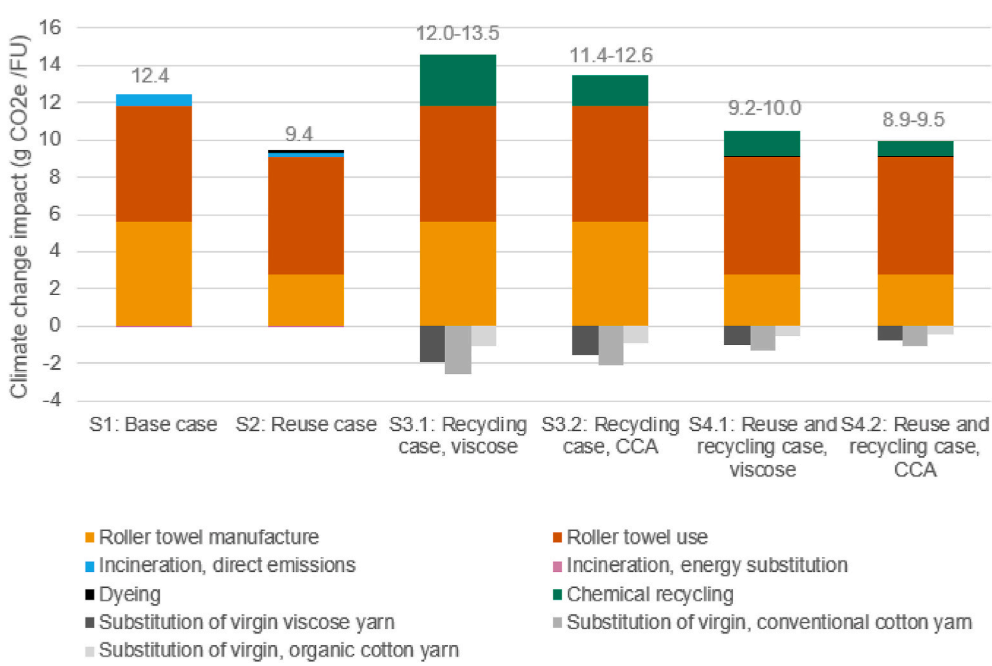


Fig. 3. Climate change impact results for scenarios 1–4. The bars below zero represent the avoided impacts through substitution. Net values are presented on top of the bars.

the number of hand dryings per towel are doubled. This is the primary reason why the reuse scenarios (S2 and S4) have the lowest climate change impacts.

Recycling the roller towel increases the climate change impact for S3 and S4. In S3, the climate change impact is even higher than in the base case (S1) as the recycling step has a higher impact than towel incineration and the number of uses remains the same. Recycling the towel into viscose generates a higher climate change impact than CCA.

The net impacts of the recycling scenarios (S3 and S4) are reduced by including the avoided emissions through substitution of virgin yarn. The avoided impacts vary depending on the yarn type substituted: most emissions are avoided if the recycled yarn replaces conventional cotton and least emissions if it replaces organic cotton. Only in S3.2 and S4.2 are more impacts avoided than caused through recycling, and only in the case where recycled CCA yarn substitutes conventional cotton yarn.

The calculated net water consumption per drying is 2.41 l for the base case (S1) and 1.28 l for the towel reused through dyeing (S2). Depending on the produced and substituted yarn type, the net water consumption varies from 0.81 to 2.44 l/hand-drying for the recycled towel (S3) and from 0.49 to 1.3 l/hand-drying for the towel first reused and then recycled (S4). The gross water consumption results for S1–S4 are shown in Fig. 4 together with total numerical net results. Detailed results for different scenarios are gathered in Table B2 in appendix B.

Roller towel manufacturing is the major water consumer, covering roughly 90% of overall consumption in all scenarios as cotton crops demand a substantial amount of irrigation. Like the climate change impact results, the water consumption of the towel manufacture per drying is also halved due to reuse, resulting in S2 and S4 having the lowest water consumption.

By substituting conventional virgin cotton yarn with recycled yarn, a notable avoidance in water consumption can be obtained. Production of virgin viscose and organic cotton consumes little water, thus their substitution effect is minor.

Differences in total net results are summarized in Table 2. The benefits of recycling vary according to the type of recycled yarn produced and virgin yarn substituted, as well as the impacts studied. The CCA-based recycling process has a lower climate change impact and water consumption than viscose-based recycling, but due to more material losses in the CCA fiber process, less emissions are avoided compared to recycled viscose. Considering climate change impact, producing recycled CCA yarn and substituting conventional cotton generates a negative net result for recycling, whereas other alternatives cause more emissions than could be avoided. In water consumption, when substituting conventional cotton with either viscose or CCA, the net impact of recycling is negative, making scenarios S3 and S4 the best in overall water consumption. When conventional cotton is substituted with the recycled material (viscose and CCA), tradeoffs emerge between the reuse and recycling scenarios: When conventional cotton is substituted in the recycling scenarios (S3.1 and S3.2), recycling becomes a more beneficial CE strategy over reuse (S2) in the case of water consumption, whereas in climate change impact the reuse scenario performs better in all situations.

The sensitivity of the climate change impact results was also studied by using alternative emission factors for the most significant variables: energy production and cotton towel manufacturing (Table B.3 in Appendix B.). Emission factors for energy production were varied for the processes with available, unaggregated energy consumption data: use, dyeing and incineration. The climate change impact of energy in use, dyeing and incineration and towel manufacture decreased, also lowering the total climate change impacts (without substitution impacts) by roughly 18% when combined. The order between different scenarios was not affected.

The results were calculated for a roller towel used for 105 hand-dryings, the full length of the towel, between washing cycles. This is often reached using sensors recognizing the optimal changing frequency. Not using these sensors may lead to fewer hand-dryings per roller towel and thus higher climate change impact and water consumption results. If the results are calculated for a towel continuously used for only 75% of its length, both the climate change impact and water consumption results of a roller towel increase by roughly 30% compared to the case where the towel is fully utilized. The environmental impact of producing and operating the towel dispenser sensor is not accounted for in the calculations.

The base assumption for defining S1–S4 is that a roller towel does not

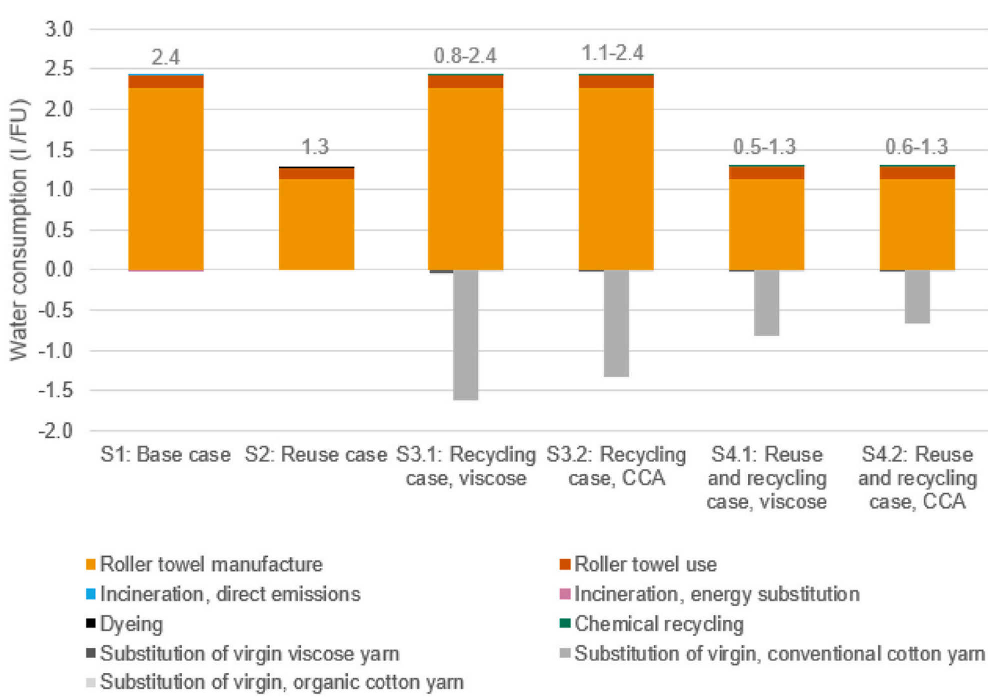
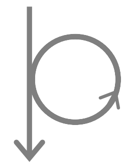
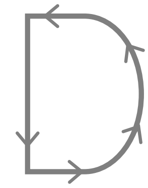
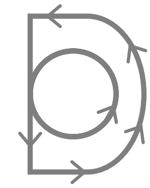


Fig. 4. Water consumption results for scenarios 1–4. The bars below zero represent the avoided impacts through substitution. Net values are presented on top of the bars.

Table 2
Net result differences to base case.

	S1 linear	S2 reuse	S3 recycling	S4 reuse + recycling
Life cycle model				
Difference in net climate change impact	Base case	−24%	−3 … +9% (viscose) −8 … +2% (CCA)	−25 … -19% (viscose) −28 … -23% (CCA)
Difference in net water consumption	Base case	−47%	−66 … +1% (viscose) −54 … 0% (CCA)	−80 … -46% (viscose) −74 … -46% (CCA)

reach its full technical lifetime of 100 washes as it gets tarnished and no longer fulfills the quality standards. Some towels reach the full 100 washing cycles without getting stained and are only then incinerated. The climate change impact in this case is 9.3 g CO_2e/hand-drying and water consumption 1.28 l/hand-drying. A towel used for 100 washing cycles can also be recycled into yarn instead of incineration. If the towel was recycled into viscose yarn, the net climate change impact would be 9.12–9.86 g CO_2e/hand-drying and water consumption 0.48–1.30 l/hand-drying, varying with the type of yarn substituted. In the case of a towel recycled into CCA yarn, the climate change impact and water consumption would be 8.80–9.41 g CO_2e and 0.63–1.29 l/hand-drying, respectively.

5. Discussion

5.1. Case specific results and uncertainty

Responding to the need to increase circularity and reduce the environmental impacts of the textile sector (Manshoven et al., 2019), this paper calculated and compared the climate change impact and water consumption of linear and CE-based roller towel life cycles. To support the use of the results for more robust decision-making (Henriksson et al., 2015), their sensitivity on assumed substitution impacts was assessed more thoroughly. The results allowed us to test Potting et al.'s (2017) prioritization between reuse and recycle as well as their combination, and provide empirical evidence required for choosing the most promising solution for implementation in the context of roller towels.

A linear cotton roller towel life cycle (S1) generates a net climate change impact of roughly 12.4 g CO_2e and water consumption of 2.4 l/hand-drying, being the worst option of almost all compared scenarios. These results are slightly higher, but in the same range with previous research in climate change impact (Gregory et al., 2013; Eberle and Möller, 2006) and water consumption (Eberle and Möller, 2006). In line with the review by Munasinghe et al. (2021), most of the environmental impacts of a roller towel arise from the manufacturing and use stages.

Compared to the linear life cycle, the effect of recycling (S3) on the climate change impact varied from −8% to +9%, and on the water consumption −66% to +1%, depending on the recycling technology and substituted yarn. Recycling performed better than the linear scenario in both impact categories, with the exception of substituting organic cotton with the recycled material. The reuse of the roller towel (S2) reduced the climate change impact by 24% being more beneficial than recycling. In water consumption, reuse was always better than the linear scenario (−47%) and mostly better than recycling, except when recycled material substituted for conventional cotton. This creates a tradeoff between the two impact categories when comparing the different scenarios.

Applying reuse and recycling simultaneously (S4) reduced the climate change impacts by 19%–28% and water consumption by 46%–80% in comparison to the linear scenario, again depending on the recycling technology and substituted product. This means that the combination scenario offers the biggest potential for reducing environmental impacts. Although the results are generally in line with Potting et al. (2017) and Levänen et al. (2021), in which reusability is favored over material recycling, the results of this study show that the prioritization is sensitive to the assumptions on substitution, recycling as well as life cycle length, as discussed below.

The assumptions on substitution caused the most result variation related to the recycling scenarios and thus to the prioritization between different scenarios. The review by Sandin and Peters (2018) found that previous studies have often assumed recycled textiles having a high replacement rate and highlighted that there is considerable uncertainty behind this assumption. The substitution potential of different products depends on the quality of fiber for specific uses, which is why viscose and CCA cannot replace cotton in all circumstances due to different fiber properties. The approach of this study can be complemented with more first-hand information on the recycling route and material substitution to reach more exact conclusions on the prioritization between different CE strategies.

Recycling processes do not seem very environmentally friendly according to the results, but recycled fibers are still required as traditional fibers cannot meet the increased fiber demand (Muthu and Gardetti, 2020; Ellen MacArthur Foundation, 2017). The environmental burden of recycling may be lowered in the future by developing the processes and making them more efficient on a large scale. Design-for-recycling could allow for more recycling opportunities as according to Stahel (2013), recycling still faces material-related restrictions. Material complexity is generally seen as a barrier to recycling (Stahel, 2013) which was not an issue in this monomaterial study. Considering a wider array of multimaterial textiles may reduce the advantages of recycling further.

The relative benefits between different CE strategies are calculated with the assumption that the life cycle length of the base case is 50 washes. This may theoretically be anything between 1 and 100 washes. If the assumed life cycle length is close to the roller towel's technical lifetime, less benefits can be gained from reuse.

The magnitude of benefits to be achieved through different CE models also depends on the textile market and consumer acceptance. If customers are not willing to absorb the modified products (such as dyed towels, recycled yarn) and their market shares remain low, then also the total benefits may remain low. Market demand may also be affected by the quality and strength of the recycled yarn, for example.

5.2. Results in a broader context and limitations of the study

This study focused on roller towels, but indirectly the results may also be reflected to other cotton products which do not reach the end of their technical life cycle. The assumption that the roller towels are often discarded prematurely due to visual discrepancies is a situation similar to other textile market segments where fast fashion trends (Niinimäki et al., 2020) or a lack of repair skills (EEA, 2021a) lead to short life cycles. Allowing a longer life cycle with various CE strategies, such as second-hand markets or textiles as a service, may also be evaluated with the proposed scenario approaches to estimate environmental benefits. Additional work to achieve a higher reusability (e.g., repairs, redesign) or to introduce new recycling processes must be accounted for.

Comparing the results to other studies assessing various hand-drying methods, the results indicate that the most efficient CE scenario (S4) has a 5% (Joseph et al., 2015) to 50% (Eberle and Möller, 2006) lower climate change impact than paper towels and 49% (Gregory et al., 2013) lower climate change impact than conventional electric dyers. The climate change impact of S4 is still 98% (Gregory et al., 2013) to 250% (Joseph et al., 2015) higher than for high-speed electric dryers. In this best-performing scenario, cotton towels cause approximately half of a paper towels' water consumption (Eberle and Möller, 2006). This means that even though cotton roller towels are able to reduce the climate change impacts they are still far from what electric hand-dryers cause. Even though these comparisons can be made from the environmental perspective, they do not consider the hygienic viewpoint. The hygienic efficiency of different hand-drying methods has been discussed during the COVID-19 pandemic and especially the hygiene level of electric dryers has been questioned (Moura et al., 2022). According to Reynolds et al. (2020), the hygiene level of hand drying with different electric dryers and paper towels varies in different studies. With these different viewpoints it is evident that decision-making cannot be based on only one sustainability aspect.

The lack of consistent data limits the findings of this study, due to which e.g. the toxic impacts caused by textile dyeing and finishing have not been considered, these deserve more attention in the future. In our study, the focus was on a monomaterial fabric, but in the case of multimaterials the results may change (Stahel, 2013). To study the implications and potential of CE in general, also the rest of the relevant CE strategies named by Potting et al. (2017) deserve comparable analytical focus as reuse and recycling here. Particularly the higher-level strategies (refuse, rethink) need a different, macro-level approach, as the implications are not visible on a product-level but rather on a system-level. Nevertheless, versatile LCA-based tools with up-to-date data will provide considerable potential to advance the field of CE-related environmental analytics and may serve as a basis for wider, system-level assessments as well.

6. Conclusion

This study responds to the societal push towards CE by considering the environmental efficiency of individual CE strategies. Moving towards a CE will require assessing common systems and their environmental impacts analytically, comparing different options and being willing to alter processes accordingly. The quantitative LCA results of cotton roller towels highlight that all CE strategies are not always equally good or even beneficial compared to linear models, even though circularity-based options are taken as environmentally favorable by default. At best, reuse and recycling used in combination can enable a decrease of 28% in climate change impact and 80% in water consumption. The results indicate that reusability is the key to reducing the climate change impact and water consumption of linear cotton life cycles (−24% and −47%, respectively), but the impacts are more ambiguous for recycling the material (−8% to +9% and −66% to +1%, respectively). The possible benefits gained from recycling vary depending on the chosen recycling technology and the type of textile product substituted. These assumptions will also affect the prioritization of the most environmentally efficient CE strategies. For increased and clear benefits from different CE strategies of cotton roller towels or any cotton textiles, there is a further need for technology development and support for selecting the correct strategies and processes.

Even though roller towels were assessed in this study, the comparative results between different CE models can be applied also to other cotton textiles, such as clothing. It is often a valid assumption that the material's technical lifetime is not reached and that there is a potential to extend the life cycle, in which case it becomes important to consider available CE strategies and their impacts, e.g. by applying the scenario approach. Studying additional environmental impacts enable a wider perspective on the sustainability of different CE strategies. The availability of more transparent, traceable and up-to-date data would offer more accurate results and thus make it easier to include these issues also in policy development.

CRediT authorship contribution statement

Kiia M. Mölsä: Conceptualization, Data curation, Formal analysis, Methodology, Investigation, Writing – original draft, Writing – review & editing, Visualization. **Susanna Horn:** Conceptualization, Data curation, Formal analysis, Methodology, Investigation, Project administration, Writing – original draft, Writing – review & editing, Visualization. **Helena Dahlbo:** Conceptualization, Writing – original draft, Writing – review & editing. **Marja Rissanen:** Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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Appendix A. Supplementary data

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