Review

Environmental impact of textile reuse and recycling — A review

Gustav Sandin [a, *], Greg M. Peters [b, c]

[a] RISE Research Institutes of Sweden, Eklandagatan 86, 412 61 Gothenburg, Sweden
[b] Chalmers University of Technology, 412 96 Gothenburg, Sweden
[c] School of Civil and Environmental Engineering, University of New South Wales, Australia

A B S T R A C T

This paper reviews studies of the environmental impact of textile reuse and recycling, to provide a summary of the current knowledge and point out areas for further research. Forty-one studies were reviewed, whereof 85% deal with recycling and 41% with reuse (27% cover both reuse and recycling). Fibre recycling is the most studied recycling type (57%), followed by polymer/oligomer recycling (37%), monomer recycling (29%), and fabric recycling (14%). Cotton (76%) and polyester (63%) are the most studied materials.

The reviewed publications provide strong support for claims that textile reuse and recycling in general reduce environmental impact compared to incineration and landfilling, and that reuse is more beneficial than recycling. The studies do, however, expose scenarios under which reuse and recycling are not beneficial for certain environmental impacts. For example, as benefits mainly arise due to the avoided production of new products, benefits may not occur in cases with low replacement rates or if the avoided production processes are relatively clean. Also, for reuse, induced customer transport may cause environmental impact that exceeds the benefits of avoided production, unless the use phase is sufficiently extended.

In terms of critical methodological assumptions, authors most often assume that textiles sent to recycling are wastes free of environmental burden, and that reused products and products made from recycled materials replace products made from virgin fibres. Examples of other content mapped in the review are: trends of publications over time, common aims and geographical scopes, commonly included and omitted impact categories, available sources of primary inventory data, knowledge gaps and future research needs. The latter include the need to study cascade systems, to explore the potential of combining various reuse and recycling routes.

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* Corresponding author.
  E-mail addresses: gustav.sandin@ri.se (G. Sandin), petersg@chalmers.se (G.M. Peters).

1. Introduction

The global demand for textile products is steadily increasing (The Fiber Year Consulting, 2015; Oerlikon, 2010), a trend likely to continue due population growth and economic development. Meanwhile, the textile industry is facing tremendous environmental and resource challenges. Sixty-three percent of textile fibres are derived from petrochemicals (Lenzing, 2017) whose production and fate give rise to considerable carbon dioxide (CO_2) emissions (Shen et al., 2010a). The remaining 37% is dominated by cotton (24%), a thirsty plant associated with water depletion − the desiccation of the Aral Sea being the most infamous example (Micklin, 2007) − and toxic pollution, due to intensive use of pesticides (FAO-ICAC, 2015). For most categories of environmental impacts, later stages in the textile production process give rise to even larger impacts (Roos et al., 2015a). Wet treatment processes (dyeing, finishing, printing, etc.) are major sources of toxic emissions (Roos et al., 2015b), and spinning of yarns and weaving/knitting of fabrics most often rely on fossil energy use, causing emissions such as CO_2 and particulates (Roos et al., 2015a). Allwood et al. (2006) suggest greenhouse emissions, water use, toxic chemicals and waste are the main environmental issues facing the textile industry. Sandin et al. (2015) estimate that, for several environmental impact categories, the impact per garment use in a western country (in this case, Sweden) must be reduced by 30−100% by 2050 if the industry is to be considered sustainable with regard to the planetary boundaries outlined by Steffen et al. (2015). Roos et al. (2016) show that such a grand transition requires a combination of different measures for impact reduction, most likely including more reuse and recycling.

Because of the aforementioned challenges, there is regulatory interest in increasing textile reuse and recycling, which would move the treatment of textile waste further up in the waste hierarchy, consistent with the EU directive on waste (European Commission (EC), 2008). Increased textile reuse and recycling could potentially reduce the production of virgin textile fibres and, in the case of reuse, also avoid engineering processes further downstream in the textile product life cycle, and thus reduce environmental impact. The potential environmental benefits of various systems of textile reuse and recycling have been assessed in the literature, using methods like life cycle assessment (LCA). To date, no review of such studies has been published in the academic literature or elsewhere, which means that there is no available comprehensive source of information on, for example, (i) what has been studied and what has not been studied (e.g. in terms of product systems and environmental issues); (ii) what the results of such studies tell us about the environmental potential of textile reuse and recycling; (iii) what methods and methodological assumptions are usually employed in such studies; (iv) whether there are general methodological challenges to resolve; and (v) what inventory data pertaining to textile reuse and recycling is available in the literature. Therefore, the aim of this paper is to review studies of the environmental impact of textile reuse and recycling, to provide a summary of the current knowledge and point out areas for further research. The intended audiences of the review are decision makers and stakeholders in the textile industry as well as practitioners and researchers involved in assessing the environmental impact of textile reuse and recycling.

1.1. A topology of textile reuse and recycling

Textile *reuse* refers to various means for prolonging the practical service life of textile products by transferring them to new owners (Fortuna and Diyamandoglu, 2017), with or without prior modification (e.g. mending). This can for example be done through renting, trading, swapping, borrowing and inheriting, facilitated by, for example, second hand shops, flea markets, garage sales, online marketplaces, charities and clothing libraries. In the academic literature, various forms of reuse have been conceptualised in terms such as collaborative consumption, product-service systems, commercial sharing systems and access-based consumption (Belk, 2014).

Textile *recycling*, on the other hand, most often refers to the reprocessing of pre- or post-consumer textile waste for use in new textile or non-textile products. In this paper, we adopt a more generous notion of textile recycling, also including the recycling of non-textile materials and products (such as polyethylene terephthalate (PET) bottles) into textile products.

Textile recycling routes are typically classified as being either *mechanical*, *chemical* or, less frequently, *thermal*. This is in many cases a simplification of reality, as recycling routes often consist of a mix of mechanical, chemical and thermal processes. For example, chemical recycling most often refers to a recycling route in which the polymers are depolymerised (in the case of synthetic polymer fibres derived from petrochemicals, such as polyester) or dissolved (in the case of natural or synthetic cellulosic fibres, such as cotton and viscose). Having thus been dissembled to molecular levels, monomers or oligomers are repolymerised, and polymers respun into new fibres. However, prior to the depolymerisation or dissolution, the recycled material is most often mechanically pretreated. Moreover, thermal recycling often refers to the conversion of PET flakes, pellets or chips into fibres by melt extrusion − but the flakes, pellets and chips have been produced from PET waste by mechanical means, which is why this recycling route is sometimes referred to as mechanical recycling (Shen et al., 2010b). Furthermore, the term thermal recycling is easily confused with thermal recovery, which is when textile waste is incinerated to generate heat and/or electricity (Schmidt et al., 2016). To complicate things further, incineration with energy recovery is occasionally labelled as recycling, although the term recycling most often refers solely to material recycling (as is the case in the present paper). So the systematisation of recycling routes into mechanical, chemical and thermal ones is ambiguous and questionable. In the present paper, instead of systematising recycling routes based on the nature of one of the processes involved, we systematise based on the level of

disassembly of the recovered material. If the fabric of a product is recovered and reused in new products, we refer to this as *fabric recycling* (sometimes this is referred to as material reuse (Zamani et al., 2015)). If the fabric is dissembled, but the original fibres are preserved, this is *fibre recycling*. If the fibres are dissembled, but the polymers or oligomers are preserved, this is *polymer/oligomer recycling*. And if the polymers/oligomers are dissembled, but the monomers are preserved, this is *monomer recycling*. Then there are various means of achieving these types of recycling routes, often by combining various mechanical, chemical and thermal processes. The above systematisation of recycling routes resembles a systemisation recently presented by the Ellen MacArthur Foundation (2017a).

Other classifications of recycling routes also deserve mentioning. For example, if the recycled material is of lower value (or quality) than the original product, this is termed *downcycling*. Today, existing textile recycling routes are in most cases downcycling. Clothing and home textiles are downcycled into, for example, industrial rags, low-grade blankets, insulation materials and upholstery (Schmidt et al., 2016). In contrast, if a product from recycled material is of higher value (or quality) than the original product, it is termed *upcycling*. As the length of the fibres and the constituent molecules are reduced by wear and laundry (Palme et al., 2014), fabric and fibre recycling typically yields materials of lower quality (if quality is defined in terms of fibre quality) than materials made from virgin fibres (unless mixed with yarn from virgin fibres). Thus fabric and fibre recycling are typically considered to be downcycling (at least in terms of fibre quality – in terms of other qualities of the end product, such as aesthetics, fit-for-purpose or material qualities defined by fabric construction rather than fibre quality, certain end products made from recycled fibres or fabrics may still be considered upcycled). In contrast, polymer, oligomer and monomer recycling typically yields fibres of similar quality to virgin fibres. It should be emphasised that just because fibre and fabric recycling are examples of downcycling (in terms of fibre quality), they are not necessarily less preferable from a waste hierarchy perspective compared to polymer, oligomer or monomer recycling. In contrast, a cascade approach could be optimal, in which the textile waste first enters fabric or fibre recycling, and once the fibre length has been reduced to a level at which the material is not fit for fabric or fibre recycling, it enters polymer, oligomer or monomer recycling.

Another classification for recycling routes is into *closed-* or *open-loop recycling*. Closed-loop recycling refers to when the material from a product is recycled and used in a (more or less) identical product, whereas open-loop recycling (also called cascade recycling) refers to processes in which the material from a product is recycled and used in another product (Ekvall and Finnveden, 2001; Klöpffer, 1996). A "product" can here refer to different levels of refinement, which means that a given recycling route may be referred to as either closed- or open-loop recycling, depending on context. For example, something that is a product in a business-to-business context (e.g. a fibre or a fabric) may not be in a retail or consumer context (where garments are key textile products). The latter viewpoint would imply that closed-loop recycling relies on, for example, a T-shirt being recycled into a T-shirt – or even a T-shirt of a certain size, colour and, perhaps most importantly, quality (e.g., fibre length) being recycled into a T-shirt of the same size, colour and quality. In contrast, a more lax definition of closed-loop recycling could, for example, be that a material category (such as packaging) is recycled into the same material category rather than another (such as textiles, as is the case in the aforementioned bottle-to-fibre recycling) (Östlund et al., 2015).

Fig. 1 summarises the above classification of various forms of reuse and recycling.

1.2. Current status of textile reuse and recycling

The interest in increased textile reuse and recycling is consistent with the increased attention being given to the circular economy concept in international and national policy, see for example the 2015 EU Circular Economy Action Plan (EC, 2017) and the 11th Chinese five-year plan issued in 2006 (Zhijun and Nailing, 2007). In the business world, circular economy has gained momentum through the work by the Ellen MacArthur Foundation, whose circular economy system diagram highlights the important role of reuse and recycling in a potential future circular economy (Ellen MacArthur Foundation, 2017b). In the textile industry, reuse and recycling (in the form of downcycling) is already well established. For example, in Europe about 15–20% of disposed textiles are collected (the rest is landfilled or incinerated), whereof about 50% is downcycled and 50% is reused, mainly through exporting to developing countries (Textile Recycling Association, 2005). There are, however, large variations within Europe: more prominent examples are Germany, in which about 70% of disposed textiles are collected for reuse and recycling, whereof a fraction is separated for incineration (Textile Recycling Association, 2005), and Denmark, in which about 50% is collected, mainly for reuse domestically or abroad (Palm et al., 2014). Still, there is a great potential to further increase reuse, as clothing items typically are disposed of long before the end of their technical service life (Roos et al., 2017; Woolridge et al., 2006). Considering the low recycling rate today, there is a great potential to also increase recycling, particularly polymer, oligomer and monomer recycling, thereby preventing textile waste that cannot be reused or fabric/fibre-recycled from being landfilled or incinerated. Polymer, oligomer and monomer recycling is, however, hindered by a lack of technologies for sorting and separation into pure enough fractions (Östlund et al., 2015), although there have recently been significant breakthroughs in the separation of cotton/polyester blends (Palme et al., 2017). There are also numerous non-technical barriers for increased textile recycling (Elander and Ljungkvist, 2016).

2. Method

The method used in the literature review consists of two steps: (i) identifying the literature to study, by a search in databases combined with a set of rules for selecting the relevant pieces of literature, and (ii) mapping the content of the selected literature by extracting information using a set of questions. These two steps are described below.

2.1. Identifying literature

We searched for literature in the Scopus, Science Direct and Google Scholar databases, in May and June of 2017, using the following Boolean search string: ("life cycle assessment" OR "life cycle analysis" OR LCA OR ((environmental OR energy) AND (assessment OR evaluation OR analysis))) AND (textile OR clothing OR garment OR fashion OR apparel) AND (recycling OR reuse OR "collaborative consumption" OR "second hand" OR library OR sharing OR leasing). To ensure identification of all relevant literature, we also included relevant studies encountered when screening or reviewing other studies. See the supplementary material for further details on the literature search.

To select a relevant and manageable set of studies among the identified pieces of literature, we set up the following selection rules:
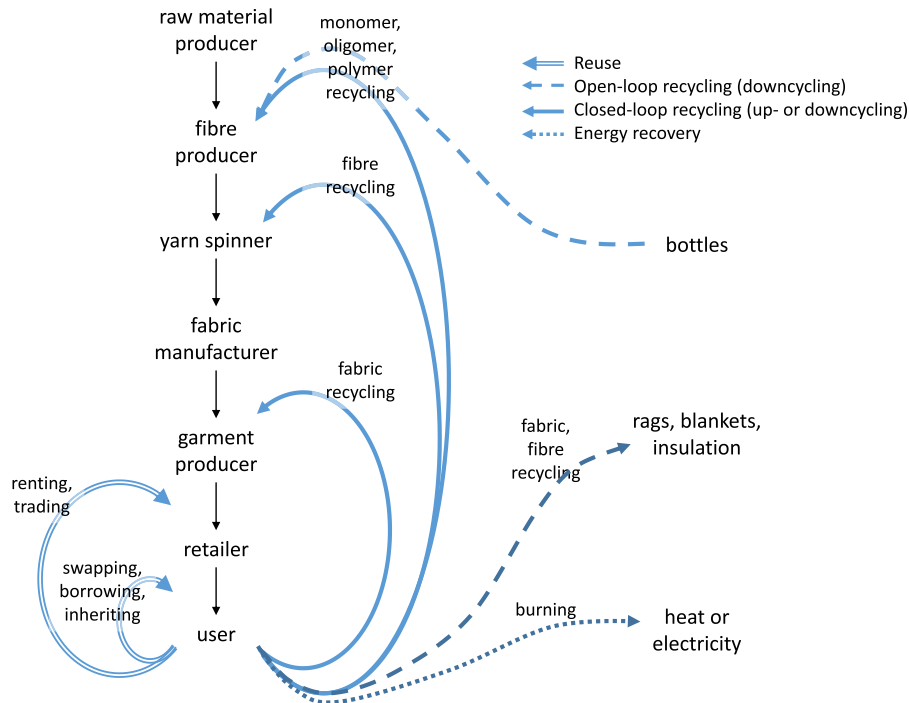
Fig. 1. A classification of textile reuse and recycling routes.

- Inclusion of any type of available study (published, whether peer-reviewed or not).
- Inclusion of studies on any category of textiles (clothing, home textiles, technical textiles, etc.).
- Inclusion of studies of any geographical scope.
- Exclusion of studies which do not include quantitative results, or which merely reproduce the quantitative results of others.
- Exclusion of studies which are older than 14.5 years (before 2003), a cut-off implemented because we could not gain access to the handful of potentially relevant studies we found from before 2003.
- Exclusion of studies in other languages than English or Swedish (the languages the authors of this report handle fluently).
- Exclusion of studies on energy "recycling" (i.e. energy recovery), as the focus of the review is on recycling of materials (specifically fabrics, fibres, polymers, oligomers and monomers).
- Exclusion of studies of "recyclable" products, unless some recycling process is included within the system boundaries.
- Exclusion of studies on comparisons of disposable vs. multiple use textiles, as this kind of reuse does not fit the definition of reuse adopted in the present study, i.e. the transferring of products to new owners, which is based on the definition by Fortuna and Diyamandoglu (2017).
- Exclusion of duplicates (e.g., if a technical report was later published in a peer-reviewed journal, or if a peer-reviewed paper was later included in a doctoral thesis, we only consider the peer-reviewed paper).

2.2. Mapping content

The content of the selected studies were mapped by extracting information using the following questions.

- What is the aim(s)?
- What method(s) is used?
- What product system(s) is studied?
- Is it on textile reuse and/or recycling?
- In the case of recycling, is it on fabric, fibre, polymer/oligomer and/or monomer recycling?
- What textile material(s) is reused and recycled, respectively?
- What is the geographical scope?
- What allocation method(s) is used?
- Is any primary inventory data shown? If so, on what processes?
- What environmental impact categories or inventory indicators are studied?
- What are the conclusions regarding the environmental impact of textile reuse or recycling? (pertaining to the specific case study)
- Which of the other studies reviewed in the present paper are cited?

3. Results and discussion

3.1. Overview of publications

The rules for selecting literature described in the method section of this paper generated a list of 41 publications: 21 peer-reviewed papers and 20 other types of publications (see Table 1). Full bibliographical details are given in the reference list at the end of the paper. The below subsections describe and discuss some content of the publications. For the full mapping of the content, using the questions of section 2.2, see the supplementary material.

Table 1 provides an overview of the content of the selected publications in terms of whether reuse or recycling is studied, the fibre content of the materials being reused or recycled, and the type of recycling routes being employed. It can be noted that it is quite common to study both reuse and recycling in the same publication (29% of publications). More publications deal with recycling (85%) than with reuse (44%). In publications of recycling, fibre recycling is the most studied recycling type (57%), followed by polymer/oligomer recycling (37%), monomer recycling (23%), and fabric

Table 1
The content of the selected publications, in terms of whether reuse or recycling has been studied, the type of materials studied, and a classification of the studied recycling routes. CO = cotton, PES = polyester, CV = viscose, PET = polyethylene terephthalate, PP = polypropylene, PA = polyamide, PAN = polyacrylic, EA = elastane, WO = wool, LI = linen, HF = hemp, SE = silk, PU = polyurethane, LDPE = low-density polyethylene, HDPE = high-density polyethylene, N/A = Not applicable.

Author and year of publication	Reuse or recycling	Reused materials	Recycled materials	Fabric, fibre, polymer/oligomer or monomer recycling
Peer-reviewed studies published in academic journals				
Dahlbo et al. (2017)	Both	CO, PES, CV	Cellulosics (CO, CV, etc.), PES, unspecified	Fibre, polymer/oligomer
Esteve-Turrillas and de la Guardia (2017)	Recycling	N/A	CO	Fibre
Fortuna and Diyamandoglu (2017)	Both	CO	CO	Polymer/oligomer
Zamani et al. (2017)	Reuse	CO, PES, EA	N/A	N/A
Bamonti et al. (2016)	Recycling	N/A	WO	Fibre
Vergara et al. (2016)	Reuse	CO	N/A	N/A
Yasin et al. (2016)	Recycling	N/A	CO	Fibre
Castellani et al. (2015)	Reuse	Unspecified	N/A	N/A
Zamani et al. (2015)	Recycling	N/A	CO, PES	Fabric, polymer/oligomer, monomer
Pegoretti et al. (2014)	Recycling	N/A	CO	Fibre
Corsten et al. (2013)	Both	Unspecified	PET bottles	Unspecified
Glew et al. (2012)	Recycling	N/A	CO, WO	Fibre
Liang et al. (2012)	Recycling	N/A	Unspecified	Fibre
Muthu et al. (2012a)	Recycling	N/A	CO, PES	Unspecified
Muthu et al. (2012b)	Recycling	N/A	CO, PES, CV, WO, PA, PAN, PP, LDPE, HDPE	Unspecified
Shen et al. (2012)	Recycling	N/A	PET bottles (petrochemical and biobased)	Polymer/oligomer
Intini and Kühtz (2011)	Recycling	N/A	PET bottles	Polymer/oligomer
Shen et al. (2011)	Recycling	N/A	PET bottles	Polymer/oligomer
Farrant et al. (2010)	Both	CO, PES	CO	Fabric
Shen et al. (2010a, b)	Recycling	N/A	PET bottles	Polymer/oligomer, monomer
Woolridge et al. (2006)	Both	CO, PES	CO	Fabric, fibres
Other types of studies				
Spathas (2017)	Recycling	N/A	CO, PES, PET bottles, unspecified	Fibres, polymer/oligomer
Bodin (2016)	Both	Unspecified	CO, PES, CV, WO, PA	Fabric
Schmidt et al. (2016)	Both	CO, PES, WO	CO, PES, WO, unspecified	Fibre, polymer/oligomer, monomer
Bjurbäck (2015)	Reuse	CO, PES	N/A	N/A
Östlund et al. (2015)	Recycling	N/A	CO, PES	Fibre, polymer/oligomer, monomer
Beton et al. (2014)	Both	CO, PES, CV, WO, LI, SE, PA, PAN, HF, PU, PP	CO, PES, CV, WO, LI, SE, PA, PAN, HF, PU, PP	Fabric
Hagoort (2013)	Recycling	N/A	PES	Fibre, polymer/oligomer, monomer
Palm et al. (2013)	Recycling	N/A	CO, PES, CV	Fibre, polymer/oligomer, monomer
Youhanan (2013)	Both	CO, PES, CV	CO, PES	Fibre, polymer/oligomer
Fisher et al. (2011)	Reuse	CO, WO	N/A	N/A
Pesnel and Perweulz (2011)	Recycling	N/A	CO, PES	Fibre, monomer
Sahni et al. (2010)	Reuse	CO, CV	N/A	N/A
Bartl (2009)	Both	CO, CV	CO, PES, CV	Unspecified
McGill (2009)	Both	CO, PES, CV, WO, PP, PA, PAN	CO, PES, CV, WO, PP, PA, PAN	Fibre
AITEX (2007)	Recycling	N/A	CO	Fibre
Korhonen and Dahlbo (2007)	Recycling	N/A	CO, PES, CV, WO	Fibre
Allwood et al. (2006)	Both	CV	CO	Fibre
Fisher (2006)	Recycling	N/A	CO, PES	Unspecified
Fisher et al. (2006)	Recycling	N/A	CO, PES	Fibre, unspecified
Patagonia (2006)	Recycling	N/A	PES	Monomer

recycling (14%). The high prevalence of fibre recycling is probably due to the fact that it is a relatively common recycling route, widely applied in commercial scale both in terms of downcycling (e.g. to insulation) and textile-to-textile recycling (e.g. re-spinning of new yarn from cotton or wool waste).

Cotton is the most studied material (covered in 76% of the studies) both for studies of reuse and recycling, followed by polyester (63%), also counting bottle-to-fibre recycling, viscose (25%) and wool (20%). Other materials are studied in no more than a few publications each. There are no substantial differences between peer-reviewed and other types of publications with regard to the studied material type. The preponderance of studies on polyester and cotton reflects the domination of fibre markets by these fibres — they occupy about 51% and 24% of the global market, respectively (Lenzing, 2017; The Fiber Year Consulting, 2015). Fig. 2 provides an overview of the prevalence of different material in studies of reuse

and certain recycling routes.

The above percentages could be underestimates as at least one the studied reused/recycled materials is not specified in four of the publications, and information on the type of recycling is missing in six.

3.2. Trends over time

Fig. 3 shows the number of publications of environmental assessments of textile reuse and recycling over time. The moving 5 year-average elucidates a steadily increasing number of publications per year, from about 1.5 a decade ago to about 4.5 in recent years.

Fig. 4 shows the number of publications each year covering textile reuse and/or specific types of textile recycling routes. No apparent trend over time can be determined with regard to the
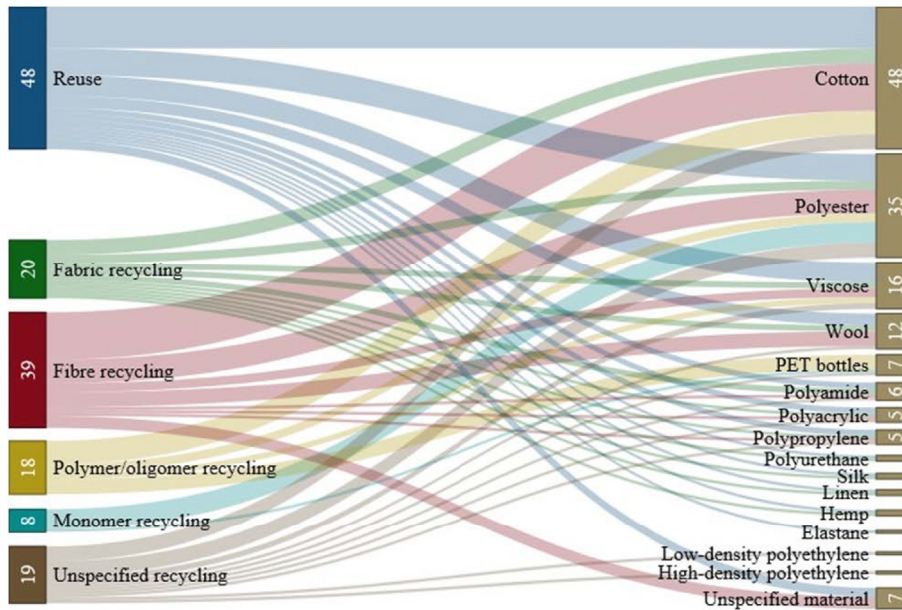
Fig. 2. Prevalence of combinations of studied reuse/recycling routes and studied materials. Numbers correspond to the number of cases examining reuse, or a specific recycling route, for a certain material. For example, there are only five publications of fabric recycling, but three of those cover fabric recycling of several materials, adding up to total of 20 studied cases of fabric recycling.
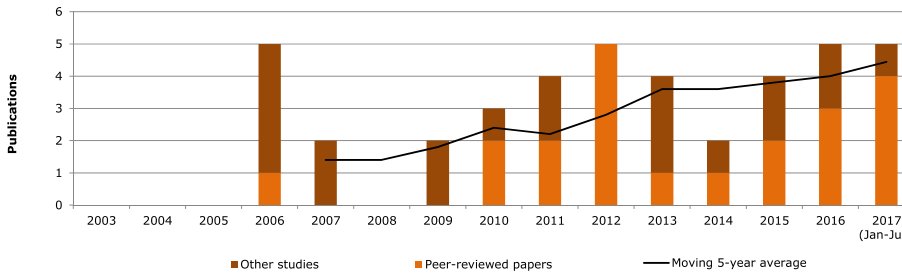

Fig. 3. Number of publications of environmental assessments of textile reuse and recycling, per year, from 2003 to June 2017.
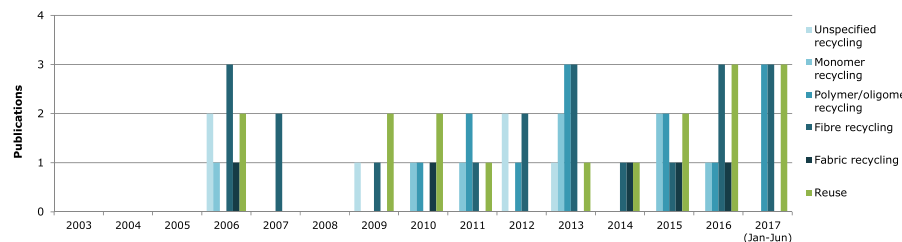

Fig. 4. Prevalence of environmental assessments of reuse and various types of recycling in publications from 2003 to June 2017. (NB: The sum of columns in a year ≥ sum of publications in a year.)

prevalence of reuse or a certain type of recycling route. As publications often cover both reuse and recycling, or several types of recycling, the number of publications in Fig. 4 exceeds the total number of publications (as shown in Fig. 3).

3.3. Aims and scopes of publications

The most commonly stated aim is some version of "to assess the environmental impact of X". This is the case in about 60% of the publications (we refrain from providing an exact number as the aims are phrased in many different ways, making an unequivocal interpretation difficult). In other words, the aim is commonly described as *what* is done in the study, rather than *why* it is done and the *intended use* of the results. So from an LCA methodological perspective, either the aims are poorly phrased, or the studies of textile reuse and recycling are driven by an interest or curiosity to increase knowledge, rather than to support specific informational needs, such as the data required by ecolabelling schemes (Clancy et al., 2015) or green public procurement decisions (Hall et al., 2016). In either case, this makes it difficult for us to generalise regarding the intended use of the publications and to what extent methods and scopes generally have been designed to fulfil the

intended use. Among the studies that do elaborate on the use of the results, national policy development is a frequent theme (see, e.g., Fortuna and Diyamandoglu, 2017; Schmidt et al., 2016; Östlund et al., 2015; Corsten et al., 2013; Palm et al., 2013; Fisher, 2006; Fisher et al., 2006).

Thirty, or 73%, of the studies concern reuse/recycling of waste generated in Europe, in which the Nordic countries (10 studies), the UK (7) and Italy (4) dominate. In most of these cases, the presumably replaced production processes, and sometimes also recycling processes, are assumed to be located in Asia. To some extent, the dominance of the UK and the Nordic countries could be explained by the languages considered in the review: English and Swedish. Still, there are more studies written in the English language exploring recycling in Sweden (7) than in the USA (3), an English-speaking country with about 30 times larger population than Sweden. This indicates that the interest for textile reuse and recycling (or at least the environmental impact thereof) is indeed greater in Europe than elsewhere, with a particularly strong interest in Northern Europe.

3.4. Methods used in publications

All 41 publications are either a full LCA or a streamlined/partial LCA, or use LCA data as input. A common type of a streamlined LCA is those focussing solely on climate impact, i.e. carbon footprints (see Yasin et al., 2016; Vergara et al., 2016; Glew et al., 2012; Muthu et al., 2012a; Korhonen and Dahlbo, 2007). In addition to these five publications, 11 studies cover only climate impact and one or two inventory-level indicators (energy and/or water use). An example of a partial LCA is AITEX (2007), which omits the life cycle impact assessment (one of the four mandatory LCA phases according to the ISO 14040 standard (ISO, 2006)), presenting results in terms of inventory indicators only. Examples where LCA data is used as input are: Muthu et al. (2012b), which use LCA data as input when applying a multi-dimensional indicator for rating the potential of textile recycling of various fibres; Fisher (2006) and Fisher et al. (2006), which combine scenario analyses on UK waste flows with LCA data to quantify environmental benefits of various policy options; and Fortuna and Diyamandoglu (2017), which combine a material flow analysis with LCA-based emission factors to optimise reuse strategies and practices with regard to greenhouse gas emissions.

The high prevalence of LCA methodology is not surprising considering the search strings employed (see section 2.1), but to find LCA elements in *all* reviewed studies indicate a consensus that LCA or some element of LCA is necessary for quantifying the environmental impact of textile reuse and recycling. Our interpretation is that the life cycle perspective is widely viewed as essential for capturing the environmentally relevant consequences of textile reuse and recycling: another type of end-of-life management compared to non-reuse/recycling scenarios and the presumably resulting avoidance of production processes.

3.5. Allocation procedures and replacement rates

Allocation procedures of many kinds have been employed in the reviewed publications, including the use of system expansion, cut-offs and mass and economic allocation. Uniquely, Pegoretti et al. (2014) employed a 50/50 split of impacts between virgin and recycled products, a method that has existed for many years (Ekvall, 1994) and has received a regulatory boost from the publication of the BP X 30-323-0 standard by the French government and its inclusion in the EC's Operational Environmental Footprint guidelines (EC, 2013) — see Pelletier et al. (2014) for a discussion. Nevertheless,

the most frequent allocation methods encountered in our review are cut-off allocation for recycled input materials and system expansion for reused products and products made from recycled materials. In other words, authors most often assume that the material input to recycling systems is a waste free of environmental burdens, and that reused products and products made from recycled materials substitute functionally equivalent products made from virgin fibres.

The calculation of the benefits of substitution depends on to what extent production is replaced (the replacement rate/factor). Most studies assume a 1:1 replacement rate without justification, which is problematic. This reduces the reliability of the evidence which these studies show for the environmental advantages of textile reuse and recycling. Studies to identify actual replacement rates have been conducted (Castellani et al., 2015; Stevenson and Gmitrowicz, 2012; Farrant et al., 2010; Thomas, 2003), and different replacement rates (i.e. not 1:1) have been considered for in some of the reviewed publications (Dahlbo et al., 2017; Fortuna and Diyamandoglu, 2017; Schmidt et al., 2016; Vergara et al., 2016; Östlund et al., 2015; Bjurbäck, 2015; Corsten et al., 2013; Farrant et al., 2010; McGill, 2009). Looking at the dates of these publications, concern for this issue appears to be increasing. All publications employing several replacement rates have found that the choice of replacement rate influences results considerably. Dahlbo et al. (2017) conclude that replacement rates as low as 50% may still result in environmental benefits both for textile reuse and recycling. Similarly, Schmidt et al. (2016) found environmental benefits for textile reuse for replacement rates as low as 10%. In contrast, Fortuna and Diyamandoglu (2017) found that low replacement rates can, under certain conditions, make textile reuse an environmentally inferior alternative compared to both incineration and recycling.

For *reuse*, a 1:1 replacement rate presumes that the new owner of the reused item uses the item as many times as the owner would have used a brand new item, which has been shown to be unrealistic (see, e.g., Castellani et al., 2015; Farrant et al., 2010). For *recycling*, a 1:1 replacement rate may be more realistic, at least for fibres produced via polymer/oligomer or monomer recycling, as the fibres are of quality comparable to fibres from virgin resources. However, increased fibre production via recycling may increase total global fibre supply and thereby reduce the price and increase the demand for fibres. In other words, some of the benefits of textile recycling might be counteracted by increased consumption (a "rebound effect" (Gielen and Moriguchi, 2002)). So whether a 1:1 replacement rate is a good enough approximation depends on the price elasticity of demand for textile fibres. To conclude, there is a need to further study the replacement rates of various fibres, materials and products, in various geographical contexts, and to apply these replacements in studies of the environmental impact of textile reuse and recycling.

It should be noted that in studies where a credit for replaced production is not directly assigned to the studied product, a comparison is still often made with a (presumably) functionally equivalent product made from virgin resources. Often such comparisons are made on a mass basis — for example, Spathas (2017) compares virgin and (partly) recycled yarn on a mass basis. Such mass-based comparisons inherently presume a 1:1 replacement rate. Also, comparisons based on items rather than mass (e.g., a T-shirt made by recycled fibres vs. a T-shirt made by virgin fibres) often presumes a 1:1 replacement rate, unless the functional unit is related to the use of the item and the number of uses is assumed to differ between the compared items. So it can be important to consider replacement rates also in studies where a credit for replaced production is not directly assigned to the studied product,

but comparisons still are made with non-recycled/reused items.

Related to the choice of replacement rate, is the common assumption that the recycled fibre only gets one additional use cycle. Perhaps this is why allocation by fibre length has not been employed in any of the reviewed studies. This method is an adaptation of the idea of allocation based on loss of quality (Tillman and Baumann, 2004). In this case, for $i=(1,n)$ use cycles:

$$Impact_{product\ i} = total\ life\ cycle\ impact \cdot \frac{fibre\ length_{product\ i}}{\sum_{i=1,n} fibre\ length_{product\ i}}$$

The French government has an extended producer responsibility target under which textile retailers will be required to ensure that 50% of the textiles sold are subsequently collected and the majority recycled for material or energy recovery (Dubois et al., 2016). The target is not yet met, but if recovery rates for used textiles increase significantly, the issue of fibre length may become more problematic for subsequent use cycles. While presumably unproblematic for monomer recycling scenarios, successive reduction in the fibre length of the recycled fabrics or fibres over multiple reuse or recycling life cycles would reduce the range of functions available to manufacturers, and allocation based on fibre length may become an obvious alternative for analysts wishing to avoid the uncertainties associated with system expansion and replacement rates.

3.6. Impact categories and inventory indicators

As mentioned in the above discussion about methods employed, several studies are limited to only considering the impact category of climate change. As climate change is also considered in all remaining publications except two — Sahni et al. (2010) and AITEX (2007) — it is by far the most studied impact category or inventory indicator. Global Warming Potential with a 100 year time horizon (GWP100) is most often the employed characterisation method for climate change, which is consistent with LCAs of other product categories (e.g., as concluded in the literature review of forest product LCAs by Røyne et al. (2016)). A few studies appear to only study CO_2 emissions, without characterisation (e.g., Yasin et al., 2016; Bjurbäck, 2015; Hagoort, 2013). The second most studied impact category, or rather inventory indicator, is total energy use (i.e., not distinguishing between renewable and non-renewable energy use), which is studied in 18 publications. Acidification (of some kind) and eutrophication (of some kind) are studied in 17 publications each, followed by water use/consumption/depletion (14), ecotoxicity (of some kind; 12), photochemical oxidant formation (12), human toxicity (of some kind; 10), ozone layer depletion (9), abiotic depletion (6), now-renewable energy use (6), particulate matter formation (5), ionising radiation (4), and waste (in kg; 4). Thirteen other impact categories/inventory indicators have been studied in three or less publications. Six publications include some kind of weighting, either endpoint indicators complementing midpoint indicators (Dahlbo et al., 2017; Beton et al., 2014; Palm et al., 2013; Farrant et al., 2010), or end-point indicators without showing results for the contributing midpoint indicators (Muthu et al., 2012b; Allwood et al., 2006). AITEX (2007) attempts to assess a range of impacts, but by omitting the characterisation and merely presenting results in, among others, the total mass (in kg) of atmospheric emissions and chemicals, the results become rather meaningless. Bjurbäck (2015) presents total chemical use in mass, but also more disintegrated inventory-level metrics (CO_2 emissions, NOx emissions, SO_2 emissions, water consumption, fertilizers (in tonnes) and pesticides (in tonnes)), which makes the results more meaningful. Some studies include non-environmental indicators, such as costs and jobs created, but these are not further discussed in the present review as they are beyond our scope. Fig. 5 summarises the prevalence of impact categories and inventory indicators covered in more than three studies each. Full information on the employed impact categories and inventory indicators can be found in the supplementary material.

Because of the strong focus on climate change, there is a risk that many studies have not managed to identify all the major environmental gains and losses of textile reuse and recycling. For example, as the potential avoidance of the production of virgin conventional cotton has been shown to be an important environmental gain of textile reuse (Dahlbo et al., 2017; Roos et al., 2017; Sahni et al., 2010; Woolridge et al., 2006) and recycling (Esteve-Turrillas and de la Guardia, 2017; Yasin et al., 2016; Östlund et al., 2015; Muthu et al., 2012a; Allwood et al., 2006), it is important to include impact categories corresponding to the environmental issues associated with conventional cotton, namely water depletion and toxicity (Roos et al., 2015a; Micklin, 2007). Likewise, land use and land transformation, and subsequent impacts on biodiversity, may be relevant impact categories/inventory indicators to account for to fully capture the benefits of avoiding production of virgin biobased fibres. Unfortunately, land use or land transformation has only been considered in three of the reviewed publications. Also toxicity should be an important impact category in many studies of textile reuse, as reuse implies the avoidance of later production stages in the textile life cycle closely associated with toxicity issues, such as wet treatment processes (Roos et al., 2015b). So the common narrow focus on climate change and energy use may not capture the real benefits of many types of textile reuse and recycling, thereby potentially contributing to problem shifting, i.e. that we mitigate climate change by increasing other environmental impacts, such as toxicity and the consequences of land transformation. We thus recommend that authors attempt to select a broader set of relevant impact categories, a selection that should be connected to the major environmental gains and losses which could be expected to be associated with the studied system, for example by considering previous studies giving broad overviews of the environmental hotspots of textile supply chains (such as Roos et al., 2015a; Beton et al., 2014; Allwood et al., 2006). Moreover, authors in general need to be better at motivating the choice of impact categories and inventory indicators and at specifying which characterisation methods that have been used — this would greatly improve the transparency of the studies. Also when utilising the data/results of others it is important to clearly show the characterisation methods used — especially when combining input from different studies, to avoid comparing or aggregating apples and oranges.

3.7. Sources of primary inventory data

Finding inventory data (i.e. data on resource use and emissions of processes of the studied system) is often a challenging task when conducting environmental assessment. To help environmental assessment practitioners in finding inventory data, Table 2 lists primary inventory data which is available in the 41 reviewed publications and which pertains to textile recycling systems. Other inventory data used in the publications were either secondary (i.e., from other publications or commercial databases, most often the Ecoinvent or Gabi Professional databases), not displayed (e.g. because of confidentiality), or not on textile recycling or reuse systems (but on, e.g., benchmark products made from virgin resources). Also, Table 2 excludes inventory data on transportation modes and distances (e.g. in the collection of textiles), as these are
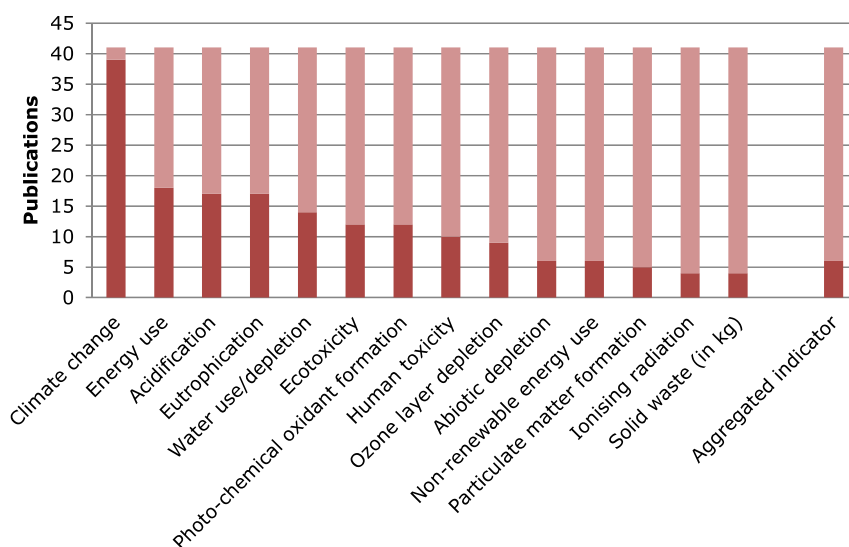
Fig. 5. Number of publications covering certain impact categories and inventory indicators. In addition to these, 13 impact categories and inventory indicators are covered in three or less publications.

Table 2
Description of primary inventory data published in the reviewed studies. Only data pertaining to textile recycling or reuse systems are included in the table.

Author and year of publication	Description of primary inventory data
Dahlbo et al. (2017)	Energy data on manual and automatic (near-infrared, NIR) sorting
Esteve-Turrillas and de la Guardia (2017)	Energy and yield data on cutting/shredding of cotton waste (the step before re-spinning of new yarn)
Bamonti et al. (2016)	General inventory data on production of recycled wool
Spathas (2017)	General inventory data on collection and sorting, mechanical recycling, and chemical recycling
Bodin (2016)	Energy data on waste management facility and two sorting facilities
Pegoretti et al. (2014)	Energy data for the production of automotive acoustic panels (partly based on recycled textile materials)
Glew et al. (2012)	Energy data on the production of beds and pocket spring mattresses (partly based on recycled textile materials)
Intini and Kühtz (2011)	General inventory data on PET bottle-to-fibre recycling
Patagonia (2006)	Energy and CO_2 emission data on dimethyl terephthalate (DMT) production from recycled PET
Woolridge et al. (2006)	Energy and plastic bag use in a textile reuse system (depot, shops)

highly specific for the context of the study and thus of less interest to replicate for other studies.

3.7. Linkages between studies and citations

Fig. 6 shows the citations made between the reviewed publications. In cases in which a citation is made to a previous version or background report of the publication — such as a citation to the master's thesis by Farrant (2008) which later was turned into the peer-reviewed paper Farrant et al. (2010) — we consider this to be a valid citation to the reviewed publication as well. An exception to this are citations to Roos et al. (2015a) — a background report for Zamani et al. (2017) — as all such citations refer to content of the report not related to Zamani et al. (2017). Furthermore, we have primarily looked for citations included in the reference list of each publication, but if encountered we have also included citations found in figures, tables or footnotes, also when these are missing in the reference list. Nonetheless, it is possible some such citations have escaped our mapping. A table with all the identified citations can be found in the supplementary material.

Based on the number of citations from other environmental assessments of reuse/recycling, Woolridge et al. (2006) appears to be considered the seminal piece of work among the reviewed studies, with 15 citations, followed by Allwood et al. (2006) with 10 citations and Farrant et al. (2010) with 9 citations. Reasons for their popularity could be that they are relatively early work and that they cover both reuse and recycling, thus rendering attention from reuse

as well as recycling studies. Also, they are not master's thesis, which tend to be harder to discover and perhaps are therefore less cited (see, e.g., Bartl (2009) and McGill (2009), which are relatively early work covering both reuse and recycling, but still have not garnered more than one citation each from the other publications in our review). Perhaps there is also a "snowball effect", i.e. that authors cite a publication because others have cited it rather than because its content and quality (Benito-León and Louis, 2013). Among more recent work, Zamani et al. (2015) and Beton et al. (2014) stand out, with 6 citations each. Notably, peer-reviewed publications have, on average, more citations: about 0.8 citations per year, compared to 0.4 for publications not subject to peer-review (accounting for studies published before 2016).

In additional to mapping the citations made between the reviewed publications, for the peer-reviewed papers we also mapped the overall number of citations from other peer-reviewed papers, in total and per year, using the reference managing service of Mendeley (see the supplementary material for details). Non-peer-reviewed studies were not included in this analysis, as their citations are not indexed by Mendeley or any other similar service. Excluding the most recent publications (from 2016 to 2017), for which the data is prone to error, numbers of publications per year span from 1.6 for Shen et al. (2012) to 13.6 for Shen et al. (2010b); interestingly, the latter was not identified as a seminal piece of work in the above analysis, which suggests it has attracted a more general interest beyond the narrow research area of environmental assessments of textile recycling. Next to Shen et al. (2010b),
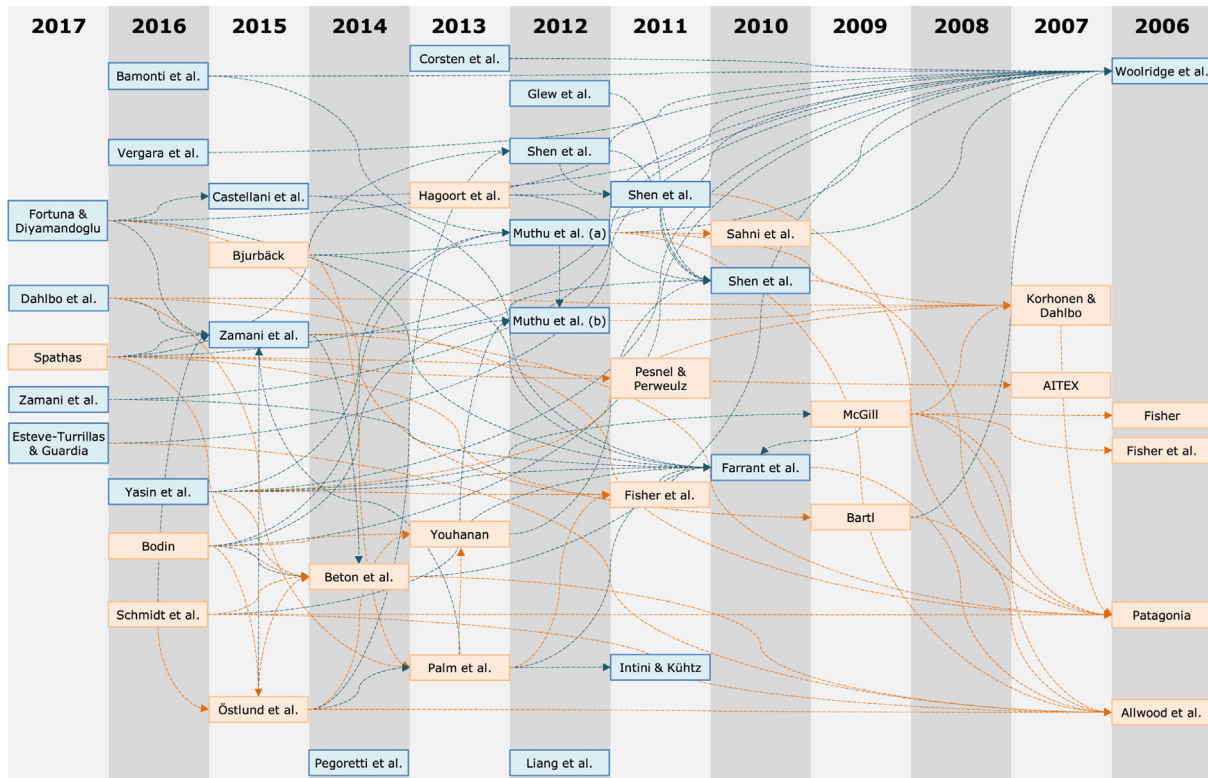
Fig. 6. Citations between the reviewed publications. Peer-reviewed publications are in blue boxes and other publications are in orange boxes. The information can also be found in a table in the supplementary material. (For interpretation of the references to colour in this figure legend, the reader is referred to the Web version of this article.)

Woolridge et al. (2006) and Liang et al. (2012) have gained most citations per year, 7.1 and 5.8, respectively. This supports the above conclusion that the work by Woolridge and colleagues is seen as a seminal piece of work. The remaining papers have received between 2.8 and 4.7 citations per year. The mean number of annual citations is 4.7.

3.8. Findings — the environmental potential of textile reuse and recycling

All reviewed publications except one indicate potential environmental benefits with textile reuse and/or recycling. The exception is Liang et al. (2012), who study the environmental impact of paper produced from various waste materials and conclude that textile waste is a questionable feedstock compared to other waste materials (for the technological pathways studied). That is, Liang and colleagues do not compare textile recycling with other textile waste options. So the reviewed literature provides strong support for the claim that textile reuse and recycling are, in general, preferable waste management options compared to incineration and landfilling. When reuse and recycling are both considered, the former is found to be more beneficial than the latter (Dahlbo et al., 2017; Schmidt et al., 2016; Zamani et al., 2015; Beton et al., 2014; Corsten et al., 2013; Palm et al., 2013; Farrant et al., 2010; McGill, 2009; Bartl, 2009), except for under certain circumstances with regard to transportation distances (Fortuna and Diyamandoglu, 2017). Thus, the literature strongly supports the waste management options preferred according to the waste hierarchy, as promoted by, among others, the EU directive on waste (EC, 2008).

The above conclusion holds for textile reuse and recycling *in general*. The literature also exposes scenarios under which textile reuse and recycling are not environmentally beneficial. For example, as the benefits of reuse and recycling are mainly due to the avoidance of the manufacturing of new products, low replacement rates can eliminate the benefits (as was discussed in section 3.5). Moreover, Shen et al. (2012) show that the choice of allocation method for handling open-loop recycling can strongly influence the preference of a recycled fibre compared to a virgin fibre. Shen et al. (2012) show that recycled fibres do not necessarily have lower environmental impact compared to all types of virgin fibres. Östlund et al. (2015) show that under certain assumptions, there is a risk that textile recycling causes certain types of environmental impacts to increase. In their case, it was shown that climate impact can increase if recycling processes are powered by fossil energy and/or if virgin cotton as a consequence is assumed to be replaced, as cotton is a fibre associated with relatively low climate impact. That certain environmental impact can increase, while others decrease, was also shown by Shen et al. (2010a, b) and Schmidt et al. (2016) for textile recycling, and by Bodin (2016) for textile reuse. Some authors identify the issue that unless the use phase is sufficiently extended, the additional transport and other efforts associated with additional life cycles may exceed the benefits of avoided production (Fortuna and Diyamandoglu, 2017; Zamani et al., 2017). Also, in scenarios where the overall environmental impact is indeed reduced, there is a risk of problem shifting between geographical regions. For example, Allwood et al. (2006) identified that increased recycling in the UK may reduce cotton cultivation (and associated environmental impact) in the USA, but increase energy use (and associated environmental impact) in the UK. Finally, it should be noted that collection and/or sorting of textile waste were fully or partly excluded in about half of the studies. In a few of these studies, collection and/or sorting were excluded because of the goal and scope, in others they were excluded because they were assumed to be negligible. Nonetheless,

the common exclusion of collection and sorting indicates that several studies have underestimated the environmental impact of reuse and recycling systems.

To conclude, the reviewed publications elucidate several potential stumbling blocks for achieving environmental benefits by increasing textile reuse and recycling. These need to be considered when promoting and designing new textile reuse and recycling systems, to avoid scenarios in which reuse and recycling lead to greater impacts. Also, the potential stumbling blocks serve as a reminder that analysts of the environmental impact of textile reuse and recycling should adopt a life cycle perspective, consider collection and sorting processes, consider all relevant impact categories, and clearly describe and motivate key methodological choices and assumptions. Otherwise, potential stumbling blocks may not be identified.

3.9. Gaps and further research

The review has identified gaps in the literature which hopefully can serve as inspiration for future studies.

First, there is a need for more detailed studies, including the generation of updated and publicly available primary inventory data, particularly for collection and sorting processes (which are often excluded) and for monomer and polymer recycling processes. Monomer and polymer recycling have been studied in several of the reviewed studies, but the modelling is sometimes based on rough estimates and/or old inventory data. For example, the modelling of synthetic monomer recycling in Zamani et al. (2015) and Schmidt et al. (2016), and one of the four synthetic monomer recycling models in Shen et al. (2010a, b), are based on inventory data from Patagonia (2006), originally from the Japanese company Teijin. This data is from an unspecified year of origin and lack information on, for example, recovery rates of certain chemicals used in the processes. Similarly, the modelling of cellulose polymer recycling in Östlund et al. (2015) and Zamani et al. (2015) are based on some rough estimates (due to a lack of available data), resulting in relatively uncertain results. Data from the latter has subsequently been used as input to the studies of Dahlbo et al. (2017) and Fortuna and Diyamandoglu (2017), thus reproducing the uncertainties. As indicated in Table 2, only 10 of the 41 reviewed studies contain primary data on reuse or recycling processes. Additional, up-to-date, verified and transparent inventory data would greatly increase the reliability of future environmental assessments of these processes.

Secondly, there is a lack of studies of the environmental potential of cascade systems designed to get the most out of a given virgin or recycled material. For example, such a system could include a certain number of reuse and fabric/fibre recycling loops, followed by a certain number of polymer/oligomer/monomer recycling loops when the average fibre length has been reduced to a certain length (this connects to the discussion in section 3.5 about allocation based on fibre length). In other words, there is a lack of studies exploring the limits of textile reuse and recycling, and the benefits of combining different types of reuse and recycling routes.

Thirdly, as mentioned in section 3.5, there is a need for studies on actual replacement rates for textile reuse and recycling, for various markets and product types. Also, there is a need to increasingly account for such realistic replacement rates in studies of the environmental impact of textile reuse and recycling. This would be a key advancement for increasing the reliability of such studies.

Finally, there is a lack of studies of future systems. Some of the reviewed publications do consider future recycling technologies (e.g. Östlund et al., 2015), but it would be valuable to see more explorative studies accounting for changes in background systems, which are also in constant flux. For example, it would be interesting to explore the preferred end-of-life treatment for textiles in scenarios in which production, recycling processes and/or transportation processes are to a larger extent powered by renewable energy. Such studies could provide useful guidance for designing future reuse and recycling systems for optimal environmental performance, and to prepare (and possibly push) for different potential future developments in the surrounding world.

4. Conclusions

In the present paper, we reviewed studies of the environmental impact of textile reuse and recycling. Below, the main findings are listed.

- Based on the selection criteria (see section 2.1), we found 41 publications, whereof 21 are peer-reviewed and 20 are other types of publications.
- Eighty-five percent of the publications deal with recycling, 44% with reuse, and 29% with both reuse and recycling. Fibre recycling is the most studied recycling type (57%), followed by polymer/oligomer recycling (37%), monomer recycling (23%), and fabric recycling (14%).
- Cotton is the most studied material (76%), followed by polyester (63%), viscose (25%) and wool (20%).
- The number of publications has increased over time, from about 1.5 per year a decade ago to about 4.5 per year in recent years.
- Europe (especially the Nordic countries) is over-represented in terms of geographical scopes.
- In terms of critical methodological assumptions, authors most often assume that textiles sent to recycling are wastes free of environmental burden (i.e., cut-off allocation) and that reused products and products made from recycled materials replace products made from virgin fibres (i.e., system expansion).
- Assumptions about the replaced production of new products influence results considerably, thus the choice of replacement rate is crucial. Often a 1:1 rate is assumed, but there is a need for studies on actual replacement rates for textile reuse and recycling, and to apply such replacement rates in assessments of textile reuse and recycling. Also, there is a need to test other allocation methods for the incoming recycled material. For example, allocation based on fibre length may be an attractive alternative.
- Climate change is by far the most studied impact category. It is covered in 39 out of 41 studies, with the second most studied indicator being energy use, covered in 18 studies. Often only one or a few indicators are studied, introducing a risk that relevant impacts are missed, potentially contributing to problem shifting and sub-optimisation. We thus recommend that authors to a greater extent select a broader set of relevant impact categories.
- The reviewed publications provide strong support for claims that textile reuse and recycling in general reduce environmental impact compared to incineration and landfilling, and that reuse is more beneficial than recycling. Benefits mainly arise because of the assumed avoidance of production of new products.
- The studies also expose scenarios under which reuse and recycling may not be beneficial, for example in cases of low replacement rates, if recycling processes are powered by fossil energy, or if the avoided production processes are relatively clean. Also, for reuse, induced customer transport may cause environmental impact that exceeds the benefits of avoided production, unless the use phase is sufficiently extended. These potential stumbling blocks for textile recycling and reuse need

to be considered when promoting and designing new textile reuse and recycling systems.

- There is a need for more studies and the generation of more inventory data, particularly on processes such as collection, sorting, monomer recycling and polymer recycling.
- There is need of more studies of the environmental potential of cascade systems designed to get the most out of a given virgin or recycled material.

Acknowledgements

Appendix A. Supplementary data

Supplementary data related to this article can be found at https://doi.org/10.1016/j.jclepro.2018.02.266.

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