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REVIEW

Fabric Waste Recycling: a Systematic Review of Methods, Applications, and Challenges

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Abstract

Fabric waste recycling is one of the key aspects to consider in moving towards circular economy in textiles. The demand for fabric waste recycling is primarily driven by the resource recovery perspective and the detrimental environmental impact of disposal and landfilling. Despite the strong desire and demand for circularity in textiles, a holistic view of fabric waste recycling has not yet been presented. To fill this gap, this paper synthesises the literature that pertains on fabric waste recycling. In particular, the current state of fabric waste recycling technologies, emerging trends in fabric recycling applications, and associated challenges were discussed. Results demonstrate the lack of effort towards fabric-to-fabric recycling and recycling of fibre blends. Most frequently studied fabric type for recycling is unblended cotton (50%), followed by cotton/polyester blends (29%). Mechanical recycling was found to be the most studied method of recycling (43%), whereas chemical and biochemical recycling accounted for 38% and 14%, respectively. Open-loop recycling is currently the dominating form of fabric waste recycling with a major focus on the construction and building sector (34%). This paper also identifies and discusses six key challenges present in fabric recycling and provides recommendations for scaling up fabric-to-fabric recycling process. Findings of this review would provide directions and opportunities for research and policy to move towards a circular textile economy.

Keywords Textile waste · Recycling · Waste management · Fabric waste · Circular economy · Closed loop recycling

Introduction

The growth of world population, economic development, and the fast fashion markets have caused an increasing global demand for textile products (Sandin and Peters 2018; Randviir et al. 2019). Textile industry is responsible for extensive usage of resources thus causing environmental pollution in the process. Textile industry is ranked as the second highest for land use, fourth highest for water use, and the fifth highest for greenhouse gas emissions (EEA 2019). Textile dyeing process requires up to 150 l of water per kilogram of fabric (Haslinger et al. 2019), and water being released after fabric treatment contains hazardous chemicals and heavy metals, which result water contamination (Donkadokula et al. 2020). Heavy metal contamination in wastewater is a serious issue since there is a distinct possibility of such contaminants entering into the food chain and thereby creating serious health issues (Bediako et al. 2016; Ghannem et al. 2016). Apart from that, textile industry generates 1.2 billion tons of greenhouse gasses every year, which represents 10% of global greenhouse gas emissions (Echeverria et al. 2019). Despite resource consumption and environmental pollution, textile industry continues to grow with ever-shortening product life cycles.

Rapid fashion cycles, global scale of production, and overconsumption have contributed to the recurrent generation of textile waste (Echeverria et al. 2019; Claxton and Kent 2020). Global textile consumption reached 100 MT/year (Shirvanimoghaddam et al. 2020); however, less than 1% of used clothing are recycled into new clothing, which represents a loss of around US$100 billion worth of raw materials every year (Ellen MacArthur Foundation 2017). Textile solid wastes are considered to be non-hazardous, and, therefore, most of the municipals do not collect them

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as a separate category, leaving the collection to charities or commercial collectors (Weber et al. 2017). Textile wastes are disposed together with non-organic mixed wastes, which eventually find their ways to landfills or incineration. Europe recycles only 25% their textile waste and the rest is either landfilled or incinerated (Haslinger et al., 2019). In the USA, textile waste generation is 17 MT/year (EPA 2020); however, only around 15% of total waste is recycled (Shirvanimoghaddam et al. 2020). These numbers continue to increase until economically, and practically feasible solutions are developed to reduce the waste generation or by closing the loop that turns waste into new products (Navone et al. 2020).

Natural fibres dominated the textile industry for a long time until the inception of synthetic fibre production. The production and consumption of synthetic fibres have gradually increased (Gounni et al. 2019) and today, around 70% of world textile consumption represents synthetic fibres such as polyester, nylon, and acrylic (Echeverria et al. 2019). Consumption of polyester has shown a rather dramatic increase compared to its counterparts. A 157% increase in polyester clothing consumption has been reported from 2000 to 2015 (Pensupa 2020). Polyester is derived from petrochemicals, and the extraction and processing of polyester fibres consume non-renewable energy sources and chemicals. Landfilling of polyester not only creates environmental burden due to its non-degradability, but is also considered as a waste of energy and valuable polymers (Fei et al. 2020). Nylon, another common synthetic fibre used in the textile industry, emits nitrous oxide during the production process, which is a powerful greenhouse gas (Pensupa 2020). Acrylic production uses fossil fuels due to high energy requirement of acrylonitrile production (Yacout et al. 2016). Environmental impact of acrylic is high due to its carcinogenic potential, non-biodegradability, and lack of recyclability (Muthu et al. 2012a; Yacout and Hassouna 2016). Cotton is a natural fibre; however, environmental impacts of cotton are associated with the heavy consumption of land, water, pesticides, and emissions (Yacout and Hassouna 2016; Ütebay and Çay 2019). Around 2.6% of global water consumption is used in cotton production (Chapagain et al. 2006), and the total pesticides used for cotton cultivation are estimated to be 11% from global pesticide consumption (Esteve-Turrillas and de la Guardia 2017). Natural fibres are degradable, yet the colours and finishes applied on fabrics may resist or slow down the degradation process. Furthermore, degradation process in various environmental conditions may release greenhouse gasses such as methane, acid leachate, and hydrogen sulphide.

The concept of circular economy is understood as an important step towards improving sustainability in the textile industry (European Commission, 2020; Geissdoerfer et al., 2017). The fundamental of a circular economy is that the resource flows are optimised, and resources are circulated in a closed loop over and over again, thereby reducing the virgin material and resources requirements (Bocken et al., 2016; Geissdoerfer et al., 2017; Kirchherr et al., 2017; Lüdeke-Freund et al., 2019). However, from an economic perspective, fabric waste recycling is not yet understood as the most viable option of material circulation, since waste-to-energy or landfilling are proven to be far more cost-effective options. Synthetic materials are well suited for incineration because they are highly combustible and produce high amounts of heat when burned (Newell 2015). However, the concept of circular economy cannot be realised with energy recovery from waste (Wanassi et al. 2016), and, therefore, textile wastes have to be recirculated in the manufacturing process through recycling or remanufacturing. Landfilling and incineration not only create environmental pollution but also a waste of valuable resources (Lv et al. 2015). Textile industry is still in the early stages of recycling where many valuable polymers are underutilised or not utilised at all (Echeverria et al. 2019). However, the volume of textile wastes ending up in landfills is rapidly increasing, and hence, the requirement of efficient and economical recycling technologies is critical in order to close the loop of material flows (Navone et al. 2020).

Previous studies demonstrate textile recycling technologies and associated challenges, which are mostly focused on open-loop recycling. Fabric-to-fabric recycling in a closed-loop system is rarely demonstrated. Moreover, a holistic review on fabric waste recycling is currently absent, to the authors' best knowledge. This study aims to fill the said gap by presenting a comprehensive review by synthesising the status of fabric waste recycling and associated challenges and barriers. This paper differs from existing studies by providing a holistic analysis of fabric waste recycling strategies, applications, and challenges for fabric-to-fabric recycling. The objectives of the study are to (i) investigate fabric waste recycling technologies, (ii) examine current applications of recycled fabric wastes, and (iii) identify associated challenges for fabric-to-fabric recycling in a closed-loop system.

Methodology

To achieve the research objectives, systematic literature review (SLR) was selected as an appropriate approach for collection and analysis of the relevant literature (Xiao and Watson 2019). This is a method of reviewing literature in a systematic, explicit, and reproduceable manner in identifying and critically appraising relevant research (Snyder 2019). This study followed five key stages in conducting the systematic review as: outlining the scope of the review, comprehensive search of the literature, identifying suitable articles, data extraction, and data analysis.

Material Collection

An online search was conducted to identify the most relevant peer-reviewed literature from the academic databases. A broad search was conducted through the ScienceDirect, Scopus, and Google Scholar. Relevant keywords were combined to search within the academic databases, and articles were screened through inclusion/exclusion criteria based on the research questions formed (Xiao and Watson 2019). Different combinations of the keywords were generated using 'textile', 'apparel', 'fabric', 'waste', 'recycling' 'reuse' with 'AND', and 'OR' mix. The search was limited to the papers published within last 20 years (2000–2020) and were written in English. The first search resulted 1974 articles. The results of the three data bases were compared to remove duplications. In total, 233 duplications were removed resulting 1741 articles. Only peer-reviewed journal articles were selected for the study, while book chapters, conference proceedings, and patents were excluded, which resulted in 1645 articles. The articles were further screened in two rounds of sorting. Inclusion/exclusion criteria based on the research questions were used in the screening process. In the first round of sorting, selection of articles was done by screening the title and abstract to answer the following research questions.

a. What are the fabric waste recycling methods and technologies?
b. What are the applications of recycled fabrics?
c. What are the major barriers and challenges for fabric waste recycling?

Research articles related to general textile and apparel studies, consumer studies on textile waste, and the studies on reusing textile/apparel were omitted in this first stage. This process identified 134 published articles that fulfil the objective of this study.

A full text reading was carried out in the second stage of the screening process. Since the main purpose of this study is to identify and evaluate the recycling technologies for textile wastes in the fabric form, the second round of sorting was carried out to filter the articles by excluding fibre or yarn recycling. Both post-industrial and postconsumer textile wastes were considered if they were used for recycling in the fabric form. Textile based products other than fabrics (e.g. carpets) were also excluded from the study. Moreover, articles without a clear indication regarding the type of textile waste used, i.e. fabrics or fibres, were also excluded from the study. This yielded 95 articles in total that focus on fabric recycling, either post-consumer or post-industrial. The SLR protocol is demonstrated in Fig. 1.

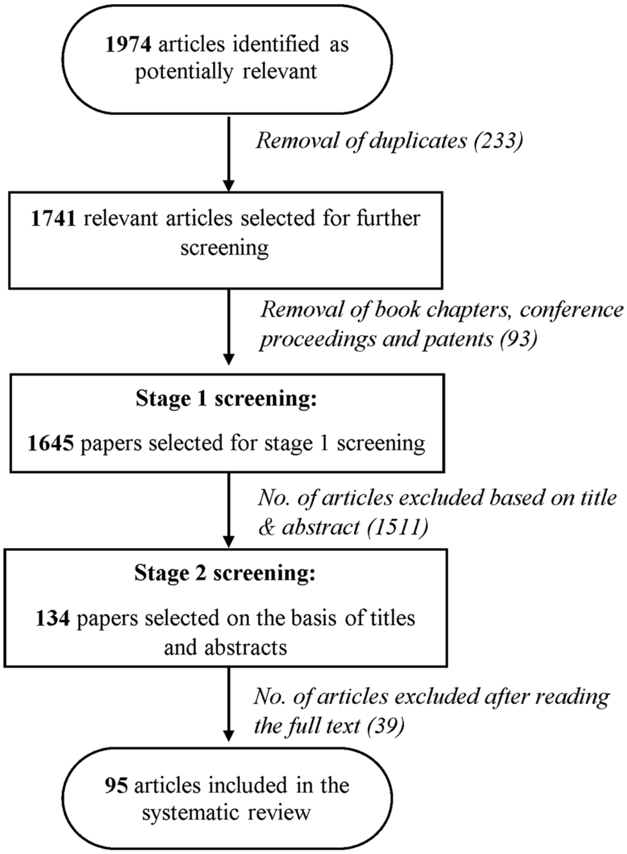


Fig. 1 Systematic review protocol

Content and Descriptive Analysis

A content and descriptive analyses of the selected 95 articles were carried out. The total of 95 articles retrieved through the two-stage filtration process were categorised based on fabric recycling technologies, their applications, and the challenges/barriers for fabric waste recycling. From total 95 articles, 42 articles directly demonstrate fabric waste recycling techniques, and all 95 articles were useful in analysing applications and challenges.

Results

Figure 2 presents the distribution of total number of publications over last 20 years. An increasing trend in the number of publications can be observed over the years, in which the highest number of publications on fabrics waste recycling was recorded in year 2019.

Fabric Recycling Technologies

Fabric recycling routes can be classified into open-loop recycling and closed-loop recycling, based on the

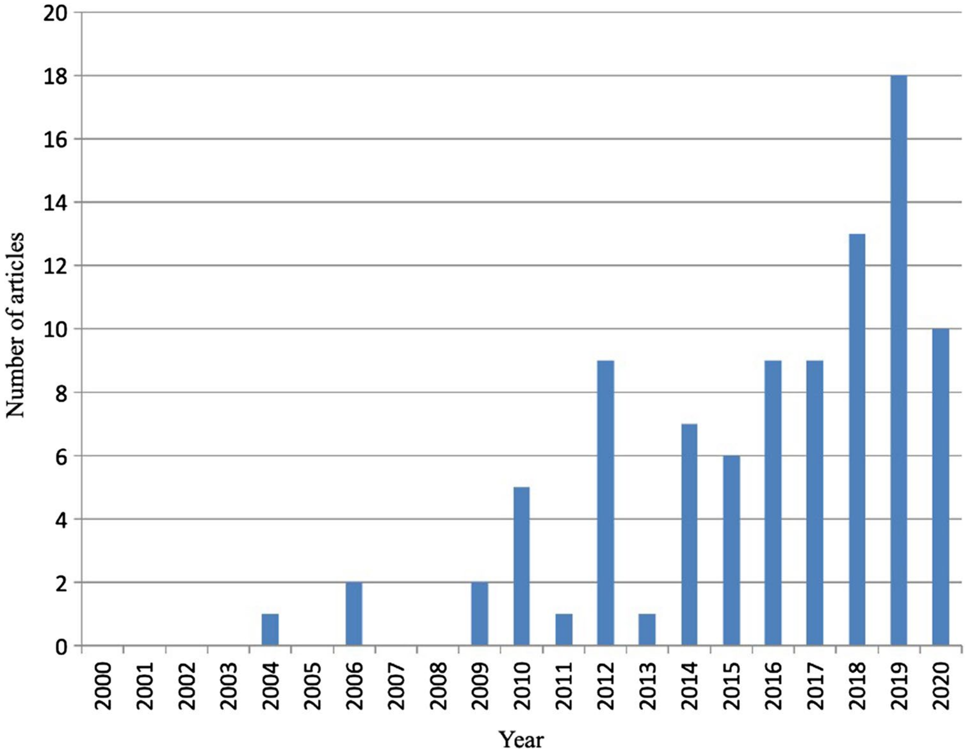


Fig. 2 Number of publications over last 20 years on fabric recycling

end-product aimed. In open-loop recycling, properties of the recycled material are different from the original material and, therefore, the recycled material is used for a different product or purpose than the original. That means open-loop recycling process converts waste material into a new form of material, which can be used as an input to another manufacturing process. In closed-loop recycling, recycled material can substitute the original virgin material (Larrain et al. 2020). This means that the closed-loop recycling process converts wastes back into a similar product as the original. Therefore, closed-loop recycling is important to reduce the environmental impacts created by the textile industry, and could be achieved once a worn-out garment/fabric is recycled by converting that to the original fibre form, which is then used to create a similar product (Asaadi et al. 2016). In open-loop recycling, the quality and inherent properties of the recycled materials may differ from the virgin materials, whereas in closed-loop recycling, the recycled material can substitute the virgin material (Huysman et al. 2015; Larrain et al. 2020). Therefore, an effective closed-loop recycling requires a sustainable supply chain and product design supported by life cycle thinking.

Fabric recycling can be mainly categorised into three technologies, which are mechanical, chemical, and biochemical approaches. Thermal recovery is used when these recycling options are not suitable; however, thermal recovery is the least preferred option in terms of resource recovery. Below section discusses these approaches in detail.

Mechanical Recycling Mechanical recycling method can be divided into two paths based on the recycling mechanism applied. First path is the melt-extrusion process where shredding, crushing, grinding of waste followed by melting, and re-extruding to obtain fibres for subsequently being re-spun into yarns or production of non-woven panels. Synthetic fabrics such as polyester or nylon can be cut into flakes and converted back to fibres by melt-extrusion either by direct extruding into fibres or by converting flakes into pellets or chips by pelletising, followed by melt-extrusion into fibres (Shen et al. 2010). Second path involves cutting, shredding, and carding of fabrics to open up the fibres that are used to produce various building and industrial applications (Hawley 2006). Shredded or crushed textile wastes are heat pressed to produce panels or sheets for various applications such as thermal and noise insulation, reinforcing materials, and industrial materials (El Wazna et al. 2017; Dissanayake et al. 2018; Peña-Pichardo et al. 2018).

Chemical Recycling Chemical recycling can also be performed in two paths. First one is the depolymerisation and repolymerisation route in which the waste matter is depolymerised back into its monomer units. In the depolymerisation process, plastic polymers such as polyester can be depolymerised into monomers or oligomers and re-polymerised into new fibres or materials (Vadicherla and Saravanan 2017; Sandin and Peters 2018). Second path is the dissolution route, in which the separation, filtration, and regeneration of fibres take place. Dissolution route is used for cellulose fibres such as cotton or viscose, in which ionic liquids are used as solvents to dissolve cellulose (De Silva et al. 2014; Mohd et al. 2017). Solvents facilitate the dissolution process of cellulose by breaking the intramolecular hydrogen bonds (Mohd et al. 2017). N-methylmorpholine N-oxide (NMMO) is the most commonly used solvent for the dissolution of cellulose because cellulose can be completely dissolved in NMMO without any degradation (Haule et al. 2016). Dissolved cellulose in ionic liquid can be regenerated by coagulation into man-made cellulose fibres, films, or various other forms such as aerogels or hydrogels (Mi et al. 2016; Paunonen et al. 2019; Zeng et al. 2019). Cellulose materials can be dissolved in chemicals to produce regenerated cellulose (Liu et al. 2019). Similarly, polyester can be dissolved by using chemicals such as dimethylisophthalate, dimethylterephthalate, or methyl-p-toluate, subsequently recovered and re-spun back into polyester.

Most textile products are composed of fibre blends rather than a single raw material. Therefore, the separation of blends using solvents has also been investigated by many researchers. For the separation of cotton/polyester blends, 1-allyl-3-methylimidazolium chloride can be used as the ionic liquid, which selectively dissolves cotton and recovers polyester with a high yield (De Silva et al. 2014). Attempts have also been made to separate cotton/nylon blends and recover nylon and cellulose via dissolution and filtration route (Lv et al. 2015).

Biochemical Recycling Biochemical process of textile recycling is an environmentally friendly enzymic treatment that breaks down polymers into monomers. Enzymes are biocatalysts that increase the efficiency of chemical reactions (Piribauer and Bartl 2019). Biochemical recycling usually starts with an acid or alkali pre-treatment process which helps to breakdown the macrostructure of the fibre. Acid pre-treatment is the most widely used pre-treatment process for cellulose-based fibres, in which the amorphous region of cellulose can be hydrolysed while crystalline region can be exposed to enzymic degradation. Alkali pre-treatment can be used to breakdown the inter- and intra-chain bonds of the cellulose molecules through the swelling effect, creating more space for the enzymic treatment. Sodium hydroxide, potassium hydroxide, and calcium hydroxide are the commonly used chemicals for alkali pre-treatment (Gholamzad et al. 2014).

Cellulose enzymes can break cellulose chains in textile wastes into small sugar molecules and generate synthetic residue, which can be filtered and re-spun into synthetic fibres (Shojaei et al. 2012). The enzymic hydrolysis of cellulose involves the dissolution of glucosidic bonds using cellulosic enzymes (Fattahi Meyabadi et al. 2014; Hasanzadeh et al. 2018). However, synthetic blended or dyed cotton do not efficiently react in enzymic hydrolysis, and therefore, an effective pre-treatment is needed beforehand (Kuo et al. 2010). Not only cellulose-based materials, but also synthetic materials such as polyester can be hydrolysed using biochemical recycling methods, which breaks the ester linkages in the polymer chain and converts them into monomers (Randviir et al. 2019). These monomers can be reused in polymer production or utilised in various other applications. However, during the hydrolysis process, big protein molecules cannot penetrate into the polyester material, and therefore, hydrolysis happens only on the surface material, which hinders the economic feasibility of the method (Piribauer and Bartl 2019).

Thermal Recovery Thermal recovery process refers to the combustion of wastes for energy production. As textile waste is composed of high amount of energy, that can be used as a raw material for energy generation (Pensupa et al. 2017). Combustion, pyrolysis gasification, and incineration are considered as main thermal recycling technologies. Combustion involves a series of exothermic chemical reactions between a fuel and oxidant to produce heat. In pyrolysis, thermal decomposition of the organic material occurs in the absence of oxygen (Larrain et al. 2020). Pyrolysis can be applied into a mix of textile materials without prior sorting, and this process produces oil or gas, which can be used to fulfil the energy demand in various applications (Piribauer and Bartl 2019). Resultant char of the pyrolysis process is a useful product which can be used in the environmental applications such as soil remediation, carbon sequestration, and water treatment (Wang and Wang 2019). Gasification is a process of converting wastes into gaseous products at high temperatures. Gasification can be divided into two forms: direct gasification where a gasification agent is used, and indirect gasification where gasification occurs without a gasification agent (Begum et al. 2012). Incineration is a controlled combustion process that converts waste into carbon dioxide and other gases, which reduces the waste volume up to 90% (Begum et al. 2012).

While all these fabric recycling technologies are extremely useful in diverting waste from landfills and recovering their embedded values such as materials and energy, each process has its own merits and demerits. Mechanical recycling method is the simplest and economical one when compared with the other methods (Altun and Ulcay 2004). Mechanical recycling process does not change the basic chemical structure of the material; however, the process cause a loss or reduction of mechanical properties (Haule et al. 2016). Mechanical recycling machines with rotating drums and metal pins can cause heavy mechanical strain and produce shorter fibres than original fibre lengths. A mixture of different material types and colours in the recycling process produces low-quality yarn after spinning and, therefore, proper sorting processes based on the types of materials and the colours are required (Piribauer and Bartl 2019). On the other hand, chemical recycling gained traction as a method of recycling fabrics without the loss of quality. However, chemical recycling is more expensive than mechanical recycling and, therefore, requires being operational in large scales to become economically feasible (Shen et al. 2010). Other obstacles of chemical recycling process include the presence of blended fibres, various dyes, finishing and processing agents, possible degradation of the fibres during the process, and the environmental impacts of using toxic chemicals as solvents. Biochemical process is considered as an environmentally friendly recycling process due to the use of enzymes as biocatalysts in the depolymerisation process, thus reducing the need of toxic chemicals (Piribauer and Bartl 2019). Thermal recovery is the least preferred method of fabric waste recycling as the materials cannot be recovered to be reused.

Regarding the average cost and energy demand associated with fabric recycling technologies, there is little data reported in the literature. Based on study conducted in Finland, Dahlbo et al. (2017) reported the electricity and heat demand for chemical recycling of polyester is 6599 kWh/t of textile input, and for cellulose-based textiles, electricity and heat demand is 7479 kWh/t of textiles input. Based on a Swedish study, Peters et al. (2019) reported that 850 tonnes of polyester/cotton mixed waste textiles required 0.61 GWh of electricity and 2.6 GWh of natural gas. While cost estimation of recycling technologies is not reported in the reviewed literature, it can be observed that the cost and energy requirements for fabric recycling are largely determined by the fabric composition, recycling technology used, reverse logistics process followed, and the geographical locations of the processing plants. Further research on the estimation of average cost and energy demand for each recycling technology is needed to compare the economic feasibility of those technologies.

Descriptive Analysis of Fabric Waste Recycling

This section provides a descriptive analysis of 42 filtered articles that directly demonstrate fabric waste recycling methods and applications. In terms of geographical representation, it can be observed that research on fabric waste recycling is currently most frequent in Asia, followed by European countries. Out of 42 articles analysed, 19 articles (45%) represent the authors based in Asia, mainly China. While 36% of the articles were written by the authors affiliated with European institutions, the balance (19%) represents the authors who are based on other countries such as USA, UK, Australia, or joint research performed by the researchers based on different countries.

The 42 articles were analysed by categorising them based on mechanical, chemical, biochemical, or thermochemical approaches. Table 1 describes the fabric recycling technologies used for different types of fabric wastes, together with their potential applications or the end-use.

The distribution of fabric waste recycling technologies is illustrated in Fig. 3. Mechanical recycling is the most studied method of recycling, which represents 43%. Chemical recycling represents 38%, which shows a study demand that is not very far from mechanical recycling. This is mainly due to the necessity of recycling fibres such as cotton and thermoplastics back into lyocell or recycled polyester fibres/yarns. Biochemical recycling represents 14%, which indicates much lower demand than mechanical or chemical recycling. Thermal recycling is found to be the least preferred method, however, is unavoidable due to rules and regulations from some vendors. In fabric recycling, a combined approach of mechanical, chemical, and thermal processes can also be employed. For instance, waste textiles can be mechanically pre-treated before the chemical treatment process or chemically pre-treated before mechanical recycling (Sandin and Peters 2018; Thiounn and Smith 2020). Combination of two or more methods could be effective in recycling various complex blends of fibres.

According to Table 1, the most widely used fabric waste material for recycling applications is cotton, followed by cotton/polyester blends. Recycling of other fibre blends than cotton or polyester is found to be very low. Unblended cotton waste gained pronounced attention in both chemical and mechanical recycling routes, accounting for 50% of the recycled fabric waste as shown in Fig. 4. In fact, cotton is the most widely used natural fibre in the textile industry and the importance of recovering cotton from waste textiles is urged to reduce environmental issues. Recycling cotton/polyester blends or mixed fabric waste has also gained research interest, which accounts to 29% of the recycled fabric waste. Recycling other types of fabrics wastes is not found to be frequent, yet random attempts can be observed targeting various end products.

Applications of Recycled Fabrics

This section focuses on categorising the applications of recycled textiles as identified through the literature.

Construction and Building Applications Applications of recycled fabrics are mainly focused on construction and building industry, which accounts for 34%, as shown in Fig. 5. Demand for recycled textiles in building sector is primarily driven by the detrimental impact of traditional building materials. Currently, the materials used for thermal insulation of buildings such as mineral wool, polyurethane, fibreglass, and polystyrene are selected based on their

Table 1 Recycling of fabric waste for various applications

	Input	Technology	Processing method	Output	Author source
1	Cotton	Mechanical	Preparation of panels by mixing cotton waste with fly ash, epoxy resin and barite	Thermal and sound insulation	Binici et al. (2012)
2	Cotton	Chemical	Chemical recycling by dissolving waste to produce regenerated fibres through wet spinning	Cotton fibres	Liu et al. (2019)
3	Cotton	Chemical	Catalytic hydrolysis of cut waste fabrics using phosphotungstic acid, heated into 130–170 °C, and then filtered and dried	Microcrystalline cellulose	Hou et al. (2019)
4	Cotton	Chemical	Small cut waste was mixed with hydrochloric acid, heated into 110–170 °C, and then filtered and dried	Microcrystalline cellulose	Shi et al. (2018)
5	Cotton	Chemical	Acid hydrolysis of shredded waste to produce microcrystalline cellulose to be used as a reinforcement for composite manufacturing	Microcrystalline cellulose reinforced composite	Sun et al. (2014)
6	Cotton	Chemical	In situ polymerisation and carbonisation treatment	Conductive electrode	Zeng et al. (2018)
7	Cotton	Mechanical	Extrusion and pressing of chopped fabric waste and manufacture of composite panels by using a special die followed by pressing	Waste cotton reinforced polymer composites	Bodur et al. (2014)
8	Cotton	Mechanical	Preparation of composite panels with chopped cotton fabrics and low-density polyethylene by using a custom-made single screw extruder	Waste textile reinforced composites	Bakkal et al. (2012)
9	Cotton	Chemical	Dissolution of dyed cotton waste in ionic liquid followed by dry-jet wet spinning	Regenerated cellulose fibres for the textile industry	Haslinger et al. (2019)
10	Cotton	Mechanical	Cutting waste into small pieces, shredding, opening fibres and the production of yarn by using open-end spinning technology	Cotton yarns	Esteve-Turrillas and de la Guardia (2017)
11	Cotton	Chemical	Dissolving waste cotton in NaOH-based aqueous solution by 2-step process	Hydrogel as a heavy metal adsorbent	Ma et al. (2018)
12	Cotton	Chemical	Acid hydrolysis of waste to produce cotton power, followed by dissolution and esterification by heating	Cellulose easters	Ratanakamnuan et al. (2012)
13	Cotton	Mechanical	Processing of pre-consumer wastes to obtain shoddy and compression moulding to obtain a composite	Automotive components	Kamble and Behera (2020)

Table 1 (continued)

	Input	Technology	Processing method	Output	Author source
14	Cotton (knitted)	Mechanical	Cutting and shredding waste to obtain fibres	Recycled fibres	Ütebay and Çay (2019)
15	Cotton (jeans)	Biochemical	Alkali pretreatment followed by enzymatic hydrolysis	Ethanol	Jeihanipour and Taherzadeh, (2009)
16	Cotton (denim)	Mechanical	Cutting, garneting, and carding the waste to open up fibres, preparing non-woven webs using thermal bonding technique, and manufacturing composites using compression moulding technique	Fibre reinforced composites	Mishra et al. (2014)
17	Cotton (denim)	Mechanical	Waste fabrics were subjected to garneting, followed by compression moulding to produce sheets, which have been milled and extruded with polypropylene and finally injection moulded	Composites for automotive industry	Petrucci et al. (2015)
18	Cotton (denim)	Mechanical	Cotton fibres obtained from denim waste were added to the polyester concrete and irradiated with gamma rays	Fibre reinforced concrete	Peña-Pichardo et al. (2018)
19	Cotton (denim)	Mechanical	Waste fabric is shredded through rag machine and teaser machine to prepare shoddy, followed by moulding	Sound insulation panels for buildings	Raj et al. (2020)
20	Cotton (denim)	Mechanical	polypropylene composites reinforced with cotton fibers prepared by compression moulding technique	Fibre reinforced composites	Araújo et al. (2017)
21	Cotton (denim)	Chemical	Dissolving denim waste in ironic liquid, followed by regeneration and drying to obtain aerogel	Cellulose aerogel	Zeng et al. (2018)
22	Cotton (denim/ easy care finished cotton)	Chemical	Dissolution of purified waste garments in N-methylmorpholine N-oxide solution and subsequent spinning into new fibres	Recycled cotton	Haule et al.(2016)
23	Cotton/polyester blend (denim)	Chemical	Textile dye leaching by using nirtic acid. Separation of polyester from cotton by using N,N-Dimethylcyclohexylamine, followed by filtration of polyester. Dissolution of organic materials and polyester using dimethyl sulfoxide and bleaching to recover cotton	Cotton and polyester	Yousef et al.(2019) Yousef et al. (2020)
24	Cotton/polyester blend (denim)	Biochemical	Pre-treatment of waste using sodium carbonate, followed by enzymic hydrolysis and fermentation	Ethanol and methane	Hasanzadeh et al. (2018)

Table 1 (continued)

	Input	Technology	Processing method	Output	Author source
25	Cotton, cotton/polyester blends	Chemical	Dissolution pre-treatment followed by cellulose hydrolysis and the hydrolysate obtained was employed as carbon source to grow G. xylinus in a static culture to produce bacterial cellulose pellicle	Bacterial cellulose	Kuo et al. (2010)
26	Cotton/polyester blend	Biochemical	Alkali pretreatment of milled waste, followed by enzymatic hydrolysis, saccharification and fermentation	Ethanol and polyester	Gholamzad et al. (2014)
27	Cotton, acrylic and cotton/polyester blend	Chemical	Low temperature carbonisation	Biochar	Çay et al. (2020)
28	Cotton/Polyester blend	Chemical	The fabric was suspended in H3PO4 at 200 °C for 24 h to produce hydrochar	Electrochemical applications	Randviir et al. (2019)
29	Cotton/polyester blends	Biochemical	Production of fungal cellulose using solid state fermentation and enzymatic hydrolysis	Glucose and polyester	Hu et al. (2018)
30	Cotton/polyester blend	Mechanical	Preparation of panels using compression moulding technique	Composites	Zou et al. (2011)
31	Cotton/nylon blend	Chemical	Dissolution of fabrics in an ionic liquid, 1-allyl-3-methylimidazolium chloride, and subsequent filtration and separation	Regenerated cellulose films and nylon 6 fibres	Lv et al. (2015)
32	Cotton/polyester mix	Mechanical	Converting cut fabric pieces into yarns by open end spinning and preparing non-woven webs by using chemical bonding process	Automotive textiles	Sakthivel and Ramachandran (2012)
33	Wool/polyester blend	Biochemical	Enzymatic treatment for the selective degradation of wool and recovering polyester	Recycled polyester	Navone et al. (2020)
34	Polyester/cotton and polyester viscose blends	Biochemical	Dissolving cellulose in N-methylmorpholine-N-oxide solution, hydrolysing by cellulase enzymes followed by fermentation to ethanol, or digest directly to produce biogas	Ethanol and biogas	Jeihanipour et al. (2010)
35	Mixed waste	Mechanical	Isothermal hot compression of a homogeneous mixture of cotton/polyester/wool/nylon textile waste and wood sawdust	Fibre reinforced composites for construction	Echeverria et al. (2019)
36	Polyester	Thermal	Pyrolysis treatment at 900 °C with zinc chloride as an activator	Activated carbon	Yu et al. (2018)
37	Lyocell fabric	Chemical	Carboxymethylation reaction to make fibres hydrophobic and soluble, followed by a crosslinking reaction	Heavy metal adsorbent	Bediako et al. (2016)

Table 1 (continued)

	Input	Technology	Processing method	Output	Author source
38	Nylon/spandex blend	Mechanical	Preparation of compression moulded panels by mixing nylon/spandex and polyurethane waste	Thermal insulation in buildings	Dissanayake et al. (2018)
39	Acrylic	Thermal	Pyrolysis of waste between 500 and 800 °C and the steam activation of the chars	Activated carbon	Nahil and Williams (2010)
40	Acrylic and wool	Mechanical	Non-woven panels prepared by using needle-punching method	Thermal insulation in buildings	El Wazna et al. (2017)
41	Acrylic	Mechanical	Reinforced waste in between a double wall	Thermal insulation in buildings	Briga-Sá et al. (2013)
42	Mixed textile waste	Mechanical	Preparation of cement blocks by mixing cement, sand and cut textile wastes	Cement blocks	Jayasinghe et al. (2010)

favoured physical properties, yet they are expensive, and also known to be hazardous to human health and the environment (Oushabi et al. 2015; El Wazna et al. 2017). Textile waste is a better alternative than traditional thermal insulation materials regarding the environmental impact (Hadded et al. 2016). Several studies have reported that textile wastes possess good thermal insulation properties and utilising them in building insulation supports preserving the environment and resources (Briga-Sá et al. 2013; Hadded et al. 2016; El Wazna et al. 2017; Dissanayake et al. 2018; Lacoste et al. 2018; Tilioua et al. 2018; Islam and Bhat 2019).

Application of fabric waste in building sector involves a mechanical recycling approach, in which fabric waste is cut into small pieces and subjected to heat and compression to produce insulation panels or composites by mixing with other suitable materials. This process is relatively easier and cheaper than a chemical recycling process, and pre-sorting of waste may not be required. Therefore, a growing trend can be expected in using recycled fabrics in building sector. Application of recycled textiles as sound insulation materials of buildings has also gained much attention in the recent past (Binici et al. 2012; Patnaik et al. 2015). Traditional materials used for sound absorption in buildings such as glass wool, mineral wool, and polyurethane attract criticism due to health and environmental concerns associated with them. Therefore, recycled fibres are desired as an alternative environmentally friendly, low-cost material. It has been reported that recycled fibres such as denim shoddy exhibit better sound absorption properties than glass wool (Raj et al. 2020), and better sound insulation properties can be obtained by incorporating various textile wastes into polyurethane, rather than using a pure polyurethane form (Tiuc et al. 2016).

The use of recycled fibres in manufacturing composite materials is yet another area of interest. It has been reported that the use of natural fibres as reinforcement fillers can increase the thermal and mechanical properties of composites, while reducing the environmental impact caused by using non-degradable materials (Araújo et al. 2017). Vasconcelos et al. (2015) used recycled cotton and polyester fibres in manufacturing lightweight composite blocks for partition walls and reported that recycled textile fibres are important in avoiding brittle tensile fractures of the material. Several authors have investigated the potential of recycled textiles as reinforcement polymers in manufacturing composites (Bakkal et al. 2012; Bodur et al. 2014; Mishra et al. 2014; Peña-Pichardo et al. 2018). Moreover, attempts have been made to manufacture bricks and concrete by incorporating fabric wastes (Rajput et al. 2012).

Fabric to Fabric Recycling Producing recycled fibres or separation of fibre blends was found to be the second highest studied area (21%), as shown in Fig. 5, in which both mechanical and chemical recycling routes are employed.

Fig. 3 The distribution of fabric waste recycling by technology of recycling

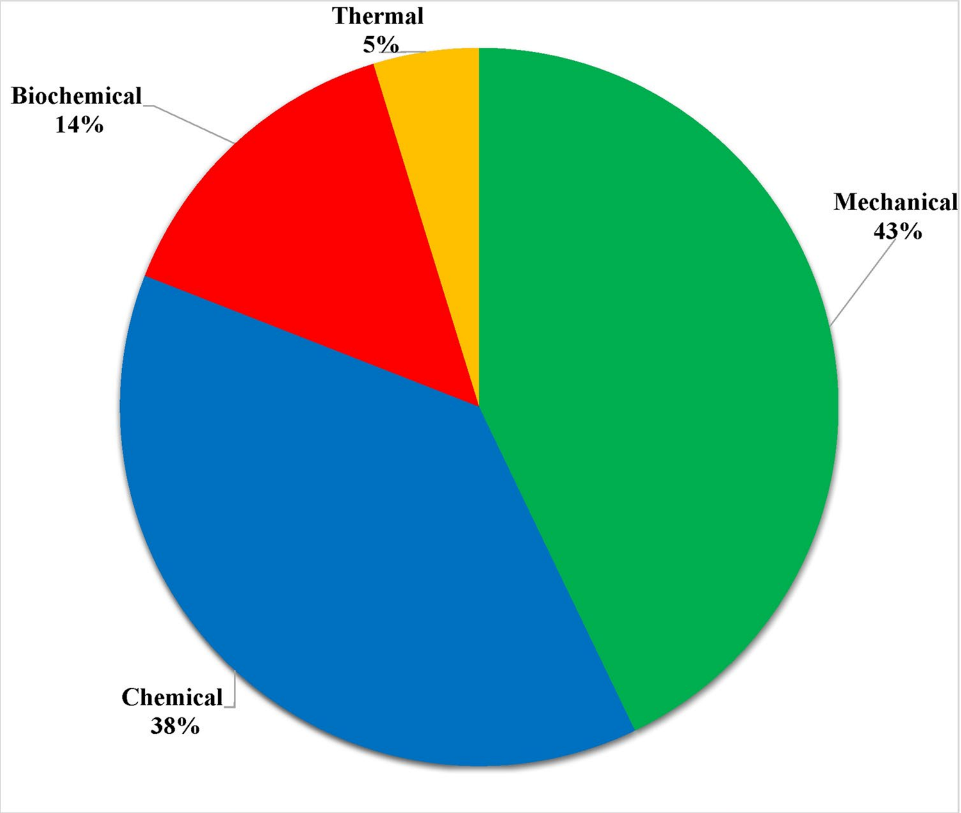
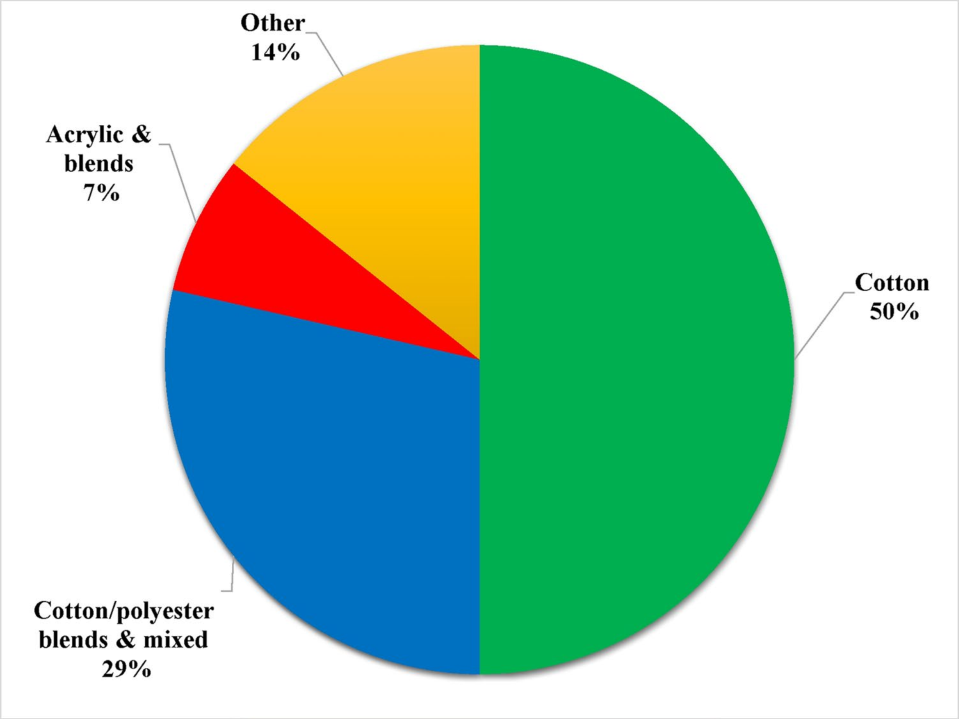


Fig. 4 Distribution of fabric recycling by fibre type



However, fibres obtained through a mechanical recycling process do not show similar properties as the virgin fibre and therefore they must be mixed with virgin fibres in textile applications. Fibres separated through the chemical

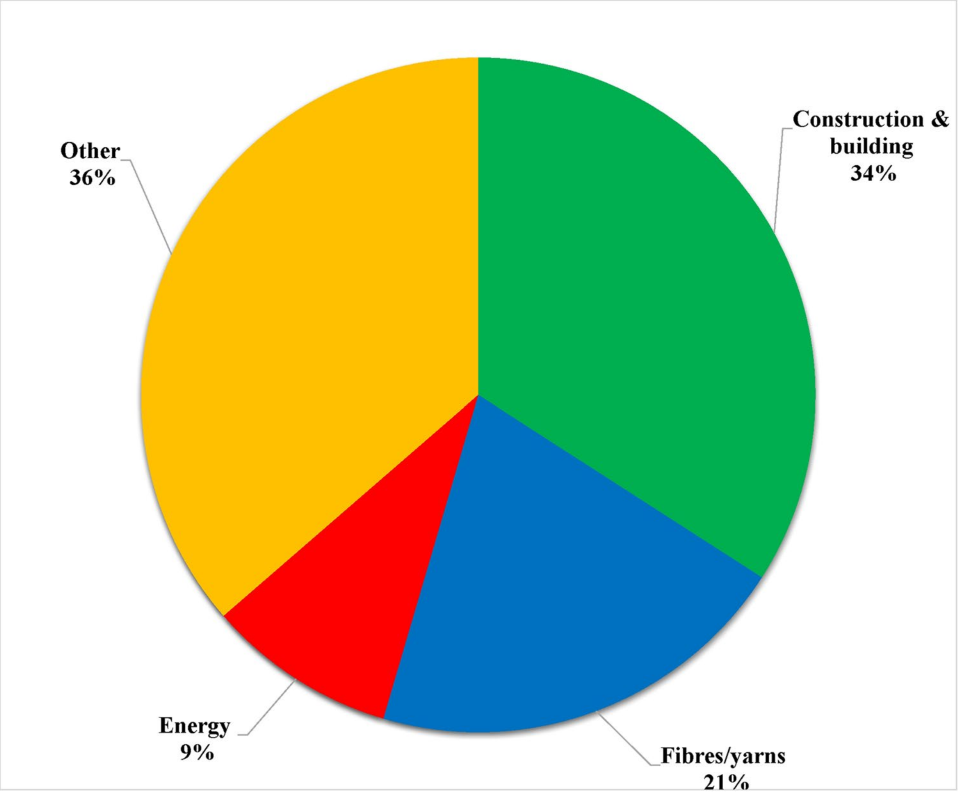


Fig. 5 Distribution of applications of recycled textile waste fabrics

recycling process are claimed to have similar properties as virgin fibres, yet applications of chemically recovered fibres/solutions are rarely demonstrated in the literature.

Recycling waste fabrics back into fibres involves a closed-loop recycling process, which is the most preferred method of waste management. Textile applications from recycled waste means the waste fabric is recycled into fibres which can be processed back into yarns and subsequently into fabrics. When recycled fibres are replaced with virgin fibres, substantial impact on reducing energy consumption and environmental pollution can be expected in the textile supply chain (Costică and Ichim 2016). The total energy saving potential ranges between 55 and 126 GJ/t, depending on the fibre type recovered (Bartl 2011). The process of recycling fabric waste into fibres involves either mechanical recycling, which is melt-extruding, or chemical recycling which is dissolving wastes in chemical solvents, and the resultant solution is re-spun into fibres (Piribauer and Bartl 2019). In the mechanical recycling process, fibre length and the quality of the resultant fibres are reduced and, therefore, recycled fibres are mostly used in non-woven applications rather than being re-spun into yarns (Piribauer and Bartl 2019). Chemical recycling is the promising approach for closed-loop recycling as the process maintains the inherent properties of fibres throughout the recycling process. Cotton and polyester are the most used fibre/fibre blends in fabrics, and studies have reported various methods of recycling cotton, polyester, and their blends. However, the application of such recycled fibres back in fabric production is hardly demonstrated.

Energy Production Fast depletion of natural resources that generate petroleum-based fuels and the subsequent environmental pollution caused by the production and consumption of those conventional energy sources have generated much interest on alternative sustainable fuel sources. The complexities in current recycling technologies lead to waste fabrics being used as a feedstock for energy production. Studies have reported that cellulosic textile waste such as cotton and viscose can be used as feedstock for the production of biogas which is an environmentally friendly energy source (Saravanan et al. 2009; Jeihanipour et al. 2010). Biogas is produced when organic waste is biodegraded by bacteria in an anaerobic environment, which is known as anaerobic digestion. Furthermore, cotton-based fabric waste can be converted to glucose through hydrolysis, followed by a fermentation process to obtain ethanol (Jeihanipour and Taherzadeh 2009; Jeihanipour et al. 2010; Gholamzad et al. 2014; Hasanzadeh et al. 2018). Similarly, production of biogas by using cellulose blended fabric waste has also been investigated (Jeihanipour et al. 2010; Hasanzadeh et al. 2018). Cotton/polyester mixed wastes have been used to produce briquettes which was found to be an economically feasible source to generate thermal energy (Nunes et al. 2018).

One of the major obstacles of biofuel production from cotton waste is the high crystallinity of cotton cellulose, which results in a low bioconversion rate and yield (Hanoğlu et al. 2019). Furthermore, textile waste is mostly composed of blends of cotton and other synthetic fibres such as polyester, in which separation of fibre blends is required prior to/during the bioconversion process. Therefore, an effective pre-treatment process such as alkaline pre-treatment is required to decrease the crystallinity of cellulose and to facilitate efficient hydrolysis and to recover synthetic fibres (Gholamzad et al. 2014; Hanoğlu et al. 2019). Pre-treatments with sodium hydroxide, sodium carbonate, or N-methylmorpholine-N-oxide have been previously used to reduce the crystallinity of cellulose (Jeihanipour et al. 2010; Gholamzad et al. 2014; Hasanzadeh et al. 2018). Direct use of textile materials as feedstock for energy is also limited due to technical problems such as diversity of waste, high moisture content, and low energy density. Therefore, converting waste into homogeneous carbon-rich structures is recommended when using as feedstock for energy production (Hanoğlu et al. 2019). However, using fabric waste as a feedstock for energy production only reduces the environmental impact of waste by diverting them from landfills, yet there is no benefit towards closed-loop production (Haule et al. 2016). Thus, using textiles in energy production may still imply a waste of potentially recoverable fibres (Yousef et al. 2020).

Other Applications Several initiatives have been pursued to recycle fabrics into various other value-added products, however, the contribution of each application is equal to or less than 5% of the studied applications. Recycled fibres are used as thermal and sound insulators of the automotive parts such as trunk liners, headliner, wall panels, and parcel shelves (Sakthivel and Ramachandran 2012). Studies have reported that fabric wastes can be recycled into various other applications such as producing activated carbon from polyester or acrylic fabric waste (Nahil and Williams 2010; Yu et al. 2018), cellulose aerogels, conductive electrodes from cotton waste (Zeng et al. 2019), and heavy metal adsorbents from lyocell fabric waste (Bediako et al. 2016). Moreover, carbon microtubes were produced by direct pyrolysis of cotton waste (Shirvanimoghaddam et al. 2019) and waste cotton derived magnetic porous carbon has been produced for microwave absorption (Wei et al. 2018). Fabric recycling is still an emerging field, especially when the waste is in fabric form and, therefore, innovations are expected to be continued. While most of the concurrent recycling strategies currently focus on recycling materials into low-value resultant products, fabric-to-fabric recycling is necessary to gain both environmental and economic benefits, and also to achieve a circular economy. Even though the use of textile waste fabrics in a recycling process is highly limited today than the use of fibres, an increasing interest and a growing trend can be observed in fabric waste recycling.

Challenges of Fabric Recycling

Fabric-to-fabric recycling in a closed-loop system remains challenging to date, and the major difficulty is the complexity of materials that consist of non-uniform blends of natural and synthetic fibres across a diverse range of mixed fabrics and products. Moreover, various dyes and chemicals used for surface treatments are contaminated with fibres and therefore may need a separate treatment process before recycling. According to Muthu et al., polyester has the highest rank in terms of recyclability potential, followed by acrylic, cotton, viscose and nylon (Muthu et al. 2012b). However, various complex issues hinder this recyclability potential of fabric wastes, which are discussed in detail below.

Material Complexity Material complexity is referred to the large variety of fibre blends, their compositions, and the structural differences vary from product to product. One of the major barriers for effective fabric recycling is their diverse mixtures. For instance, most products are not similar in terms of fibre blends and structures and a large variety can be observed (Piribauer and Bartl 2019). Therefore, developing recycling technologies is uneasy compared to other manufacturing industries where homogeneous materials are used. Mono materials are the ideal candidates for recycling, yet textiles and apparel are largely composed of multi-materials (Dissanayake et al., 2018). Some of the fibre blends are difficult to separate once combined. There have been attempts to separate multi-materials through chemical recycling routes, yet the recovery has still been limited to cellulose fibre-based blends.

Another major issue is the management of post-industrial wastes which include cutting waste, end of rolls and excess fabrics. Those fabrics are in new condition yet cannot be used due to small size resulting from cutting waste and the leftovers of fabric rolls. The presence of fibre blends, textile dyes, and other organic matters and a heterogeneous mixture make it even more difficult to recover fibres form such mixed wastes. Furthermore, most of the manufacturers have signed brand protection agreements with respective brands and, therefore, incineration is found to be the only suitable option to deal with a complex mixture of cut waste and excess fabrics.

Lack of Technological Advancement Currently, the interest on fabric recycling is limited due to the lack of cost-effective recycling technologies that can be operated in full scale. While some developments have been made in the separation of fibre blends, major obstacles with chemical recycling and solvent extraction are the high volume of chemicals involved and the associated cost, specific temperature, and pressure conditions required and the time consumed (Lv et al. 2015). The absence of economically viable and environmentally benign fibre separation and recycling technologies largely limits the recycling possibilities of fabric waste (Payne 2015). Mechanical recycling process is often a chemical free process, yet the technology must be developed to improve the quality levels of recycled fibres as per virgin fibres and to separate fibre blends. Separation of fibre blends made possible in the chemical recycling process which enables the dissolution of cellulose and the recovery of polyester. However, recovery of other fibres from fabric waste has received little attention compared to cotton and its blends. In fact, polyester has become by far the dominant fibre in the textile industry, representing nearly 70% of the fibre market, yet the technology for recycling polyester fabrics is not developed to a feasible level (Fei et al. 2020).

With ever increasing demand for functional and smart textiles, the process of fabric manufacturing is getting complicated. Fabrics are manufactured with two or more fibre blends to achieve desired properties. Current recycling technologies enable recycling only up to two fibre blends, however, are limited to mostly cotton blends. Other fibre blends such as nylon/spandex are largely being used for products such as sportswear. The absence of technology to recycle such blends results in significant volumes of such synthetic blended fabrics being landfilled or burned (Dissanayake et al. 2018). Moreover, significant amounts of post-industrial wastes are landfilled or incinerated by the manufacturers in developing countries as the process of fabric recycling is expensive and, therefore, not easily accessible for them (Mazibuko et al. 2019). In such countries, poor environmental standards together with the lack of technology know-how generate massive amounts of post-industrial fabric wastes which find their way into landfills.

Colour and Chemical Somplexity Over 8000 chemicals are used in textile processing, which include dyes, mordants, softness, finishes, and coatings. The presence of those chemicals significantly restricts the recycling possibility of fabrics (Echeverria et al. 2019). Even though technology enables recycling of PET bottles, same method cannot be used to recycle polyester fabrics due to the presence of dyes. For instance, if disperse dyes are not removed from the polyester fabric before recycling, that can reduce the degree of polymerisation during the melting process (Fei et al. 2020). Various types of chemicals applied in dyeing and finishing stage increase the difficulty of the degradation process. Moreover, there is a growing demand for high-performance and functionalised textiles. Addition of special functionalities to fabrics such as water repellence and hydrophobicity involves application of numerous chemicals as coatings. These special finishes and coatings make the recycling process even more difficult (Weerasinghe et al. 2019). Removal of such dyes and coatings can enhance the solubility and recovery process of fibres, yet that is claimed to be a chemical-intensive process. If the colours are not removed from fabrics before recycling, the resultant fibres may present various colours, which hinder the usability of recycled product.

Quality Issues Quality is an important attribute of any product. The decision on recycling of fabric waste is largely governed by the condition of the waste material. Currently, quality assessment of waste materials is based on subjective judgements and there is no universally accepted quality management process for sorting and separation of waste. The judgement of quality is dependent upon the experience of the sorters, target market, and the quality levels of the waste collected.

The process of recycling decreases the physical properties of fibres. For instance, recycled cotton yarns are shorter and show less tensile strength than virgin cotton yarns (Wanassi et al. 2015). However, untreated greige fabrics result in lower short fibre ratio compared to dyed fabrics (Ütebay and Çay 2019). Plastic fibres become shorter and degrade every time they undergo a recycling process. Maximum number of times plastic fibres can be recycled is estimated to be 7–9 times, and cellulose fibres 4–6 times, before they are no longer suitable for recycling (Echeverria et al. 2019).

Main issues with mechanical recycling of cotton are the shortened fibre length and the low quality of the resultant product (Zeng et al. 2019). In fact, quality of the recycled yarn is dependent on the properties of waste fabrics, structure, and the shredding parameters. Therefore, systematic sorting of waste and optimising shredding parameters are required to increase the quality of the mechanically recycled cotton yarns (Ütebay and Çay 2019). Conversely, chemical recycling of cotton waste is found to be challenging due to the difficulties in dissolving the high cellulose content in common organic solvents (Zeng et al., 2018).

Issues in the Reverse Logistics Process Full potential of fabric recycling is not yet realised, partly due to the complexities in managing reverse logistics process including collection and sorting (Yousef et al. 2019). In the current system, producer or the manufacturer does not hold any responsibility of the take-back systems (Dissanayake and Sinha 2015). Fabric collectors are usually third parties who are disconnected from the forward supply chain. Collection, sorting, and separation are conducted manually and thus, labour-intensive and costly. Nevertheless, for textile recycling to become effective and scalable, continuous supply of pre-sorted input is a critical necessity. Attempts have been made to develop automatic sorting process for fabric wastes using near-infrared reflectance spectroscopy (NIR) (Eriksson 2017) and ATR-FTIR methodology (Riba et al. 2020). However, scalability of such technologies is still challenging due to cost and infrastructure implications.

Traditional supply chain of textile and apparel industry is global in nature, in which the manufacturers are located in developing countries, mainly Asian, whereas the consumers are mostly located in developed countries, mainly USA and Europe. Therefore, operating a reverse supply chain as the exact backward of the forward chain is almost impossible due to the associated cost, transportation issues, and regulations of involved countries. For instance, some countries have banned importing used textiles and apparel. Consequently, fabric waste is generated in the developing part of the world; however, cheap labour in operating a properly functioning reverse logistics process is hardly accessible for them. Apart from that, manufacturers based in developing countries do not have access to the technology required for recycling post-industrial waste at an affordable cost. This situation leads to textile waste being sent to landfill in both sides of the traditional supply chain: the manufacturer in the developing part of the world and the consumers in the developing countries.

Complexities in Garment Recycling Recycling post-post-consumer clothing is more challenging than pre-consumer textiles, where garments are often multicomponent (Navone et al. 2020). Even though a garment is made from 100% cotton, labels, zippers, and other accessories attached to that are made from polyester, metal, or other materials. Therefore, removal of attachments such as labels, zippers, and buttons is necessary prior to recycling. Another major issue of recycling apparel product is the disassembly process. Component parts must be deconstructed before recycling. Even if the garment is made from a mono-material such as 100% cotton, associated seams may be stitched in 100% polyester, which creates the requirement of deconstruction and removal of sewing threads. This is currently a manual, time-consuming, and costly process, which hinders the economic feasibility of the recycling process.

In post-consumer clothing, no two products are identical, and the component parts are in different shapes and sizes. Moreover, each textile or clothing item has its own chemical and fibre blend history. The challenge of separation of fibres and blends in such a diverse range of products is the major technical and practical barrier for recycling. Sorting post-consumer textiles or clothing based on the fibre content is a strenuous task. Most of the fabrics consist of blended fibres, which have already created a demand for more reliable sorting processes than a manual one. It has also been emphasised that the fibre reclamation from post-consumer waste is challenging than pre-consumer waste, due to the presence of impurities in used products and their varied conditions at the time of disposal (Liu et al. 2019).

Discussion

Even though fabric recycling has a long history, fabric-to-fabric recycling in mass scale remains a challenge. This analysis indicates that open loop recycling is currently the dominant route, where waste fabrics are used as raw materials for other industrial products than fabric manufacturing. While open loop recycling supports material recirculation, fabric-to-fabric recycling in a closed loop system is becoming a necessity to conserve resources and achieve a circular textile economy. However, global nature of the textile supply chain and the complexity of materials largely hinder the realisation of circular economy (Piribauer and Bartl 2019). Both natural and synthetic fabric wastes can be recycled back into fibres, yet most of the processes are not yet economically feasible. Therefore, open -loop recycling is currently found to be the most desirable option.

To realise a circular economy model, a dramatic change is required in the way textiles and apparels are produced and consumed. Most products are still designed with the focus on traditional cradle-to-grave life cycle. However, 'design for recycling' is essential to facilitate recirculation of fabrics. For instance, fabrics made from a single fibre type have a great potential of recycling. Current linear system does not make a provision during the design stage for recycling fabrics. Only 1% of clothing is recycled back into clothing (Ellen MacArthur Foundation 2017), and others are mostly downcycled due to various reasons such as complexities in fibre blends, difficulties in colour removal, and lack of technology for recycling. Therefore, design for recycling is essential to increase the rate of recycling and minimise waste issues. Proper material selection is absolutely necessary because some materials make recycling impossible or uneconomical (Bell et al. 2006). For instance, fibres are often blended to achieve improved properties of textiles and to reduce production costs, yet this poses technical challenges in fibre separation in recycling (Manshoven et al. 2019). Reducing complexity of materials by minimising the use of blended materials and increase the use of mono materials would stimulate the rate of recycling (Sandvik and Stubbs 2019). Moreover, avoiding the use of different types of materials in the same product and minimising surface coating can enhance the recyclability. It has been suggested that the ability of recycling should be a key aspect when introducing new materials and fibres to the textile industry (Sandvik and Stubbs 2019). Moreover, the potential and opportunities of recycling the product must be communicated effectively along the supply chain to the end-user and to the recycler.

Even though some labels carry information on product recyclability, the question is whether that information are sufficient for the recyclers, given the complexity of the product.

Efficient recycling requires effective reverse logistics systems that include collection, characterisation, and separation of fabric wastes, and directing them to suitable recycling routes. The absence of a systematic take-back system contributes adversely to the waste handling issue. Proper sorting and grading systems are necessary and critical in order to facilitate recycling in larger scales (Dissanayake and Sinha 2015). However, developing a standard system is challenging due to the complexities presented in textiles as discussed in detail in the preceding sections. The presence of various fibre blends and the absence of technologies to identify correct composition and separate them make the fibre separation impossible (Franco 2017). Most desirable method of recycling post-consumer textiles with a large variety of fibre blends is not to recycle them back to fibres, but to downgrade and use them in suitable applications such as filling purposes.

Producers and consumers of the textile supply chain are hardly located in the same country, which creates a demand for a reverse supply chain that is disconnected from the forward supply chain. Stakeholders in the forward supply chain are reluctant to take any responsibility of product take-back, however, it is essential to implement and operate effective take-back systems and redirecting waste to appropriate sorting and recycling centres. Otherwise, collecting fabric waste is only handled by few commercial waste collectors and not regulated; thus, large amounts of wastes are ending up in landfill without any use. Product innovation for a circular economy can also be achieved through the collaboration among the stakeholders in the supply chain, which can be conceived through different types of ties, including retailer-supplier ties, manufacturing firm-supplier ties, and manufacturing firm-retailer ties (Franco 2017).

Fabric recycling is mostly based around consumer markets in developed countries, yet the waste issues in the developing countries are hidden, especially in Asia where the production facilities are located. Only a few studies have highlighted the need of identifying waste management strategies for developing countries (Yacout and Hassouna 2016; Dissanayake et al. 2018; Gounni et al. 2019). Those manufacturing facilities are almost left out from the bigger picture, and massive amounts of waste are generated and landfilled/burned daily. Therefore, the whole system requires substantial improvements in terms of taking the responsibly of generated waste, implementing decentralised product take-back systems based on waste type, and connecting the reverse supply chain process to the forward supply chain, which drives the circular economy model.

Appropriate policy implementation can play a distinct role in improving textile recycling. Policies such as tax relief for recycling businesses, payback approach, rewarding technological innovations in collection/separation/treatment, and eco-friendly labelling for recycling would be supportive to increase the rate of recycling (Hole and Hole 2020).

Finally, to improve fabric waste recycling in circular economy perspective, future research directions are provided below.

- Future research must extensively focus on ‘design for recycling’ strategies for textiles. Closed-loop systems are the key focus on a circular economy, which cannot be achieved if the products are not designed for recycling. The use of mono-materials whenever possible, avoidance of hazardous chemicals and coating in the manufacturing process are key to achieve recyclability in full scale.
- Development of effective reverse logistics processes is necessary to redirect all wastes from landfills. Research should also focus on time and cost-effective, automated sorting and grading mechanisms that quickly sort fabrics based on fibre composition and colours. Efficient and economically feasible disassembly techniques are vital in large scale recycling of postconsumer apparel.
- Economically and environmentally viable technologies must be developed that facilitate recycling of blended materials. This is currently a burning issue that reduces the recycling rates of textiles. Some of the textile products comprised of blended materials to achieve desired properties, and thus, feasible recycling solutions for such fabrics are readily needed to divert textiles from landfills and promote fabric-to-fabric recycling.
- Standard methods of assessing quality of recycled products must be in place to gain market acceptance. One of the main reasons of having a less demand for recycled products is the quality issue, which can be avoided by introducing new quality standards for recycled products. This would further support developing a standardised recycling process and the recycled products with an improved quality.

Conclusion

This paper focused on addressing fabric waste recycling methods, issues, and challenges through a systematic literature review. Forty-three percent of the selected publications focus on mechanical recycling, while thirty-eight percent deal with chemical recycling. Mostly studied fibre type is unbended cotton, followed by cotton/polyester blends. Most of the applications of recycled fibres are found in construction and building sector. The study revealed that fabric-to-fabric recycling in a closed-loop system is still emerging. Collection of waste fabrics, sorting, and recycling activities suffer a disconnect from the traditional supply chain. This analysis demonstrates a lack of effort towards fabric-to-fabric recycling and recycling of fibre blends, rather an open-loop recycling approach has been adopted in most studies. This finding emphasised the need for diversified approaches to improve fabric-to-fabric recycling of all types of fabric wastes in a closed-loop system. If fabric-to-fabric recycling were to become scalable, it would be an attractive option for economic and environmental benefits and also realising a circular textile economy. This analysis provides useful insights for the designers, researchers, businesses, and innovators to support the transition towards circular textile economy.

Author Contribution Both Authors involved in the research design and the initial review of papers. DGKD analysed the data, and DW summarised them. DGKD wrote the first draft. DW revised and edited the draft. Both authors approve the final version of the paper.

Data Availability All data gathered or analysed during this study are included in this published article.

Declarations

Conflict of Interest The authors declare no competing interests.

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