Science of the Total Environment 718 (2020) 137317

Contents lists available at ScienceDirect

Science of the Total Environment

journal homepage: www.elsevier.com/locate/scitotenv

Death by waste: Fashion and textile circular economy case

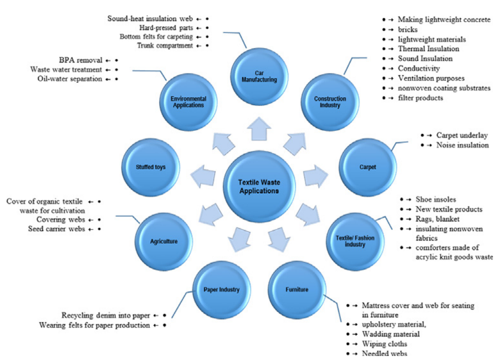
Kamyar Shirvanimoghaddam [a,*], Bahareh Motamed [b], Seeram Ramakrishna [c], Minoo Naebe [a,*]

[a] Carbon Nexus, Institute for Frontier Materials, Deakin University, VIC 3216, Australia
[b] Urban Design Team, Infrastructure and City Services, Brimbank City Council, VIC 3020, Australia
[c] Department of Mechanical Engineering, National University of Singapore, 117574, Singapore

HIGHLIGHTS

- Why circular fashion and textile industry is important?
- Reuse, recycle and repurposing methods of textile waste
- 12 principles of circular economy in fashion industry
- Cleaner Production Scenario and Fashion Foresight

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 October 2019
Received in revised form 12 February 2020
Accepted 13 February 2020
Available online 14 February 2020

Keywords:
Textile
Fashion industry
Circular economy
Sustainability

ABSTRACT

In a circular economy model the way we use the textiles needs to change at a fundamental level. A circular economy is an alternative to a traditional economy (fabrication, use and dispose) in which we keep resources in a loop for as much time as possible, try to maintain their value while in use, and repurpose for generation of new products at the end of utilization. The value of the global fashion industry is 3000 Billion dollars that accounts for more than 2% of the world's Gross Domestic Product (GDP) (https://fashionunited.com/global-fashion-industry-statistics/). In the last two decades not only the textile industry has doubled the production but also an average global annual consumption of textiles has doubled from 7 to 13 kg per person and reached to the threshold of 100 million tonnes of textiles consumption. More than two thirds of the textile goes to landfill at the end of their use and just around 15% is recycled. Various scientific studies confirm that the disposal nature of fast fashion and throw-away culture is resulting in a serious environmental, health, social and economic concern. One of the global environmental challenges arising from micro-plastic and micro-textile waste entering into the oceans that can end up in fish and eventually food chain. Herein, through a systematic literature review, the significance of circular fashion and textile is highlighted and various approaches for reuse, recycle and repurposing of the textiles waste as well as disruptive scientific breakthroughs, innovations and strategies towards a circular textile economy have been discussed. Looking into the future, remarks have been made in regards to tackling the key challenges in recycling of textile materials in different stages of their manufacturing process.

1. Introduction

The high rate of population growth, improved global incomes and living standards have resulted in steadily increasing the production

* Corresponding authors.
E-mail addresses: kamyar.shirvanimoghaddam@deakin.edu.au (K. Shirvanimoghaddam), minoo.naebe@deakin.edu.au (M. Naebe).

https://doi.org/10.1016/j.scitotenv.2020.137317
0048-9697/

and consumption of textiles and fibres in the past few decades(https://fashionunited.com/global-fashion-industry-statistics/). The Textile industry is a high-embodied energy and natural resource demanding practice, which contributes to the fast generation of the post-consumer waste stream. According to the recent industrial reports, $400 Billion worth of clothing is wasted every year (Drew and Reichart, 2019) and an average Australian purchases 27 kg of new textiles each year of which 23 kg is discarded into landfill (Spring, 2017). Two thirds of the discarded materials are man-made fibres including natural fibres that takes decades to decay. For polymer based clothing, it will take 200 years to breakdown in the landfill (ABC News, L, 2017).

With the rising concern over environmental and social sustainability, energy and water consumption, pollution, scarcity of natural resources and emission of greenhouse gases, the textile industry which generates a substantial environmental footprint from cultivation, fabric manufacturing, to the landfill disposal of post-consumer items, is facing tremendous environmental and resource challenges. Thus it is essential to adopt a more sustainable behaviour in the industry.

Due to the high volume of textile waste that is produced around the world, textile reuse and recycling can be a sustainable solution for reduction in solid waste in landfill, reducing the production of virgin materials and energy consumption as well as producing a smaller environmental footprint. In this paper, the importance of the textile waste recycling from a technical, social and environmental point of view has been discussed and various approaches for repurposing of textile waste has been highlighted. Furthermore, some of technical applications of textile waste have been reviewed in order to provide further insight into the textile and fashion circular economy approaches towards sustainability.

2. Importance

Disposal nature of fast fashion and throwaway culture is resulting in a serious environmental, social and economic problem. In the last two decades not only the textile industry has doubled the production but also an average global annual consumption of textiles has doubled (from 7 to 13 kg per person) (Milburn, 2016a; Souchet, 2019).

According to Australia Bureau of Statistics, 501,000 t of textiles and leather was sent to landfill in Australia in 2009–10 alone, which means an average of 22.7 kg per person (statistics, A.B.o, 2013), which is twice the global rate.

By using an average of 37 kg per user each year, North Americans are the biggest textile users in the world, followed by Australia (27 kg), Western Europe (22 kg) and developing countries such as Africa, India and southern Asia only 5 kg each (Milburn, 2016b). Fig. 1 shows the growth of the amount of textile waste that has been generated per person in USA over the past fifteen years. The annual environmental impact of a household's clothing is equivalent to the water needed to fill 1000 bathtubs and the carbon emissions from driving an average modern car for 6000 miles (Leblanc, 2018a).

In 2015, more than sixteen million tons of textile waste was generated in USA, according to American Apparel and Footwear Association (EPA) and only 15.28% of this amount was recycled; 19.03% incinerated for energy recovery and the rest (65.69%)was discarded into the landfill (Fig. 1c).

3. Environmental and societal impact of waste textiles

The textile manufacturing industry is one of the most polluting sector in the world.The textile production process and disposal has crucial environmental consequences such as high level of energy and water consumption in addition to causing water toxic chemical pollution, soil degradation, greenhouse emissions, and producing high carbon footprint and large quantities of waste (Allwood et al., 2006). There are three major fibre types: (1) natural, which is produced from natural resources such as cotton (cellulosic) and wool (protein bases); (2) regenerated, which originate from natural polymers but requires treatments and processing; (3) synthetic, which mostly derived from petrochemical (non-renewable) resources such as polyester and nylon.

According to Lenzing Group annual report (Lenzing, 2017), 63% of textile fibres are derived from petrochemicals and synthetic fibres and polymers derivative from petroleum extraction such as nylon, acrylic, polyester, and polypropylene whose production and fate give rise to considerable carbon dioxide (CO_2) emissions (Echeverria et al., 2019). The remaining 37% is dominated by cotton.

For production of 1.0 kg of cotton, there is a need for approximately 7000 to 29,000 L of water (Muthu et al., 2012). More specifically, for

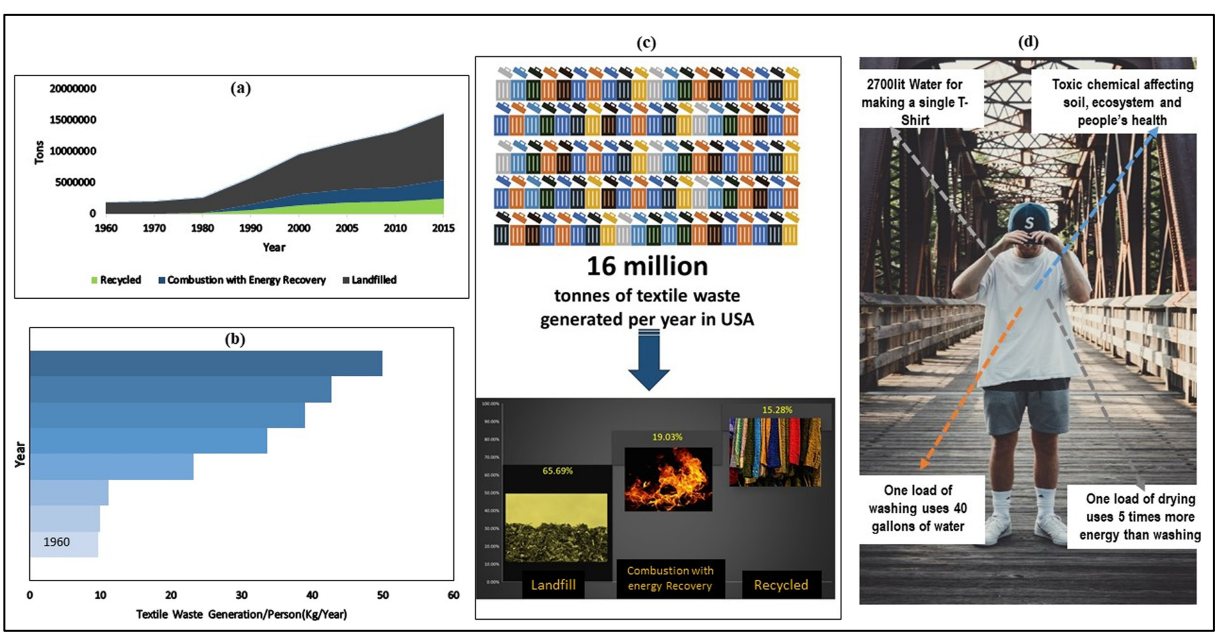


Fig. 1. Textile waste management (a) and generation per person (b) in USA 1960–2015. adapted from EPA data (EPA, 2017); The statistics of textile waste management, based on 16,030 thousands of tonnes generation of textile waste, in USA 2015. adapted from EPA data (EPA, 2017) (c); The environmental impacts of production and use of a cotton T-shirt Source: (aboutorganiccotton, 2019) and (https://www.worldwildlife.org) (d).

making a cotton T-shirt, 2700 L of water and a large amount of toxic chemicals are used which affects soil, water, ecosystem and people's health. (Fig. 1d).

Even the production of protein based fibres such as wool that requires livestock stewardship, has serious environmental consequences such as intensive grazing, land erosion, and emission of (Wiedemann et al., 2016).

In addition to the environmental impact of the production process, the later stages of textile production have even a larger impact. For example the wet treatment process, which is a source of toxic emission, and spinning of yarns and weaving/knitting, mostly rely on fossil energy use leading to significant CO_2 emissions (Roos et al., 2015). As an example production and washing of one pair of jeans results in emission of the same CO_2 as driving 69 miles (ref: Levi Strauss & Co., World Economic forum)

3.1. Other impacts

In addition to the environmental impacts of waste textile, fast fashion stream and consumerism culture, could potentially put profits ahead of human welfare (Drew and Reichart, 2019), which is associated with some occupational health issues as well as social challenges such as:

- Health issues: influence of hazardous chemicals, fibre dust, noise and monotonous repetitive processes on workers (Allwood et al., 2006).
- Ethical issues: low payment rate, lack of basic facilities, forced and child labour in the fashion industry.

For example, the Oxfam report reveals that from the amount that an Australian spends on clothing, only 4% of it goes to the garment workers (Spring, 2017).

4. Concept of circular economy

A circular economy is one that redesigns the idea of fabrication of materials and use of resources to make, use and dispose in favour of as much re-purpose and recycling as possible (http://theconversation.com/explainer-what-is-a-circular-economy-29666, n.d.). By focusing on circular economy through longer life time of the products and reusing of the materials, it prevents the over-generation of waste and gaining the full value of products (http://theconversation.com/explainer-what-is-a-circular-economy-29666, n.d.). The principles of circular e fashion industry have been proposed by Anna Bismar, from Green Strategy (https://circularfashion.com/key-principles/, n.d.) (Fig. 2b).

The aforementioned principles cover the full items involved in designing, fabrication, transportation, selling, using and recycling of textiles. It is believed that the implementation and application of these principles leads to more sustainable products and less amounts of

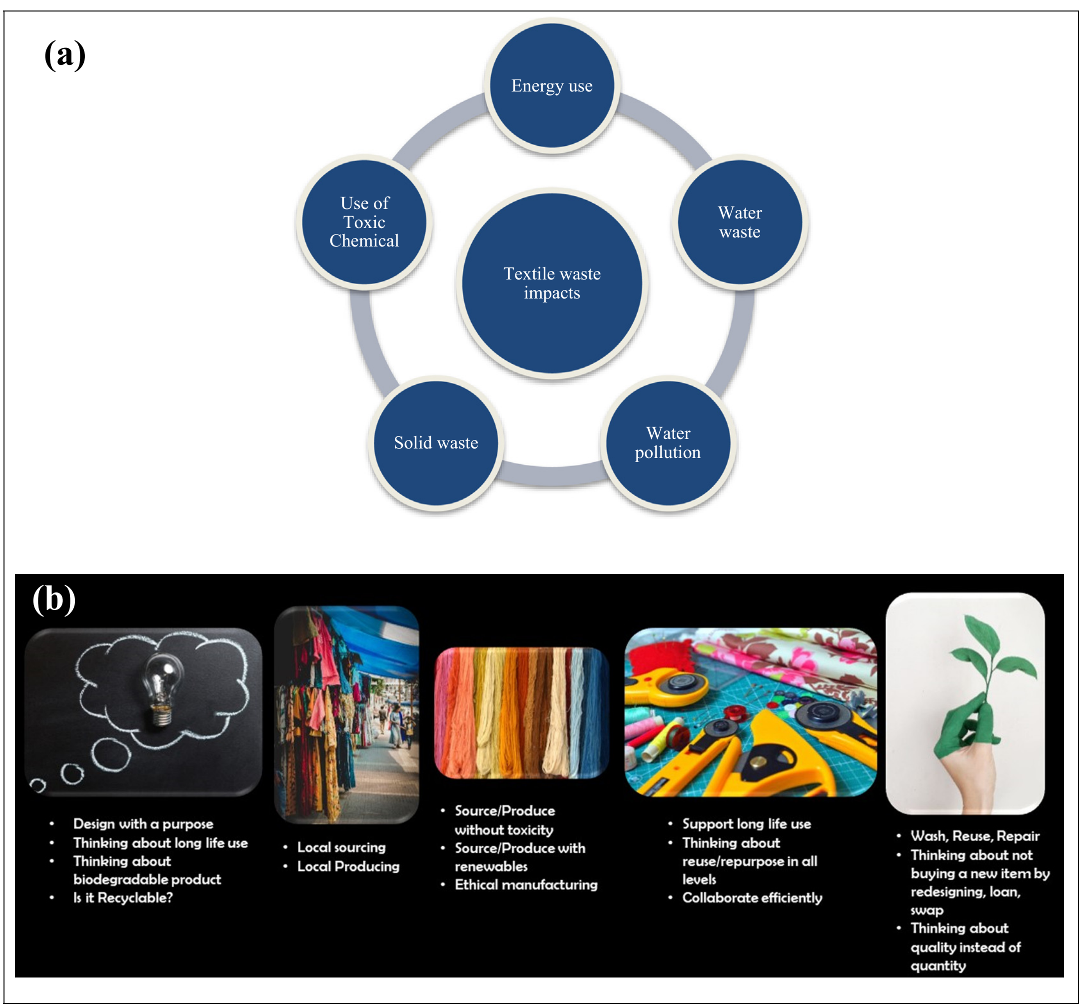


Fig. 2. (a) Major environmental impacts of textile production and waste. (b) principles for a circular textile industry, adopted from circularfashion.com (https://circularfashion.com/key-principles/, n.d.)

waste and chemicals. In terms of designing, purpose based fabrication, multi-purpose design and longer life time and biodegradable products could be an advantage to a sustainable society. Use of local materials and human resources, eliminating the toxic chemicals in fabrication process and use of renewable energy/materials need to be considered in a circular economy concept. This along with the idea of reuse and repurposing of materials and resources are the main fundamentals of the circular economy from producer's point of view. From a consumer's point of view, reuse, wash, swap, and repurposing of clothes as well as putting quality ahead of quantity need to be centre and front.

5. Types and sources of waste

The fibre waste composed of natural and synthetic polymeric materials can be categorised into (1) industry waste, and (2) post-consumer waste (Echeverria et al., 2019)(Fig. 3). Industry waste, which also is known as pre-consumer waste, refers to the waste that has been generated through manufacturing process and enormous source of secondary raw material that is not used, but can be re-injected into the market (Wang, 2010). The post-consumer waste are fibrous products discarded after their service life that can be produced by households (such as cloth, bags, beddings, carpet, curtains), packaging, and commerce and industry (such as uniforms, industrial and construction textiles).

6. Textile waste reuse or recycle

Research groups around the world have been working on different aspects of textile waste recycling and repurposing. Documents published in a field of textile recycling based on SCOPUS based on the subject area are presented in Fig. 4(a). It is clear to see that most of the works have been focused on materials science, engineering, environmental science and chemistry. The field of waste management and recycling especially in textile recycling has gained lots of interest in recent years and the number of documents published have increased from 20 documents in early 90's to near 200 documents in 2019.(All the data have been extracted from Scopus with keywords "textile + recycling").

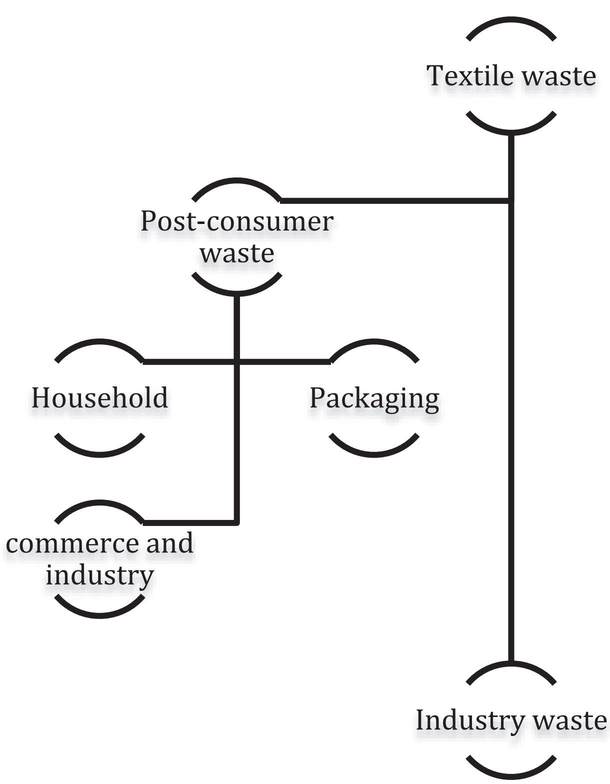


Fig. 3. Textile waste categories.

In contrast to approximately three decades ago when all waste products ended up into landfill, by changing the traditional "linear" economy model into "circular", in this environmentally conscious era, recycling and reusing are the best solution to recover and restore resources and use products to their highest value (Leonas, 2017).

Textile reusing refers to transferring products to a new owner via donating to charity or second hand shops, renting, inheriting, trading, swapping, and borrowing. According to Belk (Belk, 2014) reuse can be categorised into (1) collaborative consumption, (2) product-service systems, (3) commercial sharing systems and (4) access-based consumption. Textile recycling refers to the reprocessing of pre or post-consumer textile waste for use in new textile or non-textile products (Sandin and Peters, 2018). However Muthu et al. (Muthu et al., 2012) defines recycle as a more comprehensive term, which involves "reuse, reprocessing or reproducing a product with multiple aims of conserving raw materials, energy, water and other chemicals, diminishing waste, preserving environmental impacts".

There are various reasons for recycling and reusing of the textile and everyday clothes; (1) These wastes are valuable and can be reused easily; (2) conserve raw materials and save water and energy for fabrication of new clothes and textile; (3) reduce the carbon foot print and green house emission associated with fabrication of new clothes; (4) reduce solid waste in landfill; (5) nurture a more sustainable society in which individuals feel responsible for conserving their environment; (6) providing employment and create economic development as waste management and recycling is a highly labour-intensive process (Leblanc, 2018b).

Textile recycling routes can be categorised in different ways: (1) based on the nature of the process: mechanical, chemical and thermal; (2) the level of disassembly of the recovered material (Sandin and Peters, 2018); (3) down cycling (the product of the recycled material is of lower quality) or upcycling (the product of the recycled material is of higher quality): for example the textile recycling are often downcycling as the length of fibres and the constituent of molecules are reduced by wear, laundry and recycling process (Palm et al., 2014). (4) Open-loop (the process in which recycled material is used in identical product) or closed-loop/cascading (the process in which recycled material is used in another product (Sandin and Peters, 2018).

Given the high rate of textile waste, by reuse or recycle of the waste, there will be the opportunity to reduce the rate of textile waste and as a result it brings ample environmental and economic benefits. For example extending the average life of clothing, which is currently ~ 3 years, the carbon and water footprint and waste generation can be reduced by 5–10% (Leblanc, 2018a).

However recycling and recovery of textile waste faces several barriers including financial, technological, educational, legal, infrastructural and the cost effectiveness of the process (Echeverria et al., 2019; Gulich, 2006). Moreover, the potential recyclability of various fibres are different from one another due to several factors (Muthu et al., 2012) such as the material recycling times and the chemicals that have been used in manufacturing process such as dyes, mordant, softeners, flame-retardants and preserving agents (over 8000 chemicals are used in textile processing) (Khan and Islam, 2015).

Therefore due to its hazardous chemical and heavy metals content, in some cases the recovery of textile wastes as feedstock for new applications result in further cost (Echeverria et al., 2019).

Considering various barriers which prevent a successful textile recycling process, recycling of textile fibre needs to be done in different stages of its lifecycle i.e. manufacturing, consumption and post-consumer waste. Table 1 reveals opportunities for reducing the textile waste and recycling used textiles in each stages of its lifecycle to decrease textile waste stream as well as its negative environmental, social and economic impacts. Moreover, the willingness of public for participation in recycling process, community awareness and the request of

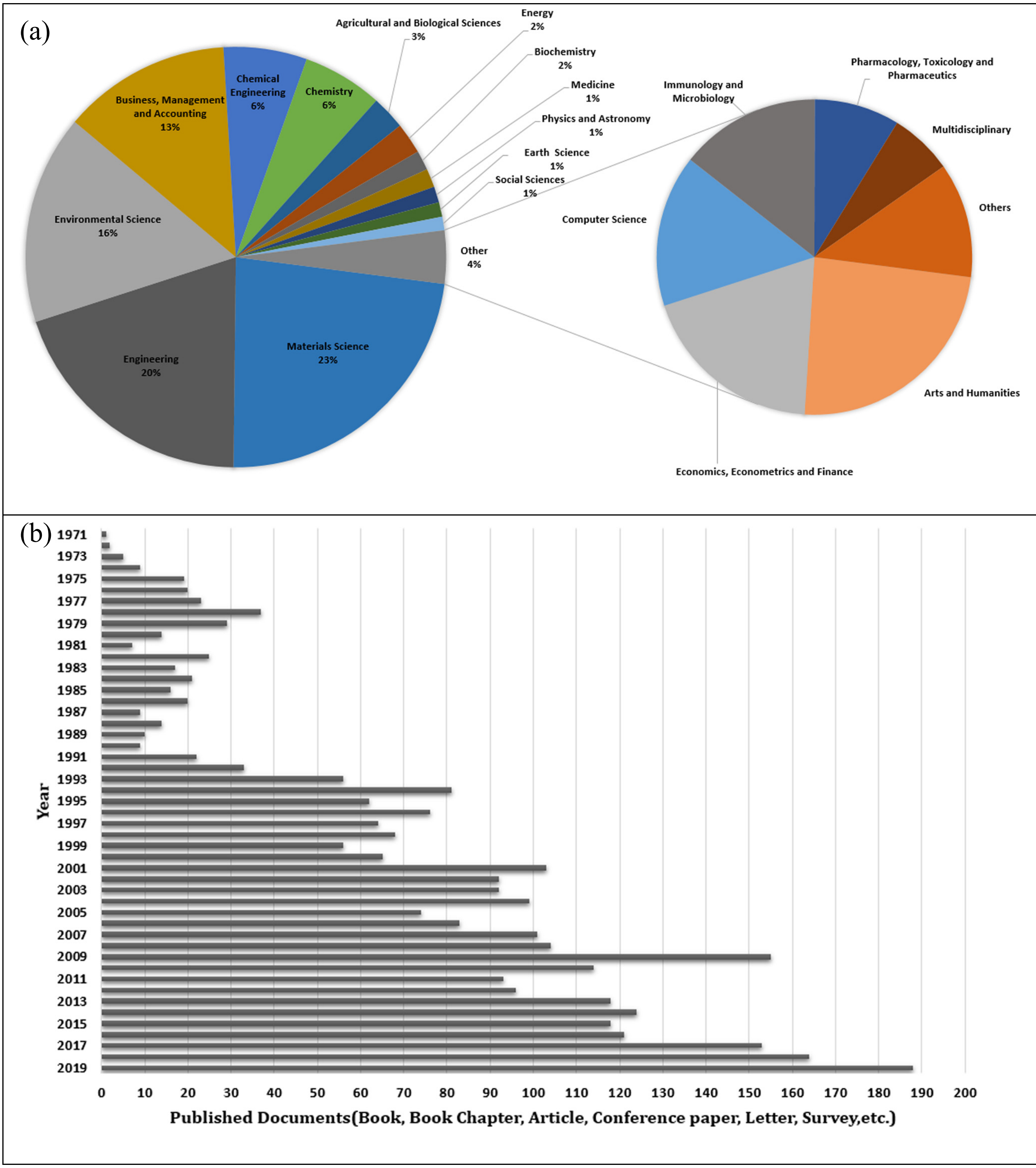


Fig. 4. Documents published in a field of textile recycling based on SCOPUS data. (a): comparison of the documents based on the subject area and (b): documents published in different years (Dec 2019).

customers for recycled products should be considered as essential elements for effective recycling (Ahmad et al., 2016).

6.1. Some case studies in technical reuse of textile waste

Textile wastes have been used in different ways to make more sustainable/valuable and effective structure from waste materials. Table 2 summarises some of the research which have been performed in a field of repurposing of the textile waste for value added products. It is observed that there are lots of opportunities to use cotton and textile waste for various applications including composites, microbial fuel cell, potassium-ion exchange, biochar environmental applications (catalyst/adsorbent), sound absorber, thermal insulator, EMI shielder etc. (see Table 2).

Echeverria et al. (Echeverria et al., 2019) reported the recovery of assorted end-of-life textiles with the emphasis on promoting multi-stage cascading use of mixed fibre bulk, as a low-carbon alternative feedstock, for the advancement of textile fibre reinforced composite (TFRC)

Table 1
Different strategies proposed in manufacturing, consumption and post-consumption of textiles for reducing the textile waste generation and recycling opportunities.

Step 1	Manufacturing	Rethink	Use renewable resources (Chen and Burns, 2006)
			Made reusable and recyclable products (Chen and Burns, 2006)
			Fully bio-gradable (Chen and Burns, 2006)
			Increase product quality
		Reduce	Reducing the energy consumption in manufacturing process
			Decrease the use of natural resources and materials
Step 2	Consumption	Rethink	Buy high quality products
			Buy for long term
			Good maintenance of the product
			Multipurpose buying
			Support sustainable products and local suppliers
		Reuse	Swap
			Borrow
			Renting, Trading (second hand shops, garage sell…)
			Donate to charities
		Repurpose	Use discarded product or its parts for new purpose (cleaning, making toys …)
Step 3	Post-consumption	Recycle	Monomer, oligomer, polymer recycling
			Fibre recycling
			Fabric recycling
		Repurpose	Use materials (recycled fabrics, fibre) for new purpose such as insulation, blanket, rags
		Repair	Repair defective products and resell it with low price
		Recover	Energy recovery (heat or electricity) via incineration

materials for construction applications. For this purpose, a homogeneous micro-fibrillated randomly oriented fine fleece constituted by polymers and bio-polymers mixture of thermoplastics (i.e. polyester, acrylic), lingo-cellulosic (i.e. cotton), and protein polymers (i.e. wool) were studied as the main filler phase. Wood fibre was used as secondary filler; and fibrillated polypropylene textile waste was incorporated as the thermoplastic matrix phase, optimizing the filler/matrix interfacial adhesion with maleic anhydride grafted polypropylene coupling agent as 6 wt%. These results confirm an effective compatibility between diverse fibre wastes as composite blend mixture for TFRCs, providing a non-toxic low-carbon alternative material for high-end building applications (Fig. 5a).

In other works developed by Shirvanimoghaddam et al. (Shirvanimoghaddam et al., 2019b; Shirvanimoghaddam et al., 2019c), cotton wastes have been used in direct pyrolysis process to fabricate high performance carbon microtubes. Different grades of carbon microtubes were prepared with change in the carbonization temperature that resulted in change in surface area of final carbon microtube and its performance in BPA removal and tannic acid adsorption (Fig. 5b–e). The cotton-derived carbon microtube has a great potential

Table 2
Some of technical research performed in a field of textile waste repurposing.

Application	System/material	Performance	Ref.
Cellulose fibres	Cotton waste	Superior properties compared to commercial Viscose or Lyocell	(Haslinger et al., 2019)
Sound absorbing	Denim waste	High efficiency comparable to glasswool	(Raj et al., 2020)
Sound absorbing	Short Cotton Fibre Waste/Recycled Acrylonitrile Butadiene Styrene Composites	High-level sound transmission loss and deficient sound absorption properties	(Can, 2019)
Microwave absorption	Nickel nitrate and waste cotton as precursors	High EM absorption behaviour for composites filled with 10 wt% of magnetic porous carbon.	(Wei et al., 2018)
Building material	Cotton and recycle paper mill waste as starting materials	Production of brick which weighs half of that of the conventional clay brick: Potential to be used as internal partition wall.	(Rajput et al., 2012)
Microcrystalline cellulose (MCC)	Waste cotton fabrics as a starting material	MCC exhibited higher crystallinity, smaller size, and narrower particle size distribution compared with Commercial sample.	(Hou et al., 2019)
Polyester concrete	Cotton fibres from Blue-Jeans	40% improvement in compressive strength and 7% in flexural strength.	(Peña-Pichardo et al., 2018)
Activated carbon	Cotton (Gossypium malvaceae) processing waste materials	High adsorptive ability for iodine, chlorine and sulfur dioxide.	(Sartova et al., 2019)
Heavy metal removal	Waste cotton fabrics and polyacrylamide(PAM)	The Cellulose/PAM double network hydrogel (DNH) exhibit fast kinetic, large adsorption capacities and reversible adsorption properties.	(Ma et al., 2018)
Heavy metal adsorbent	Waste textile Lyocell	Adsorption of Cd (II): the adsorbent was found to have ~17 times higher uptake than the original material.	(Bediako et al., 2016)
Biochar	Different types of textile fibres (cotton, viscose, polyester, acrylic) and their blends	• Temperature: have an effect on biochar yield • Fibre type: have an effect on energy densification ratio and biochar properties.	(Hanoğlu et al., 2019)
Microbial fuel cells (electrode)	Waste cotton textile	The power density of microbial fuel cells with carbonized polydopamine-modified cotton textile (NC@CCT) is 80.5% higher than that of carbon felt.	(Zeng et al., 2018)
BPA removal/tannic acid adsorption	Carbon Microtube derived from cotton waste	High catalysis and removal efficiency comparable to CNT and other commercial products.	(Shirvanimoghaddam et al., 2019a; Shirvanimoghaddam et al., 2019b)
Metal matrix composite (reinforcement)	Carbon Microtube(CMT) derived from cotton waste and Titanium	Higher mechanical performance of Ti/CMT compared to Ti/CNT and pure Titanium	(Shirvanimoghaddam et al., 2019c)
Potassium-ion storage (anode)	Wasted wet wipes	N/S-codoped porous hard carbon exhibits superior performance for potassium ions storage due to 3D structure, high surface area (357.68 $m^2\ g^{-1}$) and synergistic effects of nitrogen and sulfur codoping.	(Wang et al., 2019)

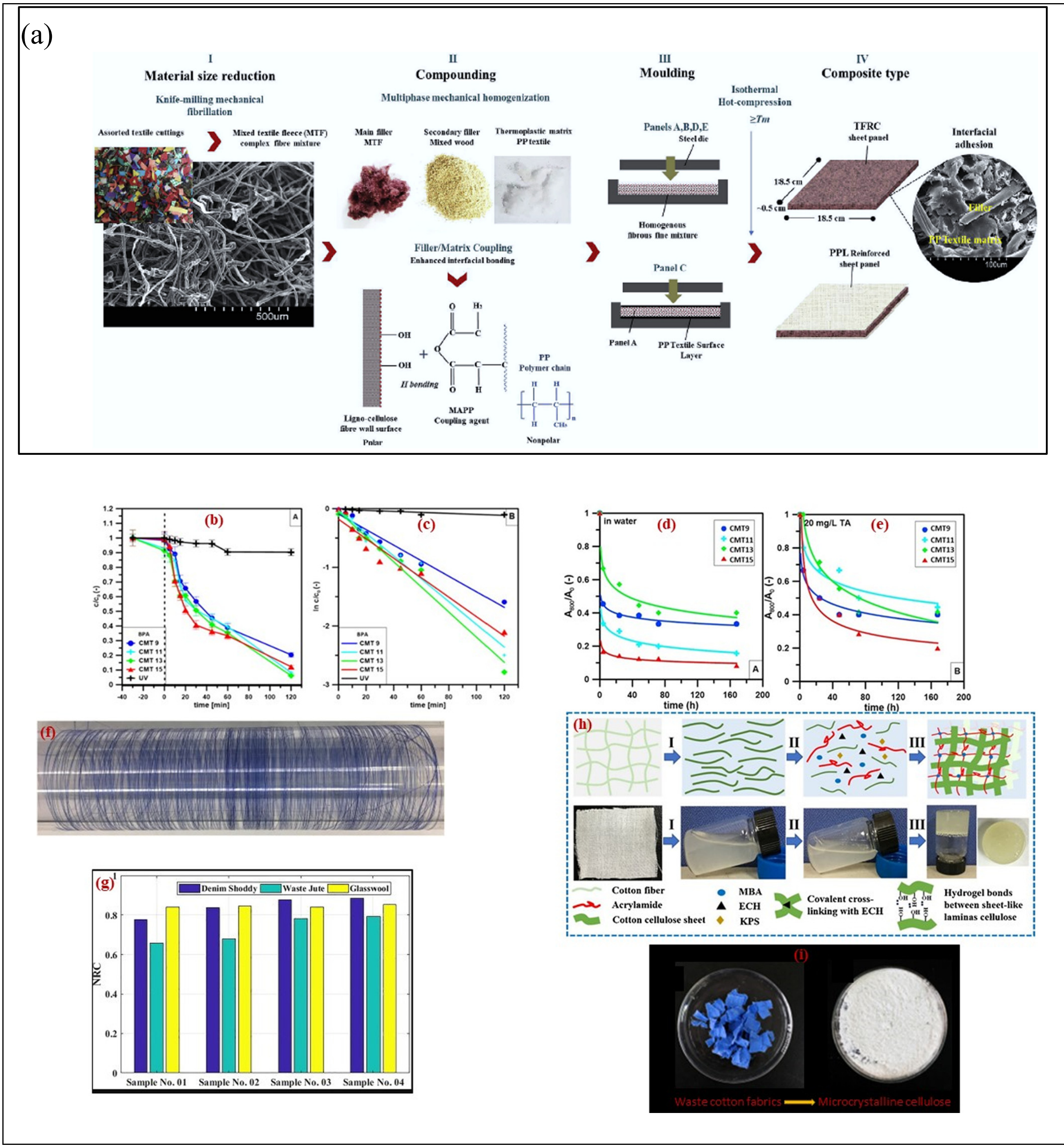


Fig. 5. Textile fibre reinforced composite manufacturing process (Echeverria et al., 2019) (a); the potential of using of textile waste for environmental applications: BPA removal (b and c) (Haslinger et al., 2019); development of carbon microtube from textile waste for tannic acid adsorption application (d, e). (Shirvanimoghaddam et al., 2019a); regenerated cellulose fibres from blue cotton t-shirt (Liu et al., 2019) (f); comparison of Noise Reduction Coefficient NRC values of denim shoddy, waste jute fibres and glasswool (g) (Raj et al., 2020). Preparation of waste cotton fabrics based double network hydrogel. (I) Dissolution of waste cotton fabric(II) preparation of sol containing cellulose solution and (III) the gelation of the obtained sol for heavy metal removal applications (h) (Ma et al., 2018); extraction of microcrystalline cellulose from waste cotton fabrics (Shi et al., 2018) (i).

to replace the currently used catalysts such as CNT in wastewater treatment. The incredibly low cost of the prepared carbon microtubes along with its excellent degradation stability and high surface area make it an ideal candidate for various environmental applications (Shirvanimoghaddam et al., 2019b).

In other work, cotton waste was chemically recycled and used for development of regenerated fibres using eco-friendly alkaline/urea solvent systems. For reducing the molecular weight of cotton fibres, both coloured and white cotton waste was shredded and hydrolyzed using sulfuric acid. Two solvent systems, i.e., sodium hydroxide/urea and lithium hydroxide/urea, were used to dissolve the hydrolyzed cotton to prepare solutions for fibre regeneration by wet spinning. Using this recycling method, fibres with tensile properties comparable to current commercial regular rayon fibres made from wood pulp could be produced, and dyes in the original cotton waste could be conserved to produce fibres with intrinsic colours, thus eliminating the need for dyeing processes. This study demonstrated an economical upcycling method for post-consumer cotton waste with environmentally friendly solvents (Liu et al., 2019).

Haule et al. (Haule et al., 2016) repurposed the cotton waste garments by fibre regeneration. Easy care finished cotton fabrics and indigo dyed waste denim garments were successfully purified, dissolved in a NMMO solvent and spun into fibres. The physical properties of the resultant fibres were compared with standard lyocell fibres spun from wood pulp and the fibres regenerated from the cotton waste garments exhibited improved mechanical and molecular properties relative to the typical fibres regenerated from wood pulp. Furthermore the results have indicated that a suitable blend of wood pulp and pulp reclaimed form cotton based waste garments can produce fibres with properties that are intermediate to cotton and lyocell fibres. It is observed the fibres spun from cotton waste garments have higher molecular weight and specific gravity than standard lyocell fibres. Furthermore results indicated that the ReCell type fibres have higher tensile performance and exhibited better wet strength recovery than the comparable lyocell fibres. It is clear that the waste cotton can be regenerated into fibres with acceptable physical/mechanical performance similar to the lyocell fibres. It is believed that there is an opportunity to mix the pulp derived waste garments with wood pulp to make high performance fibres with properties similar to lyocell (Haule et al., 2016).

The use of ionic liquid is another approach that has been used for reusing of cotton waste for fabrication of cellulosic fibre. In a work performed by Asaadi et al. (Asaadi et al., 2016) cotton postconsumer textile wastes were solubilized fully in the cellulose-dissolving ionic liquid 1,5-diazabicyclo[4.3.0]non-5-enium acetate ([DBNH]OAc) to be processed into continuous filaments. As a result of the heterogeneous raw material that had a different molar mass distribution and degree of polymerization, pre-treatment to adjust the cellulose degree of polymerization by acid hydrolysis, enzyme hydrolysis, or blending the waste cotton with birch prehydrolyzed Kraft pulp was necessary to ensure spinnability. Fibres with a tenacity (tensile strength) of up to 58 cNtex@1 (870 MPa) were prepared, which exceeds that of native cotton and commercial man-made cellulosic fibres (Asaadi et al., 2016).

The potential of textile waste to be used as a sound-absorbing structure has been studied by different groups. In a work performed by Raj et al. (Raj et al., 2020). Denim shoddy and waste jute fibres have been used as a starting materials and their absorbing performance have been compared with glasswool. It is observed that denim shoddy performed better than the commercial glasswool and have fetched a very high Noise Reduction Coefficients (NRC) (see Fig. 5h–j).

7. Recycled textile industrial applications

By revealing the importance of reuse and recycling in improving future circular economy by Ellen MacArthur Foundation (Foundation, E. M, 2017), the attention and interest of textile industry in reuse and recycling is rising rapidly (Fig. 6). Below are some examples of application of recycled textiles in various industries and products:

- Building industry and construction sector has various potential applications for recycled textiles (woven fabric waste and a waste of this residue) as a thermal and acoustic insulation (Ahmad et al., 2016), ventilation purposes, conductivity, making lightweight materials (concrete and bricks) (Briga-Sá et al., 2013);
- Use of textile waste for environmental applications: Use of cotton waste as a sustainable and inexpensive catalyst for water treatment, pollution remediation and removal of Bisphenol A (BPA) in wastewater (Shirvanimoghaddam et al., 2019a; Shirvanimoghaddam et al., 2019b).

- Paper industry: use of textile waste for wearing felts for paper production (Bhatia et al., 2014) and use of recycled denim for making paper

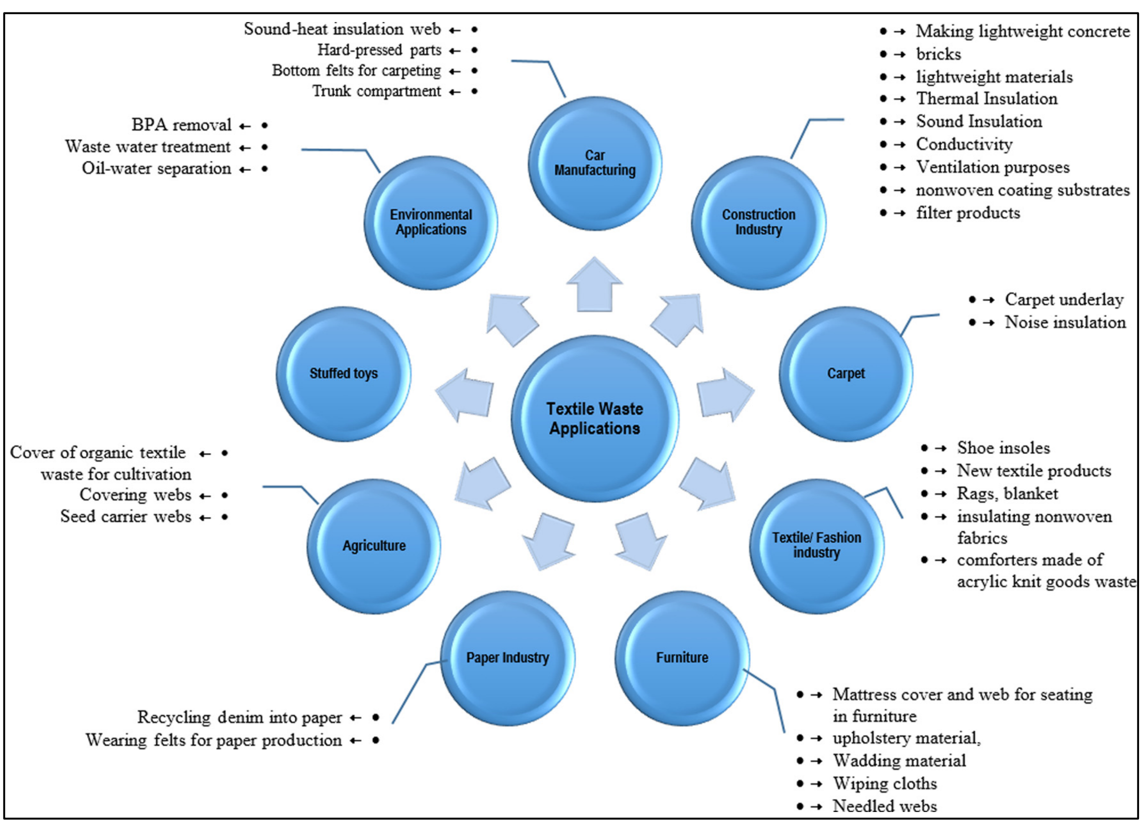


Fig. 6. Applications for recycled textile waste in different industries.

(Travers, 2017);

- Textile and fashion industry: Use of textile waste by big fashion and apparel brands for production of new textile products.
- Carpet industry: use of textile waste as a noise insulation and carpet underlay.
- Automobile industry: use of recycled textile waste as a sound and heat insulation web, making hard-pressed parts for seat linings, floors and bottom felts for carpeting (Bhatia et al., 2014).
- Agriculture industry: use of textile waste as a layer for covering the surface for cultivation which can collect more water from air humidity to promote microbial life (Eriksson, 2017). Moreover, recycled textile can be used as a covering and seed carrier web (Bhatia et al., 2014).
- Furniture industry: recycled textile waste can be used in making mattress cover and web for seating in furniture, upholstery material, wadding material and needled webs
- Toys: recycled textile waste can be used in making stuffed toys which are made from plain clothes and pile textile.

8. Concluding remarks and Fashion Foresight

With the rising concern over environmental and social sustainability, energy and water consumption and pollution, scarcity of natural resources and emission of greenhouse gases, the textile industry, which generates a substantial environmental footprint from cultivation, fabric manufacturing, to the landfill disposal of post-consumer items, is facing tremendous environmental and resource challenges. Due to the high volume of textile waste that is produced around the world, textile reuse and recycling can be a sustainable solution for reduction in solid waste in landfill, reducing the production of virgin materials and energy consumption and environmental footprint.

World Fashion leaders have committed to support and implement the 16 principles and targets that underpin the Fashion Climate Charter (https://unfccc.int/news/milestone-fashion-industry-charter-for-climate-action-launched, n.d.). It is open for other manufacturers to join, recognizes the crucial role that fashion plays on both sides of the climate equation; as a contributor to greenhouse gas emissions, and as a sector with multiple opportunities to reduce emissions while contributing to sustainable development. Based on the Paris Agreement, the Charter contains the vision for the industry to achieve net zero emissions by 2050 and defines issues that will be addressed by signatories, ranging from decarbonisation of the production phase, selection of climate friendly and sustainable materials, low-carbon transport, improved consumer dialogue and awareness, working with the financing community and policymakers to investigate scalable solutions in circular economy models (https://unfccc.int/news/milestone-fashion-industry-charter-for-climate-action-launched, n.d.). The initial target is to reduce their aggregate greenhouse gas emissions by 30% by 2030 and have defined concrete measures, such as phasing out coal-fired boilers or other sources of coal-fired heat and power generation in their own companies and direct suppliers from 2025 (https://unfccc.int/news/milestone-fashion-industry-charter-for-climate-action-launched, n.d.). The followings are the main streams that started or need to be targeted for textile waste reduction in fashion industries:

- Using of new raw materials in fashion industry that have less environmental impact:

❖ *Bamboo*: hypoallergenic, absorbent and fast-growing. Processing of bamboo uses less pesticides and fertilizers, and is considered a sustainable choice among other fabrics.
❖ Silk: Soft material with no harsh dyes in conventional silk production method.
❖ Hemp: Easy to cultivate and fast-growing with good quality for various applications (https://info.esg.adec-innovations.com/blog/alternative-materials-for-sustainable-clothing, n.d.).

- Substitution of input material used in a process (replacement of chemical dyes with natural dyes.
- Modification of technology/equipment (development of wastewater treatment on site) (Jafari et al., 2016; Tara et al., 2019; Hu et al., 2019)
- Development of high performance membrane nano reactor for textile wastewater treatment
- Targeting Energy saving in fabrication
- Implementation of Industry 4.0 and additive manufacturing to reduce the rate of waste generation in production processes.
- Optimization of chemical uses: using of automated dosing machines and controllers in different steps of production
- Use of Internet of things (IOT) technology for different stages of farming(smart farming), fabrication of textile and recycling of clothes (Abolhasani et al., 2019; Abolhasani et al., 2018; Shirvanimoghaddam et al., 2019d; Mahbub, 2020; Glaroudis et al., 2020)
- Process alternatives: pulsating rinse technology
- Water recycling and reuse:

o Recycling and reuse of cooling water
o Condensate water
o Bleach bath recovery system

- Lowering the processes temperature for energy saving(dying, printing, finishing)
- PET bottle to textile: Recycled PET based textile is an eco-friendly fabric made of recycled PET bottles.
- Processes by safe biochemical processes, which affect the properties of fibres and textiles.
- Use of Enzyme biocatalysis for treatment processes of fibres and textile materials
- Biopolymers and biomasses as new materials for surface modification of textiles
- Development of enzyme systems and extending their applications in surface treatment for functionalization of textile substrates.
- Multifunctionality of the Textile for use in wider applications: smart textiles.
- Considering Circular plastic approach for maximizing the use of Plastic waste such as PLA and PET in fashion industry

Declaration of competing interest

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

References

ABC News, L, 2017. Fast Fashion: Rivers Turning Blue and 500,000 Tonnes in Landfill.
Abolhasani, M.M., et al., 2018. Towards predicting the piezoelectricity and physiochemical properties of the electrospun P(VDF-TrFE) nanogenerators using an artificial neural network. Polym. Test. 66, 178–188.
Abolhasani, M.M., et al., 2019. Thermodynamic approach to tailor porosity in piezoelectric polymer fibers for application in nanogenerators. Nano Energy 62, 594–600.
aboutorganiccotton, 2019. When You Choose Organic Cotton You Save.
Ahmad, S.S., et al., 2016. The application of recycled textile and innovative spatial design strategies for a recycling centre exhibition space. Procedia - Social and Behavioral Sciences 234, 525–535.
Allwood, J.M., et al., 2006. Well Dressed? The Present and Future Sustainability of Clothing and Textiles in the United Kingdom. University of Cambridge, Institute for Manufacturing, Cambridge, UK.
Asaadi, S., et al., 2016. Renewable high-performance fibers from the chemical recycling of cotton waste utilizing an ionic liquid. 9 (22), 3250–3258.
Bediako, J.K., Wei, W., Yun, Y.-S., 2016. Low-cost renewable adsorbent developed from waste textile fabric and its application to heavy metal adsorption. J. Taiwan Inst. Chem. Eng. 63, 250–258.
Belk, R., 2014. You are what you can access: sharing and collaborative consumption online. J. Bus. Res. 67 (8), 1595–1600.
Bhatia, D., Sharma, A., Malhotra, U., 2014. Recycled fibers: an overview. International Journal of Fiber and Textile Research 4 (4), 77–82.

Briga-Sá, A., et al., 2013. Textile waste as an alternative thermal insulation building material solution. Construction and Building Materials. 38. Elsevier, pp. 155–160.
Can, Y., 2019. Sound insulation performance of short cotton fibre waste/recycled acrylonitrile butadiene styrene composites. Acta Phys. Pol. A 135, 772–774.
Chen, H., Burns, D.L., 2006. Environmental analysis of textile products. Clothing and Textile Research Journal (CTRJ) 24 (3), 248–261.
Drew, D., Reichart, E., 2019. These Are the Economic, Social and Environmental Impacts of Fast Fashion.
Echeverria, C.A., et al., 2019. Cascading use of textile waste for the advancement of fibre reinforced composites for building applications. J. Clean. Prod. 208, 1524e1536 Elsevier.
EPA, 2017. Textiles: Material-specific Data.
Eriksson, B.G., 2017. Organic textile waste as a resource for sustainable agriculture in arid and semi-arid areas. Ambio 46 (2), 155–161 Springer.
Foundation, E.M, 2017. Circular Economy System Diagram.
Glaroudis, D., Iossifides, A., Chatzimisios, P., 2020. Survey, comparison and research challenges of IoT application protocols for smart farming. Comput. Netw. 168, 107037.
Gulich, B., 2006. Designing textile products that are easy to recycle. In: Wang, Y. (Ed.), Recycling in Textiles. Woodhead Textiles Series, pp. 25–37.
Hanoğlu, A., Çay, A., Yanık, J., 2019. Production of biochars from textile fibres through torrefaction and their characterisation. Energy 166, 664–673.
Haslinger, S., et al., 2019. Recycling of vat and reactive dyed textile waste to new colored man-made cellulose fibers. Green Chem. 21 (20), 5598–5610.
Haule, L.V., Carr, C.M., Rigout, M., 2016. Preparation and physical properties of regenerated cellulose fibres from cotton waste garments. J. Clean. Prod. 112, 4445–4451.
Hou, W., et al., 2019. Preparation and characterization of microcrystalline cellulose from waste cotton fabrics by using phosphotungstic acid. Int. J. Biol. Macromol. 123, 363–368.
http://theconversation.com/explainer-what-is-a-circular-economy-29666.
https://circularfashion.com/key-principles/.
https://fashionunited.com/global-fashion-industry-statistics/.
https://info.esg.adec-innovations.com/blog/alternative-materials-for-sustainable-clothing.
https://unfccc.int/news/milestone-fashion-industry-charter-for-climate-action-launched.
Hu, E., Shang, S., Chiu, K.-L., 2019. Removal of reactive dyes in textile effluents by catalytic ozonation pursuing on-site effluent recycling. Molecules 24 (15), 2755.
Jafari, H., et al., 2016. Enhanced photocatalytic activities of TiO_2–SiO_2 nanohybrids immobilized on cement-based materials for dye degradation. Res. Chem. Intermed. 42 (4), 2963–2978.
Khan, M.M.R., Islam, M.M., 2015. Materials and manufacturing environmental sustainability evaluation of apparel product: knitted T-shirt case study. Textiles and Clothing Sustainability 1 (1), 8.
Leblanc, R., 2018a. Textile Recycling Facts and Figures.
Leblanc, R., 2018b. Recycling and New Job Creation. The Role of Recycling Businesses in Opening New Employment Opportunities.
Lenzing, 2017. The Global Fiber Market in 2016. Available at. http://www.lenzing.com/en/investors/equity-story/global-fiber-market.html.
Leonas, K.K., 2017. The Use of Recycled Fibers in Fashion and Home Products. Springer Science+Business Media Singapore.
Liu, W., et al., 2019. Eco-friendly post-consumer cotton waste recycling for regenerated cellulose fibers. Carbohydr. Polym. 206, 141–148.
Ma, J., et al., 2018. Fast adsorption of heavy metal ions by waste cotton fabrics based double network hydrogel and influencing factors insight. J. Hazard. Mater. 344, 1034–1042.
Mahbub, M., 2020. A smart farming concept based on smart embedded electronics, internet of things and wireless sensor network. Internet of Things 9, 1–30 100161.
Milburn, J., 2016a. Aussies Send 85% of Textiles to Landfill.
Milburn, J., 2016b. The Number on Textile Waste.
Muthu, S.S., et al., 2012. Recyclability Potential Index (RPI): the concept and quantification of RPI for textile fibres. Ecol. Indic. 18, 58–62.
Palm, D., Elander, M., Watson, D., Kiørboe, N., Salmenpera, H., et al., 2014. Towards a Nordic Textile Strategy: Collection, Sorting, Reuse and Recycling of Textiles. 2014. TemaNord Nordic Council of Ministers.
Peña-Pichardo, P., et al., 2018. Recovery of cotton fibers from waste Blue-Jeans and its use in polyester concrete. Constr. Build. Mater. 177, 409–416.
Raj, M., Fatima, S., Tandon, N., 2020. Recycled materials as a potential replacement to synthetic sound absorbers: a study on denim shoddy and waste jute fibers. Appl. Acoust. 159, 107070.
Rajput, D., et al., 2012. Reuse of cotton and recycle paper mill waste as building material. Constr. Build. Mater. 34, 470–475.
Roos, S., et al., 2015. Environmental assessment of Swedish fashion consumption: Five garments–sustainable futures. A Mistra Future Fashion Report: Stockholm, Sweden.
Sandin, G., Peters, G.M., 2018. Environmental impact of textile reuse and recycling—a review. Journal of Cleaner Production. Elsevier 184, 353–365.
Sartova, K., et al., 2019. Activated carbon obtained from the cotton processing wastes. Diam. Relat. Mater. 91, 90–97.
Shi, S., et al., 2018. Extraction and characterization of microcrystalline cellulose from waste cotton fabrics via hydrothermal method. Waste Manag. 82, 139–146.
Shirvanimoghaddam, K., et al., 2019a. Sustainable carbon microtube derived from cotton waste for environmental applications. Chem. Eng. J. 361, 1605–1616 Elsevier.
Shirvanimoghaddam, K., et al., 2019b. The light enhanced removal of Bisphenol A from wastewater using cotton waste derived carbon microtubes. J. Colloid Interface Sci. 539, 425–432.
Shirvanimoghaddam, K., et al., 2019c. Super hard carbon microtubes derived from natural cotton for development of high performance titanium composites. J. Alloys Compd. 775, 601–616.
Shirvanimoghaddam, M., et al., 2019d. Towards a green and self-powered internet of things using piezoelectric energy harvesting. IEEE Access 7, 94533–94556.
Souchet, F., 2019. Fashion has a huge waste problem. Here's how it can change. World Economic Forum: Online https://www.weforum.org.
Spring, A., 2017. Landfill Becomes the Latest Fashion Victim in Australia's Throwaway Clothes Culture. Online, The Guardian.
statistics, A.B.o, 2013. 4655.0.55.002 - Information Paper: Towards the Australian Environmental-Economic Accounts. Chapter 4 Waste.
Tara, N., et al., 2019. On-site performance of floating treatment wetland macrocosms augmented with dye-degrading bacteria for the remediation of textile industry wastewater. J. Clean. Prod. 217, 541–548.
Travers, P., 2017. War on Waste: Recycling Denim into Paper and Fostering Social Inclusion in the Process.
Wang, Y., 2010. Fiber and textile waste utilization. Waste Biomass Valor. 1(1). Springer Netherlands, pp. 135–143.
Wang, L., et al., 2019. Nitrogen/sulphur co-doped porous carbon derived from wasted wet wipes as promising anode material for high performance capacitive potassium-ion storage. Materials Today Energy 13, 195–204.
Wei, Y., et al., 2018. Waste cotton-derived magnetic porous carbon for high-efficiency microwave absorption. Composites Communications 9, 70–75.
Wiedemann, S.G., et al., 2016. Resource use and greenhouse gas emissions from three wool production regions in Australia. Journal of Cleaner Production. Elsevier 122, 121–132.
Zeng, L., Zhao, S., He, M., 2018. Macroscale porous carbonized polydopamine-modified cotton textile for application as electrode in microbial fuel cells. J. Power Sources 376, 33–40.