



Circular economy approach to recycling technologies of post-consumer textile waste in Estonia: a review

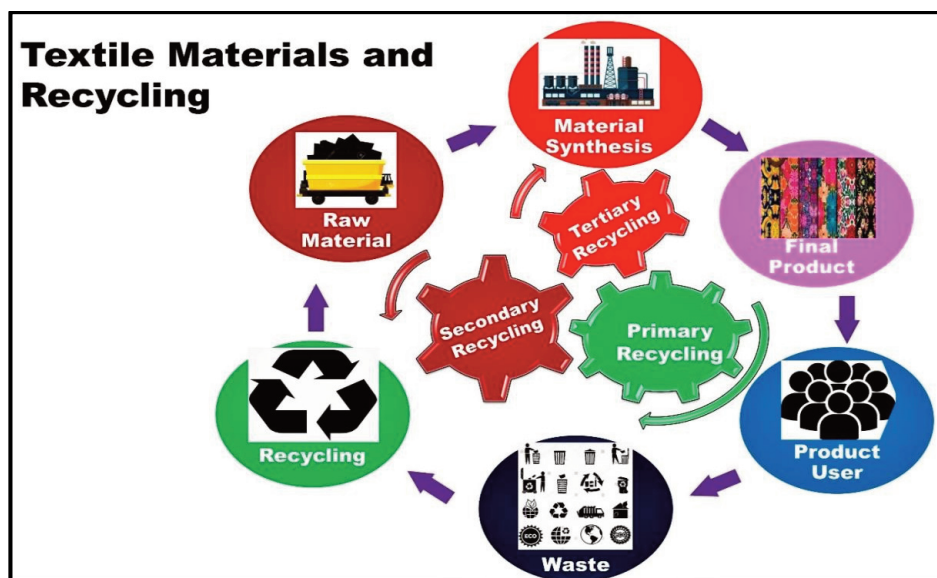
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Graphical abstract:



Abstract. Circular economy and recycling of post-consumer textile waste is gaining momentum. Its major obstacle is low-quality recycled products. This review article analyses commercial post-consumer textile materials, their recycling and applications. Modernization of fibre processing and recycling technology has assumed an indispensable role in the quality enhancement of post-consumer products. A futuristic overview of fabric materials, their processing, recycling and applications is presented by the example of commercial polymers. Different types of recycling – primary, secondary, tertiary, quaternary, and biological – used with ultramodern compatibilization and cross-linking are explored. Additionally, the conventional and proposed “Just-in-Time” (JIT) remanufacturing and recycling technologies for enhancing circular economy are demonstrated.

Key words: circular economy, post-consumer textile waste, textile recycling, waste management, end-waste, Just-in-Time manufacturing, end-of-life waste.

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1. INTRODUCTION

Circular economy is an industrial system that manufactures products with negligible waste [1]. It originates from the theory of a common industrial system [2], cradle to cradle recycling [3] and performance economy [4]. It has appeared as an innovative solution for the transformation of textile waste into valuable recycled products.

The global need for textile products and goods is climbing constantly. Generally, 63% of textile materials are procured from petrochemical products and 37% are extracted from natural resources [5]. Secondary textile material processing, e.g. weaving, knitting or spinning, as well as dyeing, finishing or printing treatments are considered to be major origins of CO₂ emissions and other types of pollution [6,7]. These provocations draw attention to recycling of textile materials, which principally enhances their service life for practical applications [8].

Natural and synthetic fibres are a prime fount of textile materials. Cotton, wool, silk and hemp are vital natural fibres used for commercial or mercantile applications. Likewise, various thermoplastics and thermosetting materials are paramount sources of synthetic fibres [9]. The quantity of the yearly produced fibres (as illustrated in Fig. 1, [10]) could be re-utilized after their initial applications.

There are two primary types of waste – pre-consumer and post-consumer waste [11,12]. Pre-consumer waste appears due to defective samples and scrap. Similarly, post-consumer waste originates because of end-use or disposed products. Representative examples of these types

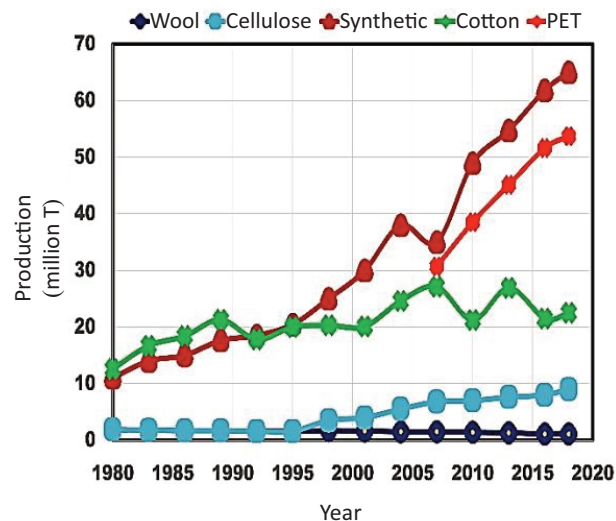


Fig. 1. Yearly quantity of world fibre production.

of waste are packaging materials (bottles, bags, etc.), abandoned goods (cars, computers, cell phones, furniture, etc.), demolished materials in construction (pipes, carpets, insulation materials, etc.) and disposable items [13,14].

Recycling and value recovery from textile waste is achieved through new applications, sorting, purification, separation and sustainable processing of waste [15,16]. End-waste (EW), post-consumer (PC) and end-of-life waste (EOL) are recycled by primary, secondary, tertiary, quaternary, and biological recycling into useful products [16,17]. Polyesters (PES), polypropylene (PP), polyvinyl chloride (PVC), high-density polyethylene (HDPE),

Table 1. Commercial post-consumer waste and recycling technology

Waste type	Textile materials	Separation operation	Recycling process	Product
EW/PC/EOL	Polyesters, cotton, thermoplastics	Collection and sorting	Primary	Respective recycled product
EW	Scrap and defective materials (natural and synthetic fibres)	Manual separation and automatic sorting	Primary & secondary	Material recovery & recycled product
EW/PC	PVC, PET, PS, PP, PU	Electrostatic and magnetic separation	Tertiary	Material recovery
EW/EOL/PC	PVC, PET, PS, PP, PU	Compatibilization and cross-linking	Feedstock	Material recovery
EW/EOL/PC	Contaminated specified waste	Manual and auto	Incineration	Energy production
EW/EOL/PC	Contaminated waste	Compatibilization	Biodegradable/quaternary	Material recovery and energy production

polyethylene terephthalate (PET), low-density polyethylene (LDPE), cotton, silk, hemp, wool and other thermoplastics are recycled commercially [18–20]. The details are shown in Table 1.

The objective of this review is to describe the processing of commercial textile waste by modern recycling technologies. A detailed description is given of the continuous recycling processing which generates a minimum amount of waste, contributing thus to circular economy and reducing textile waste. The relevant market assessment and the latest knowledge about fabric materials are also presented. Our review article focuses substantially, but not exclusively, on the recycling of textile waste that is accessible in enormous quantities or can be recycled precisely. The conventional and advanced methodologies, e.g. Just-in-Time (JIT) methodology, are also compared.

2. POST-CONSUMER TEXTILE WASTE IN ESTONIA

The total yearly utilization of textile materials in Estonia is more than 62 million tons. Of total waste, the potential for recycling is greater than 27 million tons. The entire volume of textile and apparel fabrics includes 27.212 million tons of local production, 12.064 million tons of imported textiles for shops and user applications, and more than 22 million tons are used for export. The total material outflow and inflow capacities of Estonia are 27 million tons and 26 million tons, respectively [21].

An analysis on the composition of waste reports that municipal waste in Estonia contains 25% plastics and textiles, 3% wood, 2% ferrous metals, 1% non-ferrous metals, 1% paper, 1% glass, 1% rubber and 65% other rejected waste. Of the above-mentioned waste, 11% was used for recycling, 78% for energy production, and 11% termed as neutral waste was utilized for landfill [13,14]. Figure 2 illustrates the distribution of municipal waste in Estonia [22].

3. TEXTILE MATERIALS

Textile materials can fundamentally be grouped into natural and synthetic materials. In textile engineering, fibre is a technical term specifying textile materials. Crops and animals are the principal origin of natural fibres [23,24]. As shown in Fig. 3, natural fibres such as cotton, hemp, sisal, coco, henequen, jute, kenaf, kapok and ramie are derived from plants. Silk, diverse hairs and wool fibres are procured from animals. Similarly, synthetic textile materials are classified into organic and inorganic textile materials. Plastics and thermosetting textile materials, for

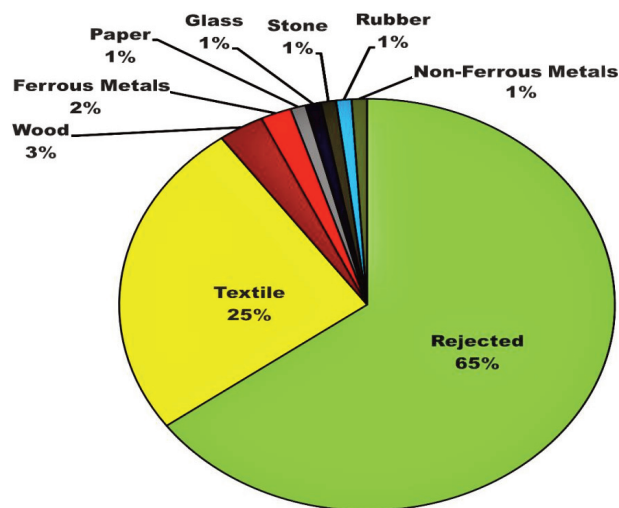


Fig. 2. Daily municipal waste distribution in Estonia.

example, PVC, PE, PET, PS, HDPE, LDPE, viscous materials, modal materials and even composites, result in waste after their service life [25]. Formally, it generates end-waste, post-consumer waste and end-of-life waste. End-waste and post-consumer waste undergo primary and secondary recycling, respectively. Mostly, end-of-life polluted waste is processed through tertiary, biodegradable and incineration recycling to produce new products or energy [26,27].

4. RECYCLING TECHNOLOGY

Fibre technology is mainly concerned with apparel, industrial and home decoration applications. The reproduction of textile materials from their waste and transformation into a useful product is termed as recycling. Generally, recycling is categorized into primary, secondary, tertiary, and quaternary processing. Industrial byproducts and scrap are usually processed mechanically in primary and secondary recycling [28,29]. On the other hand, tertiary and quaternary recycling incorporates pyrolysis and burning of textile materials for energy generation. A wide range of textile materials are produced from natural and artificial fibres. These fibres, e.g. cotton, silk, nylon, rubber, and polyester will attain optimized strength, hardness, and abrasion or wear resistance when manufactured through knitting or weaving processes. Primary textile waste may be single or complex polymers that are usually easy to recycle. Post-consumer textile waste refers to fibrous materials that are discarded after use. The biodegradability of textiles depends on their natural materials. Generally, this waste is used for manufacturing clothes, carpets, belts, and composites

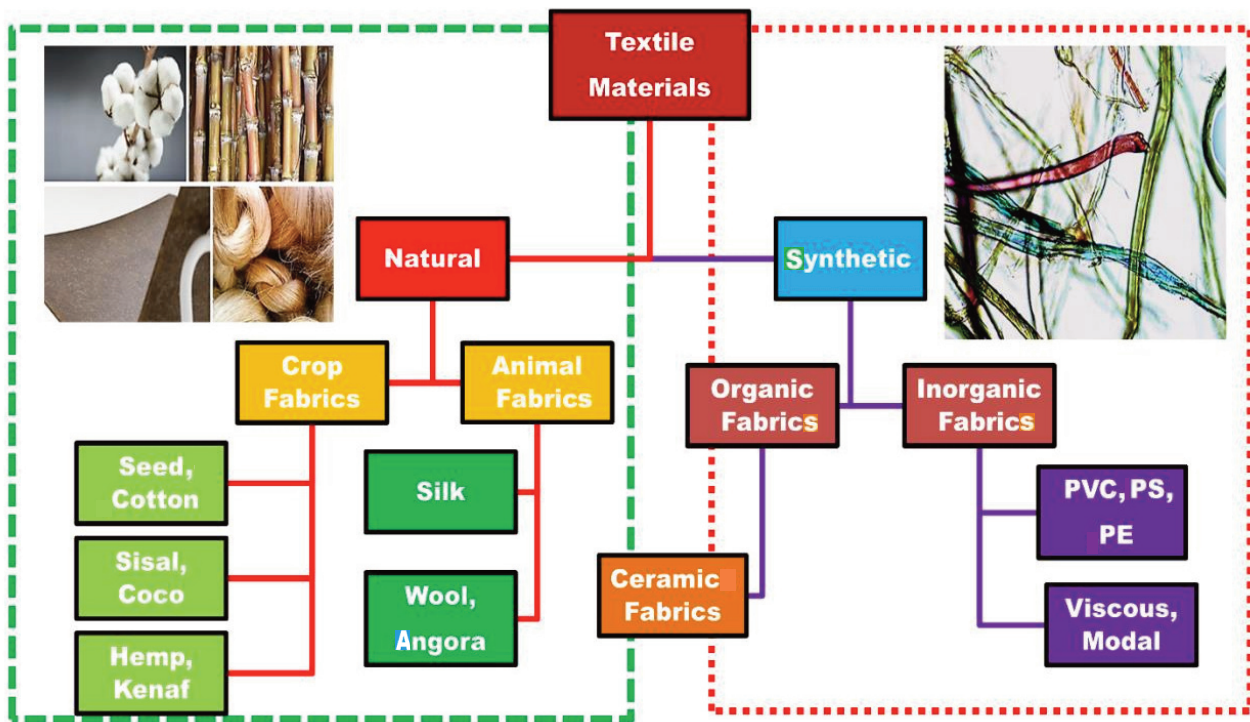


Fig. 3. Types of commercial textile materials.

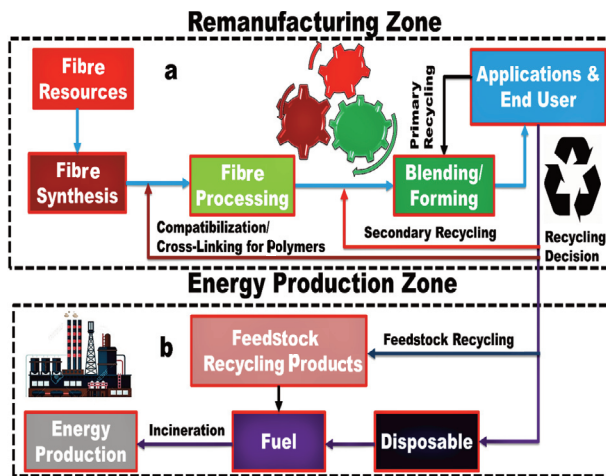


Fig. 4. Recycling flow chart for textile waste: (a) remanufacturing zone; (b) energy production zone.

[16,30–31]. Textile waste is usually shredded for reuse. Formally, automotive plastics, wool, silk, polyesters, polyethylene, and other plastic fabrics are easy to recycle when compared to thermosetting materials which cannot be re-melted or reshaped. Literature data of textile recycling and circular economy in the world is given in Table 2. The recycling flow chart proposed by the authors is demonstrated in Fig.4.

4.1. Textile waste separation and sorting

Commonly, the recycling of post-consumer waste is performed based on quality, availability, cost, the type of recycling process and the type of single or mixed textile materials [32, 33]. Before recycling of waste, the sorting process is carried out for textile material separation. Realff, Kip et al. [34,35] have developed a manual infrared spectrometer technique for wool, cotton, polyester, polyethylene, terephthalate, rubber, nylon 6,6 and other commercial polymers. In addition, a commercial automatic device was developed for separation of different textile materials. A piece of textile material is examined with the probe and transported via different tracks for identification of various fibres. The given data is estimated, analysed and displayed on the screen with the help of control units. The main objective of the separation and sorting is to separate different textile fabrics and the process is carried out either manually or preferably automatically. The recycling processing of textile waste is performed based on the sorting and separation results. After separation the waste undergoes size reduction and shredding [36].

4.2. Textile waste size reduction and shredding

After the sorting and separation process and before recycling, textile materials are shredded into small fibres

and yarns. Fibres and yarns of different sizes are shredded with hardened metal blades that are attached to rotary drums. Smaller and oversize fibres and yarns are not allowed to enter the main chamber. Optimized cutting and rotational speeds along with suitable torque are used for mechanical shredding. Almost all types of commercial polymers and textile materials are shredded with modern optimized mechanical shredders. Usually, shredding is performed to enhance mixing, increase purity of the product and optimize the respective recycling process. After size reduction, the following recycling processes (introduced in subsections 4.3–4.7) are considered for the manufacturing of new products [37–41].

4.3. Primary recycling

Primary recycling, also known as closed-loop recycling, is the process of manufacturing of a new textile product from waste with desired properties [42]. Before recycling, some more processes such as collection and sorting of textile materials are required. Initially, the textile materials are crushed, ground, shredded, or milled. After that, the fine fibres or yarns are mixed with additives and other polymer materials. The elementary processing yields

homogeneity and ease for purification or forming [50]. Usually molding, heat pressing, and extrusion are applied to polypropylene (PP), polyethylene (PE), polyethylene terephthalate (PET), and polyvinyl chloride (PVC) commercial thermoplastics for making different textile products. The primary recycling process can provide ease of production, impurity removal and stability to the product [51].

4.4. Secondary recycling

In secondary recycling processing, textile materials with unknown composition and purity are treated. Initially, some mechanical separation or purification treatments are employed to increase the purity. This purification and separation usually requires acids, additives, degassing and drying treatments which reduce the mechanical properties of textile materials [52]. In addition, contamination of the main polymer can decrease the mechanical properties of textile materials. Contamination increases due to the lowering of forming and blending compatibility or suitability with the matrix. Usually secondary processing is used for automotive, petrochemical and textile industries [43,53]. The composite is ground and the fine fibres are

Table 2. Literature data of textile recycling and circular economy in the world [43–50]

Serial No.	Author and publication year	Recycling process	Recycled materials	Recycled product
1	Esteve-Turrillas and de la Guardia (2017) [42]	Primary recycling	Cotton	Commercial production
2	Dahlbo et al. (2017) [43]	Shredding	Cotton, polyesters, cellulose	Fibres and yarns
3	Esteve-Turrillas and de la Guardia (2017) [42]	Cutting or shredding	Cotton	Fibres
4	Esteve-Turrillas and de la Guardia et al. (2017) [42]	Shredding	Cotton	Fibres
5	Zamani et al. (2017) [44]	Cutting and grinding	Elastane	Fibres and yarns
6	Beton et al. (2014) [45]	Primary and secondary recycling	Hemp, polyesters, cotton	Polymers and fibres
7	Glew et al. (2012) [46]	Primary recycling	Cotton, wool	Fibres
8	Palm et al. (2013) [47]	Primary recycling	Cotton, polyesters, cellulose	Fibres
9	Muthu et al. (2012) [48]	Primary and secondary recycling	Polyesters, polypropylene LDPE, HDPE, polyamide	Fibres
10	Williams et al. (2010) [49]	Primary recycling	Cotton and polyesters	Fibres

representative polymer materials for secondary recycling and are used for manufacturing of different automotive components. Commercially, different post-consumer textile and petrochemical materials such as PP, PE, HDPE, LDPE, PS, PET and PVC are mixed with each other in the presence of organic solvents like toluene, methanol and benzyl alcohol [54,55]. The nature of the secondary scrap, composition of the textile materials, purity grade of the final product, availability, types of additives, cost, and processing techniques are usually extensive factors which govern secondary recycling processing [56].

4.5. Tertiary recycling

Tertiary recycling (laboratory-scale technique) is also known as feedstock recycling. In tertiary recycling, hydrolysis, pyrolysis, gasification, condensation and hydrocracking are performed in the presence of transition metals [42,57]. Feedstock processing yields the monomers of polyurethane, PET, polylactic acid (PLA), polycarbonate (Poly.C) and wax by hydrolysis, condensation and gasification processing [58,59]. Other versatile and commercial plastics such as PP, PS, HDPE and PE are depolymerized by pyrolysis in the presence of transition metals [60]. The main shortcomings of tertiary recycling are that it constitutes only a subsidiary for industries, causes pollution and toxicity in terms of carbon or dioxin emissions, as well as high energy consumption [61]. Another major drawback is that it sets limits to large-scale production. Recently, in tertiary recycling a synthesis yielded nanotube production from PP, PS and PE polymer waste [62]. These aforesaid plastic polymers were transformed under reasonable conditions into respective carbon nanotubes. Sometimes transition metals are also employed for such a nanotube transformation process [63]. These newly formed nanomaterials have phenomenal applications in composites, electronic and biological industries [64].

4.6. Biodegradable recycling

Biodegradable recycling is especially performed for natural textile materials or fabrics. Special microorganisms and enzymes are utilized for degradation [65]. Hence, microorganism recycling is an advanced form of feedstock recycling. Diverse bacteria and fungi are applied under reasonable conditions [66]. Biological polymers such as cellulose, chitin, wood and hemp fibres are easily debased [5]. Moreover, organic compounds, e.g. butylene adipate-co-terephthalate, PET, polylactic acid (PLA), adipic dimethyl esters, 1,4-butanediol and hydrophilic lignocellulosic fibres, can be degraded under equitable conditions [67].

4.7. Plastic incineration and quaternary recycling

Incineration is the process of producing heat and energy from post-consumer textile waste. This textile waste is highly contaminated. In Europe, the discarded waste is commonly utilized for energy and heat production. Medical and toxic waste are main raw materials for incineration. Inorganic waste is utilized mostly for road construction. The heat and energy are typically used for cement, metal melting and chemical heating applications [68,69].

5. EUROPEAN PROJECTS ON PLASTIC RECYCLING

The following information regarding projects on plastic recycling has been presented on the European Commission website [70]:

- (1) German project LIFE00ENV/D/000348 for thermoplastics and wood fibre production. The product applications include house decoration;
- (2) Danish project LIFE04ENV/DK/000070 for manufacturing of rubber products. Chemical additives and polymer monomers are utilized for the removal of impurities. The products are blended by using the dense phase technique. Sports and rubber industries are typical applications;
- (3) German project L-FIRE undertakes the separation and recycling of Kevlar;
- (4) Belgian project FP7-ENV-2010: IRCOW addresses materials recovery from construction and post-consumer waste;
- (5) ECO/10/277225 SUPERTEX, SUPERCLEAN, DEVULCO2, PEGASUS and FP7-ECOMETEX are other similar innovative European projects on post-consumer textile waste, addressing the separation and recycling of automotive, polymer, chemical and electronic waste [27].

6. RECYCLED PRODUCT APPLICATIONS

In this section the commercial and economic aspects are presented. Generally, 24% of thermoplastics, thermosetting materials, coatings and textile fabrics of the world's production is manufactured in Europe. The major applications of post-consumers plastics include packages, products of electronics, textiles, construction and automotive industries. PS, PE, PET, PVC and nylon can be utilized to produce materials with HSLW (high-strength lightweight), high thermal and electrical resistance at a very low price.

Packaging materials account for 40% of the thermoplastic commercial applications. Usually, PET and PE are used. Construction materials, for instance, PVC (pipes, cables, electrical insulation), PO (carpets and textiles) and PU or PS (foams) supply 20% of the commercial applications. Generally, about 13% of the total volume of textile materials is utilized for underwear, outerwear, technical and industrial textile applications [13,14].

7. JUST-IN-TIME (JIT) MANUFACTURING MODEL FOR RECYCLING

JIT is a type of advanced manufacturing model based on continuous improvement and manufacturing. The raw materials which constitute mostly waste are delivered at the precise time they are required for the production process. In Fig. 5 the authors demonstrate the advanced model for recycling which enhances circular economy and reduces textile waste. First, the collected commercial post-consumer textile waste like cotton, polyester, cellulose, wool and PET are separated and sorted. The separation of post-consumer textile waste enables to decide immediately the desired process of recycling. Sorting and separation are applied to textile waste which has unknown

purity, non-homogeneity in mixing, lower mechanical properties and difficulty in blending.

After manual separation, the good quality fabric is reused directly for suitable applications. It mostly includes outerwear and innerwear. Generally, the scrap, defective and low-quality textile waste with negligible impurity and contamination undergo primary recycling. Thus, EW and PC waste is widely recycled. If impurities and contamination account for more than 20% of a particular waste material, secondary recycling is performed to manufacture a new product. This post-consumer waste is utilized as raw materials.

Tertiary recycling is used purely for contaminated textile waste. Biodegradable and incineration recycling are performed for highly contaminated and toxic textile waste to produce a new product and energy, respectively.

JIT practices and infrastructure can improve the quality and performance. It reduces the time for recycling and the cost of remanufacturing. Since JIT involves continuous improvement of manufacturing, it adds value to manufacture excellence. Primary and secondary recycling mostly process end-waste and post-consumer waste. Therefore, our model suggests that the recycling units employing primary and secondary recycling technologies should be installed in pre-manufacturing

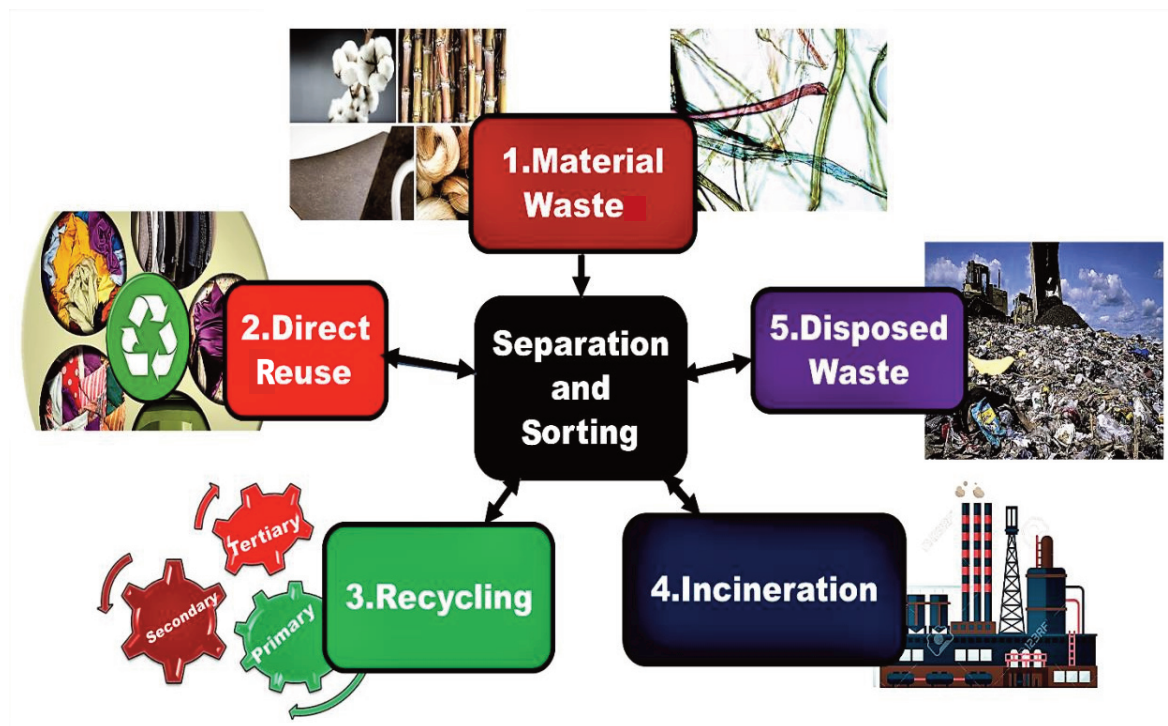


Fig. 5. Proposed JIT model for textile waste recycling.

Table 3. Terminology and abbreviations of textile materials

Abbreviation	Name of material	Abbreviation	Name of material
EPDM	Ethylene–propylene diene rubber	HDPE	High-density polyethylene
NR	Natural rubber	Poly.C	Polycarbonate
PE	Polyethylene	PET	Polyethylene terephthalate
PP	Polypropylene	PS	Polystyrene
PU	Polyurethanes	PVC	Polyvinyl chloride
EW	End waste	PC	Post-consumer
EOL	End of life waste	JIT	Just-in-Time
PES	Polyesters	LDPE	High-density polyethylene
PLA	Poly lactic acid	PAM	Polyamides

units. Tertiary recycling is still a laboratory technique. Quaternary and biological recycling mostly deal with contaminated and toxic waste. The recycling units designed for the latter should be installed outside cities and urban areas to reduce pollution and hazardous gas emissions.

8. CONCLUSIONS

The growing global demand for textile products leads to millions of tons of textile waste being disposed to landfills. A wide range of commercial post-consumer textile waste, for instance, cotton, wool, polyesters, PET, PVC, nylon, PS, and cellulose are transformed into new recycled products, mostly by using primary and secondary recycling technologies. Tertiary and biodegradable recycling technologies are mainly utilized for contaminated and polluted textile waste. Similarly, incineration can be used for disposed and even landfill waste.

In this review the authors have explored different authentic recycling technologies for circular economy. The commercial implementation of recycling technologies and the possible dependence on separation methods have been described in detail. The unsolved fundamental complications in forming, processing, collection, sorting, recycling, cost, and transportation have also been considered. Additionally, the formal and proposed models for recycling technologies to improve the quality of recycled products and reduce textile waste have been compared.

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Ringmajanduslik lähenemine tarbijajärgsete tekstiiljäätmete ringlusse võtu tehnoloogiatele Eestis: ülevaade

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Ringmajandus ja tarbimisjärgsete tekstiiljäätmete ringluse maht kasvavad pidevalt. Tihti on tõsiseks takistuseks taasinglusse võetud toote halb kvaliteet. Selles ülevaateartiklis on analüüsitud tarbijale mõeldud kaubanduslikke tekstiilmaterjale, nende ringlusse võttu ja rakendusi. Kiudude töötlemise ja taaskasutuse tehnoloogia moderniseerimine on tarbimisjärgsete toodete kvaliteedi parandamisel muutunud asendamatuks. Kangasmaterjalide töötlemise, taaskasutuse ja nende rakenduste futuristlikku ülevaadet on illustreeritud kaubanduslike polümeerimaterjalidega. Esmase, sekundaarse, tertsiaarse, kvaternaarse ja bioloogilise taaskasutuse erinevaid liike rakendatakse koos tänapäevaste ühilduvuse ning ristsidemete protsessidega. Lisaks on ringmajanduse edendamiseks esile toodud tavapäraseid ja väljapakutud “Just-in-Time”-i (täpselt õigel ajal) ümbertöötlemise ning taaskasutuse tehnoloogiaid. On tõestatud, et tavapärased ja väljapakutud “Just-in-Time”-i (JIT) ümbertöötlemise ning taaskasutuse tehnoloogiad edendavad ringmajandust.