Scientific Papers of the University of Pardubice, Series A; Faculty of Chemical Technology
28 (2022) 97–114.

UNIVERSITY OF PARDUBICE FACULTY OF CHEMICAL TECHNOLOGY

Waste textile processing and its impact on the environment

Lenka Audrlická Vavrušová*, Petra Zídková, and Anna Krejčová

Institute of Environmental and Chemical Engineering, The University of Pardubice, CZ–532 10 Pardubice, Czech Republic

Received: May 31, 2022; Accepted: June 28, 2022

The work is focused on mapping the current state of waste textile management, its possible further processing in the Czech Republic and its environmental impact assessment. More specifically, it deals with the topic of sustainability in the textile industry, textile waste in terms of legislation, and environmental impact assessment using the Life Cycle Assessment (LCA) method. Also, it maps the situation in waste management in the Czech Republic and makes comparison with data available for the European Union (EU). Data collection on textile waste management was performed. The data are further used in LCA analysis and waste treatment methods are evaluated in terms of environmental impact using GaBi software. The lowest environmental impacts are associated with the re-wearing of waste textiles. A secondary production of cleaning cloths, as well as disposal by incineration or landfilling, are more demanding for the environment. In comparison with data from other European countries, the efficiency of textile waste management ranks the Czech Republic to the forefront in the EU. The most beneficial and cheapest solution of the problem, not only in the management of textile waste, is to reduce the production of goods, the supply of producers, and strengthen market requirements so that waste is generated as little as possible. Then, there will be no need to seek a solution to dispose of excess waste.

Keywords: Green chemistry; Textile waste; Textile waste management; Recycling; Environment; Sustainability; Circular economy; Life cycle assessment

* Corresponding author, ✉ lenka.vavrusova@upce.cz

Introduction

Waste management from the perspective of the circular economy

As a way to the first climate-neutral continent by 2050, the Green Agreement for Europe is reflected in governments' efforts to reduce non-green energy resources and to come with transition to a circular economy. Measures to reduce the carbon footprint will also significantly affect the textile industry that contributes greatly to the environmental pollution and depletion of natural resources worldwide. Such indicators will be mirrored in a number of processes from the extraction of raw materials for fiber production, the production of fibers themselves, the subsequent assembly of clothing and distribution with their final disposal. About 60 % of the textile fibers are produced by petrochemical industry, and this is where large amounts of carbon dioxide emissions are generated. Another 40 % of fibers are of natural origin with a clear predominance of cotton, the cultivation of which consumes huge amounts of water and large quantities of toxic substances, especially pesticides [1]. Unlike other consumer goods, textile products are highly fashionable, change rapidly and therefore change sooner than it is necessary due to their durability. Thus, clothing companies do not try to produce products that last a longer period of use, but reduce their quality in favor of quantity, product range and the offer of the latest fashion innovations. The overall population growth contributes to the huge increase in the amount of textiles produced. Between 2000 and 2015, the production of clothing and other textile products (home and technical textiles) doubled worldwide and consumption as well as production were largely globalized. There are around 171,000 textile and clothing companies worldwide, employing about 1.7 million people. In 2017, the EU produced 7.4 kilograms and consumed 26 kilograms of textiles per person, which has indicated a significant share of imports, mainly from developing countries [2]. With the increasing production, waste naturally increases. At the end of its life, textiles end up in landfills or incinerators, or are being recycled / reused to a lesser extent. Not every material or overall product can be recycled so that the result is both economically and environmentally beneficial. Most textile waste ends up without recovery, partly due to the less public interest in sorting this waste component and partly due to the lack of recycling technologies. A possible solution to the above problems and a contribution to the fulfillment of the goals of sustainable development is the consistent implementation of the circular economy. From 2025, municipalities in the Czech Republic will be obliged to separate the textile waste [3,4].

Sustainable development aims to mitigate, preferably to eliminate completely the negative impacts of society's current way of life. In addition to the economic growth, these efforts also respect natural resources and social values and strives to balance economic, social and environmental areas [5,6]. Circularity, resource reuse, repair, renovation, product sharing or ecodesign are important

approaches to the sustainable development of industries [3]. It is a "cradle to cradle" (C2C) system that seeks to maintain the resources for as long as possible and to get the maximum value from them in use and then to regenerate materials or whole products at the end of their lifespan. It is the opposite of a linear model, where after the extraction of raw materials, production and use of the product, the life of the product ends and is no longer used ("cradle to grave" C2G). From the point of view of the circular economy, the most efficient waste-treatment procedures are based on the so-called 3R ("reduce, reuse, recycle") or even 5R ("reduce, reuse, recycle, redesign, reimagine") approaches. In the textile area, sustainable consumption and product exchange or rental make sense. The reason for a limited use of the circular approach is probably the lack of information for consumer, the small number of inspections by environmental institutions, various financial factors, non-supporting legislation or small number of organizations dealing with this issue [7,8].

From a point of view of the circular economy, the top of the waste management hierarchy is represented by **waste prevention** (i) influenced by the education of the population to reduce consumption and increased interest in the environment as a means of reducing textile overproduction [9]. **Reuse** (ii) by a new owner prolonging the life of the product can be achieved by changing clothes, lending, selling online, at flea markets or second hand, charities, etc. (collaborative consumption or commercial sharing system [1,7]).

The **recycling** of (iii) textile materials can be considered as a step in a circular direction. Waste in the production of textiles (scrap pieces, clippings, residues) is easily processed, for example, as a material for the furniture industry. Textiles after consumption are no longer used for various reasons. Its amount is comparable to the consumption of textile fibers for textile products. Although there are organizations that collect or recycle textile waste, huge amounts of waste end up in landfills or incinerators [5,10]. Up to 97 % of textile waste can be recycled into a new textile or non-textile product(s). In the literature, particular attention is paid to the recycling of fibers, followed by polymers / oligomers, as well as monomers and fabrics. Currently, attention is focused on the development of suitable technologies for textiles containing various admixtures of other materials, requiring additionally sorting into satisfactory pure fractions [8]. At present, new types of fibers are problematic for recycling, which is the case of regenerates of cotton and cellulose or recycled materials. The price of modern recycled fibers reflects the complexness of the technology and research activities, which can also affect consumer's interest [11]. Recycling can be done mechanically, chemically and, to a lesser extent, thermally [10]. The economic and environmental impacts need to be taken into account when considering an appropriate method for the management of textile waste. From the available publications, it is clear that recycling or reuse is more beneficial than incineration or landfill because it reduces the environmental impact. Reuse is a better choice than recycling, but both solutions are not always environmentally beneficial. Shipping to the customer for

further wear may outweigh the potential benefits. If only part of the fabric is recycled, the benefits may be minimal or negative. Recycling and reuse are preferred due to their importance to the circular economy. In Europe, a total of about 15–20 % of the textiles used are collected. The remaining amount is disposed of in incinerators or landfills. About a half of the collected textiles are recycled and the other half are given for reuse (also by export to developing countries). Climate change and energy consumption are most often monitored when textile-waste management practices are evaluated from a life-cycle perspective. The problem of available environmental impact studies is the small number of monitored indicators and their incomparability. The studies are most often focused on the production processes of cotton, polyester, viscose, and wool [1].

Other uses (iv) of textile materials unsuitable for re-use or recycling is as an energy source. Waste cotton textiles (cotton briquettes) have an energy potential comparable to, for example, wood pellets or wood chips and are a suitable alternative to fuels [12]. The **disposal** of (v) waste is dealt with in Part 4 of Act No. 541/2020 Coll. on waste. It is usually being carried out by landfilling without any further use. However, landfilling of waste (including textiles) does not necessarily have to be considered as its final disposal, as the solution to the problem is only postponed and left unsolved to future generations. Landfilling of waste is used due to its lower economic and organizational complexity [13].

In 2015, the European Commission adopted the Action Plan for the Circulating Economy, updated in 2020 (the New Action Plan for the Circulating Economy), which introduces the principle of circular economy and mentions the management of textile products. However, the Action Plan, as well as the Ecodesign and Ecolabel Directives, are still only on a voluntary basis and there is no functional legal set of requirements to ensure that all products placed on the EU market comply with the principles of the circular economy [14,15].

The Institute of Circular Economics (INCIEN) has been operating in the Czech Republic since 2015. It participated in the preparation of the Circular Czechia 2040 strategy and it is a part of working groups at the Ministry of the Environment and the Ministry of Industry and Trade. Its goal is to increase public awareness of the concept of circular economy and to acquaint at least 80 % of the Czech population by 2025 [16]. The strategic framework of the circular economy of the Czech Republic "Maximum Circular Czech Republic in 2040" in 2021 was developed jointly by governmental and non-governmental entities. Its aim is to improve and, at the same, strengthen technological sophistication and competetiveness. It means, e.g., a resistance to external risks related to the supply of raw materials. The strategic framework proposes the measures in ten areas that can achieve the fastest possible transition toward a circular economy in the textile industry as well [14].

Textile waste in the Czech Republic and European Union countries

It is estimated that in 2015, EU citizens bought 6.4 million tonnes of clothing (12.6 kilograms per person) and 2.79 million tonnes of household textiles. In 2017, EU households consumed a total of 13 million tonnes of textile products. In the EU, the production of synthetic fibers in 2018 was 2.24 million tons. Every year, consumers dispose of around 5.8 million tonnes of textile products (11 kilograms per person and year), a number that is increasing every year. In addition to solid waste textiles, a large amount of consumed waste water is associated with textile production. It is estimated that up to 22 million tonnes of microfibers will be released into the seas in the future [14]. The European Statistical Office (Eurostat) provides data from 15 countries (including the Czech Republic) which together produce more than 2 million tonnes of textile waste per year. Only 10 % of textile waste is reused and 8 % recycled (production of rags, production of new fibers). The remaining amount of waste is further disposed of, from which more than a half ends up in landfills and a quarter ends up in incinerators [17]. An overview of textile waste management in selected European countries is given in Tab. 1.

Table 1 Overview of textile waste management in selected European countries [17]

Textile waste/ Country	Belgium	Czech Republic	Portugal	Italy	Austria
Total [t]	169949	108273	81715	465925	62446
Per person per year [kg]	14.8	10.2	8	7.7	7
Recycled [%]	5	7	8	8	6
Reused [%]	4	6	6	6	5
Icinerated [%]	12	19	20	18	15
Landfilled [%]	27	43	46	43	34
For export [%]	53	25	21	25	40

Textile waste is contained in municipal waste in the Czech Republic in the range of 2–6 %. It is collected throughout the Czech Republic in containers, from where is travelling to non-profit organizations that reuse textiles or provide them for recycling or export. The amount of textile collected has a growing trend. In 2010, it was about 5200 tons, in 2019 then 37500 tons [2,14]. In the Czech Republic, numerous companies collect waste textiles for charitable purposes (e.g. Potex, DIMATEX, Diakonie Broumov, TexilEco, Arca Chrast, EKO-KOM) and for further processing (EKOTEX s.r.o., RETEX a.s., Fibertex Nonwovens, a.s., UO TEX, s.r.o.).

Environmental impacts and their assessment

Life Cycle Assessment (LCA) is an analytical tool used to evaluate the impact of human activities on the environment. The LCA analyzes all details of the product life cycle from its production up to its consumption: use of resources (renewable or non-renewable, way of how to obtain these resources), technologies used (obsolete, high energy or best available techniques), logistics (impacts of individual types transport), method of consumption (the impact on the environment has, e.g., high electricity consumption in household vacuum cleaners, or the release of micro-plastics into wastewater during laundry), handling of the product after its consumption (landfill filling, recycling). The environmental burden at the point of consumption may be low, but the production process at the point of production, e.g. in developing countries, may be high. The LCA aims to cover all the elements of the impact on the global environment [18]. In order to prevent the misuse of the LCA for marketing purposes, the LCA has been standardized with international validity. Current versions of the standards are ISO 14040: 2006 / AMD 1: 2020 (sets out the principles and framework of LCA, LCI, LCIA phases, life cycle interpretation phase, phase relationship) [19] and ISO 14044: 2006 / AMD 2: 2020 (sets out requirements and guidelines for LCA assessment, definitions, objectives and scope). Both standards are subject to regular review for approximately five years [20]. Using the LCA method, the four basic phases are evaluated, which are (1) the definition of objectives and scope, (2) the inventory, (3) the impact assessment and (4) the final interpretation. All phases are interlinked and the findings from one phase can influence the conclusions evaluated from the previous phase, which needs to be revised. In this way, the iterative nature that is characteristic of LCA processing can be explained [18].

LCA studies are carried out for many reasons. In many cases, companies have them processed for marketing reasons. Some studies appear also due to environmental or social reasons, where their contracting authorities are, e.g., state administration bodies. In the review of the environmental impact of textile reuse and recycling, Sandin and Peters report that 85 % of the work dealt with recycling and 41 % with textile reuse, both reducing the negative impact upon the environment that there is no additional burden, e.g. by transport. Most attention was focused on the study of fibers, namely cotton (76 %) and polyester (63 %). 63 % of textile fibers are made from petrochemicals, giving rise to significant amounts of CO_2 emissions. The remaining proportion is cotton (24 %), consuming large amounts of water and the pesticides used for its cultivation, cause toxic pollution. The authors state that the environmental benefits of different recycling and reuse are often assessed by the LCA method. It is not possible to compare the results of these studies because of incomparable data [1].

In the comprehensive life cycle inventory of clothing, Munasinghe et al. evaluates recycling, reuse, incineration, gasification, and landfilling at the final stage of the life of the materials. The process of reuse and subsequent recycling

has the least impact in terms of the energy consumption. Compared to incineration or gasification, the recycling has a lower amount of greenhouse gas emissions; however, energy consumption is high. Reuse at the end of the life of the textile has the least impact and is the best choice for handling the textile at the end of its life [21]. Dahlbo et al. focus on the context and recommendations for growing textile circulation. In Finland, 20 % of textile waste has been collected and reused mainly for charitable purposes, and only a few percent of the total textile waste are recycled. Discarded textile waste is a part of municipal solid waste and being subsequently incinerated with the recovery of energy. The aim of their study was to determine the flows of textile materials and textile waste in Finland and to assess the performance of the current system using the LCA method [22].

In this work, our goal is to map (i) the availability of information on textile waste management in the Czech Republic and (ii) based on available current data to assess the impact of their further use on the environment. The LCA method is used to assess the product life cycle, technologies, and processes which examines and evaluates environmental impacts in a broad perspective. The study responds to the efforts of voluntary, non-profit organizations to popularize the practices of circular economy in the field of textile waste, as well as to the planned introduction of the obligation of municipalities to sort textile waste from 2025.

Experimental

Life cycle assessment has a clear structure defined by international standards: (1) postulation of objectives and scope, (2) inventory, (3) impact assessment, and (4) final interpretation. The subject of this study was to examine different methods of textile waste management. The definition of the goal of the work reflects the availability of relevant data. The functional unit is defined as "the amount of collected textile waste deposited in the collection containers of the Regional Charity Pardubice (RCP) in one year". The aim of the work is to assess the impact of the handling of this collected textile on the environment.

System boundary

The boundary of the system is determined "from gate to gate", from the collection of waste textiles to its removal or use (see Figure 1). After filling the collection containers, the waste textiles are taken to be sorted for reusable items and partially left to companies where textile can be recycled and, eventually, processed into the other products. The cotton parts of textiles can then be used for the production of rags. Non-recyclable textiles are disposed of in landfills or burn up in an incinerator.

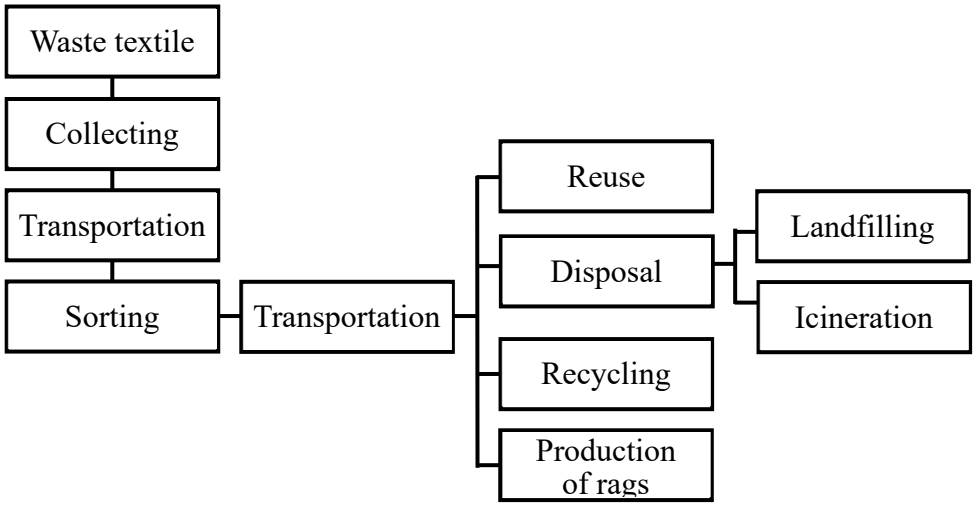

Fig. 1 Boundaries of the waste management system

Inventory – Data collection

This step of data collection was focused on mapping the issue at the level of the entire Czech Republic. Therefore, entities with nationwide operations, such as the Ministry of the Environment, the Czech Environmental Information Agency and the Institute of Circular Economics were approached. Regional data were requested from the respective office in Pardubice. The survey was also aimed at the individual companies engaged in the collection, sorting, and recycling of waste textiles. The information was obtained through electronic communication or by telephone. Data were requested on the amount of textile waste collected throughout the Czech Republic, or only in the area in which the organization operates. The data concerned the material composition of textile waste and the method of their management. Some organizations provided only limited information or referred to information publicly available on the website. Some of the addressed companies refused to provide the required data due to trade secrets or gaps in their records. The data of the RCP and DIMATEX information available on their website were used in the study. The RCP states that the amount of textile collected is 212 tons per year, when, after sorting, 53 % is reused for carrying and 47 % handed over to DIMATEX for further disposal. According to DIMATEX, 10–40 % of clothing can be re-worn, 20–40 % used for the production of cleaning rags, 5–30 % is industrially used, or exploited as a production raw material, 0.1–5 % is provided to non-profit organizations, and, finally, 1–10 % is classified as a waste and disposed of. The textile composite RETEXTIL is produced from the waste part of textiles. Furthermore, non-processable textiles are used for energy or mainly landfilled for economic reasons [23].

Impact assessment

The initial amount of textile waste collected in the RCP is set at 212 tonnes of textile waste per year. This quantity is transported to the primary sorting, from where approximately 100 tonnes are sent for disposal and 112 tonnes reused for carrying. A smaller van with a capacity of 3.5 tonnes is used to transport textile waste. The first transport for container collection is set at 10 km, the second transport for further processing 130 km (the distance Pardubice to Stráž nad Nisou). Waste textiles are divided into textiles intended for landfilling, incineration, recycling as an industrial raw material and for the production of rags. These disposal methods are evaluated in terms of environmental impact. The GaBi software with Professional version 10.6.0.110 (Thinkstep, Leinfelden-Echterdingen, Germany) is used to evaluate the environmental impacts of textile waste management using the LCA method. Potential environmental impacts are expressed by means of the ReCiPe 2016 methodology as impact categories: Climate change, Fine particulate matter formation, Fossil depletion, Freshwater consumption, Freshwater ecotoxicity, Freshwater eutrophication, Human toxicity, Marine ecotoxicity, Marine eutrophication, Metal depletion, Photochemical ozone formation, Stratospheric ozone depletion, Terrestrial acidification, and Terrestrial ecotoxicity. Figure 2 shows the process as entered into the GaBi software. The boundaries of the system were defined “from gate to gate”, i.e. from the collection of a full container to the processing of waste textiles.

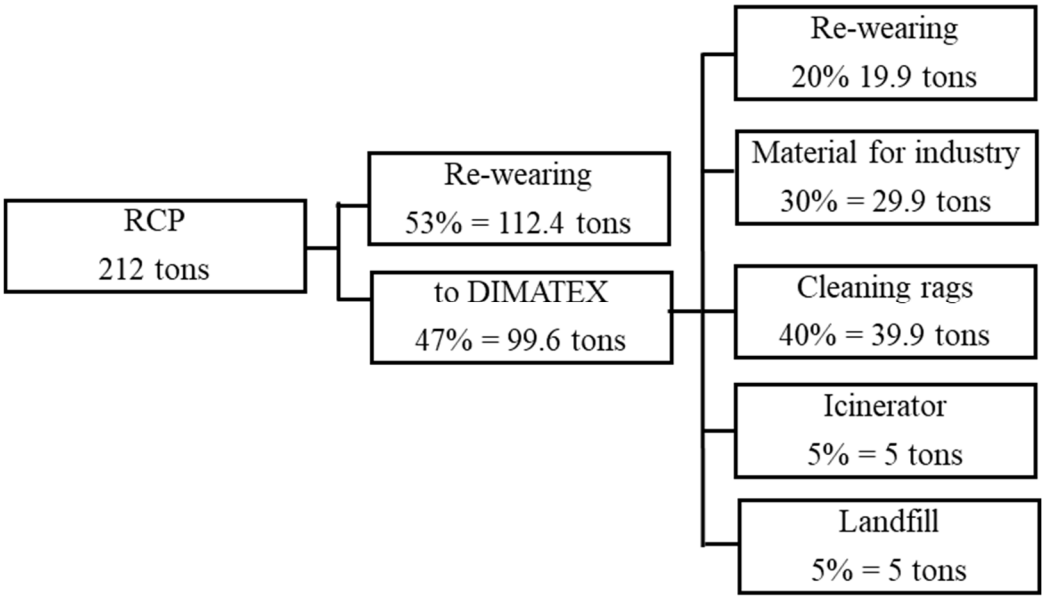

Fig. 2 Material flows of waste textiles in the functional unit

Results and discussion

Data collection

An important part of the work is the collection of data, based on which the impacts of individual methods of processing sorted textile waste using the LCA method are assessed. State institutions, such as the Ministry of the Environment and the Czech Environmental Information Agency were contacted with a request for data on textile waste in the Czech Republic in the period from 2018 to 2021. This was promised but not provided within six months of the request. Moreover, it was not clear which data was charged and in what extent. Negotiations with the non-governmental non-profit organization INCIEN were held with a similar result. The INCIEN promotes the circular economy in the Czech Republic, declares the determination to give waste a new meaning and returned materials to circulation, and popularizes the issue of waste textiles in the media and in the professional press. The promised data on the amount of textile waste in municipal waste was not provided with any further justification. Specialised companies that collect and process waste textiles, a grand total of 10 institutions, were also contacted. Specific data on the handling of collected textiles was obtained from 4 companies only; some companies providing a partial or even no information. Attention was focused locally on the city of Pardubice only and the surrounding area (Holice, Lázně Bohdaneč, Luže). Data on the amount and method of textile waste management was provided by the City of Pardubice and the Regional Charity of Pardubice. This had affected the scope of the follow-up LCA study. There are major shortcomings in the availability of information on waste management. It has been found that a large number of companies do not provide information because they do not actively collect it, as there is no legislative regulation. Waste textiles are collected in a "product" and not a "waste" mode and collection companies are not obliged to collect data on the amounts of textiles. This approach needs to be changed due to the planned introduction of separate textile waste collection in 2025 [24]. Another reason for the unwillingness to provide data might be the fact that such additional work would not be of any benefit to them. The motivation for cooperation could be a clear communication on the provision of feedback, which could be useful for their further work. Companies might also fear that the way they handle waste could endanger the environment. They could have also proved that they are actually doing greenwashing and not concerned with the real environmental protection. Communi-cation with companies should have included a guarantee of a degree of discretion or anonymity. Yet another reason might be the protection of one's own know-how. If the company has an internal regulation that prohibits the provision of any data, the data is currently unavailable. The unwillingness to work together was somewhat surprising, as environmental care, recycling, reducing the carbon footprint and extracting raw materials, regardless whether from renewable or non-renewable sources, are topics that are currently extremely debated and publicly address them.

According to a survey in the 15 EU countries, Belgium (14.8 kg) is the largest producer of textile waste per capita, followed by the Czech Republic with 10.2 kg. The most textile waste is produced annually in Italy (466 thousand tons), followed by Germany (392 thousand), France (210 thousand) and the United Kingdom (206 thousand). The share of recycled and reused textiles in European countries, including the Czech Republic, is around 5 % at average, in the incinerator ending at average 14 %, in landfills from 19 to 46 % when a significant share being represented by exports (21–68 %). As there are no rules for collecting data on the textile waste, the findings of this survey are indicative and may be significantly skewed by the methodology used [17]. When compared with data from the Ministry of the Environment on the amount of textile waste in the Czech Republic produced in 2016, the difference is significant. While the Ministry of the Environment reports on 27,293 tonnes of textile waste produced, LABFRESH quotes 108,273 tonnes of total textile waste in the same period (2016). In this example, a distinct inconsistency of data in the textile industry from different sources can be observed [2,17].

A comparison of our waste management data with the national data of European countries shows that the way in which textile waste is managed in the Czech Republic does not lag behind other EU countries. On the contrary, in a large number of cases, the practice in Czech Republic is superior. For example, Diakonie Broumov states that about 12 % of waste goes to landfill, while in the United Kingdom it is about 30 %. The way in which used textiles are handled in Germany is similar to that mentioned by the RCP, reusing 53 % for wearing, compared to 54 % in Germany. Like DIMATEX and Diakonie Broumov, Germany exploits about 40 % for the production of rags [17,23,30]. LABFRESH states that in Finland, 20 % of the textile waste collected is reused, of which only a few percent is being recycled. The data obtained by us show a significantly higher share of reusable textiles: RCP indicates 62 %, Diakonie Broumov 42 %, DIMATEX up to 40 %. Diakonie Broumov lists up to 46 % of the material on recyclation, DIMATEX approximately 35 %, the RCP 16 %. This proves a relatively high efficiency of waste-textile collection by charitable companies in the Czech Republic and testifies to the responsible approach of the Czech citizens in preparation of textiles for collection companies.

In the sorting of waste, the Czech Republic is at 6th position in the ranking of EU countries. 76 % of packaging materials are recovered (paper packaging 90 %, glass 88 %, plastics 70 %, metals 61 % and beverage cartons 24 %). From this fact, it can be concluded that the willingness of Czech citizens will also concern the sorting of textiles after introducing the obligation of municipalities to collect textile waste in 2025. The annual report of EKO KOM shows that 99 % of citizens have the opportunity to sort the waste. The average distance to separate waste containers is approximately 90 meters and there are 100 inhabitants per container [25].

This is an extremely favorable situation. In order to be effective for textile collection, both the government and municipalities should launch an information campaign in advance of the municipalities' obligation to collect textile waste.

How to dispose of waste textiles?

Based on the experience gained from the data collection, it is possible to formulate certain recommendations or to propose measures that would contribute to the improved situation. Education and awareness-raising campaigns and projects, such as lectures, information leaflets, TV spots, websites etc., all this can raise public awareness and prepare the general public for the introduction of textile waste collection from 2025. A guide to further proposals leading to the improvement of textile waste management can be the approach "3R" (reduce, reuse, recycle). According to the waste management hierarchy, the reduction of consumption is the most important factor and can be achieved mainly by educating young people who are fans of fashion trends and a major consumer group. The aim should be to raise awareness of the sustainability and importance of the circular economy. The clothing industry would be encouraged by customers to prefer a better quality, more timeless clothing that does not need to be changed so often. An example of reuse can be the donation, exchange or sale of the clothing used through various applications, swaps, and via second-hand offer. Support for the creation of re-use centers purchasing still usable textiles is also useful. Recycling can protect the resources of raw material, reduce waste in landfills or incinerators. It may not always be a cost-effective solution to a problem, it may be energy-intensive or just a marketing campaign and, in fact, greenwashing. The education of the population is also desirable in this respect.

A methodology of uniform information collection would help one in the compatibility and completeness of the data. The availability of reliable data would enable the state administration to take measures and implement uniform procedures for the management of waste textiles, and collection and processing companies would help in the planning and implementation of their activities. The support should also be targeted at small business focused on repairs not only clothing, but also home textiles, furniture, etc. The motivation could be a simplified process of starting a business, reducing the respective administration, tax breaks, or a financial contribution for start-ups.

Environmental impacts

Thanks to the impact categories, it is possible to specify the emerging environmental problem which can be attributed to a specific anthropogenic cause. The influence of various technologies of textile waste management (landfilling,

incineration, rags production, use for further industrial processing) and transport to primary and secondary sorting was monitored. The production of cotton rags has the greatest impact on the environment (8 impact categories out of a total of 14 monitored), followed by transport (4) transport, landfilling (2). It is necessary to consider the fact that the method of entering the functional unit will be reflected in the representative results of the individual methods for waste treatment. It is therefore appropriate to recalculate their impacts relative to their actual use (i.e. 50 % for rags, 38 % raw material for further processing, 6 % incineration, 6 % landfill), which is shown in Figure 3. Even after the recalculation, the production of rags would be still the largest source of negative environmental impacts for 6 categories. Regarding the waste disposal by incineration and landfilling, the number of categories with the greatest impact for these processes increased, in both cases the impacts were greatest for the 4 impact categories. The smallest impacts are again caused by recycling the textile residues by creating a raw material, in some cases being a negligible number of impacts.

The production of rags for cleaning purposes in various technical fields appears to be advantageous as an extension of the life of the textile material. However, the so-called tear treatment requires considerable energy and also burdens the environment with dust microparticles. Energy intensity is reflected in the category of Fossil depletion impact. The released microparticles correspond to the composition of the original material and, in particular, the residues of man-made fibers are reflected in the ecotoxic categories of impact. The most advantageous solution in terms of impacts seems to be further processing of textiles as a secondary raw material. Although the incineration and landfilling are in this study represented for waste treatment, their contribution to environmental impacts needs to be taken into account, especially when textile waste is not sorted and life ends in this way. Textile waste incineration has a negative impact primarily in the category of impact of Fine Particulate matter formation, Terrestrial ecotoxicity, Terrestrial acidification and Freshwater consumption. Although modern incinerators are equipped with technologies preventing emissions, incinerators in the public consciousness are associated mainly with emissions of dust particles and dioxins present in them. These, together with acid emissions, can affect soil quality and, as a result, water quality by deposition from the atmosphere. Landfilling of textile waste is only a delayed solution of a problem, and the released landfill gases and possible leaks through which chemicals used in textile production and processing enter the surface waters appear both in the categories of impact Climate change, Metal depletion and Freshwater eutrophication. An enormous increase in clothing production leads to getting rid of the old and buying a new. This cycle causes hundreds of thousands of tons of clothing to end up in landfills, especially those in Africa and South America – the final destinations for unsold or charitable clothing from Europe and/or North America.

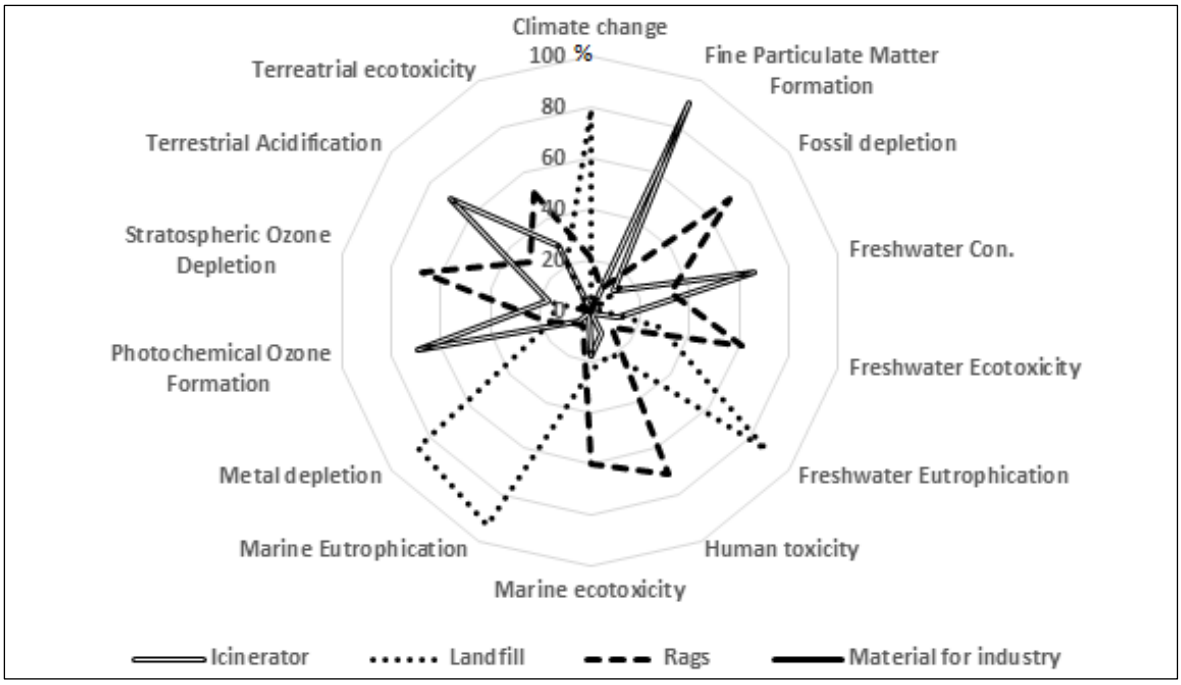

Fig. 3 Contributions of the monitored impact categories for commonly used methods of textile waste management

The economic and environmental impacts need to be considered before choosing the proper way of how to manage textile waste [1]. From the literature, it is clear that recycling of used textiles or reused textiles is more beneficial than incineration or landfilling, as it reduces the environmental impact and especially reuse is a more appropriate option. However, transport to the customer or to a site of processing which may outweigh the potential benefits, must be included in the final assessment. When only part of the fabric is being recycled, technologies may have a negative impact on the environment and the benefits may be minimal or non-existent. Recycling and reuse are preferred due to their importance for the circular economy. About a half of the collected textiles are recycled and the other half is given for reuse. In most cases, this means transport to the developing countries. Strand et al. [26] states that textile waste is collected in only a small number of municipalities and is estimated at 25 % for recycling. Textile waste that is not used otherwise is incinerated, only in the case of toxic textiles, landfilling takes place. Table 2 makes a comparison of the results of this work with available data from studies.

Reliable comparison of our results with the data from studies on similar issues is not possible, as most studies focus on the environmental impacts caused by production technologies. The corresponding studies deal with the waste management methods often according to the materials or types of clothing and determine thus the impact categories for a particular material. Depending on the calculation methodology used, the monitored impact categories differ, the data are estimated according to predictions for future or are several years old. Finally, functional units are also incomparable.

Table 2 Waste textile processing

Way of processing	Bodin [27]	Farrant [28]	Woolridge [29]	RCP + Dimatex
	Way of processing [%]			
Reuse	68	28	43	62
Recycling / material for industry	18	33	29	14
Rags	7	–	12	19
Export to developing countries	–	30	–	–
Shue reuse	–	–	9	–
Disposal	7	9	7	4

Conclusions

Our study revealed that the data on textile waste management are inconsistent or unavailable, as there is no proper procedure for their collection or an obligation under the law to record them. At the same, there is a certain reluctance to share the already existing data by state institutions (Ministry of the Environment, Czech Environment Agency), interested organizations (Institute of Circular Economics), or companies that use waste textiles as a production raw material. The most information has been provided by non-profit organizations that take care of sorting textiles when offering usable clothing for socially disadvantaged citizens as the RCP. The RCP data together with the information of the company DIMATEX, taken from the RCP textile that is not usable for charitable purposes, was used to assess the life cycle of the textile waste management method in the Pardubice region and being the basis of the practical part of this work. Data from different sources differed in many cases. One of the reasons is that there is no obligation for organizations to record and provide data on the collection of waste textiles, their quantity, and management. This inconsistency was also manifested when comparing the results of this work with other studies.

Based on the experience gained from the data collected, recommendations were formulated to increase general awareness and readiness of wide public for the introduction of textile waste collection from 2025. According to available data for sorting other types of waste, considerable willingness of Czech citizens to participate in these activities can be expected. The aim of educational activities should be an approach that would raise awareness of sustainability and importance of the circular economy. The clothing industry would thus be guided by customers to prefer a better-quality clothing with a longer lifetime. Therefore, it is important to ensure the education of young people, who are supporters of fashion trends and a group of major consumers. Further measures should be directed to the business sphere, whether it is a uniform methodology of data collection or a motivation for small businesses, e.g., repairers of not only of clothing, but also of home textiles, furniture, etc.

The RCP collects 212 tons of clothing per year, of which 53 % can be reused for wearing and 47 % is handed over to DIMATEX for secondary sorting. DIMATEX states that 40 % of waste textiles are used for rags, 30 % are raw materials for further industrial processing, 20 % can be re-worn, and 10 % end up in an incinerator or landfill. The output of the LCA study was an evaluation of the impact of individual waste management methods on the monitored impact categories, namely Global change, Freshwater consumption, Human toxicity, Fine particulate matter formation, and Metal depletion. The most significant environmental factors for the impact categories evaluated in this study are the processing of rags. The effects of their further industrial use — i.e., recycling — have the least impact. Similar studies published in the literature point out the same problem encountered in this work, the lack and inconsistencies of available data which limit the explanatory power of the results and their comparability. When considering the data from European countries, it can be stated that the efficiency of textile waste management ranks the Czech Republic at the forefront of the European Union.

In conclusion, it must be emphasized that the most beneficial and, at the same, the cheapest solution of the problem (and not only in textile waste management), is to reduce the production of goods, the supply of producers, and to strengthen the market requirements so that waste is generated as little as possible. Then, it will not be necessary to look for a solution to dispose of the excess of waste.

Acknowledgment

Authors would like to thank all the companies for providing data to this study. Authors also acknowledge a financial support for student grant (SGS_2022_001).

References

[1] Sandin G., Peters G.M.: Environmental impact of textile reuse and recycling – A review. *Journal of Cleaner Production* **184** (2018) 353–365.

[2] MŽP: *Podklady pro oblast odpadového a oběhového hospodářství OPŽP 2021–2027; Prevence vzniku odpadů* (in Czech). Ernst & Young, s.r.o.; Ernst & Young Audit, s.r.o.; E & Y Valuations s.r.o. 2020. https://www.mzp.cz/C1257458002F0DC7/cz/odpadove_obehove_hospodarstvi/$FILE/OODP-2_Prevence_vzniku_odpadu-20200529.pdf (accessed January 30, 2022)

[3] Riba J.R., Cantero R., Canals T., Puig R.: Circular economy of post-consumer textile waste: Classification through infrared spectroscopy. *Journal of Cleaner Production* 272 (2020) 123011.

[4] Rapsikevičiene J., Guarauskiene I., Jučiene A.: Model of industrial textile waste management. *Environmental Research, Engineering and Management* **75** (2019) 43–55.
[5] Muthu S.S.: *Sustainability in the textile industry.* Springer Nature Singapore, Hong Kong 2017.
[6] MŽP: *Udržitelný rozvoj* (in Czech). https://www.mzp.cz/cz/udrzitelny_rozvoj. (accessed May 23, 2022).
[7] Nayak R., Patnaik R. (Eds.): *Waste management in the fashion and textile industries* (e-Book). Elsevier 2021.
[8] Schroeder P., Anggraeni K., Weber U.: The relevance of circular economy practices to the sustainable development goals. *Research and Analysis* **23** (2018) 77–95.
[9] MŽP: *Zákon č. 541/2020 Sb., o odpadech* (in Czech) https://www.mzp.cz/www/platnalegislativa.nsf/E4044163A66CAA76C1258655002DE3C9/%24file/OL_541_2020.pdf. (accessed February 1, 2022).
[10] Yalcin-Enis I., Kucukali-Ozturk M., Sezgin H.: Risks and management of textile waste. In: Gothandam K.M., Ranjan S., Dasgupta N., Lichtfouse E. (Eds.) *Environmental chemistry for a sustainable world.* Springer Nature Switzerland AG, Cham 2019.
[11] Soldatova A.: Trhu s textilem už primární zdroje nebudou brzy stačit (in Czech). *Časopis Odpady* **2021** (2021) 12–13.
[12] Leonel J.R.N., Radu G., João C.O.M., João P.S.C.: Economic and environmental benefits of using textile waste for the production of thermal energy. *Journal of Cleaner Production* **171** (2017) 1353–1360.
[13] MŽP: *ČR nastupuje trend: od skládkování ke třídění, recyklaci a materiálovému využití na maximum* (in Czech). https://www.mzp.cz/cz/news_20201201-CR-nastupuje-trend-od-skladkovani-ke-trideni-recyklaci-a-materialovemu-vyuziti-na-maximum (accessed March 3, 2022).
[14] MŽP: *Strategický rámec cirkulární ekonomiky České republiky 2040: Maximálně cirkulární Česko v roce 2040* (in Czech). https://www.cbcsd.cz/strategicky-ramec-cirkularni-ekonomiky-cr-2040/ (accessed May 24, 2022).
[15] Evropská komise: *Sdělení komise Evropskému parlamentu, Radě, Evropskému hospodářskému a sociálnímu výboru a Výboru regionů; Nový akční plán pro oběhové hospodářství* (in Czech), Brussels 2020. https://eur-lex.europa.eu/legal-content/CS/TXT/HTML/?uri=CELEX:52020DC0098 (accessed January 30, 2022).
[16] Institu Cirkulární Ekonomiky: *Závěrečná zpráva INCIEN 2020* (in Czech). https://incien.org/wp-content/uploads/2021/07/ZS_INCIEN-2020_SV_VERZE5_kompletni.pdf (accessed March 28, 2022).
[17] Labfresh: *The fashion waste index*. https://labfresh.eu/pages/fashion-waste-index?locale=en (accessed February 3, 2022)
[18] Kočí V.: *Posuzování životního cyklu Life Cycle Assessment – LCA* (in Czech). Vodní zdroje Ekonomitor, Chrudim 2009.

[19] ISO 14040:2006: *Environmental management – Life cycle assessment – Principles and framework*.
https://www.iso.org/standard/37456.html (accessed February 1, 2022).
[20] ISO 14044:2006: *Environmental management – Life cycle assessment – Requirements and guidelines*.
https://www.iso.org/standard/38498.html (accessed February 1, 2022).
[21] Munasinghe P., Druckman A., Dissanayake D.G.K.: A systematic review of the life cycle inventory of clothing. *Journal of Cleaner Production* **320** (2021) 128852.
[22] Dahlbo H., Aalto K., Eskelinen H., Salmenperä H.: Increasing textile circulation - Consequences and requirements. *Sustainable Production and Consumption* **9** (2017) 44–57.
[23] Dimatex CS: *Kontejnery na textile* (in Czech).
https://www.dimatex.cz/sber-textilu (accessed May 24, 2022).
[24] MŽP: *Agenda 2030* (in Czech).
https://www.mzp.cz/cz/agenda_2030 (accessed March 28, 2022).
[25] EKO-KOM: *Výroční shrnutí 2020* (in Czech).
https://www.ekokom.cz/wp-content/uploads/2021/09/Ekokom_vyrocni_shrnuti_2020_elektronicke.pdf (accessed May 2, 2022).
[26] Strand J.: *Environmental impact of the Swedish textile consumption – a general LCA study*. Swedish University of Agricultural Sciences, Uppsala 2015.
https://www.diva-portal.org/smash/get/diva2:826159/FULLTEXT01.pdf (accessed May 2, 2022).
[27] Bodin R.: To reuse or to incinerate? A case study of the environmental impacts of two alternative waste management strategies for household textile waste in nine municipalities in northern Stockholm, Sweden. Master of Science Thesis, Royal Institute of Technology, Stockholm 2016.
[28] Farrant L., Olsen S.I., Wangel A.: Environmental benefits from reusing clothes. *The International Journal of Life Cycle Assessment* **15** (2010) 726–736.
[29] Woolridge A.C., Ward G.D., Phillips P.S., Collins M., Gandy S.: Life cycle assessment for reuse/recycling of donated waste textiles compared to use of virgin material: An UK energy saving perspective. *Resources, Conservation and Recycling* **46** (2006) 94–103.
[30] Diakonie Broumov (in Czech)
https://diakoniebroumov.org/ (accessed February 1, 2022).