Environmental and Climate Technologies
2023, vol. 27, no. 1, pp. 137–149
https://doi.org/10.2478/rtuect-2023-0011
https://content.sciendo.com

Decision-making Algorithm for Waste Recovery Options. Review on Textile Waste Derived Products

Anda ZANDBERGA[1*], Silvija Nora KALNINS[2], Julija GUSCA[3]

[1–3]*Institute of Energy Systems and Environment, Riga Technical University, 12-k1 Azenes iela, Riga, LV-1048, Latvia*

Received 22.06.2022; accepted 02.02.2023

***Abstract* – As the volume of textile waste steadily increases, mechanical, chemical and biological technologies for textile waste recovery are evolving. Also, the legal framework of the European Union has stated the commitments for promoting the recycling of textile waste in the Member States. So far, however, no decision-making algorithms have been developed for the selection of products recovered from textile waste. Within the present study, a hybrid multi-criteria decision-making algorithm for evaluating textile waste recovered products has been developed applying seven circular economic criteria – 'Circular economy approach of the technology', 'Added-value potential of final product', 'Share of textile waste in total waste feedstock', 'Diversity of textile mix suitable for specific technology', 'Pre-treatment of waste feedstock', 'Recovery potential' and 'Maturity of a recovery technology'. The weighting of the criteria was determined by eight waste management experts. The results of the expert-based criteria evaluation show that the most important criteria are 'Added-value potential of final product' and 'Circular economy approach of the technology'. The developed decision-making methodology has been adapted to nine textile waste recovered products – compost, refuse-derived fuel, ethanol, glucose, building insulation material from cement and textile waste mix, building insulation material from denim textile waste, terephthalic acid, recovered cotton and recovered polyester. The multi-criteria, decision-making ranking of the products textile shows that the highest potential for products recovered from textile waste is for glucose and terephthalic acid, while the lowest – for ethanol, compost and refuse-derived fuel.**

***Keywords* – AHP; circular economy; clothing waste, fibres; multi-criteria analysis; sustainability; TOPSIS; waste recovered product.**

1. INTRODUCTION

Waste management is governed by the European Union (EU) directives, which are being changed and supplemented to meet new needs in waste generated, waste disposal and treatment to achieve environmental goals and promote social and economic activities [1]. The waste hierarchy set out in the Waste Framework Directive (WFD) starts with waste prevention, followed by reduction, re-use, material recovery, energy recovery and disposal. The Waste Directive was amended in 2018 and EU Member States are required to promote re-use thus improving waste management, and the regulation requires all EU Member States to introduce sorting and separate collection of textile waste by 1 January 2025 [2]. The main goal of the amendments to the law is to reduce the amount of generated waste and increase

* Corresponding author.
E-mail address: anda.zandberga@edu.rtu.lv

©2023 Author(s). This is an open access article licensed under the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0).

its re-use and recycling, and it will have the greatest impact on the amount of waste generated [3]. The amount of textile waste in the world is increasing, and by 2030 it could reach as much as 148 million tons, which is 62 % more than in 2015. These figures indicate a large loss of resources, as textile waste is mostly nowadays incinerated or landfilled [3], [4]. The European Green Deal launched a new strategy to increase the role of the circular economy in all areas of business and to make a major contribution to achieving climate neutrality by 2050. Textile waste is on the rise, consuming 53 million tonnes of textile fibres worldwide, generating a large amount of waste, 10 % of greenhouse gas emission and 20 % of wastewater [5]. The amount of textile waste generated in the EU over the last decade is on the rise, also in case of recycled textile waste – although it must be acknowledged that the upward curve is insignificant (see Fig. 1). Furthermore, in the latest reports were mentioned that less than 0.5 % of the global fibre market was from pre-and post-consumer recycled textiles in 2020 [6].

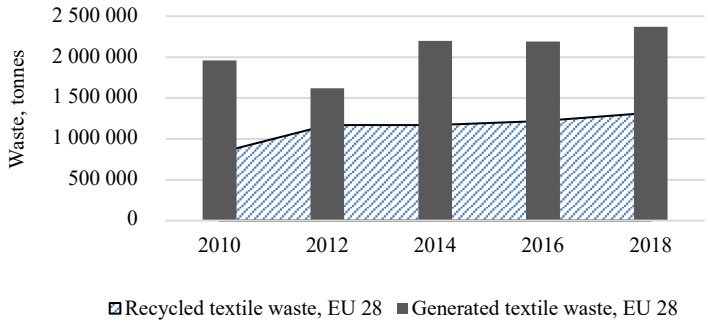


Fig. 1. Amount of generated and recycled textile waste in EU from 2010-2018 [7].

In order to achieve a closed-loop economy, it is necessary to develop the best quality textile production which is sustainable and is linked to innovative and state-of-the art technologies [8].

A distinction is made among mechanical, thermal, chemical or combined textile processing technologies [9]. Biological recycling processes in biochemical reactions use enzymes and microorganisms to convert raw materials into high value-added materials. For textiles, specific and adopted methods are used for each type of fibre and for materials with a similar composition. Natural fibres (flax, cotton, hemp, etc.) or man-made viscose fibres are rich in cellulose and can be processed in biorefineries [10].

The valorisation of textiles applying a biological method using micro-organisms has been developed relatively recently, presuming it to be more environmentally friendly than conventional processing methods [11]. The advantage of biological methods is lower energy consumption, and the use of solvents and chemicals made of renewable carbon. It must be acknowledged that biological processes do not guarantee sustainability, even though they take place in more environmentally friendly conditions, and this is due to the need to consider both economic and environmental synergies [12]. Textile raw materials require first processing, which includes both corrosive chemicals and special equipment, as well as the use of energy. The use of commercially produced enzymes significantly increases the cost and environmental impact of processes. These processes have also hampered the development of economically visible biofuels from lignocellulosic feedstocks, and it cannot be ruled out that

the same result will be achieved if textiles are used as feedstock. Another obvious disadvantage that hinders the development of biorefineries to produce bio-based products is their concentration or pure substance. When comparing these processes, it should be noted that the raw materials are not pure, although enzymatic reaction gives a good result, but still the sugar concentration is relatively low to make the process economically viable [12].

Mechanical recycling of textiles is the most used recycling process. In mechanical processing the processes are scalable, and the cost of materials is lower than in biological and chemical processes, but the result leads to cheaper materials of lower quality, that prevent them from being used in high-quality textiles [12]. The processing of textile fibres refers to the mechanical process by which the fabric is cut, but the fibre is retained, and these processes are customized to all kind of textiles. The most widely used mechanical processing method is shredding and cutting. Zippers, buttons and other finishing parts must be removed before shredding, where manual work is often required. Mechanical processing also has limitations or disadvantages, one of which is shortening of the fibre in the shredding process. In the production of new yarn, it is necessary to mix recycled and unprocessed fibres to improve the quality and durability of the yarn. Mechanical processing of cotton fibres is set up on an industrial scale [12].

Both before and after consumption, textiles can be recycled into fibres, used in the production of fabrics and new yarns, and in the manufacture of clothing. The quality of textiles is reduced by shorter fibre length, but this can be improved by blending with raw fibres [13].

Technical closed-cycles are used for synthetic polymers such as acrylic, nylon and can not only be recycled- in the same product but can also be recycled multiple times [13]. Processing of synthetic materials begins with the chemical separation of the fibres before re-polymerisation and extrusion. It must be acknowledged that polymers degrade with each new cycle, which poses a difficult task and challenge for the industry to produce qualitative fibres with a similar quality of raw fibres. The industry also needs to improve its recycling process so that it is carbon saving and efficient and does not consume too much energy in the recycling process [13]. Nowadays, products of lower quality are still produced and therefore recyclable products cannot be used multiple times, which discourages investment in the recycling of textile waste, as there is no economic justification for this. There is still insufficient market demand for recycled textiles, as there are no relevant differences in process between recycled and unprocessed textiles. Limitations for conquering the textile market are the high cost of the processing of textile and transportation expenses [13].

Thermochemical processing is used for pure synthetic fibres such as polyamide, nylon, etc., and in this process the fibres are melted and spun into a new yarn or transformed in other forms [14].

The advantage of chemical recycling is the possibility to keep materials in a closed cycle, but recycling does not include industrial production yet, as it does not have a customized technology and therefore chemical recycling reaches only 1 % [15]. There are two types of chemical processing-monomers and polymers. The processing of monomers results in fibres that are similar in quality to raw fibres, while current polymer processing methods do not allow to obtain qualitative fibres, as during processing, the polymer chain often degrades. The processing of monomers is used only for synthetic fibres, although the chemical processing method can be applied to most textile fibres. In this process, monomers disrupt the old chain to obtain intact monomers, from which new crude polymers are produced in the process of polymerisation. The process is customized to various textile fibres. In polymer processing, the fibre is separated by a mechanical process, followed by chemical dissolution. The polymer is preserved and the fibres are further recycled into yarns [8], [15].

The environmental impact of chemical recycling processes is linked to the use of energy and water, as well as the high toxicity of solvents. Chemical solvents are needed to make high-quality fibres in the recycling process. The cost of recycled fibre is high and, as a result, there is high demand for unprocessed synthetic and natural raw materials [16]. The textile industry is moving from piloting polymer recycling technologies to industrial scale production, and investments are currently being made to increase production capacity by 2030 [16].

To overcome the industry's problems, it is necessary to introduce new technologies, but in most countries, there is still a lack of quality and safety standards, regulations, textile waste classification. Various fibres and chemicals are used in the production of clothing, and their diversity makes processing more expensive. Comparing the processing of cotton fibre to polyester fibre, it must be concluded that polyester fibre has limited processing possibilities. The problem is also caused by consumer`s lack of knowledge or indifference about the environmental benefits of recycling, as textile waste is often mixed with other waste. Oil-related clothing has very low reusability and contaminated textile waste also poses a challenge, so recycling rates cannot be increased. The lack of innovation to reduce the use of organic products, as well as their high costs, prevents manufacturers from developing garments that facilitate recycling [17].

The aim of the present paper is to perform a multi-criteria decision analysis of textile waste recovery strategies to identify an outcome product with the greatest potential.

2. METHODOLOGY

2.1. Subject of the research

Within the present study, nine alternative textile waste recovered products/materials were analysed: (1) compost, (2) refuse derived fuel (RDF), (3) ethanol, (4) glucose, (5) building insulation material (cement and textile waste mix), (6) building insulation material (denim textile insulation material), (7) terephthalic acid (TPA), (8) recovered cotton and (9) recovered polyester. The selection of the products was based on the following principles: similar textile waste feedstock to ensure comparable conditions for the decision-making, various textile waste processing technologies and various waste recovered products.

In Table 1 characteristics of feedstock, treatment process and recovered products are summarised.

As extensive research data and the amount of research in this area is limited, the input data for evaluation of the textiles waste recovered products and corresponding technologies are based on information from one or several consecutive scientific publications. Hence, this study can be considered as a case-based study.

TABLE 1. DESCRIPTION OF TEXTILE WASTE RECOVERED PRODUCTS

Feedstock	Description of feedstock, process and the final product	Reference
Compost	Compost feedstock consists of paper and cardboard waste (10 %), green waste (10 %), textile waste with high lignocellulosic fibre content (80 %). Suitable composting conditions were applied. Prior to composting, the feedstock is blended into fine parts. Aerobic composting is applied (aeration with manual shaking each week). Composting phase lasted 11 months. Initial physical and chemical properties of the feedstock was the following: moisture of the textile waste – 51.28 %, green waste – 61.49 %, paper and cardboard – 11.28 %; pH of the textile waste 7.47, green waste was 6.61, paper and cardboard was 7.23; total organic carbon of the textile waste – 31.63 %, green waste – 45.67 %, paper and cardboard – 59.35 %; total nitrogen of the textile waste – 0.57 %, green waste – 1.23 %, paper and cardboard – 1.05 %; C/N ratio correspondingly 55.16, 37,23 and 56.71. The efficiency of the process was calculated on the basis of changes of organic fraction of the wasted products based on [19]: 32.64 % at the initial stage and 23.53 % after 44 weeks. Experimental setup.	[18]
RDF	Textile used for production of clothes, such as suits and shirts: moisture content – 4.14 %, calorific value – 10.46 MJ/kg, chlorine content – 0.20 %, heavy metals content within the limit values defined in the standard for the RDF. If used for electricity production, then 5.6 kWh/kg of textile waste. Pilot setup.	[20]
Ethanol	Waste blue jeans (40 % polyester and 60 % cotton blend) is used as a feedstock. Textile was cut into small pieces (2×2 cm^2) and pre-treated with sodium carbonate solution (temperature regime from 50–50 °C) for 120 min, then cooled, filtered, rinsed. Later the textile waste, with over 90 % cellulose, was subjected to enzymatic hydrolysis (enzymes of cellulose used – *Celluclast* 1.5 L, Novozymes, Denmark) and β-glucosidase (Novozym 188, Novozymes, Denmark)) and fermentation (fermenting microorganism used – *Saccharomyces cerevisiae*). The maximum ethanol yield reached 69.4 %. The mass balance: 600 g cotton and 400 g polyester as a feedstock converted to 256 g ethanol (equivalent to 130 L of gasoline). Experimental setup.	[21]
Glucose	Cotton (40 %) and polyester (60 %) blend is used as a feedstock. Pre-treatment included: soaking ground textile in a mixture of 12 % NaOH (w/v) and 7 % urea (w/v), stored at −20 °C for 6 h, thawed and washed with DI water until pH = 7.0. Submerged fungal fermentation (*Trichoderma reesei* ATCC 24449 with the highest cellulase activity of 18.75 FPU/g), cellulase production upscaled in a 5-L bioreactor. Recovery of glucose and polyester ensured via hydrolysis. Glucose recovery yield is 41.6 % if using fungal cellulase. Experimental setup.	[22]
Building insulation material (denim textile)	Recycled cotton and denim mix is used as a feedstock. Textile waste is shredded and reconstructed to fibres, mixed with cotton and treated with boric acid to protect from insects. Properties of the insulation panels: thermal conductivity 0.036–0.038 W/(m K), specific heat 1.6 kJ/(kg K), density 25–45 kg/m^3, water vapour diffusion resistance factor, μ-value = 1–2. Commercially available product [24].	[23]–[24]
Building insulation material (cement + textile)	Waste textile mix (70 % wool, 25 % viscose, and 5 % elastane) mix is used as a feedstock. Original textile waste pieces (15×15 cm) cut to smaller pieces (max 3 cm length). Later lightweight blocks mixture is produced (the composition used was 8.75 % textile waste, 32.86 % cement, 58.40 % water), followed by moulding, curing/drying processes. Characteristics of the developed insulation blocks (thickness is 10 cm) are as follows: thermal resistance R = 0.67 m^2 °C/W, thermal conductivity λ = 0.2149 W/m °C. Experimental setup.	[25]
TPA	New polycotton (cotton – 48 %, PET – 52 %) bed sheets are used as a feedstock. Prior to the hydrolysis, the sheets were cut into smaller pieces and defibrated in a mill. The hydrolysis solution contained 10 % NaOH, 0.1 mol Benzyltributylammonium chloride (BTBAC, purity ≥ 98 %) per kg solution and sulphuric acid (H_2SO_4, reagent grade, 95–97 %), solution heated to 70, 80, or 90 °C, reaction period 240–420 min. Afterwards filtration ensured to get the cotton degradation product (cotton fibres) and polyester degradation products (TPA and ethylene glycol). TPA yield from 66–100 % depending on NaOH concentration, reaction temperature and time. Experimental setup.	[26]

Recovered cotton fibre Recovered polyester fibre	Black 100 % cotton jeans and blue 80/20 cotton/polyester jeans are selected as a feedstock. Prior to processing, the jeans are washed, dried and shredded (50–150 mm^2 pieces). Processing included nitric acid leaching, dissolution process using Dimethyl sulfoxide to dissolve the organic materials from the treated fabric, including polyester and remaining organic part from textile dyes, and bleaching process using sodium hypochlorite and diluted hydrochloric acid for recovered cotton purification. Recovery efficiency is 77 wt.% for cotton and 16.2 wt.% for polyester. Pilot scale setup.	[9]

2.2. Multi-criteria decision analysis with AHP-TOPSIS methods

Multi-criteria decision analysis (MCDA) is a process consisting of a set of methods to ensure structured and transparent decision-making to compare alternative choices [27]. In this publication, a combination of MCDA techniques is applied – Analytic Hierarchy Process (AHP) and Technique for Order Preference by Similarity to Ideal Solution (TOPSIS). Combination of AHP-TOPSIS has proven its reliability in decision-making related to environmental engineering research [28], [29]. The AHP method is aimed to obtain weights of seven criteria (see Table 1), thus defining the importance of the criteria through pairwise comparison of these criteria. Criteria weighting procedure was performed via AHP based on the waste management experts' verbal evaluation.

Considering the origin and composition of textile waste, the criteria definition is based on a circular economy concept and the role of the technology for the waste management sector. In total seven criteria are defined (see the list of criteria and their brief description in Table 2). While the number and the nature of the defined criteria are proper to give the initial basis for the decision-making on textile waste recovery, upon publication of credible research data, such criterion as energy requirements and environmental performance of the production process need to be added to the methodology.

Within AHP procedure, the numerical values from 1 to 9 (where 1 is equal importance and 9 is very high importance) were assigned to each compared pair (21 comparisons for each expert) [33], the decision matrix was created, and eigenvectors were defined. The higher the eigenvectors of a specific criterion, the higher dominance of the criterion is reflected in the decision process. A consistency ratio of 7.9 % is used, that corresponds to the threshold if the multiple stakeholders are interviewed [32].

Then, the TOPSIS technique is used to calculate the textile waste recovered products alternatives' ratings. The advantages of the TOPSIS method include the small amount of data and the result reflects closeness to the ideal solution [29], [32].

In this study, the performance of the criteria applied in the TOPSIS evaluation is described in two ways: for two criteria ('Share of textile waste in total waste feedstock' and 'Recovery potential') – quantifying performance in percentages describing each recovery process, for the other criteria – characterising quantity with qualitative attributes (see Table 2).

TABLE 2. QUANTIFICATION OF THE CRITERIA BASED ON TECHNOLOGICAL PERFORMANCE

Criterion	Description of criterion	Performance attributes (higher score is better)
Circular economy approach of the technology	Conformity of the textile waste processing activity to the waste management hierarchy as defined in the WFD and aimed at efficient elimination of waste in the most environmentally-sound way.	3 – recycling, composting, anaerobic digestion, 2 – material and chemical recovery, 1 – energy recovery.
Added-value potential of final product	Correspondence of the final recovered product to the value pyramid. This describes the market value of the final product considering its market demand and production costs.	4 – fine chemicals, 3 – plastics & polymers, 2 – chemicals & materials, 1 – fuels, energy, heat.
Share of textile waste in total waste feedstock	Due to specifics of waste recovery processes, some technologies use a mix of different types (organic waste, mixed municipal waste, etc.). This criterion normalizes the input data to the amount of textile waste in the feedstock mix.	From 0–100 % based on the data provided in the case studies.
Diversity of textile mix suitable for specific technology	Collected textile waste traditionally consists of diverse fibres. Only at the later stage, collected textiles are recycled to specific fibres (cotton, polyester, etc.), but this action requires additional energy consumption.	3 – technology is not limited with textile fibre type, 2 – natural/synthetic blend is suitable, 1 – only natural fibre is suitable.
Pre-treatment of waste feedstock	Describes efforts and time spent on pre-treatment of waste feedstock prior to processing.	3 – pre-processing and pre-treatment are not required, 2 – only pre-treatment or pre-processing is required, 1 – pre-processing (shredding, washing, etc.) and pre-treatment (soaking, boiling, chemical treatment etc.) are required.
Recovery potential	Recovery potential (in %) is an indicator to quantify the efficiency of waste-to-product recovery process.	From 0–100 % based on the data provided in the case studies.
Maturity of a recovery technology	Determining the readiness of technologies for operations across different environments (simulated & laboratory environment, prototype, industry environment)	3 – industrial scale, 2 – demonstration (piloting) scale, 1 – experimental (laboratory and simulation) scale.

The first criterion ‘Circular economy potential’ describes the conformity of the textile waste processing activity to the waste management hierarchy as defined in the Waste Management Framework Directive [2] (see Fig. 2). The waste management hierarchy sets out a sequence to successfully eliminate waste and ensure that products or materials are recovered from waste in the most environmentally-sound way. In line with the textile waste recovery processes, three strategies from the waste hierarchy are proper: (1) recycling, composting, anaerobic digestion, (2) material and chemical recovery and (3) energy recovery.

Waste recovered products have market benefits due to the lower costs of raw materials (wasted materials) compared to original (non-waste) raw materials. Considering the market demand and the prices of specific product categories (for example, chemicals, agricultural products, fuels, etc.), it is possible to define the value pyramid of the waste recovered final products (see Fig. 3). Thus, correspondence of the textile waste recovered product to the value pyramid is proposed as the criterion ‘Added-value potential of final product’.

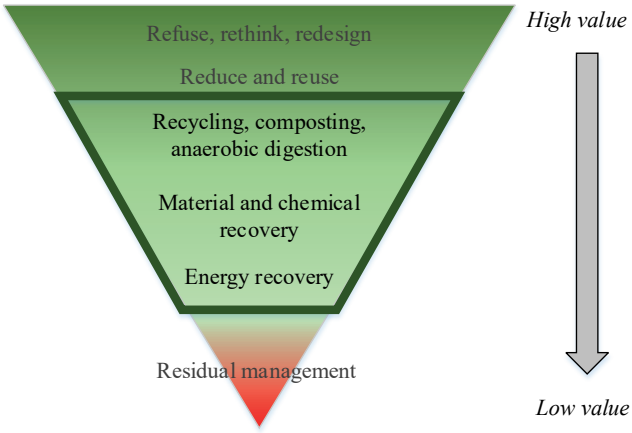


Fig. 2. Waste management hierarchy (Authors' illustration adapted from [34]).

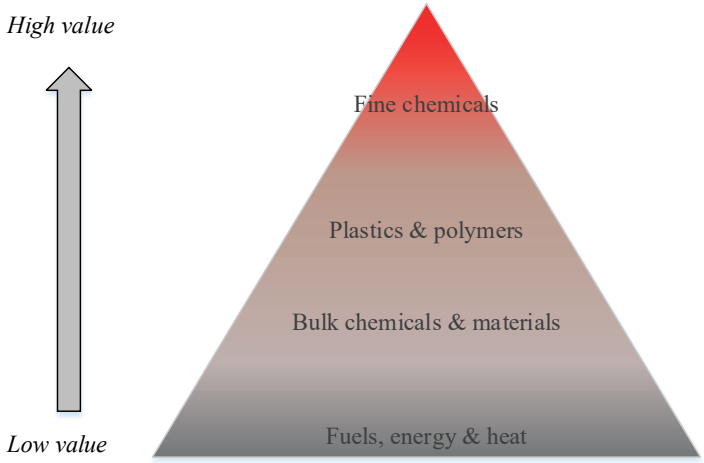


Fig. 3. Products value pyramid (Authors' illustration adapted from [35]).

Textile waste recovered products incorporate textile waste into the final product at different mass proportions depending on the specific technology and final product quality requirements. From waste reduction and recovery potential, the higher share of wasted raw material brings higher benefit. Based on that, the criterion 'Share of textile waste in total waste feedstock' is introduced.

Production of textile fibres (both natural and synthetic) reached about 107 million tonnes globally in 2018 and from the total amount 62.3 % was synthetic fibre (polyester, nylon, and other synthetics), 31.2 % natural fibre (wool, silk, cotton, down, other plant-based natural fibres) and 6.2 % man-made cellulosic fibre [36]. The use of synthetic fibres in the textile manufacturing sector is justified by their high endurance and durable properties [36], therefore polyfibres (mix of synthetic and natural fibres) are widely used. Since several textile waste recovery technologies are limited to the origin of the fibre (natural or synthetic), this is adapted in the criterion 'Diversity of textile mix suitable for specific technology'. Moreover,

the mix of natural and synthetic fibres in textile waste requires additional pre-treatment procedures of waste feedstock prior to the main recovery process (see the criterion 'Pre-treatment of waste feedstock' in Table 2).

Criterion 'Recovery potential' the efficiency of waste-to-product recovery process – the extent to which it is technologically possible to extract a value product (textile waste recovered product) from textile waste (feedstock). While the readiness of a textile waste recovery technology to be industrially applied is defined via the criterion 'Maturity of a recovery technology'.

3. RESULTS AND DISCUSSION

3.1. Criteria weighting

Pairwise criteria weighting according to the AHP procedure described in Section 2.1 was performed by 8 experts:

- 3 environmental engineering scientists – are aware and taking part in the development and research of novel waste management technologies.
- 2 representatives of local municipal waste management companies – managing textile waste collection, recycling, recovery or disposal processes.
- 1 representative of the Ministry of Environmental Protection and Regional Development – responsible for development of national waste management legal documents;
- 1 representative of the Latvian Environmental Agency – responsible for collection and processing of national waste management data;
- 1 representative of the Latvian Association of Light Industry Enterprises – the Association manages import-export processes of textile goods in the country and has a strong relationship with national textile producers.

The results of the AHP criteria weighting are given in Fig. 4.

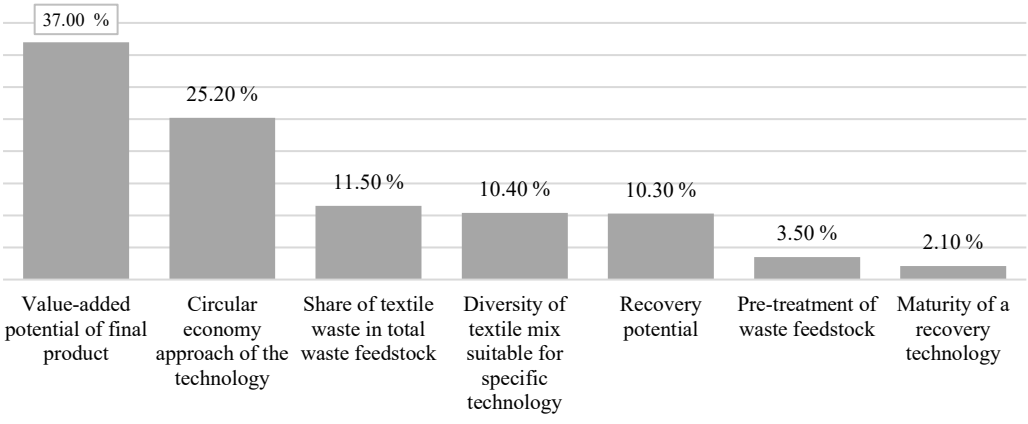


Fig. 4. Importance weighting scores for the textiles waste recovered products.

The dominant criterion for all the experts was similar and resulted in a score of 37 % for the criterion 'Value-added potential of final product'. This can be explained both by the

participation of business & industry representatives (waste recycling companies) as the evaluation experts and by the paradigm shift from 'waste is a problem and additional costs' to 'waste is a resource and profit'. As the second most important criterion is the approach of waste recovery stated (the score is equal to 25.20 %). This criterion implicitly also reflects the reduction of environmental impact and the time and resources (e.g. energy) required to reprocess the waste into the product. The criteria 'Share of textile waste in total waste feedstock' and 'Diversity of textile mix suitable for specific technology' get the higher score from the business & industry representatives (sharing 2nd and the 3rd importance ranking) due to 'the hidden costs' contained therein, while at the levelized scoring reached 3rd and 4th position with 11.50 % and 10.50 %, respectively. Criterion 'Recovery potential' was scored as the 2nd most important by the environmental scientists probably due to its 'hidden' environmental protection and technological efficiency aspect and surprisingly low importance ranking (6th position) by the governmental representatives. Criteria 'Pre-treatment of waste feedstock' and 'Maturity of a recovery technology' at the levelized scoring between all the experts reached respectively the 6th (3.5 %) and the 7th (2.1 %) importance rank.

3.2. Preference of the textile waste recovered products

To identify the most preferable textile waste recovered product, eight potential products were analysed: compost, RDF, ethanol, two types of building insulation materials, TPA, glucose, recovered cotton and polyester (see more details in Table 1). Applying expert-based AHP defined criteria importance scores and TOPSIS alternative ranking, MCDA for the textile waste recovered products were performed and the results are summarized in Fig. 5.

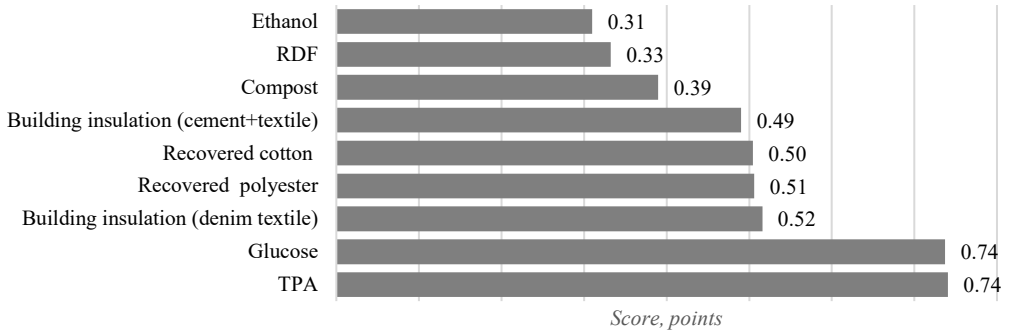


Fig. 5. Decision-making results for textile waste recovered products *via* MCDA AHP-TOPSIS method (0 – the lowest score, 1 – the highest score).

As seen from Fig. 5, the best alternative for the textile waste recovered products is production of TPA (scoring 0.74 from 1) and glucose (0.77 from 1). Both these products have high added-value potential, high share of textile waste used in the production process and flexibility to origin of wasted textile (natural and synthetic are proper).

While use of textile waste for RDF production and ethanol production do not require a high quality of raw materials as well as has high flexibility to the origin of the textiles, these products are not favourable in line with the circular economy and added-value principles as well as requires significant energy efforts in pre-processing and pre-treatment of feedstock – total score for RDF is 0.33 from 1 and ethanol is 0.31 from 1.

Application of textile waste for the production of building insulation materials are suitable only if the high content of textile waste is present in the insulation material mix: building

insulation material where only 9 % of textile waste is incorporated in the mix is ranked as the 4th worst alternative (0.49 points), while building insulation purely produced from denim textile is ranked as the 3rd favourable alternative (0.52 points).

Recovery of cotton and polyester from textile waste is ranked as the 4th and the 5th best alternative due to high recovery potential and share of textile waste used in the production process – 0.50 points and 0.52 points, respectively.

Despite the higher level of technology maturity, composting is the worst alternative for textile waste recovery due to low recovery potential (28 %).

4. CONCLUSION

Within the study, an MCDA AHP-TOPSIS methodology is developed to select the best appropriate textile waste recovered product and approbated for nine textile waste recovered products – compost, RDF, ethanol, glucose, building insulation material from cement and textile waste mix, building insulation material from denim textile waste, TPA, recovered cotton and recovered polyester.

A set of seven criteria ('Circular economy approach of the technology', 'Added-value potential of final product', 'Share of textile waste in total waste feedstock', 'Diversity of textile mix suitable for specific technology', 'Pre-treatment of waste feedstock', 'Recovery potential' and 'Maturity of a recovery technology') are defined to characterise the waste recovered product and its compliance to circular economy and added-value principles. Expert-based criteria weighting has proven that market potential of the potential product (expressed as an added-value of the product) and the type of recovery technology have the highest importance in the decision-making process. The criterion related to the maturity of technology should be analysed at a later stage (for example, at economic evaluation of the alternatives) of process selection.

At the moment of the development of the present paper, availability of research data and market data in the field of textile waste recovery was limited for several technologies. To reach a more credible and coherent decision-making methodology for textile waste recovered products, it would be valuable to include additional criteria in the developed algorithm. Energy requirements of the recovery process, market price of the recovered products, as well as generated environmental impact during the recovery process needs to be analysed upon publication of credible research and market data in this field to reach exhaustive results.

REFERENCES

[1] Pilar López-Portillo M., Martínez-Jiménez G., Ropero-Moriones E., Concepción Saavedra-Serrano M., Waste treatments in the European Union: A comparative analysis across its member states. *Helion* 2021:7(12):e08645. https://doi.org/10.1016/j.heliyon.2021.e08645

[2] Directive (EU) 2018/851 of the European Parliament and of the Council of 30 May 2018 amending Directive 2008/98/EC on waste. *Official Journal of the European Union.* 2018: L 150/108. http://data.europa.eu/eli/dir/2018/851/oj
Jäämaa L., Kaipia R. The first mile problem in the circular economy supply chains – Collecting recyclable textiles from consumers. *Waste Management* 2022:141:173–182. https://doi.org/10.1016/j.wasman.2022.01.012

[3] Schmutz M., Som C. Identifying the potential for circularity of industrial textile waste generated within Swiss companies. *Resources, Conservation and Recycling* 2022:182:106132.
Ribul M., Lanot A., Tommencioni Pisapia C., Purnell P., McQueen-Mason S. J., Baurley S. Mechanical, chemical, biological: Moving towards closed-loop bio-based recycling in a circular economy of sustainable textiles. *Journal of Cleaner Production* 2021:326:129325. https://doi.org/10.1016/j.jclepro.2021.129325

[4] Kahoush M., Kadi N. Towards sustainable textile sector: Fractionation and separation of cotton/polyester fibers from blended textile waste. *Sustainable Materials and technologies* 2022:34:e00513.

[5] Generation of waste by waste category, hazardousness and NACE Rev.2 activity. [Online]. [Accessed 22.04.2022]. Available: https://ec.europa.eu/eurostat/databrowser/view/env_wasgen/default/table?lang=en

[6] Ellen MacArthur Foundation, 2017. [Online]. [Accessed 07.04.2022]. Available: https://ellenmacarthurfoundation.org/a-new-textiles-economy

[7] Yousef S., Tatariants M., Tichonovas M., Sarwar Z., Jonuškienė I., Kliucininkas L. A new strategy for using textile waste as a sustainable source of recovered cotton. *Resources, Conservation and Recycling* 2019:145:359–369. https://doi.org/10.1016/j.resconrec.2019.02.031

[8] Yu I. K. M., Chen H., Abeln F., Auta H., Fan J., Budarin V. L., Clark J. H., Parsons S., Chuck C. J., Zhang S., Luo G., Tsang D. C. W. Chemicals from lignocellulosic biomass: a critical comparison between biochemical, microwave and thermochemical conversion methods. *Critical Reviews in Environmental Science and Technology* 2020:51(14):1479–1532. https://doi.org/10.1080/10643389.2020.1753632

[9] Subramanian K., Chopra S. S., Cakin E., Li X., Sze Ki Lin K. Environmental life cycle assessment of textile bio-recycling – valorizing cotton-polyester textile waste to pet fiber and glucose syrup. *Resources, Conservation and Recycling* 2020:161:104989. https://doi.org/10.1016/j.resconrec.2020.104989

[10] Roos, S., Sandin, G., Peters, G., Bjorn, S., Bour, G. S., Perzon, E., Jonson, C. White paper on textile recycling. Mistra Future Fashion, 2019.

[11] Leal Filho W., Ellams D., Han S., Tyler D., Boiten V. J., Paço A., Moora H., Balogun A.-L. A review of the socio-economic advantages of textile recycling. *Journal of Cleaner Production* 2019:218:10–20. https://doi.org/10.1016/j.jclepro.2019.01.210

[12] Kunchimon S. Z., Tausif M., Goswami P., Cheung V. Polyamide 6 and thermoplastic polyurethane recycled hybrid Fibres via twin-screw melt extrusion. *Journal of Polymer Research* 2019:26:162. https://doi.org/10.1007/s10965-019-1827-0

Sherwood J. Closed-loop recycling of polymers using solvents: remaking plastics for a circular economy. *Johnson Matthey Technology Review* 2020:64(1):4–15. https://doi.org/10.1595/205651319X15574756736831

[13] Ostlund Å., Wedin H., Bolin L., Berlin, J., Jonsson C., Posner S., Smuk L., Eriksson M., Sandin G. Textilåtervinning. Naturvårdsverket, 2015.

Holea G., Hole A. Improving recycling of textiles based on lessons from policies for other recyclable materials. *Sustainable Production and Consumption* 2020:23:42–51. https://doi.org/10.1016/j.spc.2020.04.005

[14] Biyada S., Merzouki M., Dėmčėnko T., Vasiliauskienė D., Urbonavičius J., Marčiulaitienė E., Vasarevičius S., Benlemlih M. Evolution of Microbial Composition and Enzymatic Activities during the Composting of Textile Waste. *Applied Sciences* 2020:10(11):3758. https://doi.org/10.3390/app10113758

[15] Vázquez M.A., Soto M. The efficiency of home composting programmes and compost quality. *Waste Management* 2017:64:39–50. https://doi.org/10.1016/j.wasman.2017.03.022

[16] Ozuysal A., Akinci G. The assessment of refuse derived fuel (RDF) production from textile waste. *Eurasian Journal of Environmental Research* 2019:3(2):27–32.

[17] Hasanzadeh E., Mirmohamadsadeghi S., Karimi K. Enhancing energy production from waste textile by hydrolysis of synthetic parts. *Fuel* 2018:218:41–48. https://doi.org/10.1016/j.fuel.2018.01.035

[18] Wang H., Kaur G., Pensupa N., Uisan K., Du C., Yang X., Sze Ki Lin C. Textile waste valorization using submerged filamentous fungal fermentation. *Process Safety and Environmental Protection* 2018:118:143–151. https://doi.org/10.1016/j.psep.2018.06.038

Asdrubali F., D'Alessandro F., Schiavoni S. A review of unconventional sustainable building insulation materials. *Sustainable Materials and Technologies* 2015:4:1–17. https://doi.org/10.1016/j.susmat.2015.05.002

[19] *UltraTouch*™ Denim Insulation. [Online]. [Accessed 12.04.2022]. Available: http://www.bondedlogic.com/ultratouch-denim-insulation/

[20] Briga-Sá A., Gaibor N., Magalhães L., Pinto T., Leitão D. Thermal performance characterization of cement-based lightweight blocks incorporating textile waste. *Construction and Building Materials* 2022:321:126330. https://doi.org/10.1016/j.conbuildmat.2022.126330

[21] Palme A., Peterson A., de la Motte H., Theliander H., Brelid H. Development of an efficient route for combined recycling of PET and cotton from mixed fabrics. *Textiles and Clothing Sustainability* 2017:3:Art4. https://doi.org/10.1186/s40689-017-0026-9

[22] Köksalan M., Wallenius J., Zionts S. An Early History of Multiple Criteria Decision Making. *Journal of Multi-Criteria Decision Analysis* 2013:20:87–94. https://doi.org/10.1002/mcda.1481

[23] Vamza I., Valters K., Blumberga D. Multi-Criteria Analysis of Lignocellulose Substrate Pre-Treatment. *Environmental and Climate Technologies* 2020:24(3):483–492. https://doi.org/10.2478/rtuect-2020-0118

[24] Zlaugotne B., Zihare L., Balode L., Kalnbalkite A., Khabdullin A., Blumberga D. Multi-Criteria Decision Analysis Methods Comparison. *Environmental and Climate Technologies* 2020:24(1):454–471. https://doi.org/10.2478/rtuect-2020-0028

[25] Vanaga R., Blumberga A., Gusca J., Blumberga B. Choosing the best nature's strategy with the highest thermodynamic potential for application in building thermal envelope using MCA analysis. *Energy Procedia* 2018:152:450–455. https://doi.org/10.1016/j.egypro.2018.09.252

[26] Rozentale L., Blumberga D. Cost-Benefit and Multi-Criteria Analysis of Wind Energy Parks Development Potential in Latvia. *Environmental and Climate Technologies* 2021:25(1):1229–1240. https://doi.org/10.2478/rtuect-2021-0093

[27] Adem Esmail B., Geneletti D. Multi-criteria decision analysis for nature conservation: A review of 20 years of applications. *Methods in Ecology and Evolution* 2018:9(1):42–53. https://doi.org/10.1111/2041-210X.12899

[28] Saaty T. L. Deriving the AHP 1-9 scale from first principles. *Proc. 6th ISAHP*, 2001. https://doi.org/10.13033/isahp.y2001.030

[29] A Zero Waste hierarchy for Europe [Online]. [Accessed 12.04.2022]. Available: https://zerowasteeurope.eu/2019/05/a-zero-waste-hierarchy-for-europe/
Stegmann P., Londo M., Junginger M. The circular bioeconomy: Its elements and role in European bioeconomy cluster. *Resources, Conservation & Recycling* 2020:6:100029. https://doi.org/10.1016/j.rcrx.2019.100029

[30] ETC/WMGE Report 1/2021: Plastic in textiles: potentials for circularity and reduced environmental and climate impacts [Online]. [Accessed 11.02.2022]. Available: https://www.eionet.europa.eu/etcs/etc-wmge/products/etc-wmge-reports/plastic-in-textiles-potentials-for-circularity-and-reduced-environmental-and-climate-impacts