Environmental and Climate Technologies
2025, vol. 29, no. 1, pp. 323–343
https://doi.org/10.2478/rtuect-2025-0023
https://content.sciendo.com

Recycling of Mixed Post-Consumer Textiles: Opportunities for Sustainable Product Development

Megija VALTERE[1]*, Tereza BEZRUCKO[2], Veronika LIBEROVA[3], Dagnija BLUMBERGA[4]

[1–4]*Institute of Energy Systems and Environment, Riga Technical University, Azenes iela 12/1, LV-1048 Riga, Latvia*

Received 24.03.2025; accepted 12.06.2025

***Abstract* – The Waste Framework Directive mandates that, starting from January 1, 2025, separate collection of textiles must be introduced in all Member States of the European Union. The aim of separate collection is to promote the circular economy in the textile system by creating favorable conditions for recycling and reuse. However, in order to promote recycling, there are still challenges in terms of textile variety and mixtures. Currently, there are no commercially viable technologies to recycle mixed textiles without sorting back into textiles or high value-added products. Therefore, the aim of this study was to determine if there are products in the research process that could be obtained from post-consumer mixed textile waste and, if so, to assess which is the most suitable for further development based on economic, environmental, social and technical factors. Two methods were applied: literature analysis and multi-criteria decision analysis. A total of 27 research articles were identified, but only four were selected for further analysis based on their relevance to the research objective. The products obtained in the selected studies were (1) bio-oil and terephthalic acid, (2) textile-reinforced composite for building applications, (3) mycelium-based composite for thermal insulation and (4) textile fibers (cotton and nylon), spandex monomers and bis(2-hydroxyethyl) terephthalate. The multi-criteria decision analysis showed that mycelium-based composite has the highest potential for further development. Future research should focus on scaling up the production of mycelium-based material and conducting a more detailed assessment of the economic, social and environmental impacts.**

***Keywords* – Circular economy; multi-criteria decision analysis (MCDA); mycelium-based material; sustainable development goals (SDGs); value-added products.**

1. INTRODUCTION

Production and consumption of textiles is increasing worldwide, and so is the amount of textile waste [1]. Globally, around 75 % of clothing waste is landfilled or incinerated, 25 % is recycled or reused and only 1 % is recycled back into textiles [2]. The transition to a circular economy in the textile sector is in line with several United Nations Sustainable Development Goals [3]. In particular, it would contribute to the achievement of Goal 12 – Responsible Consumption and Production.

Textile waste is also a pressing issue in the European Union (EU), with the fourth highest impact on primary raw material and water consumption and the fifth highest impact on greenhouse gas emissions [4]. For this reason, the EU has identified textiles as one of the

* Corresponding author.
E-mail address: megija.valtere@rtu.lv

seven key product value chains to be targeted in the transition to a circular economy. As part of this transition, The Waste Framework Directive mandates that, starting from January 1, 2025, separate collection of textiles must be introduced in all EU Member States [5]. However, separate collection of textiles is only the first step, as sorting and recycling are not yet sufficiently developed in the EU [6], [7]. If sorting and recycling capacity is not increased alongside separate collection, there is a risk that sorted textiles will end up in incinerators or landfills or be exported as waste outside the EU [7].

Textile waste can be divided into three streams: post-industrial waste, pre-consumer waste and post-consumer waste [1]. Post-industrial waste is all textile waste generated during the production process. Pre-consumer waste already exists as products, but is either damaged or has not been sold or used. The last and largest stream is post-consumer waste, which is waste generated after use. EU textile waste amounts to 15 kg per capita, 85 % of which is made up of consumer discarded clothes and home textiles – post-consumer waste [6]. In this study, this waste stream is defined as mixed post-consumer textile waste. This waste is a mixture of different types of textiles, mainly cotton and polyester, with added components such as buttons and zippers and added substances such as dyes, coatings and flame retardants [8], [9]. All of these aspects create barriers to current textile recycling technologies.

Part of the solution could be to improve sorting so that textile flows are as clean as possible, each with its own recycling options. However, there are a number of obstacles to achieving this. Firstly, sorting is currently largely done manually, which makes the process more costly and time consuming [9]. Furthermore, textiles are not just mono-materials that are suitable for recycling. Instead, textile waste is usually a multi-element waste, and often blended. Therefore, textile waste can be divided into more than 300 different categories depending on size, composition and type of fibers [1]. Some of them are difficult to recycle or need specialized technologies. In addition, the quality of textile waste is not guaranteed as textiles may be contaminated or defective [1]. These sorting barriers raise the question whether there is a solution to recycle mixed textile waste as a single stream without much sorting.

Large number of studies have been carried out on the recycling of different textiles [10]–[13], including blended textiles [14], [15]. However, to the best of the author's knowledge, no study has yet summarized research on post-consumer mixed textile waste recycling. Also, there are currently no commercially viable technologies to recycle mixed textiles back into textiles or high value-added products [8], [16]. Therefore, the aim of this study was to determine if there are products in the research process with Technology Reediness Level of 3–5 that could be obtained from post-consumer mixed textile waste and, if so, to assess which is the most suitable for further development based on economic, environmental, social and technical factors. Literature analysis was used to identify products, and multi-criteria decision analysis was used to evaluate and compare them. Multi-criteria decision analysis was chosen because it is suitable for comparing products on the basis of selected criteria [17], [18].

2. METHODOLOGY

Multi-criteria decision analysis (MCDA) is a well-established method for making decisions. It is applicable in any field where it is possible to define a problem, criteria and alternatives to be compared with each other [19]. There are several MCDA methods, but each method has its own calculation steps, so the results may differ even though the input data are the same.

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) method was chosen for this research, based on the author's previous study comparing products [18], which is also the objective of the present analysis. The TOPSIS method has the benefits of relatively simple calculation steps, an unlimited number of criteria and alternatives, and the input data can be both qualitative and quantitative [19]. The resulting score is the distance of the alternatives to the ideal point, which in this method is equal to one, meaning that the closer the score of an alternative is to one, the better the alternative. MS Excel was used for the TOPSIS calculations.

The MCDA analysis followed the steps developed in the author's previous study [18]:

1. Product identification. The first step is a literature analysis to identify products.
2. Criteria selection and data collection. This stage involves selecting criteria and collecting input data.
3. TOPSIS analysis. In this step, calculations of the analysis are carried out and the final results are obtained.
4. Sensitivity analysis. The final step is to validate the results using a sensitivity analysis.

2.1. Product Identification

The aim of the literature analysis was to identify products that can be obtained from post-consumer mixed textiles. The scope of this study was limited to the scientific literature to ensure that the focus is on peer-reviewed information. Three scientific databases, Scopus, Science Direct and Web of Science, were used. The keywords "post-consumer mixed textile recycling" were used in all databases. Only in Web of Science an insufficient number of articles was found (33 results), so the keywords were changed to "textile waste recycling products". In total, a relatively large number of publications were found for these keywords: Science direct (2678 results), Scopus (944), Web of Science (799). Content in English and less than 10 years old (from 2014) was selected. The first 100 items in all databases were reviewed sorted by relevance. This was done since, approaching 70 items, they started to be outside the study's scope, therefore it was decided to stop the review at 100 items. For further research, items were filtered based on title and abstract. This was an initial screening to find articles on textile recycling. The selected studies were then fully read to select studies according to two criteria: recycled textiles are post-consumer and mixed textiles. The aim was to find recycling process that met both criteria.

2.2. Criteria Selection and Data Collection

All the calculations are based on the input data, the selected alternatives and the criteria. For further analysis, products and product sets produced from post-consumer mixed textile waste were selected to be alternatives. The products were categorized on the basis of research articles. For example, the Andini *et al.* study [16] produced four main products, but these are not considered separately as they are all produced in the same production cycle and using the same raw material.

After determining alternatives to compare, the next step was to select the criteria. The criteria were selected on the basis of their relevance to the study objective and the available data. To assess the potential for product development, the criteria cover four categories: environmental, economic, social and technical aspects. These categories were chosen because technical parameters are important to assess the technology, while sustainability aspects are important to assess its development [20]. The nine criteria selected are shown in Table 1. For all criteria, the ideal value is the maximum value, which means the higher the value the better.

TABLE 1. CRITERIA FOR MULTI-CRITERIA DECISION ANALYSIS

Criteria category	Criteria	Description
Environmental aspects	Environmental impact	Comparison of global warming potential (GWP) from life cycle assessment of a new and a conventional product (reduction in GWP)
	Resource efficiency	Usage of other waste materials in production (weight proportion, %)
	Longevity and recyclability	Product lifetime and end-of-life potential (score)
Economic aspects	Product price	Comparison of price for the new and conventional product (reduction in price)
	Market demand	Global market size assessment (billion EUR)
Technical aspects	Technology maturity	Level of technological readiness (TRL 1-9)
	Level of research	Studies carried out on similar products (score)
	Market competitiveness	Comparison of properties for the new and conventional product (score)
Social aspects	Social aspects	Evaluation of human health and safety risks during production (score)

2.2.1. Environmental aspects

Life cycle assessment is a method for quantifying the environmental impacts of products and processes. In order to gain insight into potential environmental impacts, LCA studies were used to assess this criterion, as it has been done previously in similar MCDA studies [17], [21]. The products are innovative, so no LCA studies have yet been carried out for the specific cases. Therefore, similar products with LCA studies were selected. The GWP was used as a quantitative indicator, which is commonly used in environmental impact communication [22]. The conventional product was selected based on the intended use of the new product, what it can be compared to in terms of performance and what is commonly used now. If the study already had data on conventional products, these were used for comparison. But if not, they were obtained from the *Ecoinvent* 3.10. database using the same method as used in the comparison study. The value of the existing product was divided by the value of the new product to get estimate of the number of times the environmental impact can be reduced. If the value is less than one, this means that the environmental impact of the new product likely is higher based on the GWP. This approach was chosen to assess not only the potential environmental impacts of the alternatives, but also to compare the alternatives with the products currently in use. The life cycle impact assessment method and the scope of the system were taken into account in the comparison.

To assess the potential of the circular economy, the criterion “Resource efficiency” was included. The products studied already contribute to the circular economy because the raw material used is textile waste. Therefore, this criterion assesses whether additional by-products or waste are used during production that would increase the contribution to the circularity and avoid the use of virgin materials. It is determined by weight in proportion to the final product. If no other residues are used, the alternative receives a score of zero.

The first two criteria relate more to the production phase. The criterion “Longevity and recyclability” was introduced to also assess the use phase and end of life. It includes an assessment of the lifetime and recyclability of the product. Both aspects were evaluated on a three-point scale. Scoring system for recycling: (1) not recyclable or generally not recycled, (2) recycled or biodegradable, (3) closed-loop recycled. This rating was chosen as the circular economy prioritizes resource circularity in closed system and other uses of bio-based materials before nutrients are returned to natural system [2]. Lifetime aspect points system: (1) single use, (2) used up to 10 years, (3) longer than 10 years. The points were multiplied with each other, giving a maximum of 9 points.

2.2.2. Economic aspects

The price of a product is an important indicator of whether it will be economically viable and competitive. Price is a specific indicator (price per unit of product) rather than other economic indicators which are more difficult to compare, for example initial investment is more dependent on production volume. As with the environmental impact criterion, innovative products are unlikely to be subject to an economic assessment and will therefore be compared with similar products. The conventional product price was also identified for comparison. The value of the existing product was divided by the value of the new product to get how many times cheaper the new product would be. If the value is less than one, it means that the price of the new product is higher and it is not economically justified at this time. The other economic aspect focuses on the demand side. Global market size was used to determine whether a product is in demand. The higher the market estimate, the more the product is in demand. The market size estimates were based on publicly available data.

2.2.3. Technical aspects

The Technology Readiness Level (TRL) was assessed to determine how mature and ready for scaling up the technologies developed in the study are. The TRL has proven to be a very effective way of communicating the progress of new technologies in different fields [23]. It is assessed on a 9-point scale. In order to better understand and evaluate the products, more extensive descriptions of the TRL from J. Mankins publication [23] were used.

To assess how well a product is being researched, the criterion “Level of research” was introduced. This measured the number of publications on a given topic. In order to effectively assess this criterion, only one database was chosen, and that was Scopus. The key words for each alternative were based on the type of product, the method used and included the term “textile”. The publications found were assessed qualitatively by looking at the abstract and the title. Only publications containing the same or similar product and using textiles were selected.

The criterion “Market competitiveness” was added to assess the technical performance of the product. This criterion looked at the properties of the selected alternatives as determined by their studies and then compared them with those of the conventional product. Each product had its own characteristics, as each has its own application. If the comparison was already made in the study, it was used, if not, the characteristics of the conventional product were additionally selected. The product’s characteristics compared to similar products were evaluated with points. The scoring system for the criterion was as follows: (1) characteristics are lower than those of products on the market, (2) characteristics are more or less the same, (3) improved characteristics.

2.2.4. Social aspects

Social factors can be quantified using social LCA or indicators such as human health [17] and job creation opportunities [24]. To the best of the authors’ knowledge, no social LCA has been carried out for the alternative or similar products under consideration. Quantitative data on social factors for the alternatives were available for more generic sectors such as government, education and manufacturing. That was not applicable in this case as all alternatives fall within the same sector. It was therefore decided to assess the risk to human health in the product manufacturing process using a scoring system based on the information available in the literature. The following evaluation system was used: (1) high risk work, (2) medium risk and (3) minimal risk work.

2.3. TOPSIS Analysis

To start the calculation, the criteria must be given a weight indicating the importance of the criterion. The weight can be determined by different methods, such as the analytical hierarchy [19] process or sensitivity analysis [18]. In our case, there are more than seven criteria, which means that the analytical hierarchy process cannot be used as the results would be inconsistent [19]. In this study, it was decided that all criteria will have equal importance which means that all criteria will be given equal weight.

After determining the input data and criteria weights, the TOPSIS method was used in the following calculations. TOPSIS method has five steps [19]:

1. Normalization of decision matrix:

$$R = \frac{X}{\sqrt{\sum X^2}}, \tag{1}$$

where R is normalized matrix value and X is criteria value.

2. Calculation of the weighted decision matrix:

$$V = R \cdot W, \tag{2}$$

where V is weighted value and where W is weight of criteria.

3. Defining ideal and anti-ideal values: V^+ is maximum value of the weighed values un V^- is the minimum value.
4. Calculation of the ideal and anti-ideal values:

$$d_a^+ = \sqrt{\sum \left(V^+ - V\right)^2}, \tag{3}$$

where d_a^+ is distance to the ideal solution.

$$d_a^- = \sqrt{\sum \left(V^- - V\right)^2}, \tag{4}$$

where d_a^- is distance to the anti-ideal solution.

5. Calculation of relative proximity:

$$C_a = \frac{d_a^-}{d_a^+ - d_a^-}, \tag{5}$$

where C_a is relative proximity to the ideal solution. In the end, the best alternative can be determined by comparing the relative proximity to the ideal solution.

2.4. Sensitivity Analysis

Sensitivity analysis is carried out to examine the impact of criteria on the results and to validate the results. Sensitivity analysis steps [25]:

– In this method, the weights are initially considered to be the same:

$$w' = \frac{1}{n}, \tag{6}$$

where w' is initial weight and n is number of criteria.

– Then the weight for one criterion is changed, depending on the unitary variation ratio:

$$w'_k = \beta_{km} \cdot w', \tag{7}$$

where

w'_k weight, that is subject to change;

β_{km} unitary variation ratio;

$k = 1, 2, 3\ldots n$, $m = 1, 2, 3\ldots n$.

– To obtain the weight of the other criteria Eq. (8) is used:

$$w'_{km} = \frac{(1 - w'_k)}{(n - 1)}, \tag{8}$$

A sensitivity analysis with five unitary variation ratios was carried out ($ß_k$ = 0.01; 0.5; 1.5; 2; 2.5). Larger ratios such as 3 and 4 were also tested, but the criteria are sufficiently sensitive to change so the original ratios were kept. The ratios were increased by 0.5 steps. This means that with each further ratio, the impact (weight) of the criterion increases proportionally. The resulting weights are then applied in TOPSIS calculations to get the results of the Sensitivity analysis. This was done for all criteria.

3. Results

3.1. Identified Textile Recycling Products

Product identification resulted in 27 articles on the recycling of textiles into products. Further analysis of the articles was carried out to group the products based on two criteria concerning input textile waste: textile fiber type (polyester, cotton, mixed, etc.) and waste type (industrial or post-consumer). A list of products resulting from these articles is given in Table 2. In eight articles, the textile waste came from industry, which is not relevant for our further analysis as these textiles have not been used by a consumer. Most of the articles focused on a certain type of textile or groups of textiles, in some cases even very specific textiles like silk, denim, lyocell and leather. As shown in Table 2, the analysis resulted in only four articles covering the recycling of mixed post-consumer textiles, which was the objective of the analysis. The products obtained in the selected studies were (1) bio-oil and terephthalic acid [8], (2) textile-reinforced composite for building applications [26], (3) textile fibers (cotton and nylon), spandex monomers and bis(2-hydroxyethyl) terephthalate [16] and (4) mycelium-based composite for thermal insulation [27].

TABLE 2. SUMMARY OF PRODUCTS WHICH CAN BE OBTAINED FROM TEXTILE RECYCLING

Textile type / Waste type	Industrial	Post-consumer
Polyester	Polyurethane foams [28]	Terephthalic acid (TPA) [29], monomers like bis(2-hydroxyethyl) terephthalate (BHET) and bis(2-hydroxyethyl) terephthalamide [30], TPA and ethylene glycol [31]
Cotton	Thermal insulation [32]	Composites for industrial applications [33], glucose solution [34], [35], fashion accessories [36], vermicompost for fertilizer [37]
Nylon	–	Fine fibrous membrane [38]
Denim	Sound absorbing material [39]	Fire retarding composite board [40]
Silk	–	Luminescent carbon dots [41]
Lyocell	Adsorbent for heavy metals [42]	–
Leather	Leather-like yarns [43]	–
Cotton/polyester	–	Cellulose fibers [44], cellulose and PET films [45], 3D printing filament [46], fungal cellulase and polyester [47]
Viscose/polyester and viscose/polyamide	–	Synthetic fibers and lactic acid [48]
Acrylic and wool	Thermal insulation [49]	–
Cotton, cotton/polyester and acrylic	Biochar as fabric additives [50]	–
Mixed textile	–	Bio-oil and TPA [8], textile reinforced composites for building applications [26], BHET crystals, spandex monomers, cotton and nylon [16], mycelium-based composite for thermal insulation [27]

3.2. Input Data for Alternatives

Next products from four studies were investigated to later be compared in the TOPSIS analysis – (1) bio-oil and terephthalic acid [8], (2) textile-reinforced composite for building applications [26], (3) textile fibers (cotton and nylon), spandex monomers and bis(2-hydroxyethyl) terephthalate [16] and (4) mycelium-based composite for thermal insulation [27]. Only these studies were selected as they deal with mixed post-consumer textile recycling.

Matayeva *et al.* published a study in 2022 on the recycling of mixed textiles using hydrothermal liquefaction [8]. The study did not use actual mixed textile waste, but rather combined textile waste with a known composition based on the proportions of fibers produced globally. The processing was carried out on a laboratory scale using hydrothermal liquefaction without any pre-treatment steps such as sorting, dye removal, etc. The results showed that this method could yield 3–9 wt.% bio-oil and 38–54 wt.% TPA. TPA can further be used in the production of plastics, packaging, textiles, resins, composites, paints, etc. [51]. The composition of the bio-oil considered in the study makes it difficult to upgrade to a drop-in fuel. Instead, it could be upgraded and used as a chemical feedstock [8].

The second alternative is a textile fiber reinforced composite (TRC) for use in construction [26]. The prototype panels were produced on a laboratory scale by mechanically extruding mixed textile waste using isothermal hot pressing in a steel die. In addition, residual wood sawdust from the furniture industry was added as a secondary filler. To improve processing and the final product, maleic anhydride grafted polypropylene and polypropylene textile fleece were added as the thermoplastic matrix phase. The resulting material properties in terms of moisture resistance, load-bearing and non-load bearing applications are optimal compared to wood particleboards. Overall, they could be used in load-bearing structures as flooring, walling and division systems, as well as for interior linings such as ceilings or acoustic absorbers [26].

The third study looks at how closed-loop recycling could be promoted by extracting BHET crystals, spandex monomers, cotton and nylon from mixed textiles [16]. The method used was chemical conversion of post-consumer mixed textile waste using microwave-assisted glycolysis over a ZnO catalyst followed by solvent dissolution. As a result, the polyester from the mixed textile waste is completely converted into BHET crystals with 93 % purity. The most valuable of the spandex monomers obtained was 4.4′-methylenedianiline. However, further optimization is needed to increase its selectivity from other diphenyl-containing molecules. Formic acid and dyes have remained on the resulting cotton, making further processing more difficult. The obtained nylon has a reduced average molecular weight, which limits its use in applications requiring high tensile strength, stiffness and melting point. Overall, further development of this method has a potential to result in a global textile circularity rate of 88 % [16].

The final alternative considered was a mycelium-based composite for thermal insulation. In the reviewed study [27], a biocomposite was developed by cultivating *Pleurotus pulmonarius* fungus in agro-industrial waste (grass cuttings, dry leaves and sugarcane bagasse) and post-consumer mixed textile waste. The input material was recycled ground textiles that had already been processed by the supplier. The study succeeded in using textile materials to cultivate fungi, thus producing a sustainable and cost-effective construction material.

Before the TOPSIS calculations can be made, input data must be collected for each product. Table 3 summarizes all input data and the following subsections describe the data sources and assumptions made.

TABLE 3. INPUT DATA FOR MCDA

Criteria	**Alternatives**			
	Bio-oil and TPA	**Textile-reinforced composite**	**BHET crystals, spandex monomers, cotton, nylon**	**Mycelium-based composite**
Environmental impact, times	0.99	2.63	6.83	4.59
Resource efficiency, %	0	30	0	70
Longevity and recyclability, score	3.5	3	6	3
Product price, times	1.07	0.05	1.65	18.33
Market demand, billion EUR*	39	6	24	57
Technology maturity, score	3	5	3	3
Level of research, score	1	25	0	6
Market competitiveness, score	1	2	1	1
Social aspects, score	2	2	3	1

* The exchange rate used was 1 USD = 0.88 EUR (23.04.2025)

3.2.1. Environmental impact

The LCA studies were examined for environmental impact. For the first alternative, two products are considered at the same time, so the average value between these products is taken into account in each criteria assessment. Bio-oil was compared to a study where bio-oil was obtained from agricultural waste by hydrothermal treatment [52]. The gate-to-gate GWP of this product was 2.05 $kgCO_2eq/kg$. Carbon credits have been included in this assessment. The LCA method used was ReCiPe. In selected study, the new product was not compared to the conventional product, so the GWP was derived from the *Ecoinvent* database using the same LCA method. Crude oil was chosen for comparison because the bio-oil produced in the study is not a drop-in fuel and still needs further processing [8], [52]. As the study does not specify the region of the LCA model [52], a market activity was chosen that covers several countries but is cradle-to-gate. The transformation dataset, which is gate-to-gate, was country specific. The GWP for crude oil in the global region market is 0.65 $kgCO_2eq/kg$ [53].

There are no studies in which TPA has been produced by hydrothermal liquefaction. Therefore, it was compared with the closest product that could be found, a biobased TPA produced using miscanthus as a feedstock in a thermochemical processing (fast pyrolysis). These products have different raw materials and processes, but both focus on the sustainable production of TPA. The cradle-to-gate GWP of this product was 1.04 $kgCO_2eq/kg$ [54]. In the same study it is compared to conventional TPA and its impact was estimated to be 1.72 $kgCO_2eq/kg$.

The TRC was compared with an LCA study looking at composites made from natural fibers and recycled textiles [55]. The uncertainty arises from the fact that the study does not specifically mention what the materials could be used for. However, it was the closest product in terms of input materials and manufacturing process for which an environmental impact assessment was available. The reference material was a composite made of flax and recycled polyester fabric. Its cradle-to-gate GWP was 3.0 $kgCO_2eq/kg$. The study did not compare these materials with conventional products, so the GWP of glass fiber reinforced plastic was obtained [56]. The method used was the ReCiPe Midpoint (E) method from the study reviewed. The GWP obtained was 7.9 $kgCO_2eq/kg$.

The study on the third alternative [30] refers to a previously conducted LCA study on this recycling process. It was therefore used as a reference study. It dealt with the microwave-assisted recycling of PET bottles into BHET crystals [57]. The resulting cradle-to-gate GWP was 0.64 $kgCO_2eq/kg$. This was compared to conventional BHET oil-based production with a GWP of 4.37 $kgCO_2eq/kg$. For this alternative, only one product was considered as it is produced using the same processing method. However, the further treatment used in our alternative to separate the spandex monomers, nylon and cotton is not taken into account.

The mycelium-based material was compared with an LCA study of a mycelium isolation material using sawdust as a substrate [58]. The resulting cradle-to-gate GWP was 0.64 $kgCO_2eq/kg$. Most of the impact (95 %) was due to electricity, so the raw materials do not play a significant role. The study looks at the German situation and mentions that Germany has a high share of fossil fuels in the electricity mix. Therefore, the impact globally or in other countries could be even lower. It was compared with extruded polystyrene insulation, which has a GWP of 2.94 kg [58].

3.2.2. Resource efficiency

In only two cases – TRC and mycelium-based composites – were additional residual materials found to have been used. In the case of TRC, wood fibers from the furniture industry were used as a second filler. It accounted for 30 % of the weight of the material [26].

Mycelium-based material requires a lignocellulosic substrate on which the fungi can feed. A wide variety of plant substrates can be used as feedstock like jute, flax and straw [59]. In the study by Gomez *et al*. agro-industrial waste such as grass cuttings, dry leaves and sugarcane bagasse were used [27]. These accounted for 70 % of the substrate mass.

3.2.3. Longevity and recyclability

Bio-oil can be used as a fuel and in the production of food flavorings, aromatics, olefins, resins, adhesives, agrochemicals and fertilizers [60]. Most of these goods can be considered as single-use and nonrecyclable. TPA is used in plastics, packaging, textiles, resins, composites and paints [51]. As it can be used in the production of textiles, it was considered in this analysis to be recyclable in a closed loop. Textiles have an average lifespan of up to six years [61].

Recycling of fiber-reinforced composites is challenging due to their hardness and chemical stability [62], [63], so for this analysis it was assumed that TRC is generally not recycled. As the TRC in the present case is intended for construction, its lifetime is longer than 10 years, as the lifetime of a building is considered from 20 to over 100 years [64].

The textile fibers (nylon and cotton), spandex monomers and BHET crystals obtained in the Andini *et al*. study can be recycled back into textiles [16]. Therefore, the analysis assumes that a closed loop recycling can be established. As the recycling assumption is based on textiles, a lifetime of up to 10 years is assumed, as mentioned above.

Mycelium-based materials are considered biodegradable [65]. However, in our mycelium-based material, part of the substrate is a mixed textile containing synthetic materials. Therefore, such a material would most likely not be biodegradable as synthetic textiles are not biodegradable [66].

3.2.4. Product price

The price of TPA was taken from a socio-economic analysis of the enzymatic recycling of PET to produce TPA [67]. The study obtained a minimum selling price of 1.93 USD/kg. This was compared to the market price of virgin TPA in 2021, which was around 1 USD/kg [67]. For bio-oil, the example was taken from a study in which bio-oil was extracted from food waste by hydrothermal oxidation [68]. A minimum selling price of 104 USD/ton was obtained. The market price of bio-oil was set at 168 USD/ton [68].

There were no studies on the possible prices of TRC, so the prices of fiber-reinforced composites were investigated. A study was found which summarized the prices of hybrid natural fiber and synthetic fiber composites for many applications. The study summarized the prices of 144 products (see Table 6 in the study) [69]. The average price of 12.15 USD/kg was taken. As for the environmental impact criterion, the aim was to compare the product with a glass fiber reinforced composite. Economic performance for this material could not be found in the scientific literature, so online shops were taken into account. The price of the glass fiber reinforced composite was found to be between 0.61 and 0.71 USD/kg [70]. The average price was used in the TOPSIS calculations.

For the third alternative, it was decided not to look for a comparable price, as the process results in several products and is highly innovative. Also, the study itself carried out a socio-economic assessment, which more accurately reflects the economic performance [16]. Therefore, this alternative was an exception and it was not prices that were compared but investments. A textile feed throughput of 500 kg/h was assumed for the socio-economic assessment of mixed textile recycling [16]. For a 10-year economic life cycle of the project, an interest rate of 20 % was taken into account. This resulted in total operating costs of USD

92.3 million per year and total capital costs of USD 6.5 million per year. This was compared to the capital and operating costs of a conventional BHET production process – total operating costs of USD 173.51 million per year total capital costs of USD 38.69 million [57]. As one study reported annual capital costs and the other total costs, it was necessary to calculate total costs for comparison. The total cost was calculated using the capital recovery rate formula [71], taking into account the duration of the project and the interest rate [16].

A review article on mycelial materials [72] was reviewed to obtain an approximate price for the fourth alternative. It presented average prices for mycelium-based materials and compared them with polymer materials. Mycelium-based materials range in price from 0.07 to 0.17 USD/kg, while polymeric materials range in price from 2.1 to 2.3 USD/kg. Average values were used for comparison.

3.2.5. Market demand

All market assessments were collected for the same year, the year 2023, so that they could be compared with each other. The global market for purified terephthalic acid was estimated at USD 78 billion [73]. In the case of bio-oil, it was estimated at USD 10.7 billion in 2023 [74]. The market for construction composites was valued at USD 6.88 billion [75]. The global market size for insulation materials was estimated at USD 65.11 billion [76]. For the third alternative, it was not possible to find market valuations of the BHET crystals. Therefore, PET was considered as it is derived from BHET crystals [16]. In addition, we looked at the recycled cotton market as PET and cotton make up the majority of finished products. The global market for PET was valued at USD 48.43 billion [77] and the market for recycled cotton was valued at USD 5.2 billion [78].

3.2.6. Technology maturity

Only for one of the alternatives did the authors of the reviewed studies assess TRL. This was for the mycelium-based material [27]. They rated this technology within TRL 3. In the first two TRLs the technology concept is developed. In the third level, the proof of concept is tested analytically or experimentally [23]. In the case of mycelium material, it is developed in the laboratory and its properties are tested.

For the other alternatives, the assessment was carried out on the basis of each research paper. The article on the first alternative points out that for the first time it has been reported that hydrothermal liquefaction can process textile waste with mixed composition [8]. For this reason, the technology was assigned TRL 3. The TRC study states that the simple manufacturing process of the resulting material shows its potential to move from the laboratory to pilot scale production [26]. Therefore, it was given a TRL 5 since TRL 6 is the demonstration of a prototype in an appropriate environment [23]. The third alternative is also given a TRL of 3 as the concept is being tested in the laboratory for the first time and process improvements are still needed [16].

3.2.7. Level of research

For the first alternative, the keywords "textile hydrothermal liquefication" were used and the number of publications found was 13. The key words for the second alternative were "textile reinforced composites building" and 138 results were found. For this alternative, we added the additional keywords "AND NOT" with concrete and cement, as several articles appeared at the beginning of the review that were not relevant for the analysis. The search results for the third alternative showed two results using "microwave assisted glycolysis textile" as the key words. For the last alternative, using "mycelium composite textile" as the key words, 35 results were found.

Only one other study has been carried out on the recycling process and the resulting products of the first alternative. The second study is more recent and uses the same method to process textiles into bio-oil and TPA [79]. Both studies were carried out by the same author. The main difference is that the raw materials were different blends of cotton and polyester.

TRC is relatively well researched. More than 100 results were found, but the first 25 were reviewed. To avoid creating too large a range for the criterion and to reduce the number of articles reviewed, it was decided that the maximum score would be 25. The studies have investigated various composite materials mostly from industrial textile waste [80]–[82], using one [83], [84] or more [85], [86] types of textiles and all of them were designed for the construction industry.

A search for studies similar to the third alternative found only two results, one of which was the article analyzed. The second study that was found focused on textile treatments. It looked at the fabrication of PET textiles with highly durable hydrophilic surfaces through microwave-assisted glycolysis [87]. As the textile is treated rather than recycled, this was not considered relevant. Consequently, there is no similar research work on the third alternative.

A search for studies on mycelium and textiles revealed 35 studies, six of which were relevant to the present case. In many studies, textiles are mentioned because mycelium can be used to make leather like textiles. Two articles were found in which textiles were used as a substrate for fungi cultivation. Ruiz *et al*. developed a mycelium-based composite for the construction industry using denim and agricultural waste [88]. In the second study, biocomposites were developed as alternatives to plastic packaging products using cotton and polyester as feedstock [89]. No additional biomass substrates were added in this study. The other four studies were carried out by the same authors, Jiang et al. on one product type, a biocomposite sandwich [90]–[93]. The resulting material is a multi-layer composite, with all materials of natural origin. It uses natural textile fibers as the skin, mycelium connected agricultural waste as the core and bioresin as the matrix [92].

3.2.8. Market competitiveness

For TPA and bio-oil, yield was chosen as the main characteristic. As mentioned before, the yields achieved in the study were 3–9 % bio-oil and 38–54 % TPA [8]. The most common technology for producing TPA is the Mid-Century process, also known as the AMOCO process. The reaction typically yields 95 % TPA [51]. Typical bio-oil yields from hydrothermal liquefaction range from 24 to 64 % [94].

In the case of TRC, the test results obtained in the study were verified and compared with standard wood particleboard according to ISO 16893:2016 [26]. Thus, it was not necessary to look for the properties of a conventional material. Overall, the material properties were optimal and, in the case of moisture resistance, better than required. They were significantly lower than those required by the standard, indicating high moisture resistance characteristics [26].

Currently, for the third alternative, only one of the resulting products is comparable in quality to the conventional product: BHET crystals with 93 % purity and the possibility to decolorize and obtain ≥99 % purity [16]. The other products need further research and optimization. To increase the selectivity of 4.4′-methylenedianiline, further optimization of the treatment of the spandex monomers is needed. Reactive dyes have remained on cotton and their degree of polymerization has decreased, so further research is needed to obtain better quality. Finally, nylon has a reduced average molecular weight. Therefore, more research is needed to establish the optimum processing conditions for decolorization and to limit the reduction in molecular weight [16].

Four properties were tested for the mycelium-based material: compressive strength, tensile strength, elastic modulus and thermal conductivity [27]. As it was intended as a thermal insulation material, the thermal conductivity was chosen for comparison. Its thermal conductivity was 1.04±0.17 W/mK for grass cutting and dry leave material and 0.85 ± 0.02 for sugarcane bagasse material W/mK [27]. The authors compared these with the thermal conductivity of other mycelium materials and concluded that the addition of textiles improves this property. However, it is much higher compared to solutions on the market. For example, the thermal conductivity of expanded polystyrene is 0.030–0.045 W/mK [95].

3.2.9. Social aspects

The risks and health impacts from bio-oil and TPA production are assessed as medium (2 points), as there is no direct risk to everyday workers from hazardous chemicals or processes. However, the hydrothermal liquefaction process involves high temperatures and pressures, which pose a risk of burns and explosion [96].

In general, the production of composite materials poses risks from toxic substances and from workers inhaling liquid matrices, vapors from hardeners and solvents, and reinforcement material particles [97]. In the case of the study analyzed, textile and wood dust could pose the greatest risk [26]. Wood dust is a proven human carcinogen [98]. Therefore, the human health risk was assessed as medium.

The chemical recycling process of the third alternative was assessed as the most hazardous of all the alternatives considered. This is due to the chemicals now and potentially later used in recycling processes, such as ethylene glycol [16]. This substance is registered under Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH) and is toxic to humans [99].

The production of a mycelium-based material consists of relatively simple steps [27]. First, the substrate is prepared, the required moisture content and pH level are established and then it is pasteurized. The mushroom spawn is then added, and cultivation begins. At the end of the cultivation, the material undergoes a dehydration process to deactivate the fungi. There are no hazards during the production phase, as no relatively high temperatures and pressures and no hazardous chemicals are used. The mushrooms used are generally not harmful to humans [100]. In the reviewed alternatives case, it was edible mushroom. Another risk to consider is exposure to spores, which can cause health problems such as asthma [101]. However, most people are relatively unaffected unless they have allergies, and most of the time, these health problems are due to mold fungi [101] that are not supposed to be present in the production process of mycelium based material.

3.3. Results of the TOPSIS

After defining the input data, TOPSIS calculations were performed. The results are shown graphically in Fig. 1. According to the MCDA evaluation, the mycelium-based material is the best alternative as it scores the highest (0.63). It achieved four ideal values. This means that the input values met the ideal value conditions for four criteria. The ideal value conditions were the same for all criteria, the maximum value meaning that the best alternative for a given criterion is the one with the highest value. It also had three anti-ideal values. However, the other alternatives had more: bio-oil and TPA (4), TRC (3) and BHET crystals, spandex monomers and cotton and nylon (5). Bio-oil and TPA product group was the only alternative that did not reach any of the ideal values and also had the lowest overall score.

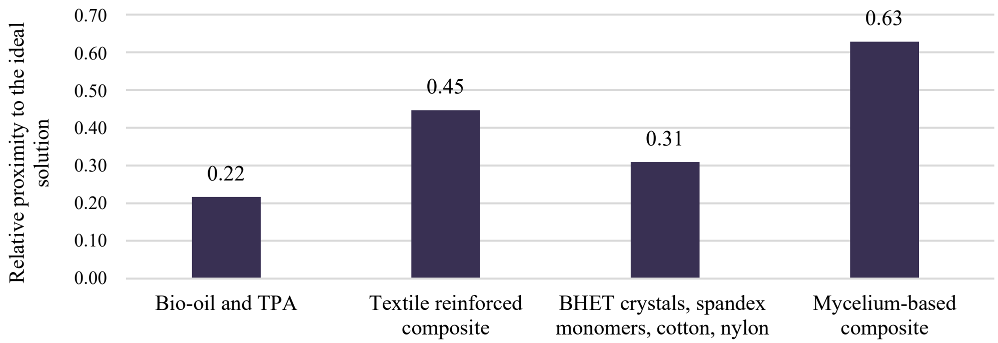

Fig. 1. Resulting rating of alternatives from TOPSIS analysis.

Normalized weighted criteria scores for each alternative are shown in Fig. 2. As can be seen, mycelium-based material has the greatest potential for further development as it is relatively well studied and have a simple manufacturing process. Its economic viability and market potential are very high. The material also has significant environmental advantages and can be produced from a wide range of waste and by-products [102]. The weakness of the product lies in its characteristics compared to the products available on the market. However, only the thermal conductivity was compared in this study. In any case, further research is needed to optimize the product properties and to explore other applications.

The results show that bio-oil and TPA, which scored the lowest, have comparable results to other alternatives in TRL level and in market competitiveness both reflecting technical performance. The alternative has the best performance at market demand. However, it scores lowest in environmental factors. The textile-reinforced composite showed visibly good results on technical aspects and fair results on environmental and social aspects. However, it had a very poor economic performance. Lastly, BHET crystals, spandex monomers and cotton and nylon showed strong results in environmental impact and longevity and recyclability, but this type of recycling is very innovative and needs further research to improve other aspects.

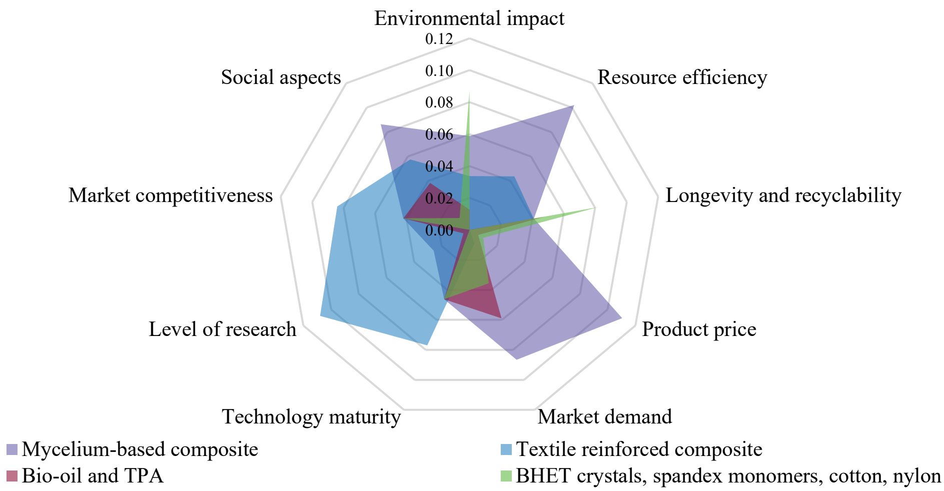

Fig. 2. Normalized weighted scores for all criteria for each alternative.

3.4. Results of the Sensitivity Analysis

A sensitivity analysis is carried out to see how the results respond to changes in the weight or impact of the criteria. The analysis was performed for all criteria. For most criteria, the mycelium-based material maintained its position as the best alternative: in eight out of nine criteria. This indicates that even if the weights were changed in the MCDA analysis, the mycelium-based material would be the best alternative. The only criterion that resulted in the mycelium-based material losing first place was the "Level of Research" (see Fig. 3). If the weight of this criterion were to increase at least 1.5 times, the best alternative would be TRC. This is mainly because TRC is the second best alternative and has been studied considerably more than the other alternatives.

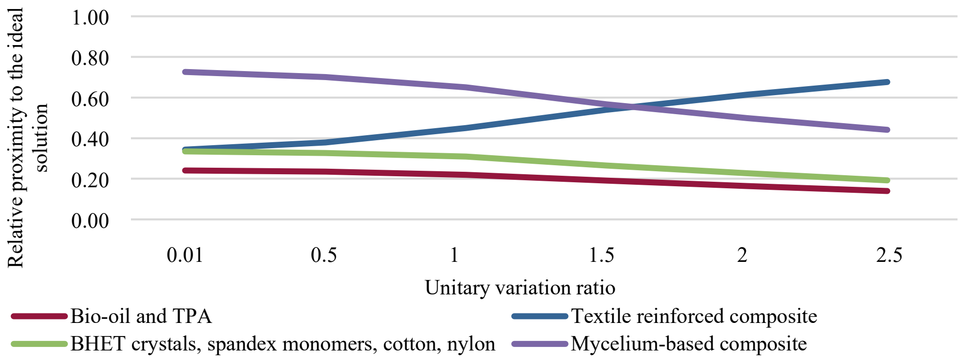

Fig. 3. Results of sensitivity analysis for Level of Research criterion.

4. Conclusions

The EU is moving towards a circular economy in textiles, but there are several obstacles in the way. Currently, there are no commercially viable technologies to recycle mixed textiles back into textiles or high value-added products. This study therefore looked at what has been researched so far on post-consumer mixed textile recycling and assessed which technology should be further developed based on economic, environmental, social and technical factors.

The literature analysis identified 27 articles on textile recycling. Only 4 of these articles met the requirements - input textiles are mixed and post-consumer. This shows that the topic is not sufficiently researched and that there are not enough technologies under development to recycle mixed post-consumer textiles.

These four products and product groups were further compared using the MCDA. Nine criteria were used. The results showed that the mycelium-based material has the highest potential for further development (0.63). It is relatively well researched, has a simple production process, has a high economic viability and market potential and has significant environmental advantages. The sensitivity analysis showed that mycelium-based material would remain the best alternative in most cases, even if the weights of the criteria were to be changed.

As the comparison of products is based on data found in the literature, further in-depth research is needed before the product can be commercialized. The technical characteristics of the product should be re-examined, an environmental, social, technical and economic assessment should be carried out and only then the product could be tested on a pilot scale.

ACKNOWLEDGMENT

This research was supported by the EU Recovery and Resilience Facility within Project No 5.2.1.1.i.0/2/24/I/CFLA/003 "Implementation of consolidation and management changes at Riga Technical University, Liepaja University, Rezekne Academy of Technology, Latvian Maritime Academy and Liepaja Maritime College for the progress towards excellence in higher education, science and innovation" academic career doctoral grant (ID 1033).

REFERENCES

[1] Abrishami S., Shirali A., Sharples N., Kartal G. E., Macintyre L., Doustdar O. Textile Recycling and Recovery: An Eco-friendly Perspective on Textile and Garment Industries Challenges. *Text. Res. J.* 2024:94(23–24):2815–2834. https://doi.org/10.1177/00405175241247806

[2] Ellen MacArthur Foundation. A new textiles economy: Redesigning fashion's future. 2017.

[3] United Nations. The 2030 Agenda for Sustainable Development. [Online]. [Accessed: 20.03.2025]. Available: https://www.un.org/sustainabledevelopment/development-agenda/

[4] European Commission. Communication from the commission to the European parliament, the council, the European economic and social committee and the committee of the regions. A new Circular Economy Action Plan. Brussels, 2020. [Online]. [Accessed: 13.02.2025]. Available: https://eur-lex.europa.eu/legal-content/EN/TXT/?qid=1583933814386&uri=COM:2020:98:FIN

[5] European Union. Directive 2008/98/EC of the European Parliament and of the Council on waste and repealing certain directives. *Official Journal of the European Union*, 2018.

[6] McKinsey & Company. Scaling textile recycling in Europe: Turning waste into value. 2022. [Online]. [Accessed: 17.03.2025]. Available: https://www.mckinsey.com/industries/retail/our-insights/scaling-textile-recycling-in-europe-turning-waste-into-value#/

[7] European Environment Agency. Management of used and waste textiles in Europe's circular economy. In EEA Briefing. LU: Publications Office, 2024. [Online]. [Accessed: 18.03.2025]. Available: https://data.europa.eu/doi/10.2800/229868

[8] Matayeva A., Madsen A. S., Biller P. Evaluation of different fiber impurities on hydrothermal liquefaction of mixed textile waste. *Resour. Conserv. Recycl.* 2023:190:106833. https://doi.org/10.1016/j.resconrec.2022.106833

[9] Seifali Abbas-Abadi M. *et al.* Advancing Textile Waste Recycling: Challenges and Opportunities Across Polymer and Non-Polymer Fiber Types. *Polymers* 2025:17(5):628. https://doi.org/10.3390/polym17050628

[10] Lu L. *et al.* Current recycling strategies and high-value utilization of waste cotton. *Sci. Total Environ.* 2023:856:158798. https://doi.org/10.1016/j.scitotenv.2022.158798

[11] Pensupa N. *et al.* Recent Trends in Sustainable Textile Waste Recycling Methods: Current Situation and Future Prospects. In *Chemistry and Chemical Technologies in Waste Valorization*, Lin C. S. K., Ed., in Topics in Current Chemistry Collections. Cham: Springer International Publishing, 2017:189–228. https://doi.org/10.1007/978-3-319-90653-9_7

[12] Shahid M. A., Raza M., Javed M. A., Khan Z., Ali S., Ahmad I. Prospects and challenges of recycling and reusing post-consumer garments: A review. *Clean. Eng. Technol.* 2024:19:100744. https://doi.org/10.1016/j.clet.2024.100744

[13] Baloyi R. B., Gbadeyan O. J., Sithole B., Chunilall V. Recent advances in recycling technologies for waste textile fabrics: A review. *Text. Res. J.* 2024:94(3–4):508–529. https://doi.org/10.1177/00405175231210239

[14] Wang S., Salmon S. Progress toward Circularity of Polyester and Cotton Textiles. *Sustain. Chem.* 2022:3(3):376–403. https://doi.org/10.3390/suschem3030024

[15] Loo S.-L., Yu E., Hu X. Tackling critical challenges in textile circularity: A review on strategies for recycling cellulose and polyester from blended fabrics. *J. Environ. Chem. Eng.* 2023:11(5):110482. https://doi.org/10.1016/j.jece.2023.110482

[16] Andini E., Bhalode P., Gantert E., Sadula S., Vlachos D. G. Chemical recycling of mixed textile waste. *Sci. Adv.* 2024:10(27):eado6827. https://doi.org/10.1126/sciadv.ado6827

[17] Patel N., Blumberga D. Insights of Bioeconomy: Biopolymer Evaluation Based on Sustainability Criteria. *Environ. Clim. Technol.* 2023:27(1):323–338. https://doi.org/10.2478/rtuect-2023-0025

[18] Valtere M., *et al*. The Versatility of the Bioeconomy. Sustainability Aspects of the Use of Bran. *Environ. Clim. Technol.* 2022:26(1):658–669. https://doi.org/10.2478/rtuect-2022-0050

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

[20] Ibáñez-Forés V., Bovea M. D., Pérez-Belis V. A holistic review of applied methodologies for assessing and selecting the optimal technological alternative from a sustainability perspective. *J. Clean. Prod.* 2014:70:259–281. https://doi.org/10.1016/j.jclepro.2014.01.082

[21] Mertzanakis C., Vlachokostas C., Toufexis C., Michailidou A. V. Closing the Loop between Waste-to-Energy Technologies: A Holistic Assessment Based on Multiple Criteria. *Energies* 2024:17(12):2971. https://doi.org/10.3390/en17122971
[22] Levänen J., Uusitalo V., Härri A., Kareinen E., Linnanen L. Innovative recycling or extended use? Comparing the global warming potential of different ownership and end-of-life scenarios for textiles. *Environ. Res. Lett.* 2021:16(5):054069. https://doi.org/10.1088/1748-9326/abfac3
[23] Mankins J. C. Technology readiness assessments: A retrospective. *Acta Astronaut.* 2009:65(9–10):1216–1223. https://doi.org/10.1016/j.actaastro.2009.03.058
[24] Ono S., Tsusaka T. W. Comparative Analysis of Environmental, Economic, and Social Criteria for Plastic Recycling Technology Selection in India, Sri Lanka, Pakistan, and Thailand. *Int. J. Sustain. Dev. Plan.* 2023:18(8):2461–2471. https://doi.org/10.18280/ijsdp.180817
[25] Li P., Qian H., Wu J., Chen J. Sensitivity analysis of TOPSIS method in water quality assessment: I. Sensitivity to the parameter weights. *Environ. Monit. Assess.* 2013:185(3):2453–2461. https://doi.org/10.1007/s10661-012-2723-9
[26] Echeverria C. A., Handoko W., Pahlevani F., Sahajwalla V. Cascading use of textile waste for the advancement of fibre reinforced composites for building applications. *J. Clean. Prod.* 2019:208:1524–1536. https://doi.org/10.1016/j.jclepro.2018.10.227
[27] Gomez T. S., *et al*. Development of a myco-material based on textile and agro-industrial waste for thermal insulation. *E3S Web Conf.* 2024:546:03003. https://doi.org/10.1051/e3sconf/202454603003
[28] Li M., Luo J., Huang Y., Li X., Yu T., Ge M. Recycling of waste poly(ethylene terephthalate) into flame-retardant rigid polyurethane foams. *J. Appl. Polym. Sci.* 2014:131(19):app.40857. https://doi.org/10.1002/app.40857
[29] Sun H., Chen Z., Zhou J., Chen L., Zuo W. Recovery of high-quality terephthalic acid from waste polyester textiles via a neutral hydrolysis method. *J. Environ. Chem. Eng.* 2024:12(3):112558. https://doi.org/10.1016/j.jece.2024.112558
[30] Ravikumar D., Mani P., Bernaurdshaw N., Vajiravelu S. Microwave-Induced Chemical Recycling of Colored Polyester Textile Wastes Promoted by $Zn[(L)Proline]_2$, as a Recyclable Homogeneous Catalyst. *Waste Biomass Valorization* 2024:15(8):4585–4598. https://doi.org/10.1007/s12649-024-02522-3
[31] Kirstein M., *et al*. Monomer Recycling and Repolymerization of Post-Consumer Polyester Textiles. *Chem. Ing. Tech.* 2023:95(8):1290–1296. https://doi.org/10.1002/cite.202200197
[32] Islam S., Bhat G., Mani S. Life cycle assessment of thermal insulation materials produced from waste textiles. *J. Mater. Cycles Waste Manag.* 2024:26(2):1071–1085. https://doi.org/10.1007/s10163-023-01882-7
[33] Hussain A., Goljandin D., Podgursky V., Abbas M. M., Krasnou I. Experimental mechanics analysis of recycled polypropylene-cotton composites for commercial applications. *Adv. Ind. Eng. Polym. Res.* 2023:6(3):226–238. https://doi.org/10.1016/j.aiepr.2022.11.001
[34] Sanchis-Sebastiá M., Ruuth E., Stigsson L., Galbe M., Wallberg O. Novel sustainable alternatives for the fashion industry: A method of chemically recycling waste textiles via acid hydrolysis. *Waste Manag.* 2021:121:248–254. https://doi.org/10.1016/j.wasman.2020.12.024
[35] Ruuth E., *et al*. Reclaiming the Value of Cotton Waste Textiles: A New Improved Method to Recycle Cotton Waste Textiles via Acid Hydrolysis. *Recycling* 2022:7(4):57. https://doi.org/10.3390/recycling7040057
[36] Cao H., Cobb K., Yatvitskiy M., Wolfe M., Shen H. Textile and Product Development from End-of-Use Cotton Apparel: A Study to Reclaim Value from Waste. *Sustainability* 2022:14(14):8553. https://doi.org/10.3390/su14148553
[37] Singh V., Wyatt J., Zoungrana A., Yuan Q. Evaluation of Vermicompost Produced by Using Post-Consumer Cotton Textile as Carbon Source. *Recycling* 2022:7(1):10. https://doi.org/10.3390/recycling7010010
[38] Opálková Šišková A., *et al.* Reuse of Textile Waste to Production of the Fibrous Antibacterial Membrane with Filtration Potential. *Nanomaterials* 2021:12(1):50. https://doi.org/10.3390/nano12010050
[39] Raj M., Fatima S., Tandon N. Recycled materials as a potential replacement to synthetic sound absorbers: A study on denim shoddy and waste jute fibers. *Appl. Acoust.* 2020:159:107070. https://doi.org/10.1016/j.apacoust.2019.107070
[40] Aman, Tonk D., Shokeen K., Singh D. K. Development of fire retarding composite board for fire compartmentation application using waste denim: A review. *Mater. Today Proc.* 2022:60:259–266. https://doi.org/10.1016/j.matpr.2021.12.513
[41] Vadivel R., Nirmala M., Raji K., Siddaiah B., Ramamurthy P. Synthesis of highly luminescent carbon dots from postconsumer waste silk cloth and investigation of its electron transfer dynamics with methyl viologen dichloride. *J. Indian Chem. Soc.* 2021:98(11):100181. https://doi.org/10.1016/j.jics.2021.100181
[42] Bediako J. K., Wei W., Yun Y.-S. Low-cost renewable adsorbent developed from waste textile fabric and its application to heavy metal adsorption. *J. Taiwan Inst. Chem. Eng.* 2016:63:250–258. https://doi.org/10.1016/j.jtice.2016.03.009
[43] Zhang J., *et al.* Fabrication of leather-like yarns using waste leather for textile application. *Prog. Org. Coat.* 2024:186:108053. https://doi.org/10.1016/j.porgcoat.2023.108053

[44] Haslinger S., Hummel M., Anghelescu-Hakala A., Määttänen M., Sixta H. Upcycling of cotton polyester blended textile waste to new man-made cellulose fibers. *Waste Manag.* 2019:97:88–96. https://doi.org/10.1016/j.wasman.2019.07.040

[45] Xia G., *et al.* Complete recycling and valorization of waste textiles for value-added transparent films via an ionic liquid. *J. Environ. Chem. Eng.* 2021:9(5):106182. https://doi.org/10.1016/j.jece.2021.106182

[46] Apostolopoulou-Kalkavoura V., Fijoł N., Lombardo S., Ruiz-Caldas M., Mathew A. P. In Situ Functionalisation and Upcycling of Post-Consumer Textile Blends into 3D Printable Nanocomposite Filaments. *Adv. Sustain. Syst.* 2024:8(9):2400132. https://doi.org/10.1002/adsu.202400132

[47] Hu Y., Du C., Pensupa N., Lin C. S. K. Optimisation of fungal cellulase production from textile waste using experimental design. *Process Saf. Environ. Prot.* 2018:118:133–142. https://doi.org/10.1016/j.psep.2018.06.009

[48] Mihalyi S., *et al.* Simultaneous saccharification and fermentation with *Weizmannia coagulans* for recovery of synthetic fibers and production of lactic acid from blended textile waste. *Resour. Conserv. Recycl.* 2023:196:107060. https://doi.org/10.1016/j.resconrec.2023.107060

[49] El Wazna M., El Fatihi M., El Bouari A., Cherkaoui O. Thermo physical characterization of sustainable insulation materials made from textile waste. *J. Build. Eng.* 2017:12:196–201. https://doi.org/10.1016/j.jobe.2017.06.008

[50] Çay A., Yanık J., Akduman Ç., Duman G., Ertaş H. Application of textile waste derived biochars onto cotton fabric for improved performance and functional properties. *J. Clean. Prod.* 2020:251:119664. https://doi.org/10.1016/j.jclepro.2019.119664

[51] Lapa H. M., Martins L. M. D. R. S. p-Xylene Oxidation to Terephthalic Acid: New Trends. *Molecules* 2023:28(4):1922. https://doi.org/10.3390/molecules28041922

[52] Guo G., He Y., Jin F., Mašek O., Huang Q. Application of life cycle assessment and machine learning for the production and environmental sustainability assessment of hydrothermal bio-oil. *Bioresour. Technol.* 2023:379:129027. https://doi.org/10.1016/j.biortech.2023.129027

[53] Ecoinvent 3.10. Crude 'petroleum' oil. RoW market for petroleum.

[54] Gian M., García-Velásquez C., Van Der Meer Y. Comparative life cycle assessment of the biochemical and thermochemical production routes of biobased terephthalic acid using *Miscanthus* in the Netherlands. *Clean. Environ. Syst.* 2022:6:100085. https://doi.org/10.1016/j.cesys.2022.100085

[55] Arya M., Skrifvars M., Khalili P. Performance and life cycle assessment of composites reinforced with natural fibers and end-of-life textiles. *J. Compos. Sci.* 2024:8(6):196. https://doi.org/10.3390/jcs8060196

[56] Ecoinvent 3.10. Glass fibre reinforced plastic, polyamide, injection moulded GLO. Market for glass fibre reinforced plastic, polyamide, injection moulded.

[57] Luo Y., Selvam E., Vlachos D. G., Ierapetritou M. Economic and environmental benefits of modular microwave-assisted polyethylene terephthalate depolymerization. *ACS Sustain. Chem. Eng.* 2023:11(10):4209–4218. https://doi.org/10.1021/acssuschemeng.2c07203

[58] Volk R., *et al.* Life cycle assessment of mycelium-based composite materials. *Resour. Conserv. Recycl.* 2024:205:107579. https://doi.org/10.1016/j.resconrec.2024.107579

[59] Elsacker E., Vandelook S., Van Wylick A., Ruytinx J., De Laet L., Peeters E. A comprehensive framework for the production of mycelium-based lignocellulosic composites. *Sci. Total Environ.* 2020:725:138431. https://doi.org/10.1016/j.scitotenv.2020.138431

[60] Panwar N. L., Paul A. S. An overview of recent development in bio-oil upgrading and separation techniques. *Environ. Eng. Res.* 2020:26(5):200382–0. https://doi.org/10.4491/eer.2020.382

[61] Valtere M., Bezrucko T., Blumberga D. Analysis of textile circularity potential. *Environ. Clim. Technol.* 2023:27(1):220–232. https://doi.org/10.2478/rtuect-2023-0017

[62] Borjan D., Knez Ž., Knez M. Recycling of carbon fiber-reinforced composites – Difficulties and future perspectives. *Materials* 2021:14(15):4191. https://doi.org/10.3390/ma14154191

[63] De Fazio D., Boccarusso L., Formisano A., Viscusi A., Durante M. A review on the recycling technologies of fibre-reinforced plastic (FRP) materials used in industrial fields. *J. Mar. Sci. Eng.* 2023:11(4):851. https://doi.org/10.3390/jmse11040851

[64] Bahramian M., Yetilmezsoy K. Life cycle assessment of the building industry: An overview of two decades of research (1995–2018). *Energy Build.* 2020:219:109917. https://doi.org/10.1016/j.enbuild.2020.109917

[65] Alaneme K. K., *et al.* Mycelium based composites: A review of their bio-fabrication procedures, material properties and potential for green building and construction applications. *Alex. Eng. J.* 2023:83:234–250. https://doi.org/10.1016/j.aej.2023.10.012

[66] Egan J., Salmon S. Strategies and progress in synthetic textile fiber biodegradability. *SN Appl. Sci.* 2022:4(1):22. https://doi.org/10.1007/s42452-021-04851-7

[67] Singh A., *et al.* Techno-economic, life-cycle, and socioeconomic impact analysis of enzymatic recycling of poly(ethylene terephthalate). *Joule* 2021:5(9):2479–2503. https://doi.org/10.1016/j.joule.2021.06.015

[68] Mahmood R., Parshetti G. K., Balasubramanian R. Energy, exergy and techno-economic analyses of hydrothermal oxidation of food waste to produce hydro-char and bio-oil. *Energy* 2016:102:187–198. https://doi.org/10.1016/j.energy.2016.02.042

[69] Suriani M. J., *et al*. Critical review of natural fiber reinforced hybrid composites: Processing, properties, applications and cost. *Polymers* 2021:13(20):3514. https://doi.org/10.3390/polym13203514
[70] Silicone coated glass fiber woven roving fiberglass reinforced composite material from factory for composite materials. [Online]. [Accessed: 13.01.2025]. Available: https://www.alibaba.com/product-detail/Silicone-Coated-Glass-Fiber-Woven-Roving_60112675930.html
[71] Hashemi A., Derakhshan G., Alizadeh Pahlavani M. R., Abdi B. Techno-economic analysis of a stand-alone hybrid wind-power fuel-cell grid system: A case study in Shahryar region of Tehran. *Environ. Clim. Technol.* 2020:24(1):691–705. https://doi.org/10.2478/rtuect-2020-0043
[72] Alemu D., Tafesse M., Mondal A. K. Mycelium-based composite: The future sustainable biomaterial. *Int. J. Biomater.* 2022:2022(1). https://doi.org/10.1155/2022/8401528
[73] Verified Market Reports. Global purified terephthalic acid (PTA) market by type (Type 1, Type 2), by application (Polyester, Polybutylene Terephthalate (PBT)), by geographic scope and forecast. [Online]. [Accessed: 18.12.2024]. Available: https://www.verifiedmarketreports.com/product/purified-terephthalic-acid-pta-market/
[74] Verified Market Reports. Global bio-oil market by type (Bioethanol, Biodiesel), by application (Industrial fuels, Transportation fuels), by geographic scope and forecast. [Online]. [Accessed: 18.12.2024]. Available: https://www.verifiedmarketreports.com/product/bio-oil-market/
[75] Starits Research. Construction composites market size, share & trends analysis report. [Online]. [Accessed: 18.12.2024]. Available: https://straitsresearch.com/report/construction-composites-market
[75] Starits Research. Construction Composites Market Size, Share & Trends Analysis Report by Resin. Forecasts, 2024–2032. [Online]. [Accessed: 18.12.2024]. Available: https://straitsresearch.com/report/construction-composites-market
[76] GVR. Insulation Market Size, Share & Trends Analysis Report by Product (Glass Wool, Mineral Wool, EPS, XPS, CMS Fibers), By End-use (Construction, Industrial, HVAC & OEM), By Region, And Segment Forecasts, 2024–2030. [Online]. [Accessed: 18.12.2024]. Available: https://www.grandviewresearch.com/industry-analysis/insulation-market
[77] FORTUNE. Polyethylene Terephthalate (PET) Market Size, Share & Industry Analysis, By Type (Virgin and Recycled), Application (Rigid Packaging, Film, Sheets & Straps, and Others), and Regional Forecast, 2024–2032. [Online]. [Accessed: 20.12.2024]. Available: https://www.fortunebusinessinsights.com/industry-reports/polyethylene-terephthalate-pet-market-101743
[78] DATAINTELO. Recycled Cotton Yarn Market. [Online]. [Accessed: 21.12.2024]. Available: https://dataintelo.com/report/global-recycled-cotton-yarn-market
[79] Matayeva A., Biller P. Hydrothermal liquefaction of post-consumer mixed textile waste for recovery of bio-oil and terephthalic acid. *Resour. Conserv. Recycl.* 2022:185:106502. https://doi.org/10.1016/j.resconrec.2022.106502
[80] Sulochani R. M. N., Jayasinghe R. A., Priyadarshana G., Nilmini A. H. L. R., Ashokcline M., Dharmaratne P. D. Waste-based composites using post-industrial textile waste and packaging waste from the textile manufacturing industry for non-structural applications. *Sustain. Chem. Environ.* 2024:8:100163. https://doi.org/10.1016/j.scenv.2024.100163
[81] Mohan S., Thilagavathi G., Rajkhowa R. Development of micro dust reinforced composite for building applications. *J. Clean. Prod.* 2024:470:143244. https://doi.org/10.1016/j.jclepro.2024.143244
[82] Kamble Z., Behera B. K. Sustainable hybrid composites reinforced with textile waste for construction and building applications. *Constr. Build. Mater.* 2021:284:122800. https://doi.org/10.1016/j.conbuildmat.2021.122800
[83] Rakhsh Mahpour A., Ventura H., Ardanuy M., Rosell J. R., Claramunt J. The effect of fibres and carbonation conditions on the mechanical properties and microstructure of lime/flax composites. *Cem. Concr. Compos.* 2023:138:104981. https://doi.org/10.1016/j.cemconcomp.2023.104981
[84] Suthatho A., Rattanawongkun P., Tawichai N., Tanpichai S., Boonmahitthisud A., Soykeabkaew N. Low-density all-cellulose composites made from cotton textile waste with promising thermal insulation and acoustic absorption properties. *ACS Appl. Polym. Mater.* 2024:6(1):390–397. https://doi.org/10.1021/acsapm.3c02076
[85] Kamble Z., Behera B. K. Fabrication and performance evaluation of waste cotton and polyester fiber-reinforced green composites for building and construction applications. *Polym. Compos.* 2021:42(6):3025–3037. https://doi.org/10.1002/pc.26036
[86] Dev B., Rahman M. A., Tazrin T., Islam M. S., Datta A., Rahman M. Z. Investigation of mechanical properties of nonwoven recycled cotton/PET fiber-reinforced polyester hybrid composites. *Macromol. Mater. Eng.* 2024:309(6):2400020. https://doi.org/10.1002/mame.202400020
[87] Zhou W., Huang H., Du S., Wang Q., He J., Cui S. Facile fabrication of polyester filament fabric with highly and durable hydrophilic surface by microwave-assisted glycolysis. *J. Appl. Polym. Sci.* 2016:133(40):app.44069. https://doi.org/10.1002/app.44069
[88] Ruiz A., Cogdell C., Mak J., Rowe A., Wan S., La Saponara V. Valorization and biorefinery of local agricultural and textile wastes through mycelium composites for structural applications. *Res. Dir. Biotechnol. Des.* 2024:2:e10. https://doi.org/10.1017/btd.2024.8
[89] Saini R., Kaur G., Brar S. K. Textile residue-based mycelium biocomposites from *Pleurotus ostreatus*. *Mycology* 2024:15(4):683–689. https://doi.org/10.1080/21501203.2023.2278308

[90] Jiang L., Walczyk D., McIntyre G. A new approach to manufacturing biocomposite sandwich structures: Investigation of preform shell behavior. *J. Manuf. Sci. Eng.* 2017:139(2):021014. https://doi.org/10.1115/1.4034278

[91] Jiang L., Walczyk D., McIntyre G., Bucinell R., Li B. Bioresin infused then cured mycelium-based sandwich-structure biocomposites: Resin transfer molding (RTM) process, flexural properties, and simulation. *J. Clean. Prod.* 2019:207:123–135. https://doi.org/10.1016/j.jclepro.2018.09.255

[92] Jiang L., Walczyk D., McIntyre G., Bucinell R., Tudryn G. Manufacturing of biocomposite sandwich structures using mycelium-bound cores and preforms. *J. Manuf. Process.* 2017:28:50–59. https://doi.org/10.1016/j.jmapro.2017.04.029

[93] Jiang L., Walczyk D. F., Li B. Modeling of glue penetration into natural fiber reinforcements by roller infusion. *J. Manuf. Sci. Eng.* 2018:140(4):041006. https://doi.org/10.1115/1.4038514

[94] Nagappan S., *et al*. Catalytic hydrothermal liquefaction of biomass into bio-oils and other value-added products – A review. *Fuel* 2021:285:119053. https://doi.org/10.1016/j.fuel.2020.119053

[95] InsulationGo. What is thermal conductivity? [Online]. [Accessed: 16.01.2024]. Available: https://insulationgo.co.uk/thermal-conductivity/

[96] Lowry P. P., Wagner K. A. Hydrothermal liquefaction treatment hazard analysis report. PNNL--24219 Rev 3, 1406834. Sep. 2016. https://doi.org/10.2172/1406834

[97] Asmatulu E., Alonayni A., Alamir M. Safety concerns in composite manufacturing and machining. In: Naguib H. E., ed. *Behavior and Mechanics of Multifunctional Materials and Composites XII.* Denver, United States: SPIE; Mar. 2018:68. https://doi.org/10.1117/12.2296707

[98] Beigzadeh Z., Pourhassan B., Kalantary S., Golbabaei F. Occupational exposure to wood dust and risk of nasopharyngeal cancer: A systematic review and meta-analysis. *Environ. Res.* 2019:171:170–176. https://doi.org/10.1016/j.envres.2018.12.022

[99] European Chemicals Agency (ECHA). Ethane-1,2-diol. [Online]. [Accessed: 19.01.2025]. https://echa.europa.eu/lv/substance-information/-/substanceinfo/100.003.159

[100] Balaeș T., Radu B.-M., Tănase C. Mycelium-composite materials – A promising alternative to plastics? *J. Fungi* 2023:9(2):210. https://doi.org/10.3390/jof9020210

[101] Baxi S. N., *et al*. Exposure and health effects of fungi on humans. *J. Allergy Clin. Immunol. Pract.* 2016:4(3):396–404. https://doi.org/10.1016/j.jaip.2016.01.008

[102] Higgins C., Margot H., Warnquist S., Obeysekare E., Mehta K. Mushroom cultivation in the developing world: A comparison of cultivation technologies. In: *2017 IEEE Global Humanitarian Technology Conference (GHTC).* San Jose, 2017:1–7