MULTICRITERIA ANALYSIS OF RECYCLED TEXTILE AND CONVENTIONAL THERMAL INSULATION MATERIALS THROUGH ECOLOGICAL AND ECONOMIC CRITERIA

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The textile industry is the second most environmentally polluting industry in the world after the petroleum industry. Approximately 25% of global chemicals are used in textile production, around 10% of the world's CO2 emissions are generated by the textile industry, and it consumes more water than any other industry. Annually, about 92 million tons of textile waste are produced, with only an estimated 10-30% of the waste being recycled. Textile waste can be reused or recycled using various methods for thermal insulation materials. The aim of this study is to analyze and compare recycled thermal insulation materials with conventional thermal insulation materials based on economic and environmental criteria. By using the DEXi software tool, a multicriteria analysis was conducted between recycled textile and conventional thermal insulation materials based on economic and environmental criteria. In terms of economic and environmental criteria, conventional thermal insulation materials have an advantage over thermal insulation materials made from recycled textiles. In conclusion, the decision on which option is better depends on the specific requirements of the project. If sustainability is a key priority, based on all available information, thermal insulation made from recycled textiles is the better choice. However, if priorities are focused on heat insulation, moisture resistance, and durability, EPS is currently the better option. According to the planned scenario, there is a possibility that the efficiency of both thermal insulation materials can be balanced through additional research and improvement.

Keywords: *DEXi, recycling, thermal insulation, EPS, textile industry, environmental pollution*

1. Introduction

The Industrial Revolution marked a turning point in technological development, accelerating the process of textile production and making it more efficient. With the introduction of these advanced techniques into production, the speed and availability of textiles greatly increased. By the end of the 20th and the beginning of the 21st century, retailers had adopted this rapid mode of production, enabling cheap and fast production of high fashion. However, this acceleration has had serious consequences for the environment.

Among various industries contributing to environmental pollution, the textile industry stands out as the second-largest polluter after the oil industry. Its impact is evident across numerous facets, including the intensive use of water, chemicals, and energy. According to research, approximately 20% of water becomes polluted through textile processing and dyeing, and about 10% of global CO_2 emissions originate from this industry [1]. Furthermore, the textile industry consumes more water than any other industry except agriculture. This process not only releases toxic chemicals into the air, water, and soil but also contributes to greenhouse gas emissions, depleting water, energy, and fossil fuel resources.

Within the construction industry, the thermal insulation sector plays a crucial role in reducing energy consumption. Effective insulation materials are of paramount importance in minimizing heat loss during winter and preventing excessive heating during the summer period. Considering that buildings in the EU account for up to 40% of total energy consumption and contribute to 36% of CO_2 emissions, reducing energy consumption in this sector has become a modern-day imperative [2].

There are multiple approaches to reducing CO_2 emissions during building construction and renovation. Enhancing energy-efficient building design, increasing the use of sustainable construction materials through recycling and reusability, incorporating renewable energy, and improving the efficiency of electrical equipment and lighting represent effective strategies. Growing awareness of ecological and health issues motivates people to transition towards using natural and recycled materials. It is precisely this awareness that fuels the rising interest in insulation materials made from safe natural ingredients and recycled products, even though many of these materials are still in the research and development phase. Utilizing waste textile materials for thermal insulation can significantly contribute to energy performance, reduce the consumption of non-renewable resources and environmental burden, and enhance both human and environmental well-being.

The aim of this research is to analyze the economic and environmental criteria of thermal insulation materials produced from recycled textiles, in comparison to a conventional material, expanded polystyrene (EPS), which is present in the domestic market. The research is conducted using the DEXi software tool. The focus will be directed towards identifying the advantages of thermal insulation materials made from recycled textiles in the context of their economic efficiency and environmental sustainability. Through this analysis, the research aims to provide a deeper understanding of the potentially favorable characteristics of recycled textile thermal insulation materials and their ability to overcome the shortcomings of conventional materials.

2. Reuse or Recycling of Textile Waste in Insulation Materials

In the context of reusing or recycling textile waste for insulation materials, there are various methods to use textile waste in order to reduce its negative impact on the environment. Reuse of waste involves extending the usability of textiles, with or without modifications, to enable new applications. On the other hand, recycling entails transforming textile waste into new products, whether retaining their original form or creating entirely new items. Recycling of textile waste can be achieved through mechanical, chemical, thermal, or combined processes, focusing on breaking down fabrics into fiber and polymer levels [3].

Despite different recycling techniques, the shared goal is waste reduction and increased sustainability. It's estimated that up to 95% of textile waste can be recycled into useful products, although recycling costs vary depending on the process and recycling categories [4]. Specifically, polyester waste, although prevalent in the fashion industry, has a low recycling rate. In 2017, only 14% of polyester waste was recycled, with a significant amount ending up in landfills [5]. Similarly, cotton fibers, constituting a significant portion of the global market, are rarely recycled, leading to a substantial amount of cotton waste. Wool fiber, with its excellent thermal insulation properties, also has a low recycling rate [5].

Overall, utilizing textile waste for insulation materials represents a significant step towards sustainability, but challenges related to recycling techniques, fiber diversity, and economic factors still persist. This approach is part of a broader quest for effective solutions to reduce the negative impact of the textile industry on the environment.

Recycling textile waste into construction insulation materials carries potential benefits across various aspects—ecological, health-related, social, and economic. The use of high-quality thermal insulation materials has the capacity to significantly mitigate negative environmental impacts. This includes reducing strain on natural resources, energy consumption, greenhouse gas emissions, landfill space requirements, air, water, soil, and noise pollution, as well as improving overall human well-being.

3. Comparison of Thermal Characteristics Between Recycled Textile Waste and Conventional Thermal Insulation Material

Table 1 presents a comparison of the thermal insulation properties of various materials, including recycled textile waste and conventional thermal insulation materials. These data have been obtained from different research studies and literature, providing insights into the thermal characteristics of the materials.

Materials are ranked by thickness (d) and density (ρ), and thermal conductivity (λ) is also provided for each material. Additionally, the data is compared with the thermal properties of some commercially available materials for comprehensive comparison. The results show significant differences in the thermal insulation properties of different materials. It is noticeable that materials prepared from recycled textile waste, such as wool and wool/recycled polyester blends, exhibit very good thermal insulation properties, with low thermal conductivity (λ). For instance, wool and 50/50 wool/recycled polyester have the lowest thermal conductivity values (λ=0.032 $Wm^{-1}K^{-1}$). Furthermore, thermal insulation materials made from recycled wool and polyester, with λ=0.032 $Wm^{-1}K^{-1}$, as well as cotton with λ=0.039 $Wm^{-1}K^{-1}$, demonstrate significantly better properties compared to lower-density natural materials. These results suggest that recycled textile waste can be a potentially efficient material for thermal insulation, exhibiting superior properties compared to some commercially available insulation materials such as fiberglass and mineral wool.

Table 1. Comparison of Thermal Insulation Properties of Various Materials

Materials	Material Thickness d [m]	Density ρ [kgm^{-3}]	Thermal Conductivity λ [$Wm^{-1}K^{-1}$]	Reference
Recycled polyester	0.016	62.50	0.035	[6]
Polyester (85% + 15% cotton)		80.00	0.046 – 0.049	[7]
100% wool		20.00	0.040	[8]
Sheep wool	0.040	40.00	0.034 – 0.039	[9]
100% wool, carpet waste	0.030	45.00	0.0311 – 0.0339	[10]

50% wool, 50% recycled polyester	0.016	62.50	0.032 – 0.004	[11]
Recycled cotton		25 – 45	0.039 – 0.044	[17]
100% acrylic		14.57	0.043 – 0.049	[10]
75% flax, 25% cotton	0.087	22.80	0.043	[9]
Polyurethane foam		15 – 80	0.025 – 0.040	
Glass wool		14 – 80	0.032 – 0.038	[8]
Mineral wool		30 – 80	0.033 – 0.039	

4. Methodology

4.1. Analysis of Economic and Environmental Criteria of Selected Thermal Insulation Materials

Multi-Criteria Analysis (MCA) is employed for decision-making in situations where multiple criteria or factors need to be taken into consideration for reaching a final decision. The multi-criteria analysis of environmental and economic criteria for the selected thermal insulation materials was conducted using the DEXi software tool, which is used for decision analysis among various alternatives under consideration. The DEXi program employs mathematical models and algorithms to analyze different criteria and enable the assessment of the best options among the chosen alternatives.

The initial step in the analysis using the DEXi program involves defining the analysis goal and the criteria that will be used for evaluating the alternatives. The objective of the multi-criteria analysis is to make a decision about the advantages of thermal insulation materials based on economic and environmental criteria, with the alternatives being textile and EPS insulation materials. After selecting the alternatives, criteria are chosen for evaluating the alternatives. Table 2 presents data for the environmental analysis criterion, which relates to the annual production quantity of textile material and EPS for the year 2021.

Based on the data from Table 2, it can be concluded that the production quantity of textile material is up to seven times greater compared to the production quantity of expanded polystyrene on an annual basis. Additionally, the recycling percentage is similar, with around 10% for expanded polystyrene and 12% for textile material.

Table 2. Global Production and Recycling on an Annual Basis in 2021

TOTAL GLOBAL ANNUAL PRODUCTION		
Materials	**/ annually [kg]**	**Reference**
Expanded polystyrene	15 610 000 000	[18]
Textile	113 000 000 000	[19]
ANNUAL RECYCLING [%]		
Materials	**/ [%]**	**Reference**
Expanded polystyrene	10%	[20]
Textile	12%	[21]

Table 3 presents the environmental criteria related to resource and energy consumption in the production process of textiles and EPS materials, encompassing the entire manufacturing process from raw material processing to the final product. The values are expressed per 1 kg of material as well as the annual quantity. Based on the data from Table 3, it can be concluded that textiles emit significantly higher amounts of CO_2 annually, and the consumption of water and energy in the textile production process is higher compared to the production of expanded polystyrene**.**

Table 3. Environmental criteria, resource and energy consumption in the production process

CO_2 EMISSIONS IN THE PRODUCTION PROCESS [KG]			
Materials	**/ 1[kg]**	**/ annually [kg]**	**Reference**
Expanded polystyrene	2.14	33 405 400 000	[22]
Textile	3.54	400 000 000 000	[23]
WATER CONSUMPTION IN THE PRODUCTION PROCESS [m^3]			
Materials	**/ 1[kg]**	**/ annually [kg]**	**Reference**
Expanded polystyrene	0.017	266 931 000	[22]
Textile	457	51 660 000 000 000	[23]
ENERGY CONSUMPTION IN THE PRODUCTION PROCESS [MJ]			
Materials	**/ 1[MJ]**	**/ annually [kg]**	**Reference**
Expanded polystyrene	85.59	1 336 059 900 000	[22]
Textile	200	22 600 000 000 000	[24]

Table 4 presents input data for the analysis of economic criteria related to installation process, cost pricing, market availability, as well as the required insulation material thickness under the same climatic conditions and building envelope area, which directly impacts the material cost. Based on the data from Table 4, it can be concluded that expanded polystyrene is simpler to install, more readily available in the market, and economically advantageous compared to textile insulation due to the fact that textile insulation is still not widely accessible in the market.

Table 4. Economic Criteria

INSTALLATION PROCESS			
Materials	simple	complex	
Expanded polystyrene	**x**		
Textile		**x**	
MARKET PRICE OF THERMAL INSULATION MATERIAL [KM/m^2]			
Materials	**/1 [m^2]**		**Reference**
Expanded polystyrene	11.90 KM		[25]
Textile	38.56 KM		[26]
AVAILABILITY OF THERMAL INSULATION MATERIAL IN THE MARKET			
Materials	**Easily accessible**	**Difficult to access**	
Expanded polystyrene	**x**		
Textile		**x**	
THICKNESS OF THERMAL INSULATION MATERIAL [cm]			
Materials	***d* [cm]**		**Reference**
Expanded polystyrene	10		*Author analysis*
Textile	12		*Author analysis*

4.2. Selection of the Ranking Scale for the Evaluation of Thermal Insulation Materials

In order to accurately assess the criteria, weights are assigned to each criterion, followed by the evaluation of alternatives based on the selected criteria (Table 5). The rating scale is formulated based on the provided criteria (Table 2, Table 3, Table 4), and it is divided into three levels of importance for evaluating the thermal insulation material according to environmental and economic criteria, namely:

the chosen material is unfavorable, the chosen material can be used, and the chosen material is favorable.

Table 5. Parameters for assigning criterion weights

ATTRIBUTES	SCORING SCALE		
Rating of Thermal Insulation Material Based on Environmental and Economic Criteria	**The selected material is unfavorable**	**The selected material can be used**	***The selected material is favorable***
Environmental criteria, Global Production and Recycling on an Annual Basis in 2021	**The selected material is extremely unfavorable**	**The selected material is unfavorable** **The selected material is favorable**	***The selected material is extremely favorable***
- Total global annual production	Large (80 to 120 million tons annually)	Medium (40 to 80 million tons annually)	*Small* (up to 40 million tons annually)
- Annual recycling	1–25 %	25 – 50 %	*50 – 75 %* *75 – 100 %*
Environmental criteria, resource and energy consumption in the production process	**The selected material is extremely unfavorable**	**The selected material is unfavorable** **The selected material is favorable**	***The selected material is extremely favorable***
- CO_2 emissions in the production process	High CO_2 emissions (7 to 10 kg)	Medium CO_2 emissions (3 to 7 kg)	*Low CO_2 emissions* (up to 3 kg)
- Water consumption in the production process	Large water consumption (350 to 500l / 1 kg)	Moderate water consumption (150 to 350l /1kg)	*Low water consumption* (up to 150 l / 1kg)
- Energy consumption in the production process	Large energy consumption (150 to 200 MJ / 1 kg)	Moderate energy consumption (75 to 150 MJ / 1 kg)	*Low energy consumption* (up to 75 MJ per 1 kg)
Economic criteria	**The selected material is extremely unfavorable**	**The selected material is unfavorable** **The selected material is favorable**	***The selected material is extremely favorable***
- Installation process	Complex (dificult) installation process	Standard installation process	*Simple installation process*
- Market price of thermal insulation material	High price	Average price	*Low price*
- Availability of thermal insulation material in the market	The selected material is difficult accessible		*The selected material is easily accessible*
- Thickness of thermal insulation material	The chosen material requires a thicker insulation layer	Average thickness	*The chosen material requires a thinner insulation layer*

Once all alternatives are evaluated, the DEXi program generates a ranking list of alternatives based on their overall ratings. At the end of the analysis, the DEXi program generates graphs and reports to facilitate informed decision-making. These reports can be used to assess and compare alternatives, identify the best option based on set criteria, and evaluate potential future scenarios for enhancing the chosen alternative to achieve a specific goal.

5. Results

5.1. Multi-Criteria Analysis of Selected Thermal Insulation Materials Based on Given Criteria

After evaluating the attributes presented in the table (Table 5), results have been obtained, based on which final assessments have been made for each attribute of the selected materials (Table 6).

Table 6. Results of the evaluation of selected alternatives (conventional thermal insulation material and textile insulation)

ATTRIBUTES	Thermal insulation material - EPS	Thermal insulation material - recycled textile
Evaluation of Thermal Insulation Material Based on Environmental and Economic Criteria	The selected material can be used	The selected material is unfavorable
Environmental criteria, Global Production and Recycling on an Annual Basis in 2021	The selected material is unfavorable	The selected material is extremely unfavorable
- Total global annual production	Small	Large
- Annual recycling	1 – 25%	1 – 25%
Environmental criteria, resource and energy consumption in the production process	*The selected material is favorable*	The selected material is unfavorable
- CO_2 emissions in the production process	*Low CO_2 emission*	Medium CO_2 emission
- Water consumption in the production process	*Low water consumption*	Large water consumpition
- Energy consumption in the production process	Moderate energy consumption	Large energy consumption
Economic criteria	*The selected material is highly favorable*	The selected material is unfavorable
- Installation process	*Simple process*	Standard process
- Market price of thermal insulation material	*Low price*	Average price
- Availability of thermal insulation material in the market	*The selected material is easily accessible*	The selected material is difficult accessible
- Thickness of thermal insulation material	Average thickness	Average thickness

Figure 1 depicts a comparison of the percentage of recycling and global production of textile and EPS materials. It's observed that the recycling percentage is similar (ranging from 1 – 25%), however, the annual production quantities of these materials significantly differ (EPS production quantity is characterized as small, while textile production is characterized as large) (Table 2). This directly affects the quantity of recycled material. Increased production volume consequently results in a higher amount of waste and, consequently, a greater environmental impact in terms of pollution.

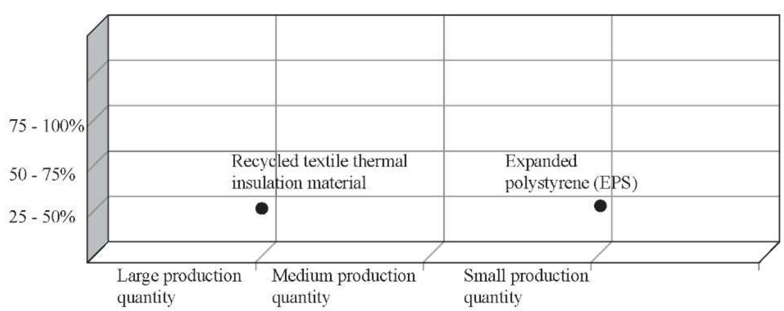

Figure 1. The percentage of recycling and the volume of raw material production of selected thermal insulation materials on an annual basis

Based on the given criteria, the comparison of recycling percentage and total production (Figure 2) displays a result that shows EPS has an unfavorable environmental impact but is better compared to textile, which is characterized as extremely unfavorable (Table 6).

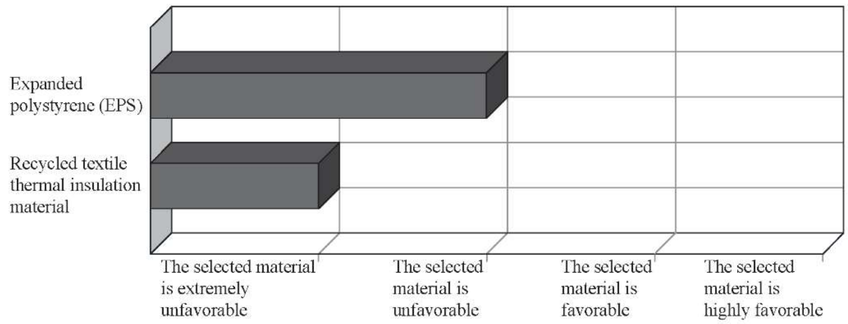

Figure 2. Environmental criteria, global production, and recycling of selected thermal insulation materials on an annual basis

Figure 3 illustrates the comparison of environmental criteria related to resource consumption, energy use, and CO_2 emissions in the production process of selected materials based on 1 kg of produced material. From the graphs, it's evident that water consumption (resource), energy use, and CO_2 emissions are significantly higher in the textile production process compared to the production process of expanded polystyrene.

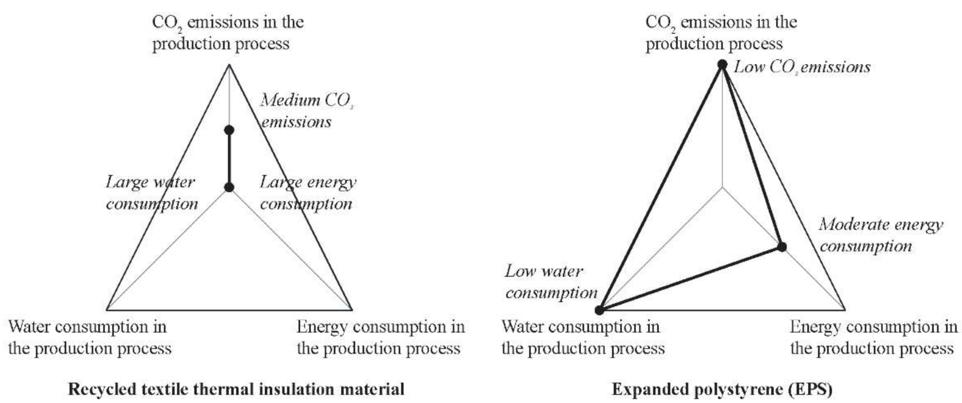

Figure 3. Resource consumption, energy use, and CO_2 emissions in the production process of selected materials

Based on the selected environmental criteria in the production process, from the graph (Figure 4), it can be observed that the production of expanded polystyrene is favorable compared to textile production as a raw material for thermal insulation material.

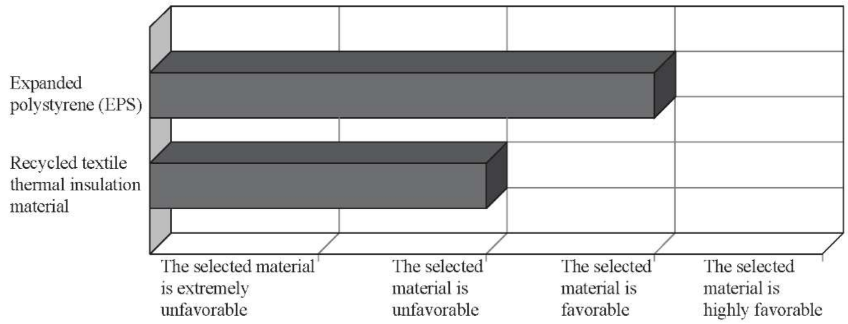

Figure 4. Environmental criteria, resource consumption, energy use, and CO_2 emissions in the production process of selected materials

In the graphs (Figure 5), it can be observed that the installation process of conventional thermal insulation materials, market price, and market availability are better compared to textile thermal insulation material. However, the required thickness of the thermal insulation layer is characterized as average, as approximately the same thickness of thermal insulation materials is needed to meet the same condition.

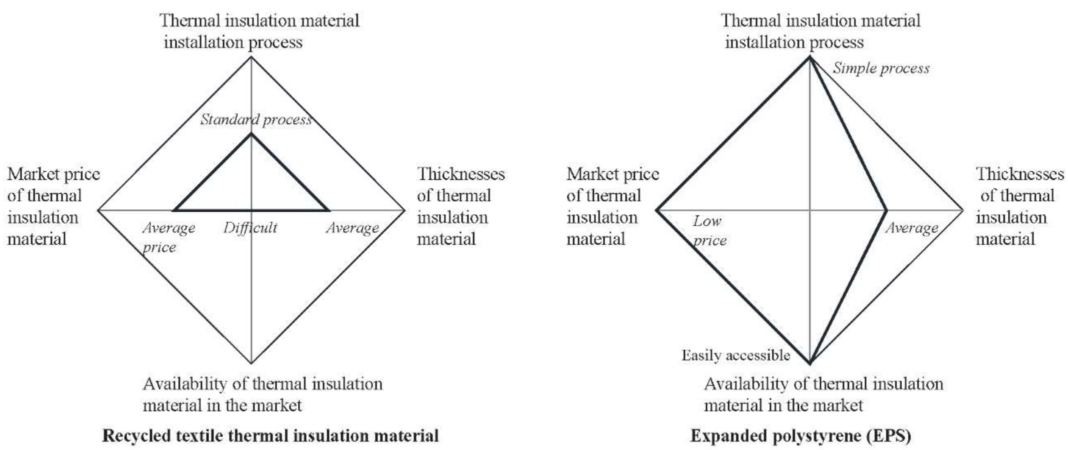

Figure 5. Economic criteria of selected thermal insulation materials

Based on the economic criteria (Figure 6), the results have shown that the thermal insulation material - EPS is extremely favorable compared to textile thermal insulation material due to its affordability, cost-effectiveness, and ease of installation. On the other hand, the textile thermal insulation material is still in the research phase and not widely available on the market.

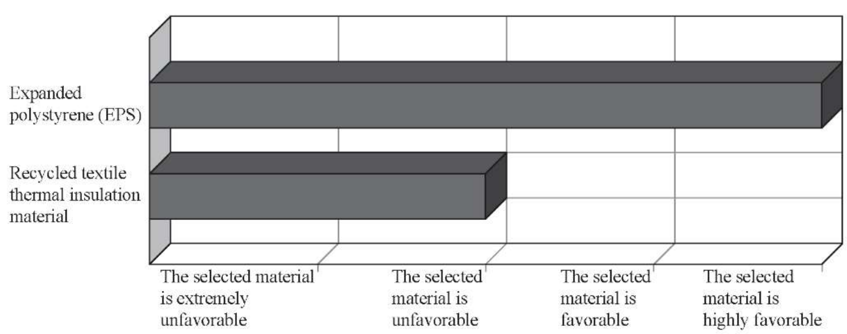

Figure 6. Comparison of economic criteria of selected thermal insulation materials

On the graph (Figure 7), the assessment of the selected thermal insulation materials is depicted, where we observe that EPS is rated as " the chosen material is favorable," while the textile thermal insulation material is rated as " the chosen material can be used." The results have arisen from the overall evaluation of economic and ecological criteria, but also, the assessment was conducted based on 1 kg of material for a more accurate assessment. Taking into consideration that the annual textile production (Table 2) is greater compared to the production of EPS and causes more environmental pollution, it is essential to find a solution to commercialize textile thermal insulation materials to make them more accessible, thereby reducing the pollution caused by the production process. Additionally, the difference between the selected materials is that EPS is purposefully manufactured for building insulation, whereas recycled textile would be produced to mitigate the harmful environmental effects caused by the textile industry. Given that textile insulation material can possess similar thermal insulation characteristics as commercial thermal insulation materials, it has the potential, with further research and improvements, to become readily available on the market at affordable prices with a simple installation process.

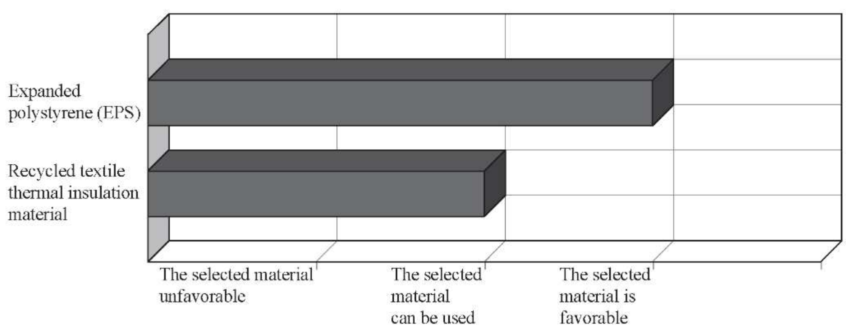

Figure 7. Assessment of Selected Thermal Insulation Materials Based on Chosen Economic and Ecological Criteria

5.2. Creating Scenarios to Equate Economic and Ecological Criteria of Selected Attributes

Based on the obtained results of evaluated alternatives, a possible scenario was created to equalize the ratings of selected materials (Table 7). If the annual production of textiles were reduced and consequently the percentage of recycling increased, and if the product became easily accessible in the market at affordable prices and easy to install, the ratings based on economic and ecological criteria would be equalized (Figure 8).

Table 7. Results of evaluating alternatives according to the scenario

ATTRIBUTES	Thermal insulation material - EPS	Thermal insulation material - recycled textile
Evaluation of Thermal Insulation Material Based on Environmental and Economic Criteria	The selected material can be used	The selected material can be used
Environmental criteria, Global Production and Recycling on an Annual Basis in 2021	The selected material is unfavorable	The selected material is unfavorable
Total global annual production	*Small*	Medium
Annual recycling	1 – 25%	25 – 50%
Environmental criteria, resource and energy consumption in the production process	*The selected material is favorable*	The selected material is unfavorable
CO_2 emissions in the production process	*Low CO_2 emission*	Medium CO_2 emission

Water consumption in the production process	*Low water consumption*	Large water consumption
Energy consumption in the production process	Moderate energy consumption	Large energy consumption
Economic criteria	*The selected material is highly favorable*	*The selected material is highly favorable*
Installation process	*Simple process*	*Simple process*
Market price of thermal insulation material	*Low price*	*Low price*
Availability of thermal insulation material in the market	*The selected material is easily accessible*	*The selected material is easily accessible*
Thickness of thermal insulation material	Average thickness	Average thickness

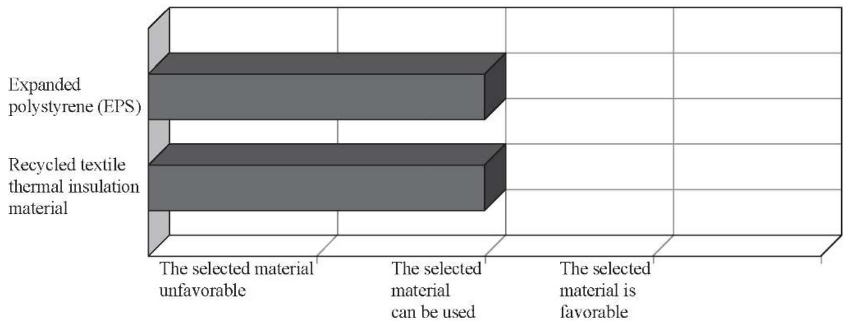

Figure 8. Rating of selected thermal insulation materials according to the scenario based on chosen economic and ecological criteria

6. Conclusion

The current market is largely dominated by conventional synthetic thermal insulation materials, but there is potential for them to be replaced by recycled textiles. In some cases, thermal insulation materials made from waste textiles show similar results compared to currently available dominant market products. However, research on using textile waste as a thermal insulation material is still in its early stages due to the incomplete characterization of most explored materials.

Based on a multi-criteria analysis of economic and environmental criteria, expanded polystyrene (EPS) insulation and recycled textile insulation exhibit different characteristics and advantages, making it not always straightforward to compare which option is better.

EPS is frequently used in building insulation due to its good thermal insulation properties, low cost, and easy installation. EPS is also resistant to mold, pests, and partially resistant to moisture, making it durable. However, EPS production has a negative environmental impact as it relies on fossil fuels and can be difficult to degrade.

On the other hand, recycled textile insulation utilizes repurposed materials, which can reduce waste and contribute to sustainability. This type of thermal insulation has a thermal conductivity coefficient similar to conventional options but can be sensitive to moisture and mold if not used correctly. The installation of recycled textile thermal insulation might be more complex and costly compared to EPS installation.

Based on the obtained results for evaluated alternatives, a possible scenario has been devised with the aim of aligning the ratings of selected materials. In the case of reducing annual textile production, leading to increased recycling rates, coupled with easier market access at reasonable prices and simple installation, ratings based on economic and environmental criteria could be equalized. Ultimately, the final choice will depend on specific project requirements and values. If sustainability is a key priority, recycled textile insulation represents a more favorable option. On the other hand, if thermal insulation, moisture resistance, and durability are critical, expanded polystyrene currently presents a better choice.

However, efforts to enhance the environmental profile of insulation materials, such as recycled textiles, could lead to more sustainable options in the future. The study underscores the importance of considering both environmental and economic aspects when making decisions about construction materials to achieve a harmonious balance between ecological responsibility and economic viability.

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