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The Versatility of the Bioeconomy. Sustainability Aspects of the Use of Bran

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***Abstract* – As food consumption increases, so does the number of agricultural by-products. That is why it is necessary to find the best possible uses for them, operating by the principles of the bioeconomy. This work aims to gather information on the possibilities of using grain byproducts to develop new products and evaluate which bran products are the most suitable for commercialisation based on economic, environmental, social, and technical factors. Two methods were used in this work: literature review and multi-criteria decision analysis. As a result, 30 products were identified that could be made by using wheat bran, straw, husk, and dust. The products were divided into six groups – packaging materials, building materials, adsorbents, fuel, thermal insulation materials, and chemicals. In multi-criteria decision analysis, it was looked at seven bran products of which the best alternative for further commercialisation is mycelium-based biocomposite.**

***Keywords* – Grain byproducts; multi-criteria decision analysis (MCDA); sustainable development; TOPSIS; value-added products; wheat**

1. INTRODUCTION

The bioeconomy is one of the main directions of economic development that will allow achieving the goals of the European Green Deal [1]. An essential aspect of the bioeconomy is gathering the existing knowledge and highlighting and evaluating new strategies and technological processes to choose the best directions for development, considering global, regional, and local specificities [2]. Global food consumption is projected to increase by 59 %–98 % by 2050 compared to 2005 [3]. All of this indicates that agricultural production and the number of byproducts generated will increase. Approximately 1.3 billion tons of food waste, including food byproducts, and yearly losses are generated worldwide. At the level of food production, 39 % of food waste and loss occurs [4]. The circular economy model promotes byproducts as a raw material for new products, thus creating new business models with more resource-efficient industrial management [5]. The circular economy aims to move away from a linear economy model and introduce an economy based on the 3Rs principle of reducing, reusing, and recycling [6]. Traditionally, grain byproducts are disposed of as waste or added to livestock feed [7]–[10]. It harms the environment, such as wheat bran disposal releases 259 $kgCO_2eq$ into the air [11]. Also, the possibility of producing value-added products such as single-cell oil is lost [12]. The use of agricultural residues in higher value-added products is in line with at least three of the seventeen UN Sustainable Development Goals (Goal 2;9;12) [13]. The concept of a cascade implies using biomass in a resource-

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efficient and closed-loop manner [14]. The idea has appeared in European Union (EU) policy planning since 2012 in documents such as the EU Forest Strategy, the EU Bioeconomy Strategy, and the EU Circular Economy Action Plan [15].

In Europe, the cultivated area under cereals in 2020 was 52.5 million hectares, and the yield was 286.5 million tons [16]. Globally, wheat is the most common type of cereal and one of the primary raw materials in the food industry. In 2017, the world produced 770 million tons of wheat, of which 150 million tons were grown in Europe [9]. In 2020, the wheat harvest in Europe was 126.7 million tons [16].

In 2020, the agricultural land in Latvia accounted for 36 % or 2.3 million hectares, of which 753.7 thousand hectares of the area was under cereals. Cereal production is one of the most important agricultural sectors in Latvia, as it does not only provides food for people and feeds the livestock sector. The grain yield in 2020 was 3.5 million tons, and the yield per hectare was 46.4 quintals. In 2020, 20 314 farms were engaged in growing cereals in Latvia. In recent years, summer and winter the growth of wheat was the highest, up to 66.2 % [17]

The cereal sector can be divided into three stages – 1) grain cultivation and harvesting, 2) grain primary and secondary processing, and 3) grain food retail and consumption [5].

Byproducts such as grain screenings, husk, bran, germ, dust, and straw are generated during cultivation, harvesting, and processing stages [10], [18], [19]. In grain cultivation, straws are produced, which can be used as a raw material in various industries, such as medicine and animal farming [20]. In the case of wheat, approximately 1.3 to 1.4 kg of wheat straw is produced per kilogram of grain obtained [21]. In primary processing, the grains are cleaned and dried. Grain screenings and dust are generated in this stage [19]. They account for about 0.9 % of the total weight [22], [23]. Dust, husk, bran, and germ are generated in secondary processing. Husk and bran are byproducts of flour milling, representing approximately 14.5–25 % by weight of the grain [8], [11], [24].

There have been several studies on what can be obtained from grain byproducts. Berthet *et al*. studied wheat straw as a source to obtain lignocellulosic fibres, which can be used as a filler in Poly(3-hydroxybutyrate-co-3-hydroxyvalerate) (PHBV). The material is further used as a film for fresh food packaging [25]. Wheat straw can be used as a source to get bio-polyol. It is a partial substitute for castor oil in biodegradable polyurethane foams, which can be used as a thermal insulation material in the agricultural sector [26]. Hernández-Martínez *et al*. described how to extract silicon from wheat husk ash, which can be used to produce solar cells [27]. Katileviciute *et al*. compiled several studies on using wheat bran to produce enzymes, proteins, organic acids, and other products [28]. The studied products can be classified into six groups: packaging materials, building materials, adsorbents, fuel, thermal insulation materials, and chemicals. The most studied grain byproducts are bran, straws, and husk. There are studies on their use as raw materials [29], [30], filler [9], [11], [31], binder [32], nutrients [5], [28], [33], and the source of various chemicals [34]–[36]. Most of the research looks at only one of the grain byproducts.

Looking at several articles on bioeconomy [37]–[40], we observed that the literature review is regularly used to gather information. It is used to collect data and data, which is further analysed using other methods, depending on the purpose of the work. In a review of the extraction and use of phenolic compounds from coffee byproducts, a literature review was conducted to identify and evaluate research on the studied topic [37]. Fiallos-Cárdenas *et al*. use the literature review method in their paper to compile quantitative studies on the use of banana lignocellulosic residues [38]. An overview of current scientific, technological, and commercial trends in using bio-waste in various industries conducted a literature review on the circular bioeconomy of agri-food and forest processing waste [39]. Corrado and Sala provided an overview of studies on food waste generation worldwide and in Europe. Ten

scientific articles were selected using a literature review, and the underlying quantification methodologies of these studies were further systematically analysed [40]. For the current research it is necessary to do a literature review to compile scientific articles that review products obtained from grain byproducts.

A multi-criteria decision analysis (MCDA) method can compare options and set priorities [41]. Lokesh *et al*. used a two-tier MCDA to identify promising biological value chains essential for EU bioeconomy planning. Twelve EU-based value chains, such as 'Starch to Bioplastic Food Packaging,' were selected for the study and evaluated against six criteria. As a result, the authors recommend using the research methodology in practice to make informed decisions about bio-based products that have the potential to replace fossil-based products [15]. Pieratti *et al*. conducted a study using MCDA to evaluate different forest management strategies at the local level. Six criteria based on the 4R principle of the circular bioeconomy were set, and five scenarios were analysed. The authors conclude that the main advantages of this method are that the results are easy to understand and compare. But before the results are used in practice, they should be analysed and checked [42].

Stephen *et al*. in his work he used a combination of MCDA and visualization technique to analyse the long-term and sustainable use of forest resources. The results obtained during the survey for obtaining criteria for MCDA were presented in the program for 3D visualization of various scenarios for the development of the task. This combination allowed the author to determine a number of optimal tools and measures to solve the problem and put forward ways to solve it.

Barney *et al.*, using MCDA, explored scenarios for decarbonizing the energy sector by converting it to renewable energy sources. The author included in the analysis the factors of three directions – economic, social and environmental, which made it possible to carry out the analysis as versatile as possible for the chosen task. The use of additional programs such as EnergyPlan, LCOE and TOPSIS deepened the result, making it closer to reality. Combining MCDA with various programs and methods allows you getting a result that can be applied in practice, regardless of the location of the object or territory under consideration.

The analysis of the literature on the optimal research methodology indicates that MCDA will show the required result for this work as well. Based on the conclusions about the method, this study will use MCDA to compare different products that can be made using wheat bran.

Several studies have been conducted on this topic, but primarily byproducts are considered separately. Review articles already summarise information on a specific byproduct and its use [28]. However, as far as we know, no summary of several grain residues has been made in one study. Therefore, this study aims to gather information from the scientific literature on the possibilities of using grain byproducts in developing new products and to assess which bran product is the most suitable for commercialisation based on economic, environmental, social, and technical factors.

2. METHODOLOGY

The methodology was selected based on the reviewed scientific articles in the bioeconomy field and their suitability for this research. Two methods have been chosen to identify and evaluate the products that can be made using grain byproducts – literature review and MCDA. The operation algorithm can be described by the following 5 steps, all of which are important and in order to get precise result, cannot be skipped:

1. Product identification. The step required to determine the main product, its needed properties and qualities;
2. Collection of information in the available literature and its analysis for a deeper study

of the selected product, its availability and diversity on the market;

3. Based on the analysis of the literature, the choice of criteria required for subsequent analysis. The right choice of criteria will allow you to comprehensively evaluate the product based on the required qualities. In case of technology, these criteria may be its readiness level, availability on the market and sustainability;
4. Conducting MCDA analysis based on selected criteria;
5. Product realization based on the results of the MCDA analysis (see Fig. 1).

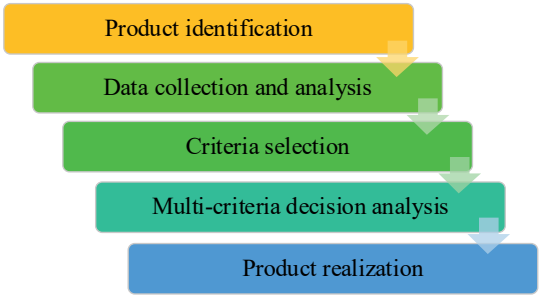


Fig 1. The stages of the research methodology.

The scientific databases ScienceDirect and the Web of Science were used in the literature review. Publications were searched using keywords. They were based on 'products from grain…' and in ellipsis place, different words were used: 'byproduct', 'germ', 'pulp', 'husk', 'chaff', 'bran', 'straw' and 'screenings'. Twenty-nine studies published between 2006 and 2021 were selected for the next phase, in which articles were grouped and analysed. The selected papers were in English and corresponded to the topic of this study.

The selected articles were grouped based on the byproduct used in the study and the final product. All final products were divided into the six groups shown in Table 1. The selected articles are about wheat byproducts because most articles on this topic research wheat residues. Wheat is also the most common type of cereal in Latvia and the world [2], [17].

TABLE 1. PRODUCT CLASSIFICATION INTO GROUPS

Product group	Wheat byproducts	The final product
Packaging materials	Bran, straw, dust, and husk	Bio-based composite with polypropylene (PP) [11], [43], food film with antioxidant properties [24], bio-based food packaging [5], biocomposite – film for fresh food packaging [25], thermoplastic [8].
Building materials	Straw, husk	Concrete [10], lightweight concrete [9], [31].
Adsorbents	Bran, straw, and husk	Siliceous lignin microparticles as an adsorbent [35], adsorbent for Reactofix golden yellow 3 RFN dye [44], carbon microspheres [45], and absorbent for eliminating dyes and other toxic effluents from the textile industry [29].
Fuel	Bran, straw	Fuel pellets [30], phenolic bio-oil and biochar [46], biofuel [28], [47].
Thermal insulation materials	Bran, straw, and husk	Thermal insulation biocomposite [32], clay bricks [48], mycelium-based composite [33], polyurethane foam [26].
Chemicals	Bran, straw, and husk	Silicon [27], hydrogen [7], organic acids – ferulic acid, lactic acid, itaconic acid and fumaric acid [28], [49], enzymes [28], protein [28], medicines and vitamins [28], cosmetics [28], single cell oil [12], antioxidant and antimicrobial extracts [50], xylanase [51], lignin [34], mesoporous biogenic silica nanoparticles [36].

MCDA method can be used to compare several options using different criteria. This method helps to process large amounts of information consistently [41]. In MCDA, the input data can be quantitative and qualitative [42]. The Technique of Order Preference Similarity to the Ideal Solution (TOPSIS) was used to compare different products and determine the optimal option. Obtained result of the TOPSIS method is the distance of alternatives to an ideal point. Alternative with the shortest distance to the ideal point is the best. Calculations this study performed analyses using formulas and calculation steps. Study calculations were made in *MS Excel*. MCDA three steps:

1. Input data Regardless of the chosen MCDA method, input data is an essential part of the analysis, as all calculations are based on them. It is necessary to set criteria and alternatives [52]. Alternatives in our study are products that can be obtained from grain byproducts, and the criteria are from four categories: environmental, economic, technical, and social. The selected six criteria are shown in Table 2.
2. Weight of criteria. Criteria need a weight that reflects their importance compared to other criteria. The Analytical Hierarchy Process method can be used at this stage. The weights obtained in this method can be further used in all MCDA methods [52]. In our case, the weight of the criteria was obtained using Sensitivity Analysis. Sensitivity analysis can be performed to investigate the effect of criterion weights on alternatives [53]. The resulting weights are used in the TOPSIS calculations to obtain the results of the Sensitivity Analysis. This was done for all criteria, and based on the results, the criterion weights were selected for the final TOPSIS analysis.
3. Calculations of the TOPSIS method. The TOPSIS method was used after defining input data and the criteria weights.

TABLE 2. CRITERIA FOR MULTI-CRITERIA ANALYSIS

Criteria category	Criteria
Environmental aspects	Sustainability – compliance with the 12 UN Sustainability Goals (1–5)*
	Environmental impact – comparison of emissions from the production process for the new and existing product (1–5)*
Economic aspects	Product price comparison – the price difference between the product currently used and the new product (%)
	Market demand – global market size assessment (1–5)*
Technical aspects	Availability of technologies – assessment of the production of the new product, taking into account the level of technological readiness (TRL) (1–5)*
Social aspects	Social aspects – product job creation assessment (1–5)*

* The criterion is evaluated in a 5-point system: 1 – does not meet the requirements; 5 – meets the requirements.

As a result, the best alternative can be determined by comparing the relative proximity to the ideal solution.

3. RESULTS

The literature review summarised 30 products shown in Table 1. The studied products were obtained from four wheat byproducts – bran, straw, husk, and dust. Of these byproducts, bran is the most widely used, while dust is used to produce only one product, bio-based packaging [54]. This study divided the products into six groups: packaging materials, building materials, adsorbents, fuels, thermal insulation materials and chemicals.

From the reviewed products, seven products were selected for MCDA. The analysis aims to find the product with the most significant potential for commercialisation, considering environmental, social, economic, and technical aspects. Of all product groups, fuels and building materials weren't considered further, as these products don't have a relatively high added value. This study found that wheat bran is the most widely used raw material, so their products were examined in MCDA. For bran, nine publications were reviewed, summarising information for thirteen products. When evaluating the data available for these products, the products shown in Table 4 were selected for MCDA.

Table 3 shows the input data for MCDA. Except for the product price comparison, all criteria were assessed on a five-point scale based on aggregated data and expert judgment. As the products are novel, they have not yet been studied extensively, and in many cases, data were taken from similar products.

The TRL of the product was evaluated for the availability of technology. TRL was assessed based on expert opinion. If the TRL was four or less, it was given a score of 1 to 2; if the TRL was 5 or 6, it was 3 points; and if the TRL was 7 or 8, the product received 4 points [55].

TABLE 3. INPUT DATA OF MCDA

	Alternatives						
Criteria	Mycelium-based composite	Adsorbent	Bio-based PP composite	Bio-based film	Enzymes	Lactic acid	Single-cell oil
Availability of technologies	3	4	3	3	4	4	3
Sustainability	5	4	4	4	5	5	5
Product price comparison, %	92.5	92.6	14.2	0.01	50	32.6	37.9
Market demand	4	2	4	2	2	3	5
Environmental impact	4	5	3	2	3	4	5
Social aspects	5	4	5	5	3	3	4

The product's sustainability was assessed for compliance with the UN Sustainable Development Goals [13]. Using agricultural residues in higher value-added products aligns with at least three of the seventeen goals. If the product met all three goals, 5 points were given; if there were fewer goals, then correspondingly fewer points.

The possible prices of the products were compared with the products traditionally used and expressed as a percentage of the price difference. Using agricultural and industrial byproducts, the raw material cost of a mycelium-based biocomposite is 0.06–0.15 EUR kg^{-1} [56]. There are no data on total production costs, but the authors believe that raw materials make up the majority. Such material was compared to polystyrene, which costs between 1.85–2.02 EUR kg^{-1} [56]. The cost of commercial activated carbon is 5.85 EUR kg^{-1}, which is used as an adsorbent, while bioadsorbents cost is 0.05–0.43 EUR kg^{-1} which is significantly cheaper [29]. Biocomposite with PP was compared to a study where coriander fibres were used instead of wheat bran. For PP granules, adding 40 % coriander fibres reduced the price from 1.27 EUR kg^{-1} to 1.09 EUR kg^{-1} [57]. Food film with antioxidant properties as compared to PLA, a natural material made from fermented vegetable starch. In 2016, PLA film cost 2 EUR kg^{-1}, while low-density polyethylene (LDPE), a fossil-based plastic, cost 1.25–1.45

EUR kg^{-1} [58]. In our case, the product price would probably be lower because it would be obtained using low-cost residue. A rough price comparison for the production of enzymes showed that using wheat bran as a raw material would reduce the price by up to 50 % [28]. The price of lactic acid obtained from the brewery's spent grain is 0.76–1.11 EUR kg^{-1}, but lactic acid usually is 1.64 EUR kg^{-1} [59]. This could be like our lactic acid price because the study also used byproducts as raw materials. If single cell oil was produced using glucose at zero cost, assuming waste or byproduct streams, it would cost 2.99 EUR kg^{-1} at 10 000 tonnes per year. If the price of glucose is assumed to be 351.68 EUR t^{-1}, the cost of producing single-cell oil would be 4.82 EUR kg^{-1} [60]. In this case, the data is also based on assumptions because, in reality, wheat bran has an economic value.

Market demand was measured by the size of the global product market. The global biocomposite market was 18.44 billion EUR in 2020 [61]. In 2020, the global adsorbent market was 3.43 billion EUR [62]. The global bioplastics market was estimated at 5.1 billion EUR in 2020 [63]. The value of the global enzyme market in 2019 was 7.6 billion EUR [64]. The market for organic acids in 2021 was 9.69 billion EUR [65]. In this study [12], the authors believe that single-cell oil could be added to non-biofuel markets such as producing higher-quality fatty acid-based oleochemicals. In 2020, the global market for oleochemicals was 27.62 billion EUR [66]. As the base years of the data differ, experts' opinions were also taken into account. Demand in the market was expressed in a five-point system comparing product market volumes.

Environmental impact was assessed on a five-point basis, considering emissions from the product during production compared to products currently in use. The higher the emission savings, the higher the rating of the product. Collected data were incomplete, so experts were also involved in this criterion. The mycelium-based composite was compared to MycoBamboo, a material with bamboo particles and mycelium. Production of such a sample emits 86 gCO_2eq per plate but 27 gCO_2eq per plate if renewable energy is used instead of natural gas. Each sample of MycoBamboo weighed approximately 33 g [67]. The material could be compared to extruded polystyrene foam with a global warming potential of 13.22 $kgCO_2eq$ to 1.75 kg foam [68]. Using wheat bran fibre to produce biocomposite with PP can reduce emissions by 1470 $kgCO_2eq$ t^{-1} and create energy savings of 2130 MJ t^{-1} compared to pure PP material [11]. The food film was compared to a PLA film with emissions of 0.27 $kgCO_2eq$ $(m^2)^{-1}$. The weight of the film is 0.6 kg per 10 m^2 [69]. PLA was compared with LDPE film with emissions of 0.11 $kgCO_2eq$ $(m^2)^{-1}$ and a weight of 0.5 kg per 10 m^2 [69]. The reviewed studies also consider emissions from the extraction of raw materials, which could be lower for the products in our study because the raw materials are agricultural byproducts.

From a social point of view, the experts assessed the amount of labour involved in the product's production process. If the production of the product is automated and doesn't require a lot of work, then it was given 1–3 points because, in that case, the factory will not create a relatively large number of jobs. But if the production process isn't fairly automated, then 4–5 points were given because the factory would create new jobs that would improve the social situation in the country.

Criteria weights were determined using Sensitivity Analysis. The sensitivity analysis showed that the sustainability aspect has the lowest sensitivity to changes in weight, which can also be determined by looking at the input data, as all alternatives scored 4 to 5 points. Therefore, this criterion was given the lowest weight (0.05). The technical and social aspects also had a small weight change compared to the other criteria, so they were given a weight of 0.15. The environmental impact and market demand became more sensitive to changes in weight when the unitary variation ratio ranged from 0.5 to 1.5, so the importance given to those criteria is 0.2. The product prices comparison reacted the most to the change in weight,

most likely because the input data differed more. After all, they were not expressed on a five-point scale. The sensitivity analysis results for this criterion are shown graphically in Fig. 2.

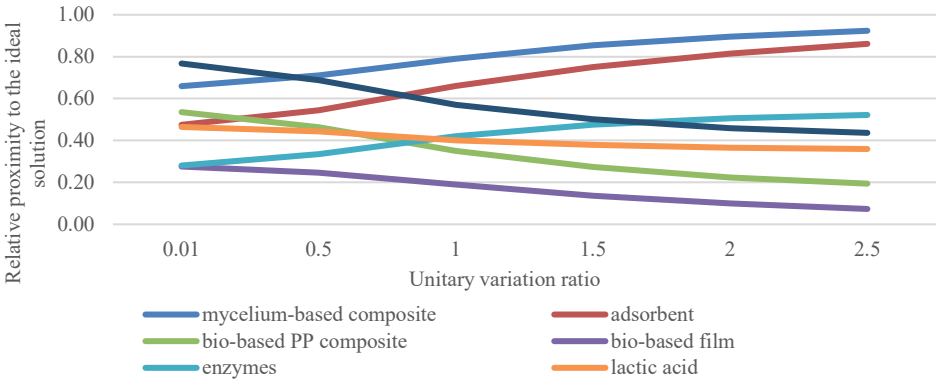


Fig. 2. Results of sensitivity analysis for product price comparison.

All criteria weights are shown in Fig. 3.

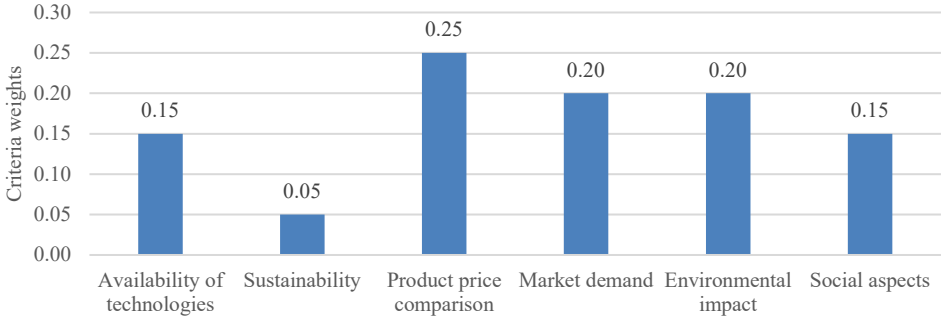


Fig. 3. Weight of criteria in TOPSIS.

TOPSIS calculations were made using the input data and the obtained criterion weights. Obtained results are shown graphically in Fig. 4. The results showed that the highest relative proximity to the ideal solution of the analysed products is for mycelium-based biocomposite material. This has been mainly due to the relatively high difference in product prices. Had this criterion not been considered, single cell oil would have gotten the highest result, which can also be assessed by looking at the input data. The adsorbent also has relatively good results, as its price and environmental impact are much lower than those currently used adsorbents. The worst result got the food film with antioxidant properties. This is because data for this product were used from PLA parameters, and PLA was compared with LDPE, which currently has lower production emissions and prices than bioplastics. Also, bioplastics have smaller market demand, which needs to be improved. However, the data was not taken specifically for our product. Product parameters are better because they are obtained from bran and not maise, with different extraction characteristics, such as water consumption and yield [69].

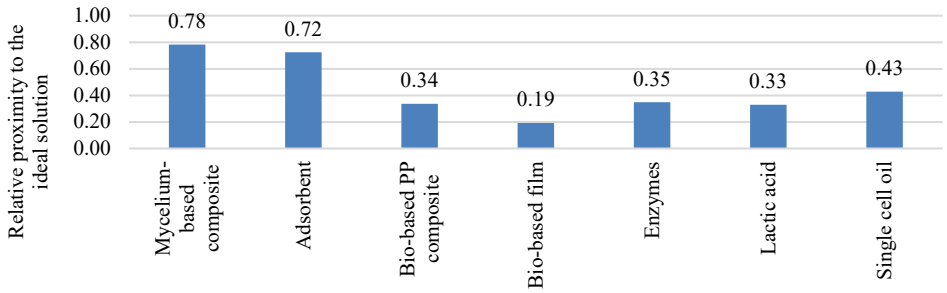


Fig. 4. Results from TOPSIS.

4. CONCLUSIONS

Traditionally, grain byproducts are disposed of as waste or added to livestock feed. Therefore, several studies have been conducted to find better applications that provide higher added value. Byproducts such as grain screenings, husk, bran, germ, dust, and straw are generated during cereal production's cultivation, harvesting, and processing stages. This study gathered information on the potential use of grain byproducts in developing new products. It conducted MCDA to find the most suitable commercial product from wheat bran.

In the literature review, we identified 30 products that can be obtained using wheat bran, straw, husk, and dust. The studied products are classified into six groups – packaging materials, building materials, adsorbents, fuel, thermal insulation materials, and chemicals. Most products were obtained using bran, so seven bran products were selected for further analysis.

Six criteria from environmental, economic, technical, and social aspects were selected for MCDA. The analysis showed that the best alternative to move towards implementation is a mycelium-based biocomposite material (0.78). Its price (0.25) and environmental impact (0.20) are lower than the current thermal insulation materials. It is in demand on the market and would contribute to sustainable development.

As the input data for MCDA were based on many assumptions, it is necessary to perform an environmental and economic evaluation study for the mycelium-based composite material before it is commercialised. The study only compared bran products, so straw and husk pr products could be reached in future studies.

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