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Multi-criteria decision analysis of wood waste ash and glass foam: toward sustainable material selection for biomethanation

Z. Kusnere*, D. Lauka and K. Spalvins

Riga Technical University, Institute of Energy Systems and Environment, Azenes iela 12/1, LV 1048 Riga, Latvia
*Correspondence: zane.kusnere@rtu.lv

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Abstract. The study examines the potential applications of wood waste ash and waste glass, by-products of various industrial processes, which have conventional applications such as composting and soil improvement. A new development, vulcanised wood ash material, is studied analysed, drawing parallels between its industrial production process and that of clay pellets. Vulcanised wood ash material and glass foam, which are characterised by advantageous chemical and physical properties, are proving to be versatile resources for various technical applications. Employing a systematic decision-making approach, the study utilises multi-criteria decision analysis and the Technique for Order of Preference by Similarity to Ideal Solution method to evaluate materials for biotrickling filter reactors in ex-situ biomethanation. The comparative analysis includes ash filter material, glass foam, and other industry alternatives, emphasising environmental impacts. The findings reveal expanded clay pellets as the most suitable carrier material, closely followed by polyurethane foam, while glass foam demonstrates remarkable performance despite ranking third. The innovative qualities of glass foam, such as high porosity and thermal insulation, position it as a viable option for biotrickling filter reactors, promoting sustainable practices and circular economy principles. However, further development is required to optimise vulcanised wood ash for biomethanation, potentially enhancing its efficiency through pH adjustment and porosity optimisation.

Key words: biomethanation, glass foam, glass waste material, mcda, TOSPIS, vulcanised wood ash material.

INTRODUCTION

Biogas upgrading is a growing concern due to rising production costs, necessitating technologies that achieve high efficiency with minimal energy consumption. Biotrickling filter reactors are one of the most promising biomethanation methods (Angelidaki et al., 2018; Baransi-Karkaby et al., 2020; Sieborg et al., 2020), with the carrier material in the reactor playing an important role in promoting methanogenesis efficiency (Kusnere et al., 2021). However, there is a need for more sustainable and cost-effective solutions. Industries are investigating alternative materials derived from various by-products to address this demand in order to comply with sustainable standards and achieve operational efficiency goals. The circular bioeconomy concept focuses on using by-products from bioprocesses to generate new products, promoting resource efficiency and minimising waste. (Jensen et al., 2021).

The energy produced in industrialised countries is the future generation of electricity, anticipated to be generated from the combustion of waste and residues made from biomass. (Kalak, 2023). This transition underscores the critical role of efficient biomethanation processes in leveraging renewable energy sources effectively. Biomethanation, in particular, plays a dual role in energy production and storage, with emerging methods such as Power-to-Gas or, more specifically, Power-to-Methane offering innovative solutions (Götz et al., 2016; Ghaib & Ben-Fares, 2018; Daniarta et al., 2024). By converting surplus renewable energy into methane, biomethanation enables the storage and utilization of renewable energy resources, thereby bolstering grid stability and ensuring energy security. In the broader context of the green energy transition, biological methanation emerges as a pivotal technology for upgrading biogas and advancing sustainable energy practices (Gallo et al., 2016; Blanco & Faaij, 2018).

Given the shift towards renewable energy sources, there has been considerable focus on using biomass wastes for energy generation. Nevertheless, the management of biomass combustion leftovers, such as wood ash, poses significant difficulties due to its elevated ash concentration and the existence of heavy metals and inorganic compounds (Bachmaier et al., 2021). Not withstanding these difficulties, there is an increasing interest in investigating novel methods to reuse these by-products for sustainable energy use. Wood ash, a common by-product of biomass combustion operations, poses challenges for disposal due to its high ash percentage and the presence of heavy metals and inorganic compounds (Zhai et al., 2021). However, these substances can be recycled to enhance energy output and process efficiency (Demeyer et al., 2001; Kusnere et al., 2023b). The circular bioeconomy entails utilising by-products from bioprocesses to generate new products (Bharathiraja et al., 2017). Wood ash is energy waste with few application possibilities, such as forestry and soil amendment, (Zhai et al., 2021; Elliott et al., 2022), for example, it can serve as a mineral fertiliser that can be utilised to deacidify soil and replace calcium fertilisers (Stankowski et al., 2021). Developing novel materials like vulcanised wood ash and glass foam presents opportunities to repurpose wood ash waste and waste glass for biomethanation applications.

The study explores the potential applications of wood waste ash and glass waste, focusing on the innovative development of vulcanised wood ash material and glass foam material('Green Gravels'; Lauka et al., 2015). Specifically, the research delves into these materials' chemical and physical properties to identify prominent characteristics in selecting carrier materials for ex-situ biomethanation, a crucial parameter in biotrickling bioreactors (Jensen et al., 2021). To achieve this objective, multi-criteria decision analysis (MCDA) and the Technique for Order of Preference by Similarity to Ideal Solution method (TOPSIS) are employed to make systematic decisions. The research compares wood waste ash, glass foam, and other alternatives using predetermined criteria and data to provide insights into sustainable material selection for biomethanation processes.

MATERIALS AND METHODS

The research algorithm (Fig. 1) starts with literature analysis as a foundation for choosing alternatives and defining criteria. After defining criteria and choosing alternative materials, the decision making matrix is made where criteria weights are calculated from an expert questionnaire. The study explores the complexities of MCDA, with a focus on the TOPSIS. Additionally, a sensitivity analysis is conducted to enhance the dependability of the findings.

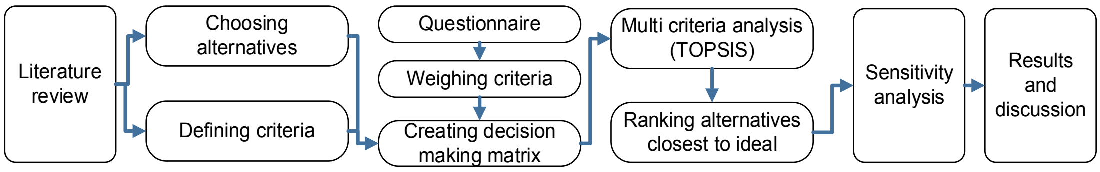

Figure 1. Research algorithm.

This research algorithm is used to rank the alternatives based on their performance against the defined criteria, ultimately leading to the selection of the most suitable material for *ex-situ* biomethanation.

Choosing alternatives

For the biomethanation in biotrickling filter reactors, choosing materials is a crucial aspect because their properties can influence microorganism growth (Jensen et al., 2021; Kusnere et al., 2023a). In this study, two packing materials derived from waste materials are chosen: filter material obtained from the bottom ash of wood chips (VAM) and material made from glass waste (GF). Two alternatives were chosen to be previously studied in the field (Ashraf et al., 2020). Expanded clay pellets (CP), such as Leca®, is a readily available, cost-effective natural material that has a wide range of uses in gardening and is now being utilised in construction (Rashad, 2018). In order to compare materials that have completely distinct origins and qualities, polyurethane foam (PUF) was selected. PUF, an artificial substance derived from fossil fuels, is characterised by its low cost, excellent porosity, and extensive surface area (Kusnere et al., 2021).

Selection of criteria

The chosen criteria are grouped into four groups of aspects - environmental aspects, economic aspects, technical aspects, and performance aspects. All criteria are quantitative, and data was collected from literature and previous studies (Kusnere et al., 2023b, 2023a).

Table 1. Criteria for multi-criteria analysis for material application in biomethanation

Criteria category	Criteria
Environmental aspects	Energy for production of the material °C
	Source of the raw material (fossil or not) 0–1 points
Economical aspects	Material costs EUR m^{-3}
	Material availability, Mt $year^{-1}$
Technical aspects	Material pH
	External porosity %
	Bulk density kg m^{-3}
	Specific surface area m^2 m^{-3}
Performance aspects	Average biomethane yield NmL $L_{material}^{-1}$
	Water retention %

Table 1 lists criteria for multi-criteria analysis for material application in biomethanation. The criteria were separated into four categories: environmental aspects, economical aspects, technological aspects, and performance aspects. By analyzing these criteria, its is possible to determine the most suitable materials for biomethanation applications that strike a balance between environmental sustainability, economic viability, technical feasibility, and performance efficiency.

Weighing criteria

Multi-criteria matrixes weights for materials were based on expert evaluation. People who have studied or worked in biology, environmental engineering, biotechnology and chemistry, and civil, industrial, and mechanical engineering were targeted as potential experts. Together, thirty experts participated in the evaluation. Of these experts, 11 had doctoral degrees, 15 had master's degrees, and 4 had bachelor's degrees. Google Forms was used to perform the questionnaire. The weights for each criterion were established using a questionnaire-based method, in which participants assessed each criterion on a scale ranging from 1 to 5. The total of the ratings given to each criterion was divided by the total of the ratings given to all criteria. This algorithm ensured that the weights allocated to each criterion collectively totaled 1, so creating a normalised foundation for comparison and decision-making.

Evaluating materials using TOPSIS

To find the ideal solution closest to a favorable option, TOPSIS (Ishizaka & Nemery, 2013). Using this method, this approach utilises the numerical values of the previously defined criteria (Ishizaka & Nemery, 2013). The TOPSIS analysis involves a series of five consecutive processes that can be employed to calculate the closest to the ideal solution (Fig. 2).

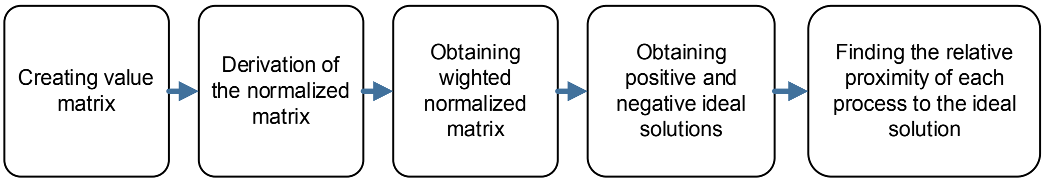

Figure 2. Toolbox for applying Technique of Order Preference Similarity to the Ideal Situation (TOPSIS) method.

At first, the matrix of values is created. It is based on chosen criteria. After constructing the matrix of values, a normalised matrix is formed by dividing each value by the sum of all square roots linked with the respective criterion, as calculated using Eq. (1).

$$r_{ai} = \frac{x_{ai}}{\sqrt{\sum_{a=1}^{n} x_{ai}^2}} \tag{1}$$

where r_{ai} – normalised value; x_{ai} – indicator value; i – criterion; a – alternative.

A weighted normalised matrix is created from normalised matrix values. Each rai value multiplied by w yields the weighted normalised matrix values. The sum of all criteria should be one. Once the weighted normalised matrix is obtained, the positive ideal and negative ideal solutions are identified. It is done by selecting the highest and lowest values from the previously calculated weighted normalised values. Subsequently, the numerical value of each alternative is measured in terms of its distance from both the positive ideal solution and the negative ideal solution. Eq. (2) was applied to calculate the distance from the positive ideal solution, while Eq. (3) was used to find the distance from the negative ideal solution.

$$d_a^+ = \sqrt{\sum_i (v_i^+ - v_{ai})^2} \quad (2)$$

$$d_a^- = \sqrt{\sum_i (v_i^- - v_{ai})^2} \quad (3)$$

where d_a^+ – distance from the positive ideal solution; d_a^- – distance from the negative ideal solution; v_i^+ – positive ideal value; v_i^- – negative ideal value; v_{ai} – weighted value.

The relative proximity coefficient is calculated based on the distances determined from the positive and negative values using the given Eq. (4):

$$C_a = \frac{d_a^-}{d_a^+ + d_a^-} \quad (4)$$

where C_a – coefficient of relative proximity; d_a^+ – distance from the positive ideal solution; d_a^- – distance from the negative ideal solution.

The relative closeness coefficient ranges from zero to one, with a higher value indicating a more favourable alternative that can be regarded as more sustainable.

The values are subsequently employed to ascertain both positive and negative ideal values, which are then utilised to derive the relative proximity coefficient. A graph is used to illustrate the relative closeness coefficient in order to facilitate the analysis of the results.

Sensitivity analysis

After TOPSIS multi-criteria analysis, sensitivity analysis was performed to determine criteria stability. The sensitivity study illustrates how much the TOPSIS performance of each alternative changes when the criterion weight is altered. A matrix was developed for each criterion to display the relative proximity coefficient of each choice when the weighting is altered. The overall weighting of all criteria should be one, as specified. This means that modifying the weighting of one criterion distributes the remaining weighting value evenly among the remaining nine criteria. The weighted value of each criterion was changed from 0.1 to 0.9 in stages of 0.1. Eq. (5) determined the weighting of the remaining criteria, subtracting the criterion's value from one and dividing it by ten, which is the number of criteria. Thus, the remaining weighted value is spread equally among the criteria.

$$w = \frac{1 - w_0}{10} \quad (5)$$

where w – weight of each remaining criterion; w_0 – weight of sensitivity analysis criterion.

After the sensitivity analysis, graphics are constructed using the modified matrix of each criterion to demonstrate how the results ranking of the alternatives change due to the adjustment of criteria weights. According to the sensitivity analysis, the most suitable outcome has the most upward curves and adjusts well to criteria adjustments. The number of upward curves for each choice was deducted from the number of downward curves. The best option has the highest numerical result.

RESULTS AND DISCUSSION

Weights of criteria

The results obtained from the questionnaire were calculated to give the criteria weights. The results are shown in Table 2. The weights for each criterion were established using a questionnaire-based method, and the sum of all criteria weights is 1.

Table 2. Weights for criteria

Number of criterion	Criterion	Unit of measure	Weight
C1	Average biomethane yield	NmL $L_{material}^{-1}$	0.125
C2	Water retention %	%	0.084
C3	Energy for the production of the material	°C	0.102
C4	Raw material costs	EUR m^{-3}	0.112
C5	Material availability	t $year^{-1}$	0.101
C6	Source of the material	Points 0–1	0.091
C7	pH	0–14	0.099
C8	External porosity	%	0.099
C9	Bulk density	kg m^{-3}	0.081
C10	Specific surface area	m^2 m^{-3}	0.105

The average biomethane yield was given the highest weight of 0.125, reflecting its crucial role in determining the overall success of the material.

Analysis of TOPSIS Results

The results of the TOPSIS multi-criteria analysis calculations carried out to assess the materials for biomethanation against the stated are shown in Fig. 3.

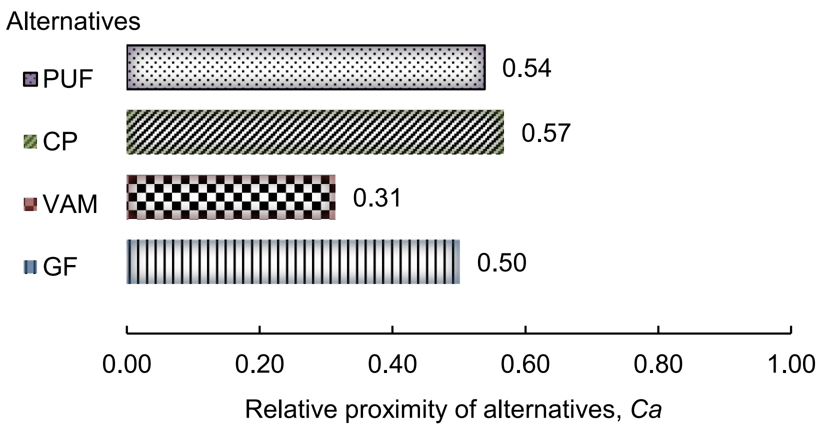

Figure 3. TOPSIS analysis results. The relative closeness coefficient ranges from zero to one, with a higher value indicating a more favorable alternative. PUF – polyurethane foam; CP – expanded clay pellets; VAM – vulcanised ash material; GF – glass foam.

Based on the coefficient of relative proximity values as shown in Fig. 3, it is evident that expanded clay pallets and polyurethane foam are the closest to the ideal result.

Among these alternatives, expanded clay pallets have a coefficient of 0.57, indicating that they are the most suitable carrier material for biomethanation according to the given criteria. However, it should be noted that the relative coefficient values are similar for two other alternatives – polyurethane foam and glass foam material. The value of PUF differs from CP by only 0.03, and GF comes in third, differing from CP by 0.07. The results show that the alternatives or materials whose values are closest to the ideal result. This means that polyurethane foam has good properties as a carrier material for ex-situ biomethanation. Nevertheless, it is evident that the values for glass foam products and clay pallets are very similar to those for PUF. This implies that the hierarchy of alternatives in the sustainability evaluation may fluctuate as the materials and their manufacturing methods progress.

Results of Sensitivity analysis

A criterion sensitivity analysis was conducted for all criteria within each aspect category to enhance clarity on the results. This analysis facilitated comprehension of the extent to which each criterion impacted the study's overall findings. By analysing several weight allocations for each criterion, the key parameters that have the most influence on determining the outcomes were successfully identified. The thorough examination improved the strength and dependability of conclusions, resulting in a more comprehensive comprehension of the research outcomes. Figs 4–13 show changes when criteria weights are changed and which alternatives have upward curves. Understanding the significance of these criteria enables the consideration of modifying materials and their parameters to better align with the selected application. If the criteria values may be enhanced to approach ideal values, the results will vary appropriately.

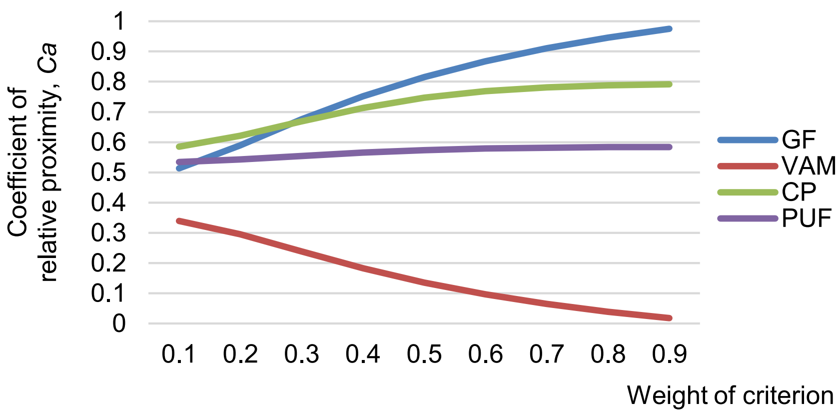

Figure 4. C1 – Changes in results by changing the weight of biomethane yield from 0.1 to 0.9 in stages of 0.1.

Figs 4 and 5 display the graphs of the alterations in the performance criteria. Fig. 4 illustrates the impact on results when the weighting of the biomethane yield criterion is altered, while Fig. 5 demonstrates the effect of changing the weighting of the water retention criterion. While the change in the relative proximity coefficients varies for all options, it is evident that the glass foam results increases for both criteria. This demonstrates that glass foam has the potential to be feasible option.

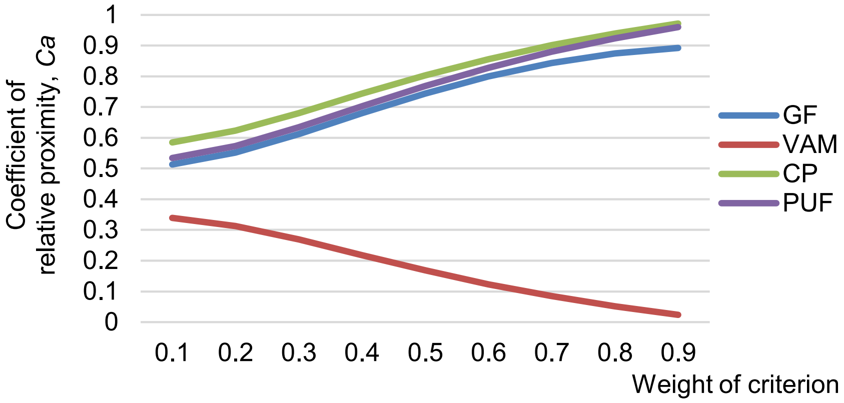

Figure 5. C2 – Changes in results by changing the weight of water retention from 0.1 to 0.9.

By increasing the criterion weighting of raw material costs value of expanded clay pellets decline dramatically (Fig. 6). However, by increasing the weight of material availability, the relative closeness coefficients of all alternatives drop, except expanded clay pellets (Fig. 7).

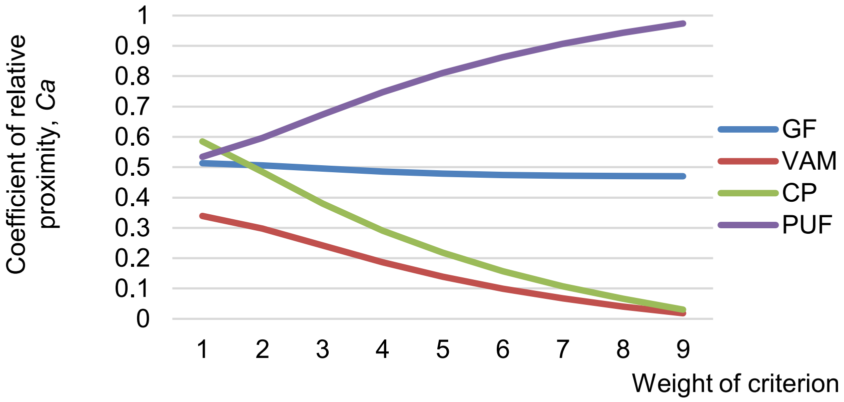

Figure 6. C3 – Changes in results by changing the weight of raw material costs from 0.1 to 0.9.

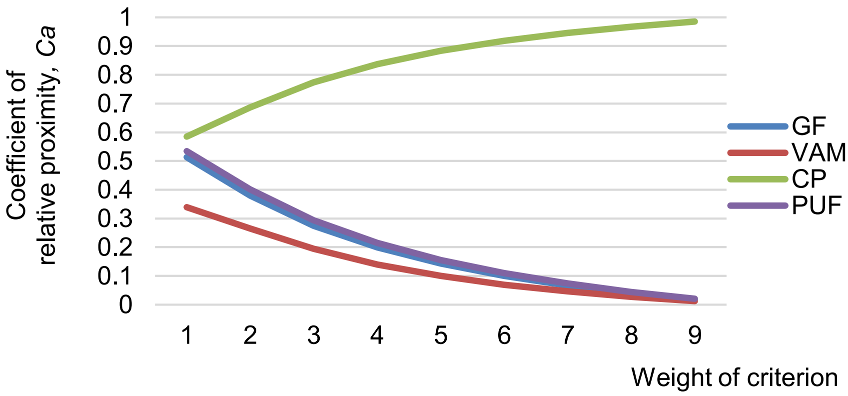

Figure 7. C4 – Changes in results by changing the weight of material availability from 0.1 to 0.9.

Reducing the importance of weight of energy for production of the material (as shown in Fig. 8) decreases the value all alternatives except polyurethane foam. The opposite results occur if the weight of source of material is increased (Fig. 9). The relative closeness coefficients of all alternatives drop, except polyurethane foam.

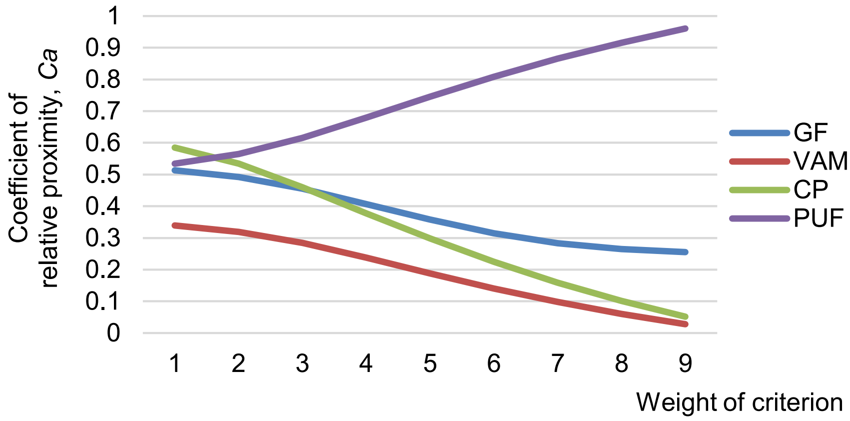

Figure 8. C5 – Changes in results by changing the weight of energy for production of the material from 0.1 to 0.9.

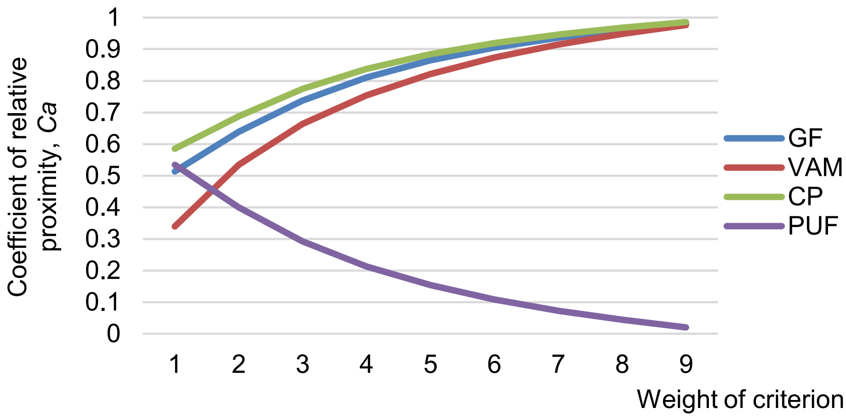

Figure 9. C6 – Changes in results by changing the weight of source of material from 0.1 to 0.9.

Figs 10–13 show changes in ranking alternatives if different technical criteria weights are changed. By increasing the weights of pH value, external porosity, bulk density, and specific surface area, polyurethane foam value increases, while vulcanised ash material decreases dramatically for all these criteria. These technical parameters could be improved for some of these materials in development.

Based on the sensitivity analysis, the optimal outcome shows the highest number of upward curves and demonstrates a strong ability to adapt to alterations in criteria. The number of positive curves for each option was subtracted from the number of negative slopes in Figs 4 to 13. The optimal choice has the greatest numerical outcome. This numerical outcome suggests that the optimal choice is most flexible and capable of promptly adjusting to variations in the weights assigned to different criteria.

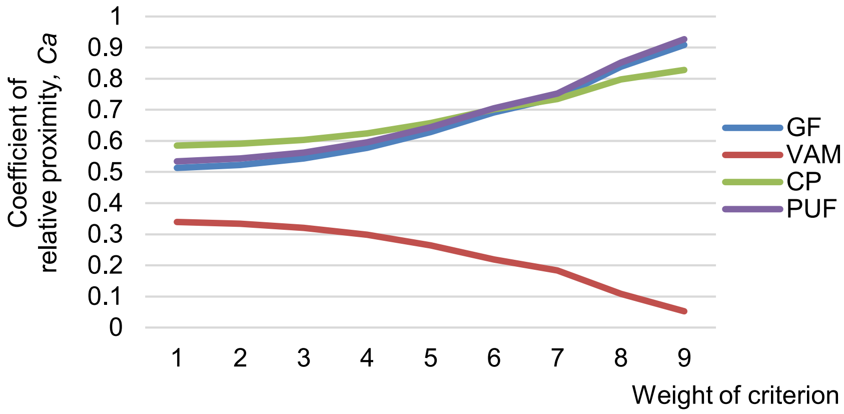

Figure 10. C7 – Changes in results by changing the weight of pH value from 0.1 to 0.9.

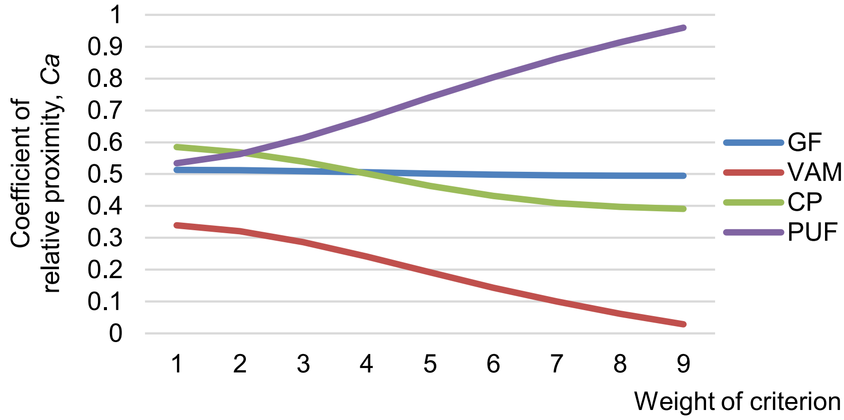

Figure 11. C8 – Changes in results by changing the weight of external porpsity from 0.1 to 0.9.

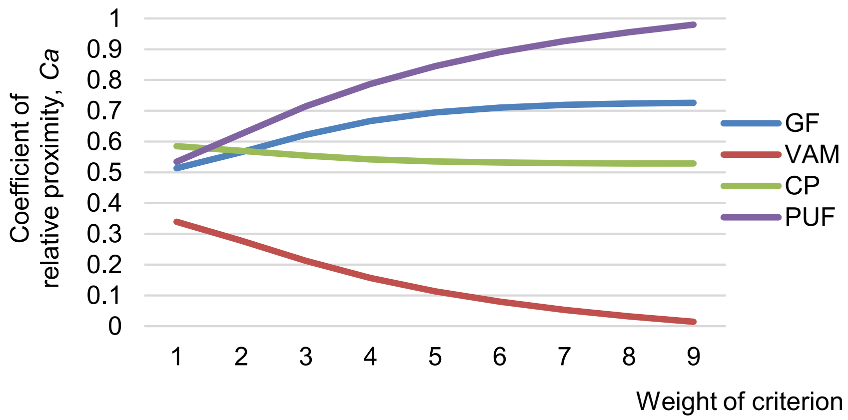

Figure 12. C9 – Changes in results by changing the weight of bulk density from 0.1 to 0.9.

Based on the sensitivity analysis, the optimal outcome shows the highest number of upward curves and demonstrates a strong ability to adapt to alterations in criteria. The number of positive curves for each option was subtracted from the number of negative slopes in Figs 4 to 13. The optimal choice has the greatest numerical outcome. This numerical outcome suggests that the optimal choice is most flexible and capable of promptly adjusting to variations in the weights assigned to different criteria.

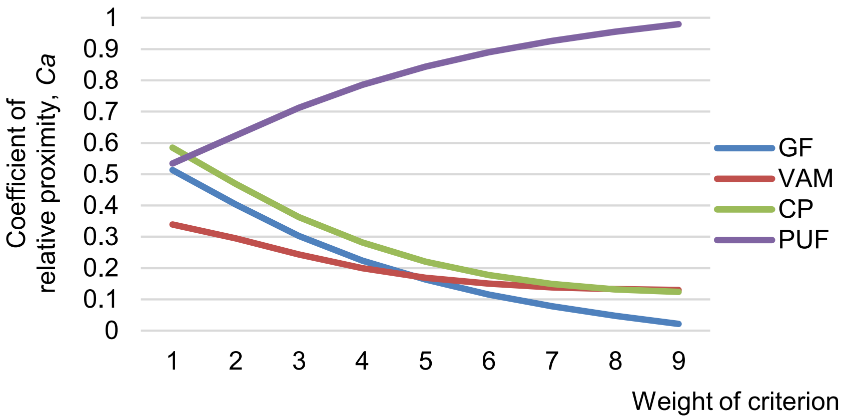

Figure 13. C10 – Changes in results by changing the weight of specific surface area from 0.1 to 0.9.

The sensitivity analysis results in Table 3 provide valuable insights into the performance of each alternative material. Polyurethane foam emerges as the top choice based on the number of upward curves and margin scores. Following closely behind are glass foam and expanded clay pellets, both showing promising results.

Table 3. Sensitivity analysis results

	Glass foam	Vulcanised ash material	Clay pellets	Polyurethane foam
Number of upward curves	4	1	4	8
Number of downward curves	6	9	6	2
Margin	-2	-8	-2	6

However, vulcanised ash material falls short in comparison, indicating that improvements are necessary in technical and performance aspects for it to be considered a viable option.

CONCLUSIONS

As part of a systematic decision-making approach, a multi-criteria decision analysis and the Technique for Order of Preference by Similarity to Ideal Solution method are used in this study to determine which of the chosen materials would be a better solution for biotrickling filter reactors used for ex-situ biomethanation. According to the coefficient of relative proximity values, it is clear that expanded clay pallets and polyurethane foam are the most similar to the ideal solution. CP have a coefficient of 0.57, which makes them the most appropriate carrier material for biomethanation based on the specified parameters. The disparity between PUF and CF is 0.03, while GF, ranking third, deviates from CP by 0.07. Among the four selected options, the PUF yields the most favorable outcomes in sensitivity analysis, showcasing its robust capacity to adjust to changes in criteria weights. However, GF, made from recycled glass, also demonstrates exceptional performance. Glass foam can be considered an innovative concept for use as a carrier material for biomethanation. Furthermore, glass foam exhibits excellent properties such as high porosity, good thermal insulation, and low density, making it an ideal choice for biotrickling filter reactors. The utilisation of waste materials in ex-situ biomethanation, where it serves as a carrier material, not only enhances the overall efficiency of the process but also promotes sustainable practices. Moreover, the innovative quality of glass foam highlights the possibility of generating value from otherwise discarded resources following the ideas of a circular economy. Hence, due to its advantageous attributes and positive environmental impact, glass foam presents itself as an appropriate solution for biotrickling filter reactors.

Several undesirable characteristics and factors hinder using vulcanised wood ash as a filter material for biomethanation purposes. However, it is now undergoing development and can be enhanced to meet the requirements of biomethanation technology better. The vulcanised wood ash material has the potential to be selected for biomethanation by enhancing specific values. For instance, altering the pH value can improve microorganism growth and biomethane yield. Adding foaming agents can lead to changes in porosity, increasing specific surface area. This enhances the efficiency of the material. With further research and development, vulcanised wood ash material also has the potential to become a highly efficient and sustainable solution for biomethanation processes. Developing and improving innovative materials such as vulcanised wood ash and glass foam offers the possibility to reuse wood ash waste and waste glass for biomethanation purposes.

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